

Standardization of Distributed Energy Storage Systems Sizing In a Probabilistic Context

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Abstract—This paper questions the sizing standardization of small scale energy storage systems in a context of high penetration of renewable energies and non-deterministic load within the power grid. The future electrical grid is more precarious than the classic one by many reasons, inter alia, abrupt meteorological variations are hard to predict. Therefore, the geographic expansion beside high penetration of renewables certainly enhance the grid viability. Furthermore, the employment of energy storage systems, to mitigate the intermittence of renewable energy output and uncertainty of the load, is necessary, however, storage is conditioned by the randomness of the two aforesaid outputs. Although the difficulties, once the randomness is decently defined, the overall system is more secure. Accordingly, our procedure, then, evaluates a standard probabilistic sizing by including probabilistic calculations and applying the central limit theorem in order to achieve more standard results which increase the system scalability and efficiency. Finally, simulations with historical real data was used to run a numerical case.

Keywords—Energy storage, Renewable energy sources, Sizing, Standardization, Uncertainty.

NOMENCLATURE

Acronyms

c.d.f	Cumulative distribution function
CLT	Central limit theorem
ESS	Energy storage system
p.d.f	Probability density function
PSP	Probabilistic Sizing Procedure
r.v.	Random variable
RES	Renewable energy source

Indices

mis^+	Index for positive power mismatch, Charging power for the ESS
mis^-	Index for negative power mismatch, Discharging power for the ESS
L	Index for the Load power.
mis	Index for the mismatch power.
re	Index for the RES power.
st	Index for Storage
t	Index for time.

Variables

Δt	Length of time interval in hours
$\mathcal{N}(\mu_X, \sigma_X^2)$	Normal Distribution with mean μ_X and variance σ_X^2
\bar{E}_n	Standard energy rating
\bar{P}_n	Standard power rating
\bar{X}	The sample mean of the random variable X
E	Energy
F_X	c.d.f of the r.v. X
f_X	p.d.f of the r.v. X
P	Power
T	Number of time intervals in the operating window
t	Time variable (discrete or continuous)

I. INTRODUCTION

The adverse prevailing energetic conditions have urged the world to consider renewable energy resources as an inevitable alternative. Renewable energy is collected from natural resources which are naturally restored such as sunlight, wind, tides and geothermal heat. The data generated by [1] shows a dominance of Hydropower technologies with a total installed capacity of 1.02 TW in 2015, followed by Wind technologies (420 GW) and then Solar ones (223 GW). However, solar and wind powers abide by an increasing pattern of total installed capacity which might be octuplicated by 2030. Despite the attention favoring high penetration of these two resources, their randomness and intermittence negatively impact stability, reliability and security of the power grid. This impact has furthered energy storage systems (ESS) to be integrated in operations, planing and scheduling of the future grid with various technologies such as Hydro pump stations with a total rated power worldwide of 18.9 GW in 2015, Thermal Storage (2.1 GW), Electro-chemical (0.8 GW), and Electro-mechanical storage (0.2 GW) [2]. The purpose of ESS is to store energy in base-load hours, and supply it in peak-load hours. Drawn benefits from this energy concession are unquestionable whether for active or reactive power management within the grid [3]. When ESS supplies active power, they serve to mitigate power fluctuations, frequency variations, and improve the dispatchability of RES, also, while supplying reactive power, the voltage profile is more stable.

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High penetration of renewable energy resources is ubiquitously becoming unavoidable. Besides, distributed configurations have taken a major place along this grid metamorphosis, a rewarding yet challenging configuration [4] due to renewable energy intermittence, reverse power flows, voltage rise and effects on protection systems. Therefore, combining high penetration of small scale RES-ESS plants is strenuous [5] since the feasibility of this scheme is still questionable and distributed control strategies are not standardized. To lessen these difficulties, the foremost investigation is to properly assess each effect in order to find optimal solutions. Hence, this paper concern is to measure the intermittence effect on sizing energy storage for renewable energy and to standardize this process.

