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Power-Heat Generation Sources Planning in Microgrids to Enhance Resilience against Islanding due to Natural Disasters

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***Abstract*— Natural disasters can cause the long inaccessibility of microgrids to main power/gas networks. In this paper, the combination and size of different power/heat generation sources including fuel-based distributed generation (DG), combined heat and power (CHP), electrical to heat (ETH) unit, thermal energy storage (TES), electrical energy storage (EES), photovoltaic (PV) and wind turbine (WT) units are optimized using a stochastic multi-objective model. The proposed model is formulated to minimize the planning cost of power/heat sources while maximizing the system resilience through minimization of the expected energies not served during islanding conditions due to natural disasters. To solve the model, ε-constraint method is implemented. The impact of DR program and the vulnerability of PV against natural disasters are also investigated on the planning cost of power/heat sources and system resilience.**

Keywords*— *Epsilon constraint, generation sources, microgrid, natural disasters, resilience.

NOMENCLUATURE

Indices

c_e, C_e	Index and number of electrical curtailable loads
c_h, C_h	Index and number of heat curtailable loads
s, *S*	Index and number of scenarios
$t,\ t'$	Time indices

Parameters

$cap_i^{\max}$	Maximum allowable installed capacity of power/heat generation sources including PV, wind turbine, CHP, EES, TES, ETH and DG
$cap_{PN-MIC}^{\max}$	Maximum capacity of link between power network and microgrid
$gn(t,s)$	Gas network availability at time *t* in scenario *s*
$hchr^{\max}, hdch^{\max}$	Maximum heat charging/discharging rate of TES
IC_i	Cost of *i*th power/heat generation sources per kW or kWh including PV, wind turbine, CHP, EES, TES, ETH and DG
$pn(t,s)$	Power network availability at time *t* in scenario *s*
$pchr^{\max}$, $pdch^{\max}$	Maximum electrical charging/discharging rate of EES
$pload(t,s), hload(t,s)$	Power/heat demand at time *t* in scenario *s*
$pload_{shift}^{\max}(t,s)$, $hload_{shift}^{\max}(t,s)$	Maximum shiftable power/heat load at time *t* in scenario *s*
$pload_{cur}^{\max}(c_e,t,s)$, $hload_{cur}^{\max}(c_h,t,s)$	Maximum curtailable power/heat load c_e / c_h at time *t* in scenario *s*
$SoC_{EES,TES}^{\min}$	Minimum allowable state of charge of EES, TES
$Tload_{cur}^{\max}(c_e)$, $Tload_{cur}^{\max}(c_h)$	Maximum duration that power/heat load c_e / c_h can be curtailed
t_0^s, T^s	Initial and final time of microgrid inaccessibility to main power or gas network in scenario *s*
ρ_s	Probability of scenario *s*
$\eta_{e,h,ETH}$	Efficiency of EES, TES, ETH
μ	Heat to power ratio of CHP

Variables

$hchr(t,s)$, $hdch(t,s)$	Charging/discharging heat of battery at time *t* in scenario *s*
$h_i(t,s)$	Heat output of *i*th heat generation including CHP,TES and ETH
$le(c_e,t,s), lh(c_h,t,s)$	Binary variable denotes if an electrical/heat load c_e / c_h is curtailed or not
$p_i(t,s)$	Power output of *i*th power generation including PV, wind turbine, CHP, EES and DG
$p_{imp}(t,s)$	Imported power by microgrid from upstream network at time *t* in scenario *s*
$p_{usp}(t,s), h_{usp}(t,s)$	Amount of electrical/heat load which is shedded at time *t* in scenario *s*
$pcl(c_e,t,s), hcl(c_h,t,s)$	Amount of electrical/heat load c_e / c_h which is curtailed at time *t* in scenario *s*
$pchr(t,s)$, $pdch(t,s)$	Charging/discharging power of battery at time *t* in scenario *s*
$psh(t,s), hsh(t,s)$	Amount of electrical/heat load which is shifted from or to time *t* in scenario *s*
$pshift(t,t',s)$, $hshift(t,t',s)$	Amount of power/heat load which is shifted from time *t* to t' time in scenario *s*
$SoC_e(t,s)$, $SoC_h(t,s)$	Electrical/heat state of charging of EES/TES at time *t* in scenario *s*
X_i	Capacity of *i*th power/heat generation including PV, wind turbine, CHP, EES, TES, ETH and DG
$\pi_{WIND}(t,s), \pi_{PV}(t,s)$	Wind/PV output uncertainty at time *t* in scenario *s*.

