Effects of Wind and PV Energy on Optimal Determination of Energy Storage and Spinning Reserve Capacity

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Abstract

Today, there is an ever-increasing tendency towards the use of renewable energy resources due to the depletion of fossil fuels ones. This study presents an approach based on the probability density functions (PDF) of wind speed and solar irradiance level by which different scenarios for the output power of the resources are extracted. Then, the production schedule of power system in the electricity market is developed based on the extracted generated powers. In the next step, the scenario of the use of battery as an energy storage system (ESS) is put forward in order to compensate the uncertainty of the output power of renewables. Consequently, the optimal capacity of the battery is obtained interactively with the market in the form of an optimization problem using differential evolution algorithm (DE). In addition, the use of battery as a no-spinning reserve of system with the aim of reducing the spinning reserve (SR) level of system is evaluated. The proposed method will be tested on a distribution feeder in Wellington, New Zealand and the obtained results will be analyzed.

Index Term

Differential evolution algorithm, Energy storage system, Photovoltaic energy, Spinning reserve, Wind energy.

1. Introduction

Environmental concerns and the ever-increasing demand for energy on the one hand and the increased price of fossil fuel in recent years and the reduction of such resources in the world on the other hand have resulted in the increased use of renewable energy resources such as wind and solar energies.

Power production of wind and solar units depends on the climate condition of the site in which they are installed so that the power produced by the units varies proportional to the wind speed and solar irradiance level. The uncertainty of wind speed and solar irradiance in the site makes it difficult to accurately schedule the power production of renewables. On the other hand, the system operator needs definite productions of the units on hourly basis in order to schedule power production of such resources relying on such data. Despite the uncertainty of the power production of renewables, they have been remained in power system structure and are being utilized due to low operation cost and benefiting from free fuel. In such conditions, it seems necessary to develop a strategy on how to utilize power systems in the presence of traditional power plants and renewable energy-based units with uncertain nature. There are different studies on the presence of renewables, including wind and solar resources, in power system where each study has addressed different aspects of such resources.

There is a comprehensive study in [1] about the economic advantages of adopting very big ESSs in power system in the presence of wind farms. It presents a computer-based model for simulating the behavior of the presence of ESS in a wind farm on Portland, Australia. Ref [2] determines the optimal capacity of a pumped-storage in order to compensate the part of energy not supplied by wind farm. It indicates that pumped-storage hydroelectricity (PSH) has a high capability in solving the problem of energy loss of wind resources. Considering the limitations of financial resources of the system, the study adopted numerical methods to determine the optimal size of turbine and the number of pumps. It discusses three types of ESS: hydro-pump energy storage, compressed air energy storage (CAES) and thermal energy storage (TES). According to results, CAES is the most optimal storage to be connected to and utilized in power systems from economic and dynamical points of view.

Ref [3] discusses the scheduling of battery ESS in order to compensate the power shortage of wind farms and to supply scheduled required power. It uses Monte Carlo simulation to model the variations of output power of wind farms. According to results, battery decreases the occurrence of power outage and reduces the likelihood of load loss to a large extent.

Ref [4] discusses reliability in the presence of wind farms. There are two main factors affecting the reliability of a wind power system: 1) continuous change of wind speed and 2) generator outage. Therefore, Copula was used to model the uncertainty of the dependency of generator outage on the variations of wind speed. In addition, linear probabilistic methods were used to generate different scenarios for reliability models. The obtained results indicate the direct effect of the variation of generated power and generator outage on reliability indices.

Ref [5] introduces a coordinated two-stage control method to decrease the fluctuations of the output power of wind farms using ESS. The main aim of that study is power profile smoothing associated with the power injected to grid.

Ref [6] determines the optimal charging and discharging structure of electric vehicle batteries in order to provide the probability of sustainable generation for photovoltaic

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$$P_{GW} = \begin{cases} 0 & 0 \le VS_i \le V_{cut-in} \quad or \quad VS_i \ge V_{cut-out} \\ P_r(A + B \times VS_i + C \times VS_i^2) & V_{cut-in} \le VS_i \le V_{rated} \\ P_r & V_{rated} \le VS_i \le V_{cut-out} \end{cases} \tag{3}$$

systems. It uses Monte Carlo simulation to repeat scenarios generated by ARMA time series. It is observed that the use of electric vehicle batteries can acceptably decrease the fluctuations of power profile in grid.

Our review reveals that different ESSs have been studied and their optimal capacities have been derived with different purposes. However, there is no study on the joint modeling of spinning reserve and optimal capacity of ESS aimed at decreasing the effect of the uncertainty of the output power of wind and solar resources on the functioning trend of a system.