The last two decades have witnessed a considerable literature on sizing procedures of energy storage for renewable energy. ESS sizing methods can be mainly categorized as (i) time domain approaches and (ii) frequency domain approaches. In [6], authors proposed an optimal design and management of a residential PV-Battery system in which the sizing procedure is given by minimizing the daily electric bill, this design included degradation of the system performances too. In [7], the distributed configuration had been induced and compared to the aggregate one as to minimize the total microgrid expansion planning cost. This perspective showed that the number of ESS in a distributed configuration affects the grid cost on different levels which stressed disadvantages in [8]. Similar studies lay distributed ESS in a critical position requiring more consideration. A frequency method was proposed in [9] to find an optimal ESS size to lessen fluctuations of wind energy in high penetration context.

Notwithstanding this spotlight, most researchers have focused on steady state and deterministic analysis and depreciated the dynamic and probabilistic behavior of renewable energy and load which result in the ESS behavior. Presumably, the shortage of data as well as properly definite models of load and renewable energy outputs have had the major role in this research gap, which is not to say that no analysis has been conducted for this purpose. For instance, in a probabilistic extent, authors of [10] present a heuristic probabilistic-based PV and ESS sizing tool according to historical load data to give a clear comparison of the sizing possibilities. Also, [11] provides new tools to stochastically optimize the size of ESS including forecast errors of the RES and assuming a predictive control of the model. Furthermore, oversimplified ESS models have been usually considered, thus, drawn conclusions might lack in accuracy. Recent studies have started to include more sophisticated features such as degradation and ESS lifetime.

In this paper, we have brought our attention to intensely distributed configuration of RES-ESS. Since climatic conditions, e.g. solar radiance, wind speed, temperature and so forth, change as the location changes, we have reevaluated the

geographic disposition of renewable energy within a scaled-down area. Results showed that the grid responses smoother to abrupt climatic variations. In this scope, we introduced storage systems without specifying their types as long as we focused only on the sizing procedure. ESS are sized according to the required active and reactive powers which correlatively respond to the uncertainties of the load and the RES. Hence, the sizing should involve probabilistic features in order to reach more accurate results. Generally, ESS sizing in literature is based on investigating the optimal size regarding operation and economic constraints through a deterministic day-ahead unit commitment including renewable energy and storage units. Herein, we adopt a similar approach with respect to the random behaviors of load and renewable energy to assess the ESS uncertainties. This assessment is done using the central limit theorem CLT as the configuration contains a large number of components to model the energy and power ratings of a storage system, no optimal size is sought in this paper. The probabilistic sizing procedure PSP is meant to identify the size of the standard ESS.

The rest of the paper is organized as follows: Section II presents a brief data analysis and describes the configuration, Section III elaborates the PSP to emphasize the lack in accuracy in deterministic sizing procedures. Section IV provides numerical results of a configuration of ten distributed RES-ESS micro-plants, thence, the paper is concluded in Section IV.

II. CONFIGURATION DESCRIPTION

A. Data analysis and problem statement

Distributed configurations are greatly advantageous for the future grid. Indeed, many existing applications are motivated by this configuration, for instance, control systems have been recently based on distributed and decentralized technologies. Similarly, the aforesaid configuration cannot be less than beneficial to improve the grid reliability and resiliency. Small-scale generators have been widely investigated and incrementally implemented worldwide. In this paper, dense embedment of RES and ESS is investigated. This scheme is illustrated in Fig.1 and interpreted as the massive implementation of RES and ESS within the microgrid/grid.

The idea behind this concept is threefold: i) unexpected and unpredictable meteorological variations are local, then, the wider is the grid, the more controllable are these variations Fig.2, ii) the grid is conveniently expandable, and iii) it includes the novel economic image of the power grid market.

