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Bi-level Two-stage Stochastic Operation of Hydrogen-based Microgrids in a Distribution System

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Abstract—**This paper deals with the bi-level two-stage operation scheduling of hydrogen-based microgrids within a distribution system where the wind and solar generation and load demands are considered as uncertain variables. The distribution system is considered as a leader in the upper level and microgrids as followers in the lower level. Unlike previous approaches, the upper-level is within the day-ahead market and considered a deterministic problem, and the lower-level is considered a stochastic problem and consists of two stages. The first stage determines the purchasing power from the distribution system, while the second stage adjusts the outputs and power dispatch for any realizations of scenarios. This model is transformed from a bi-level to a linear single-level model by applying the Karush–Kuhn–Tucker (KKT) optimally conditions, strong duality, and Fortuny-Amat methods. Several comparisons have been carried out regarding the single clearing price for all microgrids or separate prices for each microgrid. Furthermore, power exchange and dispatch in the distribution system are investigated under the mentioned frameworks.**

Keywords—**Bi-level programming, Operations scheduling, Hydrogen-based microgrids, Uncertainty.**

NOMENCLATURE

	Indices and acronyms
t	Time periods
i	Microgrids
s	Scenarios, s= 1, 2, …, S
DG	Distributed Generation
LC	Load Curtailment
WT	Wind Turbine
PV	Photovoltaic units
$P2H$	Power to hydrogen units
$H2P$	Hydrogen to power units
HS	Hydrogen storages
MGO	Microgrid operator
DSO	Distribution operator
$DISCO$	Distribution company
MG	Microgrid
max/min	Upper/lower limits

	Variables and parameters
$SOH_i^{t,s}$	State of hydrogen in hydrogen storages [MWh]
$L_i^{t,s}$	Load demand of microgrid i at time t and scenario s and [MW]
$VoLL_i$	Value of loss of load of microgrid i [$/MWh]
ρ_s	Probability of scenario s
$P_{MG_i}^t$	Power exchange of microgrid i with distribution system [MW]
$\pi_{MG_i}^t$	Clearing power price of microgrid i with the distribution system [$/MW]
P_{DA}^t	Purchased day-ahead power by DSO [MW]
π_{DA}^t	Purchased power price [$/MW]
$P_{DG_i}^{t,s}$	Output power of DG in microgrid [MW]
π_{DG_i}	Marginal price of DG in microgrid i [$/MW]
$P_{LC_i}^{t,s}$	Curtailed load of microgrid i [MW]
$P_{H2P_i}^{t,s}$	Output power of fuel cells in microgrid i [MW]
$P_{P2H_i}^{t,s}$	Output hydrogen power of electrolyzers in microgrid i [MW]
$P_{WT_i}^{t,s}$	Output power of wind turbines in microgrid i [MW]
$P_{PV_i}^{t,s}$	Output power of photovoltaic systems in microgrid [MW]
μ, λ	Lagrange multipliers
M	A large positive constant
η	Efficiency of units
u	Axillary binary variables for linearization

I. INTRODUCTION

A. Motivation and Background

Microgrids can be described as a group of distributed energy resources within the distribution system to serve the load demands. From the viewpoint of the distribution system operator (DSO), a microgrid acts as a prosumer (both consumer and producer) that is operating in both on-grid and off-grid modes [1]. Microgrids' typical resources include microturbines, distributed generators, renewable energy sources (RES), storage, etc. On the other hand, environmental concerns have been initiated by the generation, conversion, and energy consumption during the recent years [2].

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Recently, green hydrogen-based networks considered to be one of the most operative solutions to have a better environment. Green hydrogen-based microgrid is an anticipated future in which power to hydrogen units (P2H), hydrogen to power units (H2P), hydrogen vehicles, and energy storages are utilized in order to phase out fossil fuels and limit global warming. In this active distribution system, due to the presence of microgrids with hydrogen production and the hierarchical nature of decision-making between DSO and microgrid operators (MGOs), the operation problems are complex compared with that of passive distribution systems.

Optimizing the objectives of the DSOs and MGOs should be performed independently while working together simultaneously. As a consequence, it follows that the operation model is a hierarchical problem. In this regard, the collaborative operation of the distribution system and microgrids should be modeled as a bi-level problem.