This paper has been constructed in five sections. Following introduction, section 2 discusses system operation structure and determines optimal capacity of battery and spinning reserve level. Section 3 presents differential evolution algorithm and section 4 presents the results of simulation and numerical studies. Finally, section 5 concludes the paper and provides recommendations for future studies.

2. Modeling Power System Components

A.Modeling output power of wind farms and solar panels

Considering the inherent instability of wind and solar resources, it is not rational to rely on predicted production levels in the process of scheduling the production of such resources because the predicted amounts always go with error. This is why it is not a fit approach for ISO (independent system operator) to use decisive planning methods for scheduling the units and providing acceptable reserve. In this study, we need wind speed and solar irradiance level in the studied region. As the first step, a Weibull PDF is fit on wind speed data.

This function is presented as relation (1) where $c > 0$ and $k > 0$, are scale factor and shape factor, respectively and V stands for wind speed [7].

$$f_v(V) = \frac{k}{c}\left(\frac{V}{c}\right)^{k-1} \exp\left[-\left(\frac{V}{c}\right)^{k}\right] \tag{1}$$

Then, the PDF derived for each hour (hourly PDF) is divided into six parts or six scenarios and the probability of each scenario can be derived from relation (2).

$$prop_i = \int_{VS_i}^{VS_{i+1}} f_v(V)dv, \qquad i = 1, 2, ..., S_N \tag{2}$$

In relation (2), VS_i stands for wind speed at scenario i. Wind speed is converted to its corresponding power using relation (3). Finally, six scenarios will be derived for the wind farm production on hourly basis. P_{GW} stands for power generated at each scenario.

Fig. 1 shows V_{cut-in} , $V_{cut-out}$ and V_{rated} values in the relation (3), P_r is the rated wind power and A, B and C are constants [8].

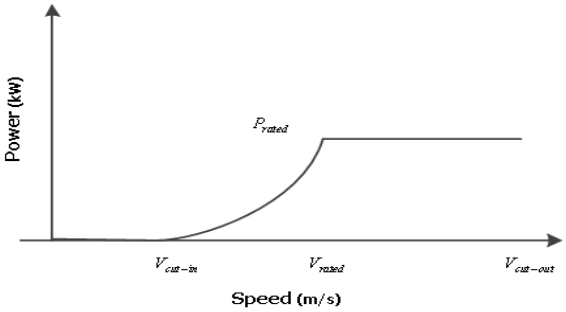


Fig. 1 curve for converting wind turbine speed to its corresponding power

The stochastic scheduling tries to model the stochastic behavior of wind products in the optimization program associated with establishing joint energy and reserve markets. It should be noted that it is assumed that as a task of ISO, wind production level is predicted before market implementation.

In the next step, a beta distribution is fit to solar irradiance in order to model the variations of solar irradiance level in the studied region. Beta PDF is shown as relation (4) [8].

$$f_w(P_w) = \frac{\Gamma(a+b)}{\Gamma(a)\Gamma(b)}\left(\frac{P_{pv}}{P_{pv}^{\max}}\right)^{a-1}\left(1 - \frac{P_{pv}}{P_{pv}^{\max}}\right)^{b-1}$$

$$a = \mu\left[\frac{\mu(1-\mu)}{\sigma^2 - 1}\right] \tag{4}$$

$$b = (1-\mu)\left[\frac{\mu(1-\mu)}{\sigma^2 - 1}\right]$$

μ and σ^2 are mean and variance of changes, respectively. Then, the PDF derived for every hour is divided into 4 parts or 4 scenarios so that the probability of each scenario can be derived from relation (5).

$$prop_i = \int_{WS_i}^{WS_{i+1}} f_w(W)dv, \qquad i = 1, 2, ..., S_N \tag{5}$$

WS_i is solar irradiance in scenario i. Solar irradiance is converted to its corresponding power using relation (6) and eventually four scenarios is derived for the production of solar unit on hourly basis. P_{GPV} is the power generated by each scenario.

$$P_{GPV} = \eta SI(1 - 0.005(t_0 - 25)) \tag{6}$$

η is the conversion efficiency of solar cell arrays in percent, S stands for the cross section area of solar cells in m, I is the solar irradiance intensity in kW/m^2 and t_0 is ambient temperature in ^{o}C.

Roulette wheel mechanism is used, as per Fig. 2, to select PDF-based scenarios [9].