I. INTRODUCTION

The U.S. Hurricane Sandy in 2012 caused inaccessibility of approximately 7 million people to electric power [1]. The 2011 Earthquake in Japan damaged all important energy infrastructures such as power and gas networks [2]. According to [3], the restoration of damaged energy infrastructures due to natural disasters is hard and it takes a long time. So, it is vital to make the energy communities more resilient against low-probability high-impact events.

Microgrids are one of the resilient energy communities which are proved during harsh conditions. The Sendai microgrid survived for two days in islanded mode during the 2011 earthquake in Japan [4]. Microgrids as small-scale networks integrate different generation sources, loads and energy storages. Microgrids can work under grid-connected mode or islanded mode. In [5], microgrids are implemented to enhance the resilience of distribution systems. The operation and survivability of microgrids especially in specific applications such as hospital or military are an important concerns after natural disasters. The normal operation of microgrids is based on economic and emission goals. In normal conditions, the microgrid can consider the main network as an energy source. But, in harsh conditions due to natural disasters and also when the main network is not available, the objective of the microgrids is to meet the maximum local loads as long as possible [6, 7]. Ignoring the required actions of an islanded network can trigger catastrophic events [8].

Due to many benefits such as increasing the conversion efficiency of sources, optimal market interaction and increasing the flexibility of energy systems, the concept of multi-energy microgrids is emerged [9]. In multi-energy microgrids, different types of energy such as electricity and heat can be supplied. In most of the previous works such as [10, 11], the multi-energy microgrid is designed with different generation source based on economic views. Environmental concern is the other objective function which is considered in the design of microgrids [12].

Main electric power and gas networks are two important and vital infrastructures for supplying power and heat to the loads. The long inaccessibility of microgrids prime movers (such as combined heat and power units-CHP) to these infrastructures causes their inability in meeting the power and heat demands. Although in some previous works such as [13, 14], the reliability concern is considered in designing of multi-carrier energy microgrids, only high-probability but low-impact contingencies (such as one source outage) are studied.

One of the important concern in resilience enhancement planning problems is that how much cost should be spent to increase the resilience. In [15], the investment cost and resilience improvement are considered as constraint and objective function, respectively. But, in this paper both investment cost and resilience improvement are formulated as objective functions. In other words, the problem is modeled in the form of a multi-objective problem. So, each planner can choose the best solution in pareto front by considering the kind and importance of microgrid.

Demand Response (DR) can be defined as the changes in electricity or heat consumptions to achieve specific goals including operation cost or emission reduction, voltage and frequency regulation and reliability improvement [16]. In this paper, DR program is utilized with the objective of improving the resilience of microgrid.

In light of the reviewed literature, the main contribution of this paper is to enhance the resilience of microgrids with planning of different power/heat generation sources such as PV, wind turbine, CHP, electric to heat (ETH), thermal energy storage (TES) and electric energy storage (EES) in harsh conditions when the microgrids cannot access the main power/gas networks and must be operated in islanded mode. The problem is formulated as a stochastic multi-objective model that aims to increase the resilience of microgrid and to decrease the investment cost. Furthermore, stochastic programming is implemented to cover important uncertain parameters including power/heat demands, renewable generations output, month and hour occurrence of natural disasters, severity of natural disasters or in other words the inaccessibility of microgrid and its duration to power/gas networks. The impact of DR program is also studied on the resilience improvement planning of the microgrid. Finlay to solve the problem, ε-constraint is implemented to solve the problem.