Fig.3 compares real output powers generated from five Photovoltaic sources and their sum over a day. The RESs are identical in terms of their type, specifications, and size, also, they are closely located in California, USA. The curves are derived from real data [12] and show that small scale plants inter-balance such that the sum is smoothed and variations are less acute. In particular, losses are less intense in this scheme since the RES-ESS plants are embedded

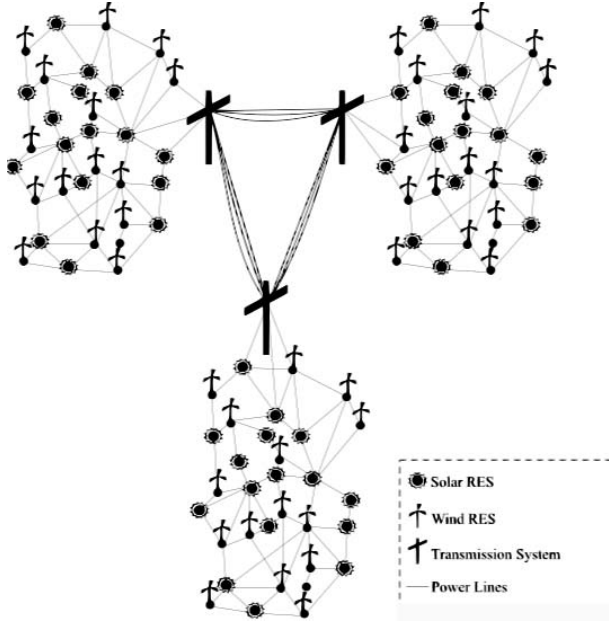


Fig. 1: Densely embedded configuration of RES-ESS micro-plants in a meshed network of three areas (Interconnected Microgrids)

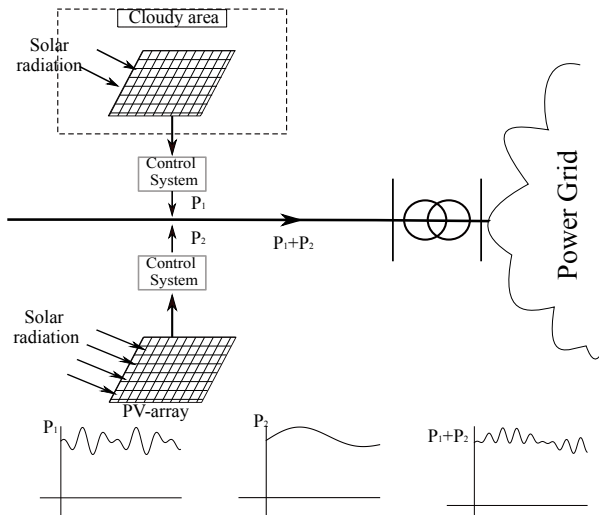


Fig. 2: Illustration of the geographical expansion of the grid impact on renewable energy output abrupt variations: a case of two PV generators located in two different areas

beside the loads if not exactly at the load points. Thus, as abrupt climatic variations might occur locally and affect only several generation points, or at least, slowly the overall system; a densely embedded configuration is favorable to mitigate abrupt variations of the RES. Nevertheless, RES are insufficient to completely meet the grid demand, embedding the system with ESS is still mandatory. This embedding should be done accordingly to the RES configuration which is significantly high distributed. Our goal is to evaluate the

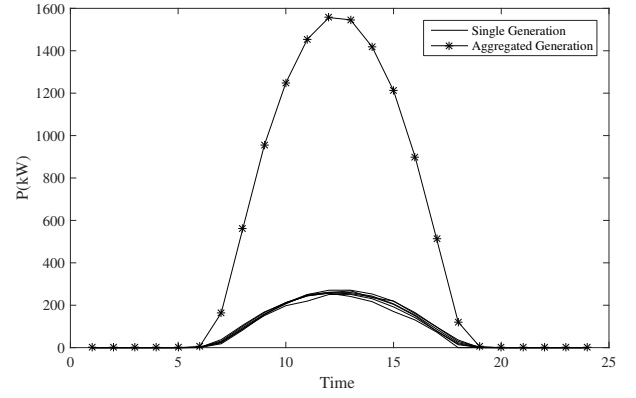


Fig. 3: PV output power of five identical and closely located stations in California and their aggregate output power

various system parameters in this new scheme. The first considered issue herein is the sizing of storage units.