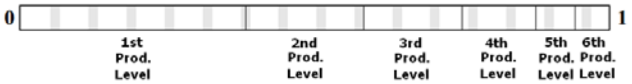


Fig. 2 Roulette wheel to generate a scenario

Naturally, the higher the number of generated scenarios in this step, the wider the covered uncertainty space of the optimization problem. On the other hand, as the number of scenarios increases, the problem becomes more complex and the calculation and running time increases proportionally. Therefore, it is necessary to exclude low-value scenarios from the pool of generated scenarios in order to lower the number of scenarios. This paper uses K-Means technique to lower the number of scenarios and to classify them. Eventually, 10 wind generation scenarios (or models) and 10 solar generation scenarios are formulated for the next 24 hours which will be used in stochastic scheduling process.

A. Modeling the contribution of ESS to energy and reserve market

Different methods have been presented for the role to be played by consumers in power system interactions. Due to their considerable capability in reducing the uncertainty level of power production, ESSs have great potential in facilitating the active contribution of renewable DG resources such as wind and solar units to the interactions of power system. The next section explains the governing equations of the behaviors of ESS.

1) Cost considerations

The addition of an ESS to the grid can absorb or inject active or reactive power in an off-grid manner. Therefore, it can improve setup capacity and economic function of the system. In order to conduct an economic analysis, investment costs, operation costs, maintenance costs and energy purchase costs of ESS should be taken into account.

1.1) Investment costs

The return on capital criterion is a factor to be used for calculating the annual rate of return on capital. The considered term for the return on investment criterion is as per relation (7):

$$C_c(r,n) = \frac{r(1+r)^n}{(1+r)^n - 1} \tag{7}$$

Where *r* is interest rate and *n* is depreciation period over a year [10-12].

ESS investment cost is defined in the form of a function constituted by two main parts: the first part covers storable energy and the second on covers the maximum power to be delivered by ESS. Thus, ESS daily investment cost is defined as equation (8):

$$C_{cap}^{BAT} = \frac{24}{k_i.T_a} C_c(r,n)(C_P P_M + C_W W_M) \tag{8}$$

Where $P_M\,(kW)$ and $W_M\,(kWh)$ are power and energy capacities, respectively and $C_P\,(\$/kW)$ and $C_W\,(\$/kWh)$ are their corresponding specific costs. The number of hours of a day is 24, k_i is capacity factor (investment costs vary proportionally to the installed capacity per kW) and T_a is the number of daily operational hours.

1.2) Replacement cost

ESS replacement cost can be defined as equation (9) [10-12]:

$$C_{rep}^{BAT} = \frac{24}{k_i.T_a}\left(\sum_{i=1}^{L}(C_{rep}^{P}P_M + C_{rep}^{W}W_M)F_{rep}^{BAT} \times SFF(r, L^{BAT}) - \sum_{i=1}^{L} S^{BAT} SFF(r, L_{proj})\right) \tag{9}$$

Where $C_{rep}^{P}(\$/kW)$ is the replacement cost of ESS power capacity, $C_{rep}^{W}(\$/\mathrm{kWh})$ is the replacement cost of ESS capacity, F_{rep}^{BAT} ESS replacement factor, L^{BAT} is ESS life cycle, L_{proj} is project life, SFF is sinking fund factor and S^{BAT} is the scrape value of storage.

1.3) Operation and maintenance costs

ESS hourly operation and maintenance cost is defined in the form of a function constituted by two main parts: the first part is ESS rated power and the second part is hourly discharge energy [12].

$$C_{om}^{BAT} = \sum_{P(t)\neq 0, t=1,2,\dots,24} C_O P_M + \sum_{P(t)=0, t=1,2,\dots,24} C_M W_{hourly} \tag{10}$$

Where $C_0\,(\$/kW)$ and $C_M\,(\$/kWh)$ are the specific operation and maintenance costs, respectively.

A. Joint energy and reserve stochastic scheduling modeling

This section explains the problem-solving model of the joint energy and reserve market scheduling using stochastic optimization along with all details. First, the considered objective function, i.e. the excepted operation cost, is investigated and then constraints for which this function should be minimized are discussed.

1) *Objective function*

The aim of solving join energy and reserve scheduling problem is to minimize system operation cost in the wide presence of solar and wind resources. It should be noted that similar to other units, ESS is taken into account in the objective function and the resources are scheduled stochastically.

The objective function for the use of stochastic optimization model is proposed as equation (11). The first row of this equation shows startup costs and the second row shows spinning reserve cost [13-14]. The third row shows ESS cost and finally the last row shows unintended power outage imposed to consumers and restrictions on wind and solar production.

$$
\begin{aligned}
EC = \sum_{t=1}^{T} \Bigg\{ & \sum_{i=1}^{I} \left(CSU_{it} \right) \\
& + \sum_{i=1}^{I} \left(\pi_{it}^{SR} SR_{it} \right) \\
& + \sum_{d=1}^{NDRP} \left(ESS_{dt} \right) \\
& + \sum_{n=1}^{N} (SC_{Wind}) + (SC_{PV}) \Bigg\}
\end{aligned}
\tag{11}
$$

Where CSU_{it} is the startup cost of unit *i* at hour *t*, *d* is ESS index, NDRP is the number of ESS, *I* is the number of power plants, π_{it}^{SR} is spinning reserve price proposed by unit *i*, SR_{it} is the scheduled capacity of spinning reserve of unit *i* per hour, *N* is the number of busbar of system loads, SC_{Wind} is wind production loss at hour *t* and SC_{PV} is photovoltaic productions loss at time *t*.