The rest of this paper is organized as follows: Section 2 explains the problem formulation and solution methodology. Section 3 presents the simulation results. Finally, Section 4 concludes this paper.

II. PROBLEM FORMULATION AND SOLUTION METHODOLOGY

Fig. 1 shows the candidate power/heat generation sources.

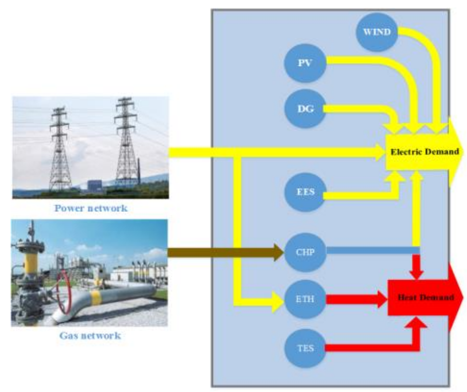

Fig. 1. Schematic of power/heat generation sources in a microgrid

The objective of this paper is to optimize the size of each candidate power/heat sources to enhance the resilience of microgrid. Renewable energies including PV and wind turbine as clean but strongly uncertain sources can produce electricity for microgrid without any dependency on power or gas network. The other candidate power source for microgrid is fuel based distributed generators (DGs). Although, this option is not efficient in normal operation of microgrid due to environmental concerns, it can be a good choice to meet electrical demand in emergency conditions, especially when the main power network is not available.. EES is an efficient option for microgrid to supply the power demand in both normal and emergency conditions provided that the size of EES is properly chosen. CHP is also an efficient means of generating heat and electricity simultaneously. The input of CHP is gas which is supplied from the main gas network. If the gas network is damaged, CHP operation will be affected. ETH is another heat source that depends on the availability of the main power network. Finally, TES can be regarded a buffer that allows thermal energy to be stored and used in a desired period.

According to (1)-(2), the objective functions of the problem is to minimize the cost of installing power/heat generation sources and the expected energy not served (EENS) of electrical and heat loads during the inaccessibility of microgrid to power or gas networks. In this paper, this interval time is also called emergency period.

$$OF_1 = \text{Minimize} \sum_{i \in \left\{ \substack{DG,TES,EES,PV \\ WIND,ETH,CHP} \right\}} X_i IC_i \tag{1}$$

$$OF_2 = \text{Minimize} \quad [EENSe + EENSh], \\ \begin{bmatrix} EENSe = \sum_{s=1}^{S} \rho_s \sum_{t=t_0^s}^{T^s} p_{usp}(t,s) \\ EENSh = \sum_{s=1}^{S} \rho_s \sum_{t=t_0^s}^{T^s} h_{usp}(t,s) \end{bmatrix} \tag{2}$$

The operation of fuel based DG is modeled by (3)-(4). Eq. (3) limits the power generation of DG to the installed capacity. Due to the environmental and also fuel storage concerns, (4) limits the maximum installed capacity of DG. The same constraints apply to other sources.

$$p_{DG}(t,s) \le X_{DG} \qquad t \in [t_0^s, t_0^s + T^s], s \in \{1,2,...,S\} \tag{3}$$

$$X_{DG} \le cap_{DG}^{\max} \tag{4}$$

Maximum power that microgrid can import from the main power network is limited by (5). In case of a damage in the mains, this power is set to zero.

$$p_{imp}(t,s) \le cap_{PN-MIC}^{\max} pn(t,s) \; t \in [t_0^s, t_0^s + T^s], s \in \{1,2,...,S\} \tag{5}$$

Constraints (6)-(12) express EES operation. Equations (6)-(7) show the allowable range of electrical State of charge (*SoCe*) of EES. The level of stored energy in EES in each interval is calculated by (8). The maximum charging and discharging rates of EES are enforced through (9)-(12). Equation (13) limits the maximum capacity of EES to be installed.