The Density N denotes the number of micro-plants in the grid. As the grid is assumed to hold a large number of micro-plants ($N \rightarrow \infty$) which they are random, independent and unnecessarily identical, it is legitimate to apply the central limit theorem and cut down the study to the sample mean \bar{X} , where X denotes the random variable associated to the considered metric.

$$\bar{X} = \frac{1}{N}(X_1 + X_2 + \dots + X_N) \quad (1)$$

$\{X_1, X_2, \dots, X_N\}$ are the observations gathered from each micro-plant. The sample mean portrays the standard ESS.

B. Sample Mean: Standard unit

1) Assumptions and Notations:

Hereafter, E in (kWh) is the electrical energy transferred at the rate P to which is associated with:

$$E(t) = \int_{t-\Delta t}^t |P(\tau)| d\tau \quad (2)$$

P denotes then the electric power in (kW), it is positive when it is generated and negative when consumed.

To simplify, variables are assumed to remain constant for the given period Δt . The power would be seen then as a linear function of E . Hence:

$$E(t) = |P(t)| \cdot \Delta t \quad (3)$$

For a continuous random variable (r.v) X , a probability density function (p.d.f) f_X , and a cumulative distribution function (c.d.f) F_X are defined as:

$$f_X(x) = \frac{d}{dx} F_X(x) \quad (4)$$

If $X \sim \mathcal{N}(\mu_X, \sigma_X^2)$, then X has a normal distribution with the mean μ_X and variance σ_X^2 . Its p.d.f is f_X and c.d.f is F_X :

$$\begin{aligned} f_X(x) &= \frac{1}{\sqrt{2\pi\sigma_X^2}} e^{-\frac{(x-\mu_X)^2}{2\sigma_X^2}} \\ F_X(x) &= \frac{1}{2} \left[1 + \operatorname{erf} \left(\frac{x - \mu_X}{\sqrt{2\sigma_X^2}} \right) \right] \end{aligned} \quad (5)$$

Where erf is the error function.

For simplification intentions, dependencies between load and renewable energy outputs are omitted, as well as temporal dependencies among renewable energy outputs.

2) System Modeling:

The study framework consists of N ($\rightarrow \infty$) micro-plants, each one consists of an ESS and RES, an aggregate load is associated to the overall system. The ESS stores energy when the RES outcome is greater than the load, and releases energy when demanded. For each micro-plant i , we define $P_{L,i}(t)$ as the load power and $P_{re,i}(t)$ as the RES output power at time t . The fundamental objective of the grid is to match the load power to the generation, since renewable power and load power are usually mismatched, $P_{mis,i}(t)$ denotes the difference between these two outputs at time t for each micro-plant. As N is large, the central limit theorem is applied to find their sample means $\bar{P}_L(t)$, $\bar{P}_{re}(t)$, and $\bar{P}_{mis}(t)$

$$\forall t \in \{1, 2, \dots, T\} : \quad \bar{P}_{re}(t) + \bar{P}_L(t) = \bar{P}_{mis}(t) \quad (6)$$

Energy ought to be stored in the ESS when $\bar{P}_{mis}(t)$ is positive, RES output is greater than the load, and supplied by the ESS otherwise. ESS size requirements depend mainly on this mismatch.