2) *Constraints*

The objective function associated with the optimization of stochastic implementation of joint energy and reserve markets problem should be defined in a manner that it does not violate the technical constraints of grid, production units and grid lines.

$$\sum_{i=1}^{I} P_{it} + \sum_{d=1}^{NDRP} P_t^{Wind} + P_t^{PV} = \sum_{n=1}^{N} D_{nt} \tag{12}$$

$$P_i^{\min} z_{it} \le P_{it} \le P_i^{\max} z_{it} \tag{13}$$

$$CSU_{it} \ge \pi_{it}^{SU} \left(z_{it} - z_{i,t-1} \right) \tag{14}$$

$$CSU_{it} \ge 0 \tag{15}$$

$$0 \le SRU_i \le \left(P_i^{\max} - P_{it} \right) z_{it} \tag{16}$$

$$0 \le SRD_i \le \left(P_{it} - P_i^{\min} \right) z_{it} \tag{17}$$

Equation (12) shows the constraint of hourly production-consumption balance throughout the system. The production rate of power plant units should be between the minimum and maximum production rates indicated by equation (13). Constraints (14) and (15) show startup costs of the units [13-14]. Constraints (16) and (17) assure that in the event of joint scheduling of the unit in the energy and reserve market, the maximum and minimum production limits will be observed.

P_{it} is the scheduled power generated by unit *i* at hour *t*, P_t^{wind} is power generated by wind at hour *t*, P_t^{PV} is power generated by photovoltaic system at hour *t*, D_{nt} is demand for busbar *n* load at hour *t*, z_{it} is a binary variable indicating that whether the unit is up or down, π_{it}^{SU} is the startup cost of unit *i* at hour *t*, SRU_i is the maximum spinning reserve rate of unit *i*, SRD_i is the minimum spinning reserve rate of unit *i* and $P_i^{\max/\min}$ is the minimum and maximum production capacity of unit *i*.

Equation (18) gives ESS constraints including the minimum and maximum power generated by the SEE unit. Equations (19) and (20) give the maximum stored energy and the maximum storable energy at excess energy production time, respectively.

$$P_{ESS}^{\min} \le P_t^{ESS} \le P_{ESS}^{\max} \tag{18}$$

$$W_{ESS} \le W_{ESS}^{\max} \tag{19}$$

$$W_{ESS} \le \left(\sum_{i=1}^{N} P_i^{Wind} + P_i^{PV} + SR_{it} \right) t - W_{D_{nt}} \tag{20}$$

Where $P_{ESS}^{\max/\min}$ is ESS minimum and maximum power production rate, P_t^{ESS} is the power generated by ESS at hour t, $W_{ESS}^{\max}$ is the maximum deliverable energy of ESS and $W_{D_{nt}}$ is the energy demand of network at time unit.

A power plant is a mechanical unit. Therefore, the variation rate of the power generated by a unit cannot exceed a given limit. The limits include the maximum increasing change rate and the maximum decreasing change rate, which are considered as follows. In equations (21) and (22), RUR_i and RDR_i are the maximum increasing ramp rate and the maximum decreasing ramp rate, respectively.

$$P_{i,t+1} - P_{it} \le RUR_i \tag{21}$$

$$P_{it} - P_{i,t+1} \le RDR_i \tag{22}$$

In addition, the constraint of the minimum down time and the minimum unit commitment, shown as equations (23) and (24), are considered in this scheduling. In the following equations, MU_i is the minimum up time of unit *i* and MD_i is the minimum down time of unit *i*.

$$\sum_{t'=t+2}^{t+MU_i} \left(1 - z_{it'}\right) + MU_i \left(z_{i,t+1} - z_{i,t}\right) \le MU_i \qquad (23)$$

$$\sum_{t'=t+2}^{t+MD_i} z_{it'} + MD_i \left(z_{it} - z_{i,t+1}\right) \le MD_i \qquad (24)$$

Differential evolution heuristic algorithm is used to solve the optimization problem.