$$SoCe(t,s) \le X_{EES} \qquad t \in [t_0^s, t_0^s + T^s], s \in \{1,2,...,S\} \tag{6}$$

$$SoCe(t,s) \ge SoC_{EES}^{\min} \qquad t \in [t_0^s, t_0^s + T^s], s \in \{1,2,...,S\} \tag{7}$$

$$SoCe(t,s) = SoCe(t-1,s) + pchr(t,s)\eta_e - \frac{pdch(t,s)}{\eta_e} \\ t \in [t_0^s, t_0^s + T^s], s \in \{1,2,...,S\} \tag{8}$$

$$pchr(t,s) \le \frac{X_{EES} - SoCe(t-1,s)}{\eta_e}, t \in [t_0^s, t_0^s + T^s], s \in \{1,2,...,S\} \tag{9}$$

$$pchr(t,s) \le pchr^{\max} \qquad t \in [t_0^s, t_0^s + T^s], s \in \{1,2,...,S\} \tag{10}$$

$$pdch(t,s) \le (SoCe(t-1,s) - SoC_{EES}^{\min})\eta_e, t \in [t_0^s, t_0^s + T^s], s \in \{1,2,...,S\} \tag{11}$$

$$pdch(t,s) \le pdch^{\max} \qquad t \in [t_0^s, t_0^s + T^s], s \in \{1,2,...,S\} \tag{12}$$

$$X_{EES} \le cap_{EES}^{\max} \tag{13}$$

The limitations of TES are similar to the constraints of EES. So, it is only necessary to replace $SoCh$, X_{TES}, $SoC_{TES}^{\min}$, $hchr$, $hdch$, η_h, $hchr^{\max}$, $hdch^{\max}$, $cap_{TES}^{\max}$ instead of $SoCe$, X_{EES}, $SoC_{EES}^{\min}$, $pchr$, $pdch$, η_e, $pchr^{\max}$, $pdch^{\max}$, $cap_{EES}^{\max}$, respectively.

CHP operation constraints are explained in (14)-(16), which show power output limitation, heat-to-power ratio and maximum allowable installed capacity, respectively.

$$p_{CHP}(t,s) \le X_{CHP} gn(t,s) \qquad t \in [t_0^s, t_0^s + T^s], s \in \{1,2,...,S\} \tag{14}$$

$$h_{CHP}(t,s) \le \mu p_{CHP}(t,s) \qquad t \in [t_0^s, t_0^s + T^s], s \in \{1,2,...,S\} \tag{15}$$

$$X_{CHP} \le cap_{CHP}^{\max} \tag{16}$$

According to (17), ETH supplies heat from electricity. The dependency of ETH on main power network is shown in (18). Maximum allowable capacity of ETH can be installed is enforced by (19).

$$h_{ETH}(t,s) = \eta_{ETH} p_{ETH}(t,s) pn(t,s), t \in [t_0^s, t_0^s + T^s], s \in \{1,2,...,S\} \tag{17}$$

$$p_{ETH}(t,s) \le X_{ETH} pn(t,s) \qquad t \in [t_0^s, t_0^s + T^s], s \in \{1,2,...,S\} \tag{18}$$

$$X_{ETH} \le cap_{ETH}^{\max} \tag{19}$$

As other energy sources, the maximum capacity of PV and wind turbine units which can be chosen to be installed are limited by (20) and (21), respectively.

$$X_{PV} \le cap_{PV}^{\max} \tag{20}$$

$$X_{WIND} \le cap_{WIND}^{\max} \tag{21}$$

Power and heat balance constraints in each interval and scenario are shown in (22) and (23), respectively. Equations (24)-(25) explain amount of electrical and heat loads which are shifted to/from each time interval of each scenario, respectively.