Given that $\forall t \in \{1, 2, \dots, T\}$

$$\bar{P}_L(t) \sim \mathcal{N}(\mu_{\bar{L},t}, \sigma_{\bar{L},t}^2), \quad (7a)$$

and,

$$\bar{P}_{re}(t) \sim \mathcal{N}(\mu_{\bar{re},t}, \sigma_{\bar{re},t}^2), \quad (7b)$$

we have

$$\bar{P}_{mis}(t) \sim \mathcal{N}(\mu_{\bar{re},t} + \mu_{\bar{L},t}, \sigma_{\bar{re},t}^2 + \sigma_{\bar{L},t}^2), \quad (7c)$$

where,

$$\begin{aligned} \mu_{\bar{X}} &= \frac{\sum_{i=1}^N \mu_{X_i}}{N}, \\ \sigma_{\bar{X}}^2 &= \frac{\sum_{i=1}^N \sigma_{X_i}^2}{N}, \end{aligned} \quad (7d)$$

are the mean and the variance of the sample mean for each r.v X , X stands for re , L and mis .

III. PROBABILISTIC SIZING PROCEDURE

Two parameters are needed for each random variable which are the mean and the variance, appropriate weather and load data are then required for better results. The so-called typical meteorological year (TMY) is a collation of weather data for a specific location, generated from a data bank which is longer than one year. Its purpose is to present the range of weather conditions for the location in question such as solar radiation, wind speed, temperature and so forth which are consistently averaged according to many years. Means and variances of each r.v. are then drawn from this meteorological model in order to find the distribution of each r.v.

A. Renewable Energy Source

Several methods are used for sizing Renewable energy sources. For probabilistic methods, a simulation tool is used to generate the TMY corresponding to the desired location, after selecting the desired module, generation values are derived according to the module specifications, such as the short circuit current, open circuit voltage, and so forth. In this paper, only photovoltaic PV sources are considered.

Generally, the most straightforward procedure to size a PV source are designed for the steady state. This procedure consists on dividing the annual energy consumption in kWh by 365 (days per year) to find the average daily consumption, then divide by the average of peak-sun hours which is assumed to be 5.5 hours per day as PV modules collect energy only during these hours. Finally, the PV array size is given after taking into account the efficiency of modules. This size is given to a simulation tool to provide its hourly generation along one year using TMY for meteorological conditions.

B. Energy Storage System

To size the standard ESS, two main characteristics are sought, the standard power rating \bar{P}_n in (kW) which is the highest input power allowed to flow through the ESS, and the standard energy capacity \bar{E}_n in (kWh) which is the highest amount of energy that can be charged in or discharged from the ESS. These characteristics ought to be found for the ESS sample mean using the CLT.

The r.v $\bar{P}_{mis}(t)$ is decomposed into the difference of its positive and negative parts:

$$\bar{P}_{mis}(t) = \bar{P}_{mis}^+(t) - \bar{P}_{mis}^-(t) \quad (8a)$$

where

$$\bar{P}_{mis}^+(t) = \max\{P_{mis}(t), 0\} \quad (8b)$$

and

$$\bar{P}_{mis}^-(t) = \max\{0, -\bar{P}_{mis}(t)\} \quad (8c)$$

which are not, in general, independent. The negative part denotes the discharging power whose c.d.f is $F_{mis^-,t}$, while the positive part, with a c.d.f $F_{mis^+,t}$ indicates the charging power.

By definition we have:

$$F_{mis^+,t}^-(P) = \mathbb{P}(\bar{P}_{mis}^+(t) < P) \quad (9a)$$

Which leads to:

$$F_{mis^+,t}^-(P) = \mathbb{P}(\bar{P}_{mis} \leq P, 0 \leq P) \quad (9b)$$

Hence:

$$F_{mis^+,t}^-(P) = \begin{cases} 0 & \text{if } P < 0; \\ F_{mis,t}^-(P) & \text{otherwise.} \end{cases} \quad (9c)$$

Also:

$$F_{mis^-,t}^-(P) = \begin{cases} 0 & \text{if } P < 0; \\ 1 - F_{mis,t}^-(P) & \text{otherwise.} \end{cases} \quad (9d)$$

Where $F_{mis,t}^-$ is the c.d.f of the r.v. $P_{mis}(t)$.