2. Differential Evolution Algorithm

Differential evolution heuristic algorithm (DE) is a heuristic algorithm widely used as a heuristic approach with rapid convergence capability thanks to its special nature and property. This provides a simple, effective and adaptive approach to calculating global optima in continuous and discrete optimization spaces. Fig. 3 shows a schematic view of DE behavior [15].

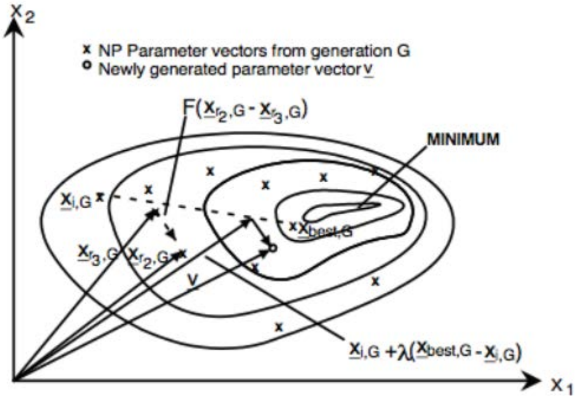


Fig. 3 Schematic view of DE behavior

Fig. 4 shows the general flowchart for DE implementation. This flowchart shows that similar to many other heuristic algorithms, DE uses the same trend and operators including: 1) generation of the initial population, 2) mutation, 3) displacement, 4) selection of the parent vector, 5) selection of survivor for the next generation and 6) stopping condition. Similar to other evolutionary algorithms, DE deals with a set of people. The first version of DE was proposed for solving continuous problems. Then, it was improved and used for solving discrete problems. Like other heuristic algorithms, DE has three main operators: mutation, crossover and selection. In addition, it has three important parameters which are respectively NP (number of population), F (mutation parameter) and CR (crossover).

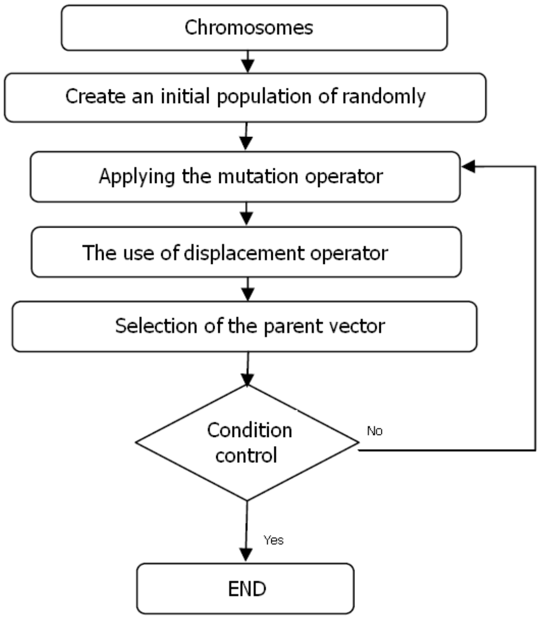


Fig. 4 General flowchart of DE heuristic algorithms

3. Simulation and Numerical Studies

The case study system is a distribution network including domestic and commercial loads. This study assumes photovoltaic systems, wind units with ESS (battery) and DC/AC convertors connected to different points of the grid as available DG resources. Fig. 5 shows the curve of the overall load of network (one year) associated with RFN1102 bus of Wellington in New Zealand [16]. According to this figure, the fluctuation of hourly delivered load in one year is generally between 300 to 450 kW. Fig. 6 shows the load level of the grid in a given day. Annual load level data are necessary for determining the optimal capacity of production resources while daily load level data are necessary for determining the layout of production units. Table 1 and table 2 show technical details of the wind and solar units which are used in this study. Table 3 shows the technical and economic specification of equipment [17].

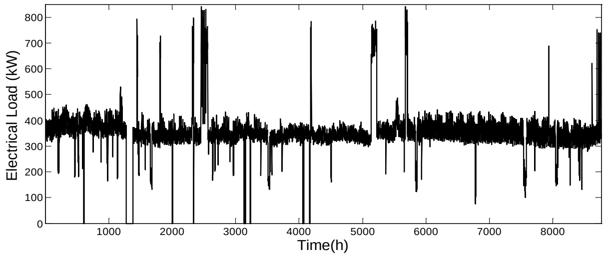


Fig. 5 Annual load level of microgird

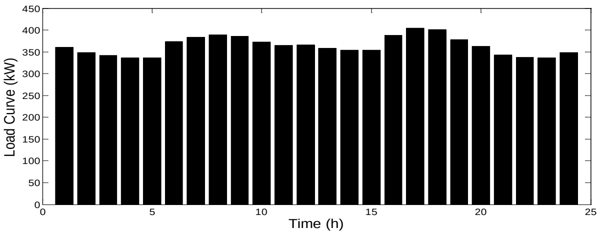


Fig. 6 Variations of microgrid load in a given day

Table 1 Technical specifications of wind unit

	Rated Power (kW)	Nominal Power (kW)	Cut-out Wind Speed (m/s)	Rated Speed (m/s)	Cut-in Wind Speed (m/s)
Wind Turbie	7.5	8.1	25	11	3