$$pload(t,s) + psh(t,s) - \sum_{c_e=1}^{C_e} pcl(c_e,t,s) - p_{usp}(t,s) + p_{ETH}(t,s) = \\ p_{DG}(t,s) + pdcr(t,s) - pchr(t,s) + X_{WIND}\pi_{WIND}(t,s) + X_{PV}\pi_{PV}(t,s) \\ + p_{CHP}(t,s) + p_{imp}(t,s), t \in [t_0^s, t_0^s + T^s], s \in \{1,2,...,S\} \tag{22}$$

$$hload(t,s) + hsh(t,s) - \sum_{c_h=1}^{C_h} hcl(c_h,t,s) = h_{CHP}(t,s) - hchr(t,s) + \\ hdch(t,s) + husp(t,s) + h_{ETH}(t,s), t \in [t_0^s, t_0^s + T^s], s \in \{1,2,...,S\} \tag{23}$$

$$psh(t,s) = \sum_{t'=t_0^s}^{t_0^s+T^s} \left[pshift(t',t,s) - pshift(t,t',s) \right] \\ t \in [t_0^s, t_0^s + T^s], t \ne t', s \in \{1,2,...,S\} \tag{24}$$

$$hsh(t,s) = \sum_{t'=t_0^s}^{t_0^s+T^s} \left[hshift(t',t,s) - hshift(t,t',s) \right] \\ t \in [t_0^s, t_0^s + T^s], t \ne t', s \in \{1,2,...,S\} \tag{25}$$

In the proposed DR program, electrical and heat loads are categorized into fixed, shiftable and curtailable loads. According to (26)-(27), electrical curtailable loads are allowed to be curtailed by microgrid for specified duration. This methodology is also applied to heat demand as shown in (28)-(29). Equations (30)-(31) limit the amount of electrical and heat load that can be shifted from each time interval to another time, respectively.

$$pcl(c_e,t,s) \le pload_{cur}^{\max}(c_e,t,s)le(c_e,t,s)$$
$$t \in [t_0^s, t_0^s + T^s], s \in \{1,2,...,S\}, c_e \in \{1,2,...,C_e\} \tag{26}$$

$$\sum_{t=t_0^s}^{T^s} le(c_e,t,s) \le Tload_{cur}^{\max}(c_e)$$
$$t \in [t_0^s, t_0^s + T^s], s \in \{1,2,...,S\}, c_e \in \{1,2,...,C_e\} \tag{27}$$

$$hcl(c_h,t,s) \le hload_{cur}^{\max}(c_h,t,s)lh(c_h,t,s)$$
$$t \in [t_0^s, t_0^s + T^s], s \in \{1,2,...,S\}, c_h \in \{1,2,...,C_h\} \tag{28}$$

$$\sum_{t=t_0^s}^{T^s} lh(c_h,t,s) \le Tload_{cur}^{\max}(c_h)$$
$$t \in [t_0^s, t_0^s + T^s], s \in \{1,2,...,S\}, c_h \in \{1,2,...,C_h\} \tag{29}$$

$$\sum_{t'=t_0^s}^{t_0^s+T^s} pshift(t,t',s) \le pload_{shift}^{\max}(t,s), t \in [t_0^s, t_0^s + T^s], s \in \{1,2,...,S\} \tag{30}$$

$$\sum_{t'=t_0^s}^{t_0^s+T^s} hshift(t,t',s) \le hload_{shift}^{\max}(t,s), t \in [t_0^s, t_0^s + T^s], s \in \{1,2,...,S\} \tag{31}$$

ε-constraint method is applied to solve the multi-objective problem. This approach transforms the multi-objective problem to a single objective problem [17]. Consider a multi-objective problem with *k* objective functions.

$$\max\ (OF_1(x), OF_2(x), ..., OF_k(x)), \quad x \in S \tag{32}$$

According to (32), by applying ε-constraint, one of the objective function will be optimized by changing the other objective functions to constraints.

$$\max\ OF_1(x) \quad \text{S.t.} \begin{cases} OF_2(x) \ge \varepsilon_2 \\ \vdots \\ OF_k(x) \ge \varepsilon_k \\ x \in S \end{cases} \tag{33}$$

With changing the right hand side of the constraints in an appropriate range, the pareto front will be obtained.