B. *Relevant Literature*

In the past decade, the centralized operation scheduling of microgrids [3] and multi-carrier energy systems [4], [5] are defined without considering the hierarchical and collaborative nature of decision-making between the entities. However, several research works addressed the bi-level operation modeling of microgrids [6], [7], virtual power plants [8], and local energy systems [9]. However, a few research projects have examined the bi-level operation of hydrogen-based microgrids in distribution grids. Capturing the uncertainties in bi-level problems, a bi-level stochastic operation scheduling problem considering the uncertainties of demands, pool prices, and rival-retailer prices is proposed in [10]. A bi-level two-stage approach for coordinated management of networked microgrids is proposed in [11]. The first stage determines the output of non-dispatchable units, while the second stage sets the outputs of units based on realized scenarios.

C. *Contributions and Organization*

As far as we know, this is the first work that investigates the operation scheduling of hydrogen-based microgrids in a distribution network using a bi-level two-stage stochastic model considering the uncertainties of load demands, solar radiation, and wind speed. In the following, the contributions of this paper are highlighted.

i) A novel mathematical modeling for bi-level two-stage stochastic short-term planning of microgrids within distribution systems is proposed. Unlike the previous works as [10], [11], in this paper, the lower-level considered as a two-stage stochastic problem.

ii) Compared with previous research works like [12], [13], more resources such as hydrogen systems with fuel cells, hydrogen storages, and electrolyzers are included in microgrids to enhance the flexibility of MGO while participating in DSO operation.

Here are the rest of the sections in this paper. Sections II and III outline the proposed problem formulation and problem-solving methodology, respectively. Section IV and V provide a case study and results, respectively. Finally, results are concluded in section VI.

II. BI-LEVEL PROBLEM DESCRIPTION AND FORMULATION

A. *Framework*

This model is a bi-level two-stage programming problem that maximizes DSO's profit, whereas the expected operation cost of supplying loads in the microgrid is minimized. The general structure of the suggested model is introduced in Fig. 1. Decisions of the upper level are the electricity prices for microgrids and acquired power from the day-ahead market to maximize DISCO's profit. The lower level is corresponded to each MGOs and determines the amounts of power exchange with the distribution system at the first stage. Finally, procured power from distributed generations, scheduling of hydrogen units, and load curtailments are obtained from the second stage.

B. *Upper-level: operation model of DSO*

Equation (1) represents the objective function of the upper-level problem subject to constraints in (2)-(4). The revenue of the sold power to the microgrid and the cost of acquired power from the day-ahead electricity market is illustrated in the first and second terms of the objective function, respectively.

Equation (2) maintains the power price for each microgrid within a reasonable range. The limitation of purchased power from the day-ahead market is shown in (3). Finally, the purchased and sold power balance are ensured in (4).

$$Maximize\ Profit \sum_{t=1}^{T}\sum_{i=1}^{I}\{P_{MG_i}^{t}.\pi_{MG_i}^{t} - P_{DA}^{t}.\pi_{DA}^{t}\} \tag{1}$$

$$0 \leq \pi_{MG_i}^{t} \leq \pi_{MG}^{max} \tag{2}$$

$$0 \leq P_{DA}^{t} \leq P_{DA}^{max} \tag{3}$$

$$\sum_{i=1}^{I} P_{MG_i}^{t} \leq P_{DA}^{t} \tag{4}$$

C. *Lower-level: operation model of MGO*

The cost minimization objective function of the lower-level problem is shown in (5). The first term is the cost of power purchased from the DSO. The second and third terms are the expected cost of the procured power from the distributed generations and not supplied loads, respectively. The permissible power exchange with the distribution system is described in (6). Constraint (7) guarantees the generation limits of DGs, and the acceptable amount of electrical load curtailment is ensured in (8). Equation (9) defines the balance of power at each microgrid.

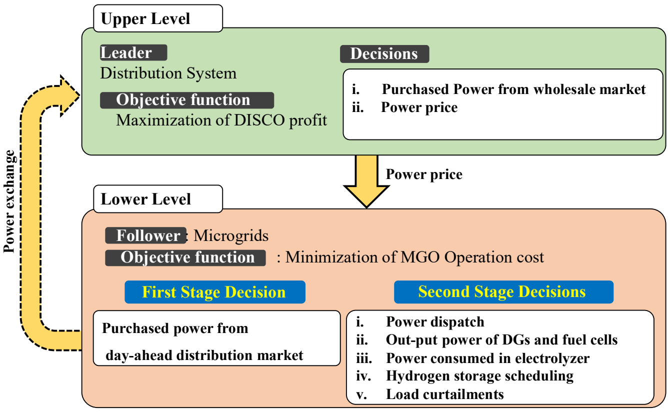

Fig. 1. Bi-level two-stage operation scheduling framework

The constraints of hydrogen storage units are defined in (10)-(13). Equations (10) and (11) describe the hydrogen balance and limitations in hydrogen storages, respectively. The amount of power and hydrogen generation in P2H and H2P units are limited in (12) and (13), respectively.