Table 2 Technical specifications of solar unit

	Rated Power (kW)	Cross Section (m^2)	Efficiency (%)	Temperature Index (℃)
Solar Panel	5	60	0.9	25

Table 3 Technical and economic specifications of equipment

Equipment	Initial equipment cost (NZD/unit)	Replacement cost (NZD/unit)	Maintenance costs (NZD/unit)
Wind turbine	19400	15000	75
Solar arrays	7000	6000	20
Battery	2000	1500	25
AC/DC converter	800	750	8

The specifications and data associated with the studied battery, including investment costs, operation costs, maintenance costs and technical specifications, were derived from DPRI and DOE 2013 reports about the technical specification of different batteries and ESSs of power system [18]. After extracting the meteorological data of Wellington [19] and studying the annual output power of the studied wind unit, a Weibull distribution is fit to the powers based on the iteration frequency of different output powers. Fig. 7 shows the Weibull distribution where $c = 0.6$ and $k = 3.5$.

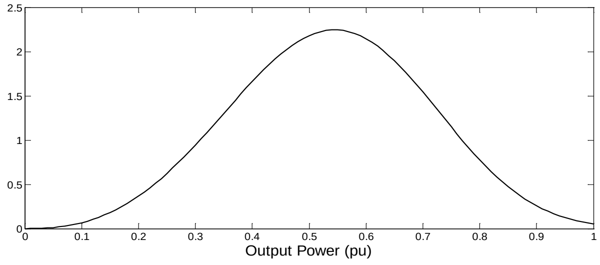
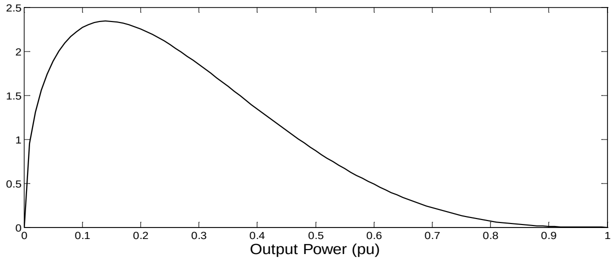


Fig. 7 Weibull distribution associated with the output power of the studied wind unit

In addition, the annual output power of the studied solar unit is studied and a beta distribution is fit to the ouput power of the unit, as per Fig. 8, based on the iteration frequency of different output powers and using curve fitnes technique. Beta distribution parameters are considered to be $a = 1.5$ and $b = 4$. The previously obtained PDFs will be used to determine the output power level of the studied wind and solar units. To this end, for each hour, 8760 samples are randomly selected from PDFs within 365 days. Figures 9 and 10 show the annual ouput power level of the studied wind and solar units, respectively.



Fig, 8 Beta distribution associated with the output power of the studied solar unit

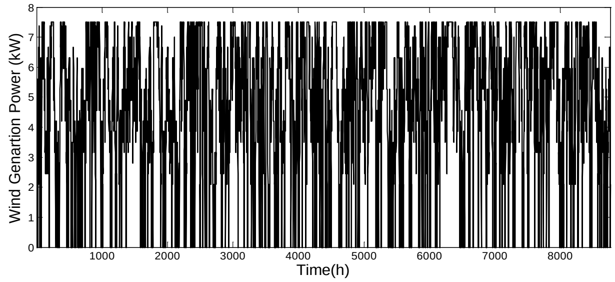


Fig. 9 Available power level of a wind turbine

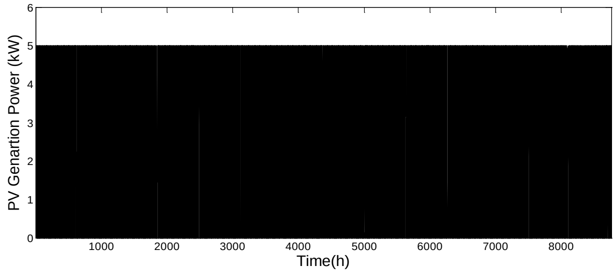


Fig. 10 Available power level of a solar panel

In addition, the studied network is operated interactively with the electricity market and prices are determined based on the instantaneous prices of electricity in the market. Therefore, we need the annual variations of electricity price in the market. The data is derived from New Zealand power market data (Haywards) and is illustrated in Fig. 11[15].