III. SIMULATION RESULTS

The proposed method for power/heat generation sources to enhance resilience of microgrid against islanding due to natural disasters is applied to a microgrid. The characteristics of microgrid including electrical/heat demands and the deterministic output of renewable generation in one day of each season are depicted in Fig. 2. For the renewable energies, the normalized values based on the installed capacity are reported.

Considering the importance of uncertain parameters, they are categorized into two groups. The first group includes renewable energies output, electrical/heat demands, season and hour occurrence of natural disasters. The uncertainties of the renewable energies output and electrical/heat demands are modeled with normal distribution functions with 5% and 3% error in predictions, respectively. The probability of natural disasters occurrence in each season is reported in TABLE I.

The time of occurrence of a natural disasters in a day is randomly chosen between 1 and 24. Initially, 1000 scenarios are produced for the first group of uncertain parameters and finally 10 scenarios are chosen with backward reduction method.

The second group includes the severity of natural disasters and duration of power/gas networks unavailability. In this paper, the severity of natural disasters are categorized into four groups. As the severity of natural disasters increases, the inaccessibility duration of microgrid to the main power and gas networks increases. The required information about the second group of the uncertain parameters is shown in TABLE II.

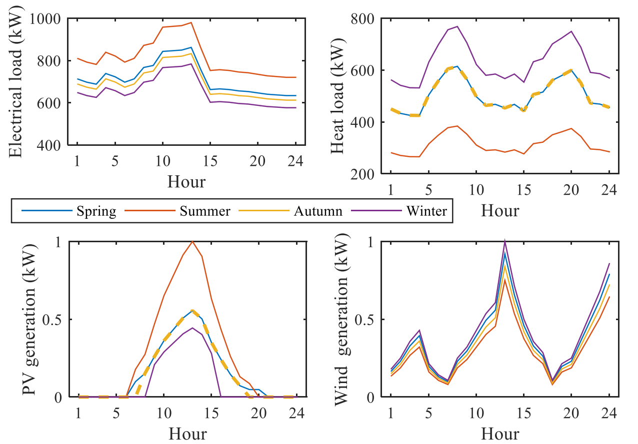

Fig. 2: The charecteriscts of the tested microgrid

TABLE I. SEASONAL PROBABILITY OCCURENCAE OF A NATURAL DISASTER

Season	Spring	Summer	Autumn	Winter
Natural disasters occurrence	0.3	0.4	0.2	0.1

TABLE II. THE OCCURRENCE PROBABILITY OF EACH GROUP OF NATURAL DISASTERS AND POWER/GAS NETWORKS UNAVAILABILITY DURATION

Severity of natural disaster	1	2	3	4
Occurrence probability	0.4	0.3	0.2	0.1
Power network unavailability duration (hours)	6	8	12	20
Gas network unavailability duration (hours)	0	0	14	24

In order to produce the final scenarios, the 10 chosen scenarios of the first group will be multiplied by the 4 scenarios of the second group, so a total number of 40 scenarios will be studied.

The characteristic of the candidate power/heat sources are obtained from [18] and also are indicated in TABLE III.