$$\mathit{Minimize\ Cost} \tag{5}$$

$$\sum_{t=1}^{T}\sum_{i=1}^{I} \{P_{MG_i}^{t}.\pi_{MG_i}^{t} + \rho_s.\sum_{s=1}^{S} P_{DG_i}^{t,s}.\pi_{DG_i} + P_{LC_i}^{t,s}.VoLL_i\}$$

$$0 \le \mu_{1,i}^{t} \perp -P_{MG}^{max} \le P_{MG_i}^{t} \le P_{MG}^{max} \perp \mu_{2,i}^{t} \ge 0 \tag{6}$$

$$0 \le \mu_{3,i}^{t,s} \perp P_{DG_i}^{min} \le P_{DG_i}^{t,s} \le P_{DG_i}^{max} \perp \mu_{4,i}^{t,s} \ge 0 \tag{7}$$

$$0 \le \mu_{5,i}^{t,s} \perp 0 \le P_{LC_i}^{t,s} \le P_{LC_i}^{max} \perp \mu_{6,i}^{t,s} \ge 0 \tag{8}$$

$$P_{MG_i}^{t} + P_{DG_i}^{t,s} + P_{H2P_i}^{t,s} - P_{P2H_i}^{t,s} + P_{WT_i}^{t,s} + P_{PV_i}^{t,s} = L_i^{t,s} - P_{LC_i}^{t,s} \perp \lambda_{1,i}^{t,s}\ \mathit{unrestricted} \tag{9}$$

$$SOH_i^{t,s} = SOH_i^{t-1,s} + \eta_i^{P2H}.P_{P2H_i}^{t,s} - 1/\eta_i^{H2P}.P_{H2P_i}^{t,s} \perp \lambda_{2,i}^{t,s}\ \mathit{unrestricted} \tag{10}$$

$$0 \le \mu_{7,i}^{t,s} \perp SOH_i^{min} \le SOH_i^{t,s} \le SOH_i^{max} \perp \mu_{8,i}^{t,s} \ge 0 \tag{11}$$

$$0 \le \mu_{9,i}^{t,s} \perp 0 \le P_{P2H_i}^{t,s} \le P_{P2H_i}^{max} \perp \mu_{10,i}^{t,s} \ge 0 \tag{12}$$

$$0 \le \mu_{11,i}^{t,s} \perp 0 \le P_{H2P_i}^{t,s} \le P_{H2P_i}^{max} \perp \mu_{12,i}^{t,s} \ge 0 \tag{13}$$

D. Uncertainty Modeling

In the scheduling process, the microgrid operator faces several uncertainties. This problem is defined as a scenario-based problem in which solar radiation, wind speed, and loads are considered uncertain variables. In order to model the uncertainties, the forecast error of solar irradiation, wind speed, and loads are modeled by Beta, Weibull, and Normal probability distribution functions (PDF), and the corresponding scenarios are generated using these models.

From the above models, a vector of scenarios for all times is given with equal probability. The Forward method with the SCENRED tool in GAMS software [14] is implemented to reduce the primary set of scenarios.

III. SOLUTION METHODOLOGY

This bi-level two-stage problem cannot be solved using straightforward methods. Therefore, the problem should be transformed into a linear single-level problem. The first step is to substitute the lower-level MGs operation problem in (5)-(13) with the Karush–Kuhn–Tucker (KKT) optimally conditions, and the single-level mathematical programming with equilibrium constraints (MPEC) is obtained. For the next step, the nonlinear terms in the objective function and constraints are linearized using the Fortuny-Amat method and strong duality methods. Due to the paper space limits, those equations of transformations are omitted. Finally, equation (14)-(33) demonstrates the equivalent single-level linear objective function and constraints.