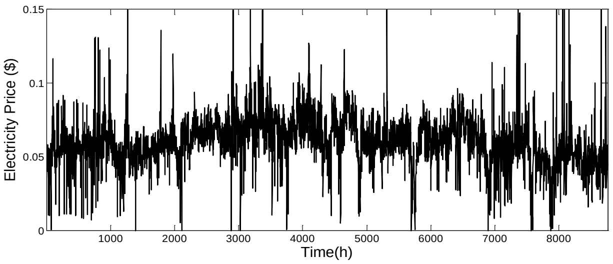


Fig. 11 Instantaneous change of electricity price in the power market

DE algorithm with mutation factor of 0.9 and selection factor of 0.76 is used to optimize the studied problem. In heuristic algorithms, operator factors are being selected empirically based on the problem behavior. The number of each generation members is selected to be 40 and the optimization process is repeated for 3000 times. Eventually, the most expert member with the lowest cost function is selected as the optimal solution. The main aim of this study is to determine the optimal capacity of ESS in order to minimize the effect of the uncertainty of renewables including wind and solar units. To demonstrate the effect of ESS and spinning reserve on the reduction of system uncertainties, four scenarios are studied.

The first scenario assumes that there is no ESS and the operator has allocated no spinning reserve to the system. In this case, the operation cost within 24 hours and the down time cost, induced from power shortage and load curtailment, are calculated and shown in table 4.

Table 4 Operation cost in the case of no ESS and SR

Sources	Scenario 1	Costs (NZD)	Scenario 1
Wind Turbine Unit	29	Equipment	835790
Photovoltaic Unit	37	Income Of Sale	6545
Battery Unit	0	Cost of load curtailment	348480
		Total Cost	1177700

One can observe that in the cases where there is no ESS and spinning reserve, a significant cost is imposed to the network in terms of down time costs which are generally originated from the uncertainty of the output power of wind and solar units.

Before implementing optimization program and determining variations of cost and production layout, it is first necessary to generate scenarios form the PDFs of the wind and solar units. This study extracted 5 highly probable scenarios for every PDF as per tables 5 and 6. Considering all production units, optimization is implemented for each scenario and for hourly load levels using DE heuristic algorithm.

Table 5 Highly probable scenarios for the output power of solar unit

Scenario	1	2	3	4	5
Output Power (kW)	69.39	94.32	64.67	77.08	74.19

Table 6 Highly probable scenarios for the output power of wind unit

Scenario	1	2	3	4	5
Output Power (kW)	117.17	104.6	108.53	114	124.1

Following the implementation of optimization program and determination of optima, it can be observed that photovoltaic system fails to supply power in some hours of a day i.e. from 1 to 6 Am and from 20 to 24 PM due to the lack of sun light. Therefore, the required power of the wind unit is supplied through the battery. The production layout of units are obtained for remaining hours depending on the available power of the production units, especially that of renewable units. In some hours, the required power of solar units is supplied through battery due to low wind speed and consequently low output power of the wind unit.

The second scenario assumes system battery as ESS. First, the optimal capacity of ESS is obtained interactively with the electricity market using introduced objective function which is of cost type. Then, DE is used to solve the optimization problem. Consequently, the optimal capacity of production resources and battery as well as the operation cost is derived as per table 7. It should be noted that since this study aims to design the studied systems, the available wind and solar units have flexible capacities and are adopted in accordance with uncertainty level as well as the selected capacity for the battery.

This scenario lacks any limitation in terms of available cost for determining the optimal capacity of ESS and energy resources and defining the level of contribution to the upper power grid. It can be observed that in this scenario the electricity load is well supplied thanks to the sufficient available capacity and power. Indeed, this scenario lacks any load curtailment and a satisfactory level of energy is sold to upper grid thanks to available excessive power. On the other hand, the presence of ESS improves the performance of system and the system does not experience frequent down times over a year. It can be observed that connecting excess capacity to the units, especially to the solar unit, is an approach to covering and compensating the negative effects of the uncertainty of the output power of renewable units.

Table 7 Optimal capacity and microgrid operation cost in the second scenario

Sources	Scenario 2	Costs (NZD)	Scenario 2
Wind Turbine Unit	50	Equipment	1981000
Photovoltaic Unit	65	Income Of Sale	58683
Battery Unit	225	Cost of load curtailment	27947
		Total Cost	1960300

The third scenario takes load growth and investment limitations into account at the same time. Load growth is an inevitable event in a distribution network and it cannot be accurately predicted. Although it may be possible to predict load growth throughout a power system with an acceptable accuracy, it is impossible to accurately predict the extent to which load growth should be happened in each feeder in order to plan the spread of DG resources across distribution network. Moreover, system operator has a limited amount of annual investment budget and this reduces its maneuver ability. This scenario increased the annual load level by 25% and limited the available budget to 1,500,000 NZD. Table 8 shows the optimal capacity of resources and costs.