TABLE III. THE CHARECTERISTCS OF GENERATION SOURCES

PV	Wind turbine	CHP	DG
IC= 2.5 $cap_{PV}^{\max} = 5000$	IC = 4.39 $cap_{WIND}^{\max} = 5000$	IC = 2.37 μ =1.31 $cap_{CHP}^{\max} = 5000$	IC = 0.756 $cap_{DG}^{\max} = 500$
TES	EES	ETH	IC (k$/kW or k$/kWh), $hchr^{\max}, hdch^{\max}$, $pchr^{\max}, pdch^{\max}$ (kWh), $cap^{\max}$ (kW)
$IC = 0.5$ $\eta_h = 0.95$ $hchr^{\max} = 400$ $hdch^{\max} = 400$ $cap_{TES}^{\max} = 5000$	$IC = 0.588$ $\eta_e = 0.95$ $pchr^{\max} = 400$ $pdch^{\max} = 400$ $cap_{EES}^{\max} = 5000$	$IC = 0.866$ $\eta_{ETH} = 0.95$ $cap_{ETH}^{\max} = 5000$	

It is assumed that 10 % of the electrical/heat loads are shiftable in electrical/heat DR programs. Furthermore, there are three curtailable electrical/heat load groups with 5%, 3% and 2% of the total demand. Each one of them is allowed to be curtailed for 2 hours in the emergency period due to natural disasters. The proposed multi-objective model is solved using GAMS optimization package utilizing CPLEX.

Case 1: In this case, the multi-objective problem is solved for conditions where DR programs are considered or not. The pareto fronts of the both scenarios are depicted in Fig. 3. There are many solutions in the pareto front and the planner can make decisions based on the available criteria and their importance.

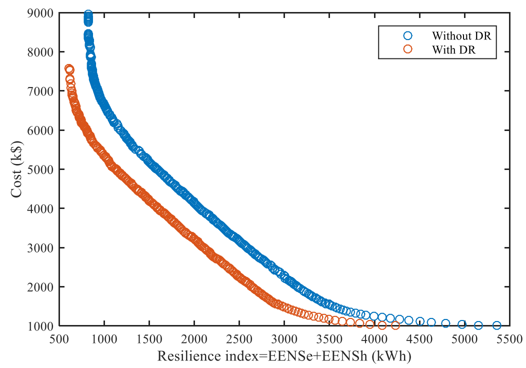

Fig. 3: The pareto front of case 1

To know more details about some solutions of the pareto front, some of them are chosen and their characteristics are tabulated in Table IV. As seen in Table. IV, DG as independent power source is chosen in maximum allowable capacity in all solutions. The reason of this choice is that this independent power source is cheaper than other power sources such as PV or wind turbine. However, as mentioned before, the environmental concerns and fuel storage, limit the use of this source. By increasing the planning cost and also increasing the resilience of microgrid, the installed capacities of independent and expensive power sources including PV, EES and wind turbine are increased. However, when the capacity of renewable sources increases, the system's uncertainties will be increased which can be mitigated by increasing the EES capacity accordingly. Due to the dependency of CHP on gas network, the capacity of CHP is chosen approximately in a close range. Similar to independent power sources, the installed capacity of TES will be increased if the planning budget is also raised. Finally, when the power sources capacity is increased, the portion of electric power that is converted to the heat by ETH, so, the capacity of ETH is also increased in this condition.

The other important point understood from Table IV is the impact of DR program on resiliency. According to Fig. 3 and Table IV, considering a specific resilience index, DR program can significantly decrease the planning cost. This impact is more highlighted when more resilience level of microgrid is required. So, it is improtant to the the planner to well identify the kind and importance of each load in microgrid and provide the infrastructure to run the DR programs.

Case 2: In case 1, it was assumed all power/heat sources in microgrid are not vulnerable against natural disasters. This assumption is reachable. Providing safe places against natural disasters for installation of DG, EES, CHP, TES, ETH is possible. The structure of wind turbine also can be designed safe enough against natural disasters. The most vulnerable source against natural disaster is PV which is installed nearly at the ground surface. Table V shows the probability of per kW installed PV vulnerability against natural disasters. The problem is solved again when the PV is vulnerable. Fig. 4 shows the pareto fronts of both states which PV is vulnerable or not.