1) *Energy Rating Sizing*: The stored energy level in the ESS \bar{E}_{st} is given by the following iterative equation:

$$\forall t: \quad \bar{E}_{st}(t) = \bar{E}_{st}(t-\Delta t) + \eta_c \cdot \Delta t \cdot \bar{P}_{mis}^+(t) - \eta_d \cdot \Delta t \cdot \bar{P}_{mis}^-(t) \quad (10)$$

Where η_c and η_d are the charging and discharging efficiencies respectively. If $\eta_c = \eta_d = \eta$ and $E_{st}(0) = E_{min}$, the cumulative energy at the time t is:

$$\bar{E}_{st}(t) = \bar{E}_{min} + \eta \cdot \Delta t \sum_{\tau=1}^t \bar{P}_{mis}(\tau) \quad (11)$$

And this r.v has a normal distribution:

$$\bar{E}_{st}(t) \sim \mathcal{N}(\bar{E}_{min} + \eta \cdot \Delta t \cdot \sum_{\tau=1}^t \mu_{\bar{E},\tau}, \eta^2 \cdot \Delta t^2 \cdot \sum_{\tau=1}^t \sigma_{\bar{E},\tau}^2) \quad (12)$$

The system is decently sized if and only if $\bar{E}_{st,t}$ does not attain negative values.

The energy rating is the maximum capacity which could be held by the ESS:

$$\bar{E}_n = \max_{t \in \{1, \dots, T\}} \{\bar{E}_{st}(t)\} \quad (13)$$

If $F_{\bar{E}_n}$ defines the c.d.f of the standard energy rating \bar{E}_n , it is expressed then by definition as in:

$$F_{\bar{E}_n}(E) = \mathbb{P}(\bar{E}_n = E) \quad (14a)$$

Accordingly:

$$F_{\bar{E}_n}(E) = \mathbb{P}(\bar{E}_{st}(1) < E, \dots, \bar{E}_{st}(T) < E) \quad (14b)$$

Which leads to:

$$F_{\bar{E}_n}(E) = \mathbb{P}(\bar{E}_{st}(1) < E) \times \dots \times \mathbb{P}(\bar{E}_{st}(T) < E) \quad (14c)$$

Finally:

$$F_{\bar{E}_n}(E) = \prod_{t=1}^T F_{\bar{E}_{st}(t)}(E) \quad (14d)$$

Where $F_{\bar{E}_{st}(t)}(E)$ is the c.d.f of the cumulative energy at time t defined in (12) and given by (5).

TABLE I: Locations and stations IDs

Location	Station ID
Arcata	24283
Bakersfield	23155
Camarillo	723926
Dagget	23161
Fresno	93193
Imperial	747185
Los Angeles	23174
Sacramento	23232
San Diego	23188
Sandberg	723830

2) *Power Rating Sizing*: The second part of the sizing procedure is to determine the standard power rating \bar{P}_n , defined by,

$$\bar{P}_n = \max_{t \in \{1, \dots, T\}} \{|\bar{P}_{mis}(t)|\} \quad (15a)$$

Then,

$$\bar{P}_n = \max \left(\max_t \{\bar{P}_{mis}^+(t)\}, \max_t \{\bar{P}_{mis}^-(t)\} \right) \quad (15b)$$

Where $|\cdot|$ is the absolute value. The distribution of \bar{P}_n can be deduced as follows:

$$F_{\bar{P}_n}(P) = \prod_{t=1}^T F_{mis^-,t}^-(P) \times \prod_{t=1}^T F_{mis^+,t}^-(P) \quad (16a)$$

Finally,

$$= \prod_{t=1}^T F_{mis,t}^-(P) \times \left(1 - F_{mis,t}^-(P)\right) \quad (16b)$$

IV. SIMULATION & RESULTS

This evaluative study was done using real historical data for a photovoltaic PV source and residential loads and run on Matlab. Annual Load and renewable energy data had been taken from System Advisor Model SAM developed by NREL [12].