$$\mathit{Maximize\ Profit}\sum_{t=1}^{T} -P_{DA}^{t}.\pi_{DA}^{t} + \sum_{t=1}^{T}\sum_{i=1}^{I}\sum_{s=1}^{S}\rho_s\{ -P_{MG}^{max}.\mu_{1,i}^{t,s} - P_{MG}^{max}.\mu_{2,i}^{t,s} + P_{DG_i}^{min}.\mu_{3,i}^{t,s} - P_{DG_i}^{max}.\mu_{4,i}^{t,s} -P_{LC_i}^{max}.\mu_{6,i}^{t,s} + (L_i^{t,s} - P_{WT_i}^{t,s} - P_{PV_i}^{t,s}).\lambda_{1,i}^{t,s} +SOH_i^{min}.\mu_{7,i}^{t,s} - SOH_i^{max}.\mu_{8,i}^{t,s} -P_{P2H_i}^{max}.\mu_{10,i}^{t,s} - P_{H2P_i}^{max}.\mu_{12,i}^{t,s}\} \tag{14}$$

Subject to:

$$(2)\text{-}(4), (6)\text{-}(13)$$

$$\pi_{MG_i}^{t} - \mu_{1,i}^{t,s} + \mu_{2,i}^{t,s} - \lambda_{1,i}^{t,s} = 0 \tag{15}$$

$$\pi_{DG_i} - \mu_{3,i}^{t,s} + \mu_{4,i}^{t,s} - \lambda_{1,i}^{t,s} = 0 \tag{16}$$

$$VoLL_i - \mu_{5,i}^{t,s} + \mu_{6,i}^{t,s} - \lambda_{1,i}^{t,s} = 0 \tag{17}$$

$$-\mu_{7,i}^{t,s} + \mu_{8,i}^{t,s} + \lambda_{2,i}^{t-1,s} - \lambda_{2,i}^{t,s} = 0 \tag{18}$$

$$-\mu_{9,i}^{t,s} + \mu_{10,i}^{t,s} + \eta_i^{P2H}.\lambda_{2,i}^{t,s} - \lambda_{1,i}^{t,s} = 0 \tag{19}$$

$$-\mu_{11,i}^{t,s} + \mu_{12,i}^{t,s} - 1/\eta_i^{H2P}.\lambda_{2,i}^{t,s} + \lambda_{1,i}^{t,s} = 0 \tag{20}$$

$$\mu_{x,i}^{t,s} \le M.\left(1 - u_{x,i}^{t,s}\right)\ \ \forall x = 1,2,\dots,12 \tag{21}$$

$$P_{MG_i}^{t} + P_{MG}^{max} \le M.u_{1,i}^{t,s} \tag{22}$$

$$-P_{MG_i}^{t} + P_{MG}^{max} \le M.u_{2,i}^{t,s} \tag{23}$$

$$P_{DG_i}^{t,s} - P_{DG_i}^{min} \le M.u_{3,i}^{t,s} \tag{24}$$

$$-P_{DG_i}^{t,s} + P_{DG_i}^{max} \le M.u_{4,i}^{t,s} \tag{25}$$

$$P_{LC_i}^{t,s} \le M.u_{5,i}^{t,s} \tag{26}$$

$$-P_{LC_i}^{t} + P_{LC_i}^{max} \le M.u_{6,i}^{t,s} \tag{27}$$

$$SOH_i^{t,s} - SOH_i^{min} \le M.u_{7,i}^{t,s} \tag{28}$$

$$-SOH_i^{t,s} + SOH_i^{max} \le M.u_{8,i}^{t,s} \tag{29}$$

$$P_{P2H_i}^{t,s} \le M.u_{9,i}^{t,s} \tag{30}$$

$$-P_{P2H_i}^{t,s} + P_{P2H_i}^{max} \le M.u_{10,i}^{t,s} \tag{31}$$

$$P_{H2P_i}^{t,s} \le M.u_{11,i}^{t,s} \tag{32}$$

$$-P_{H2P_i}^{t,s} + P_{H2P_i}^{max} \le M.u_{12,i}^{t,s} \tag{33}$$

IV. CASE STUDY AND DESCRIPTION OF TEST SYSTEM

A. Description of the Test System

To evaluate the proposed two-stage bi-level model, a distribution system with four microgrids is considered a test case, as shown in Figure 2. The elements of microgrids are distributed generators, hydrogen systems, wind turbines, and solar photovoltaic systems. The maximum range of offered power price to microgrids and maximum power exchange between microgrids and distribution system are considered 50 $\$/MWH$ and 4 MW, respectively.