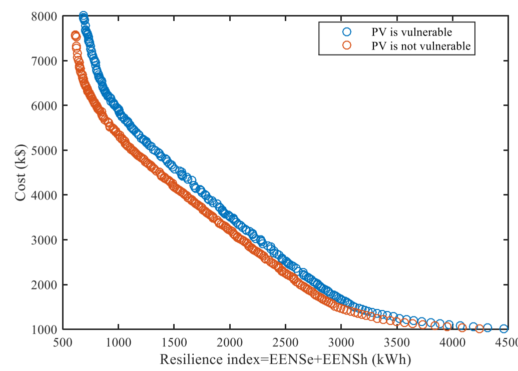

Fig. 4: The pareto front of case 2

To compare the results, the details of some solutions in pareto front of case 2 are provided in Table VI. According to this Table, in all solutions when PV is not vulnerable, no capacity of PV is chosen to be installed. When PV is vulnerable, the planning cost will be increased to reach the same resilience level compared to the state when PV is not vulnerable and it is chosen to be installed. In this situation, the increasing wind turbine capacity is preferred. Therefore, the planner should consider the vulnerability of power/heat sources in the problem.

TABLE IV. THE DETAILS OF SOME SOLUTIONS IN THE PARETO FRONT OF CASE 1

Resilience index (kWh)	Cost (k$)	X_{DG} (kW)	X_{EES} (kWh)	X_{ETH} (kW)	X_{TES} (kWh)	X_{CHP} (kW)	X_{PV} (kW)	X_{WIND} (kW)	DR is considered?
611.3	7575	500	2241.3	602.7	5000	244.1	326.4	337.8	Yes
827.1	5900	500	1034	390.8	5000	168	370.6	175.6	Yes
827.7	8400	500	2153.3	630.4	5000	266	135	629.3	No
2004.8	3200	500	312.6	266.6	2493.3	273.3	213.4	0	Yes
2003.7	4125	500	553.9	272.3	4011.2	248.2	244.9	0	No
4237.4	1000	500	0	115.3	0	229	0	0	Yes
5361.8	1000	500	0	98.9	0	235	0	0	No

TABLE V. THE VULNERABILITY PROBABILITY OF PV PER KW AGAINST NATURAL DISASTERS

Severity of natural disasters	1	2	3	4
Vulnerability probability per kW	0.1	0.3	0.5	0.7

TABLE VI. THE DETAILS OF SOME SOLUTIONS IN THE PARETO FRONT OF CASE 2

Resilience index (kWh)	Cost (k$)	X_{DG} (kW)	X_{EES} (kWh)	X_{ETH} (kW)	X_{TES} (kWh)	X_{CHP} (kW)	X_{PV} (kW)	X_{WIND} (kW)	PV is vulnerable?
685.2	6600	500	1330.6	573.7	5000	152.1	386.1	259.1	No
685.7	8000	500	1683.2	697.8	5000	172.5	0	715.2	Yes
2146.1	2925	500	233.2	268.5	2033.4	273.2	213.4	0	No
2148.5	3200	500	104.3	258.3	2709.5	281.9	0	121.8	Yes
4084.2	1025	500	0	119.5	0	238	0	0	No
4072.5	1075	500	0	165.4	0	242.3	0	0	Yes

IV. CONCLUSION

In this paper, the power/heat generation sources planning for enhancing the resilince of microgrid against islanding due to natural disasters was investigated. A stochastic multi-objective model was proposed to consider both conflicting objective functions namely planning cost and resilience index. Using ε-constraint method, the problem was solved and it was shown by installing independent sources such as renewable energies, EES and TES, it is possible to reach a high level of resilience. The impact of DR program on the problem was also studied. It was proved that by implementing DR program, the cost of power/heat sources planning to achieve a same high level of resilience could be decreased as much as 29.8% compared to the situatio where DR program is not used. In other case, the impact of PV vulnerability on the problem was studied. It was demonstrated that to provide the same high resilience level as compared to the state when the PV is not vulnerable, it is necessary to increase the planning cost of power/heat sources by 17.5%.

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