The purpose of this paper is to measure uncertainties of renewable energy and load on the ESS sizing. This measure allows for having more control on ESS specifications within high penetration context of renewables. The optimal size is beyond the scope of this paper. For the given load, the same module specifications were simulated for ten locations in California, USA Tab. I.

First, hourly data is rearranged so the probability density function of load power and PV power at each hour is to be specified using TMY3 given by [12], then, hourly means and variances are determined for renewable energy and the load. Applying the CLT, the sizing procedure was executed only to the standard ESS (sample mean) in order to find the standard size ESS. Figures. 5 and 4 show wide ranges of possible values for power and energy ratings. For P_n which is the maximum power that could be taken by the ESS whether to charge or to discharge, and by the mismatch of the load to the RES outputs, oscillates between $140kW$ and $280kW$ and averages at $210kW$. Furthermore, E_n range is more important, which

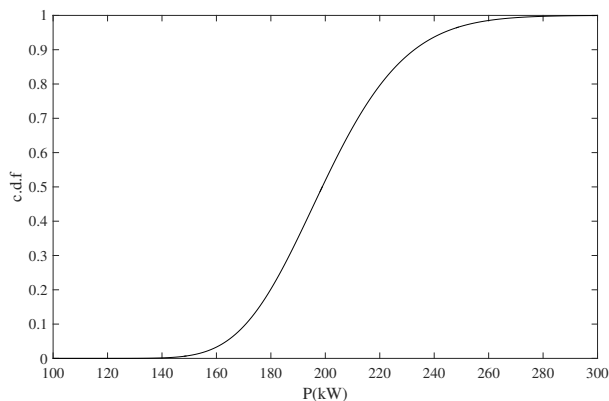


Fig. 4: Cumulative Distribution Function of the standard power rating P_n

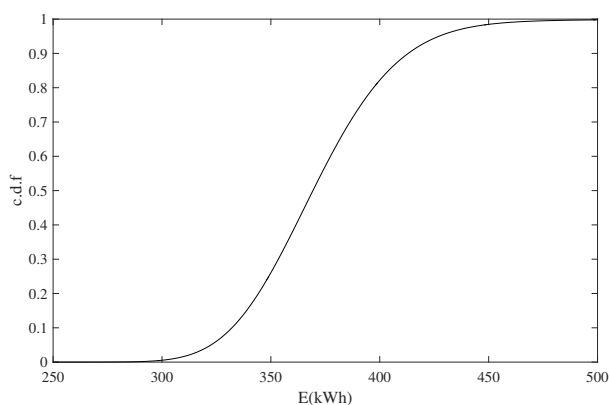


Fig. 5: Cumulative Distribution Function of the standard Energy Rating E_n

is the capacity in kWh of the ESS, and is given between $3000kWh$ and $500kWh$ with a mean of $400kWh$.

As shown by results, high penetration of renewable energies lead to important range of energy and power ratings of ESS. Although, our procedure defines these intermittence effects which is significantly helpful in further operations upon the grid. The application of the CLT is useful since it includes all possible values for RES generation and load in a single model, the study of the sample mean paves the way toward more standardized procedures.

V. CONCLUSION

This paper investigates the densely embedded configuration of RES-ESS for the future grid and presents a straightforward probabilistic procedure of storage sizing within this scope.

Our study highlights two extents: first, the noteworthiness of densely embedding the grid by RES and ESS, and second measuring the impact of high penetration of renewable energy and load randomness on the storage sizing. It can be concluded from this evaluative analysis that the randomness of the sizing process is significant and it should be included for accurate and satisfactory results, although no optimal size was to be found. The application of CLT for similar studies is relevant since it allows to more standardized results, in particular, standardization is the more critical feature of distributed configurations. Therefore, more characteristics could be investigated for the densely embedded configurations of RES-ESS namely for control strategies.

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