Table I describes the characteristics of resources in this system, and the efficiencies of hydrogen facilities are considered 0.6. In this table v_{cin}, v_{cout}, and v_r are cut-in, cut-out, and rated wind speed, respectively. Furthermore, the model of hydrogen system units is demonstrated in Figure 3. This model contains P2H units (i.e., water electrolyzer units), H2P units (i.e., fuel cell units), and hydrogen storages [15], [16]. This model increases the flexibility of the MGO since it can convert the power to hydrogen in low-price hours and store it in hydrogen tanks to be converted to power in the high-power hours.

For the uncertainty modeling, the Normal, Weibull, and Beta PDFs are utilized to generate 1000 scenarios for demands, wind speeds, and solar radiation in each period, respectively. Each scenario's probability is 0.001 and consists of three uncertain variables (i.e., electrical load, wind speed, solar radiation). The mean value and standard deviation are considered as the average of forecasted values and 5% of them, respectively. Using the SCENRED tool, the generated scenarios are reduced to eight scenarios. Figure 4 illustrates the scenarios of electrical demand, wind speed, and solar radiation. In Figure 4-c, the dashed line is the day-ahead electricity price.

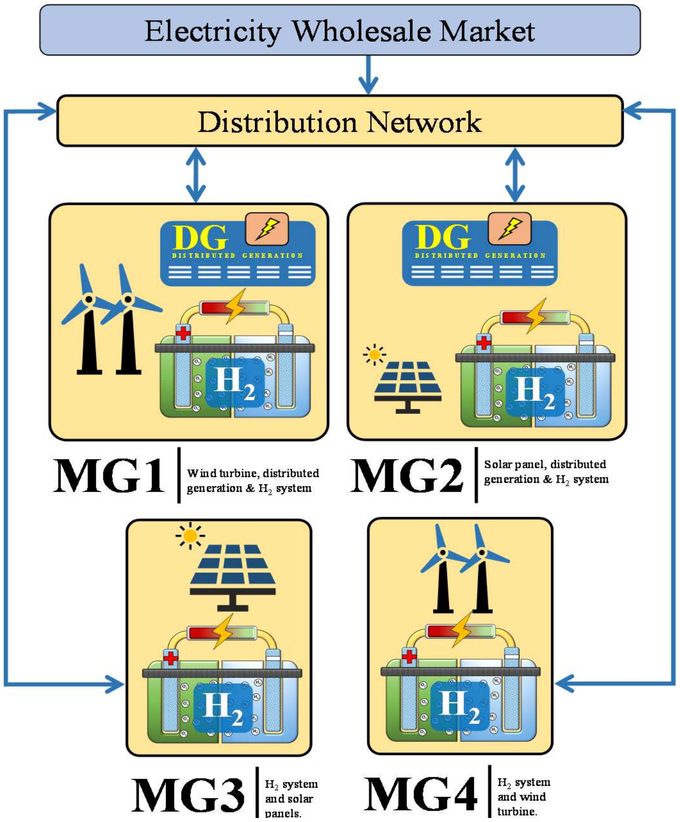

Fig. 2. Model of the test distribution system

TABLE I
CHARACTERISTICS OF RESOURCES IN MICROGRIDS

Hydrogen System	SOH_i^{min} $[MWh]$	SOH_i^{max} $[MWh]$	P_{P2H}^{max} $[MW]$	P_{H2P}^{max} $[MW]$
All MGs	0	2	0.19	0.48
Diesel Generator	$\pi_{DG}[\$/MWh]$		P_{DG}^{min} $[MW]$	P_{DG}^{max} $[MW]$
MG1	55		0	5
MG2	45		0	5
Wind Turbine	$P_{wt,r}$ [MW]	v_{cin} [m/s]	v_{cout} [m/s]	v_r [m/s]
MG1	1.2	3	50	12
MG4	2.4	3	50	12
Solar System	Installed capacity $[MW]$		Efficiency of Solar system	
MG2	2		0.186	
MG3	2		0.186	