The obtained results reveal that the load growth has resulted in a situation in which considering investment limitations the increase of production resource capacity cannot respond load growth. Therefore, the system operator will have no choice to shed the load of consumers. In this case, the microgrid cannot sell power to upper grid due to power shortage and it gains no income in practice. Therefore, operation costs will be duplicated. To solve this problem, either load growth should be avoided, which is impossible in practice, or the available investment budget should be increased to a satisfactory level in order to avoid load curtailment and extreme increase of operation costs.

Table 8 Optimal capacity of resources and microgrid operation cost in the third scenario

Sources	Scenario 3	Costs (NZD)	Scenario 3
Wind Turbine Unit	33	Equipment	1236100
Photovoltaic Unit	45	Income Of Sale	6067
Battery Unit	112	Cost of load curtailment	255040
		Total Cost	1500000

Following the determination of optimal capacities aimed at connecting ESS to the grid and decreasing uncertainty of output powers, one can observe that in the third scenario, due to load growth in microgrid and limitations of investing on connecting further production units and ESS, a part of loads should be shed at hours in which the network fails to supply power.

The 4th scenario uses spinning reserve to cover the uncertainty of the output power of wind and solar units. This scenario calculates spinning reserve based on the values obtained in the third scenario. The objective function of this scenario consists of two components: a) operation cost and b) decreased uncertainty level by adding spinning reserve to the system.

When the layout of production units is determined, system reserve is scheduled and the structure of supplying reserve by the units is defined. Apparently, reserve scheduling is practiced after determining the layout of production units so that the available excess capacity of each unit can contribute to the reserve market. There are generally different approaches to determining required reserve level of the system.

Generally, 10% to 15% of the load of whole network is considered as the reserve load. Accordingly, this study considers 10% of network load per hour as the reserve load and the allocated reserve level is derived in accordance with table 9. Table 9 shows overall operation cost as well as cost associated with the power outage imposed to consumers. It should be noted that equipment investment costs have been excluded from the operation cost indicated in table 9. If we wish to consider equipment cost, it will be equal to the third scenario i.e. 1,236,100 dollars. One can observe that the joint use of ESS and spinning reserve compensates the uncertainty of the output power of renewable units to a satisfactory extent and avoids load curtailment in the network.

Table 9 Operation costs in the 4th scenario

Sources	Scenario 4	Costs (NZD)	Scenario 4
Wind Turbine Unit	33	Equipment	1236100
Photovoltaic Unit	45	Income Of Sale	6067
Battery Unit	112	Cost of load curtailment	186800
Spinning Reserve (kw)	45	Total Cost	1446000

4. Conclusion

Considering different parameters and cost functions, this paper tried to obtain the optimal capacity of production units and to study the optimal operation of the units based on derived results. In addition, it studied the effect of battery ESS and spinning reserve on decreasing system uncertainty. Generally, the findings of this study can be concluded as follows based on conducted evaluations:

1. Different parameters, including investment cost, maintenance cost, load curtailment cost and income from selling excess electricity to upper grid, play a role in the trend of determining the optimal capacity of production units.
2. If there is no limitation on investment cost associated with connecting production units to grid and the instantaneous price of electricity is in an ideal level, the operator will always tend to maximize income through selling power to upper grid by increasing the level of capacity connected to the system. In practice, however, the operator experiences investment budget limitation. Therefore, the resources capacity is optimized in a manner that it results in the maximum profitability of microgrid using the maximum available capital.
3. According to results, a limited increase in network loading level and maintaining investment costs in a fixed

level will increase operation cost due to increased times of power outage imposed to consumers.

4. The obtained results indicate the satisfactory efficiency of DE in optimizing the studied problem and no trapping into local optimum points.
5. The use of battery ESS and spinning reserve decreases power outage imposed to consumers, which is induced from the uncertainty of the output power of wind and solar units, to a satisfactory extent.

It is recommended to conduct further studies on the determination of the optimal capacity of a central controlled network composed of a set of microgrids connected to each other in order to model the capability of power exchange between microgrids and their interactions aimed at supplying power at different hours. In addition, it is recommended to conduct studies on the determination of optimal capacity of production resource of microgrids considering voltage stability and transient stability indices. Indeed, they are used as a term in stability cost function. Moreover, it is recommended to evaluate the effect of spinning reserve and ESS on the market interactions and to analyze DG resource contribution to the market in order to avoid sudden price jumps.

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