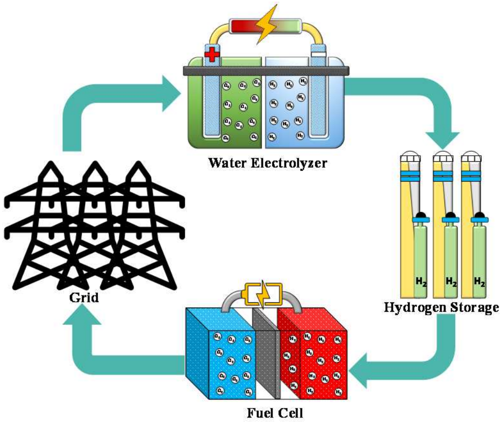

Fig. 3. Model of hydrogen system units

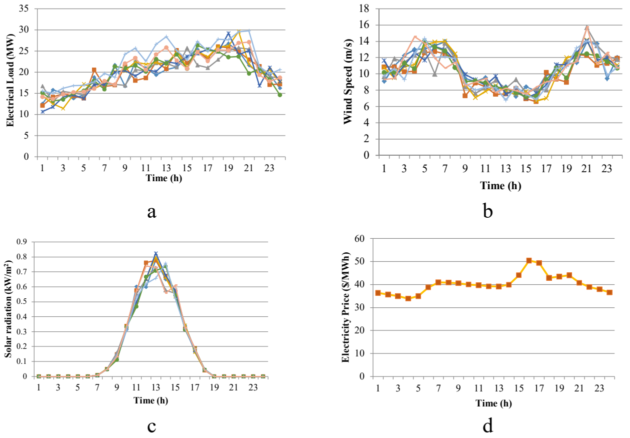

Fig. 4. Scenarios of a: electrical demand of all microgrids, b: wind speed, c: solar radiation, and d: day-ahead electricity market price

V. RESULTS AND SENSITIVITY ANALYSIS

The proposed operation scheduling problem is solved by the CPLEX solver as a MILP executed in GAMS software [17]. Results are presented in the following case studies.

Case 1: Market will be cleared by a similar power price for all microgrids.

Case 2: Market will be cleared by separate power prices for each microgrid.

Table II demonstrates the revenue, cost, and profit of the distribution system in both above cases. As exposed, in Case 2 with the different prices for microgrids, DISCO's revenue is increased, and consequently, the profit is increased up to $2832. The operation cost of DSO is almost similar in both Cases since it depends on wholesale market prices.

Furthermore, the operation costs of all microgrids are demonstrated in Table III. As shown, the most operating costs in Scenario 7 are observed, and the least are run in Scenario 1. On the other hand, by considering separate power prices for microgrids, the expected operation cost of microgrids is increased up to 8%.

TABLE II
DISTRIBUTION SYSTEM PROFIT

	DSO Revenue ($)	DSO Cost ($)	DSO Profit ($)
Case 1	16648	15276	1372
Case 2	18081	15249	2832

TABLE III
MICROGRIDS OPERATION COSTS IN SCENARIOS

Scenario No	MGO Cost ($) Case 1	MGO Cost ($) Case 2	Probability
1	17693	19100	0.157
2	17811	19233	0.169
3	17716	19124	0.180
4	18423	19912	0.144
5	17694	19112	0.091
6	17882	19330	0.076
7	20584	22129	0.079
8	18486	19961	0.104
Expected Cost	18148	19591	1

Table IV demonstrates the offered power price to microgrids in Case1 and Case 2. As expected, the clearing power prices for all microgrids are the same and set to 45 $\$/MWh$ in Case 1. Contrary to Case 1, the clearing prices in Case 2 are higher and set to 50 $\$/MWh$, which is the maximum acceptable range of power price for all microgrids except MG2. In this microgrid, there is a DG with a marginal price of 45 $\$/MWh$, which is preferred to be utilized instead of purchasing power from the distribution system.

Figure 4 represents the purchased power by DSO from the electricity market and the microgrids load profile. As shown, the purchased power is almost similar in both cases and has the same pattern with load profile. As shown in Figure 5, the state of hydrogen in hydrogen tanks increases in hours with low demand (i.e., hour 1-12) and decreases due to discharging at hours with high demand (i.e., hour 13-21) in both Cases.

Figure 6 for Case 1 and Figure 7 for Case 2 shows the procured electrical power of MG2 in Scenario 7.

As shown, the solar photovoltaic generation is similar in both cases. Also, fuel cell power generation is almost the same in Case 1 and Case 2 since its scheduling is determined by load level, not based on the power price of microgrids. Furthermore, the distributed power generation in Case 2 is more than that of in Case 1. In contrast, the purchasing power from the distribution system in Case 2 is lower than in Case 1.

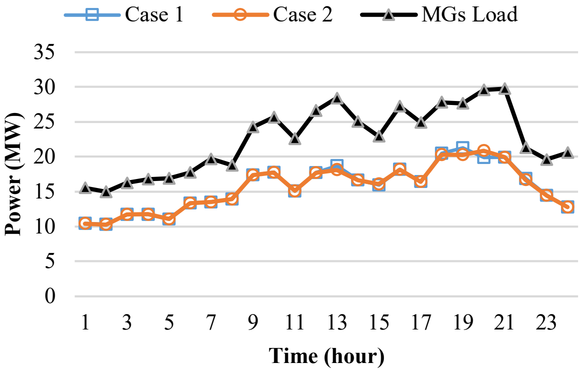

Fig. 4. Procured power by DSO vs. MGs loads

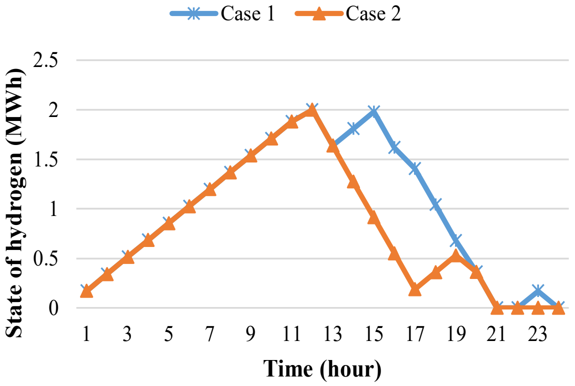

Fig. 5. State of hydrogen in hydrogen tanks in Case 1 and Case2

TABLE IV
DISTRIBUTION SYSTEM OFFERED PRICE TO MICROGRIDS

	MG1	MG2	MG3	MG4
Case 1 ($/MWh)	45	45	45	45
Case 2 ($/MWh)	50	45	50	50

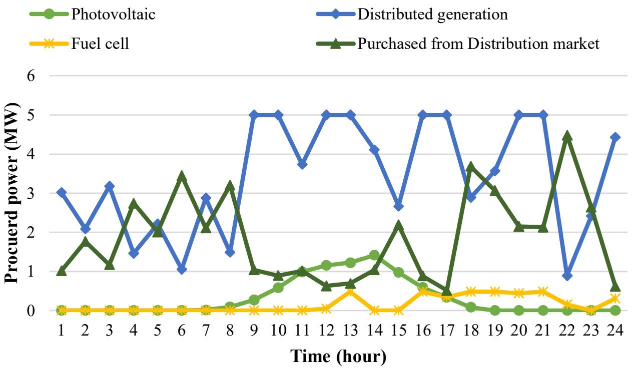

Fig. 6. Power dispatch in Case 1

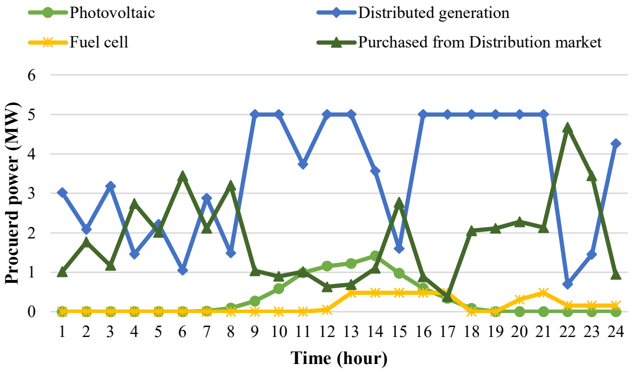

Fig. 7. Power dispatch in Case 2

VI. CONCLUSION

Recently, rapid advances in the field of operation scheduling of multi-entity hydrogen-based systems have occurred. Considering the hierarchical nature of decision-making and facing the uncertainties, this paper proposed a novel two-stage bi-level approach to deal with the operation scheduling problem of hydrogen-based microgrids within a distribution system. The model was applied to a distribution system with four microgrids with uncertainties of loads, solar radiation, and wind speeds. It is concluded that considering a similar power clearing price for all microgrids instead of separated ones in the mathematical modeling has many benefits for microgrids with respect to the distribution system. In other words, in this case, there is less operation cost for MGOs and less profit for the DISCO as well. Furthermore, it has been shown that the clearing power prices of microgrids depend on not only the DSO offered price, but also on availability, capacity, and marginal price of distribution generations in microgrids. Finally, it has been demonstrated that the power dispatch and scheduling of hydrogen systems in microgrids within the distribution system depends on the amount of power exchange between the lower and upper levels.

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