Optimal Coordination of Hydrogen Vehicle Stations and Flexible Resources in Microgrids

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2021 IEEE International Conference on Environment and Electrical Engineering and 2021 IEEE Industrial and Commercial Power Systems Europe (EEEIC / I&CPS Europe) | 978-1-6654-3613-7/21/$31.00 ©2021 IEEE | DOI: 10.1109/EEEIC/ICPSEurope51590.2021.9584761

***Abstract*—Hydrogen vehicle stations (HVSs) that convert electricity into hydrogen have appeared as a new arrival asset to the power system with the raising interest in hydrogen vehicles (HVs). In order to safely power these new assets, microgrids, including different flexible resources, are an ideal option. This paper presents an efficient MG scheduling in the presence of HVSs, renewable energy resources, energy storage systems (ESS) and demand response. This model also takes the uncertainties associated with electrical loads, renewables, and HVs into consideration. In order to create an MILP problem, linearized AC optimal power flow equations are considered. A 21-bus MG is examined by applying the proposed model to various case studies, thereby proving that the MG schedule meets the demand of HVs and electrical load. Employing DR programs can reduce operation costs and reduce the load during peak usage hours. Furthermore, the physical constraints of the network satisfy the security in operation. Finally, numerical analysis illustrates the effectiveness of the proposed method.**

Keywords—Microgrids (MG), Hydrogen vehicle station (HVS), Stochastic scheduling, Demand response (DR), energy storage system (ESS)

I. NOMENCLATURE

Variables

P^{MG}, Q^{MG}	Aggregated provided power by energy markets (MW, MVar)
P^{DA}, Q^{DA}	Provided power by DA market (MW, MVar)
P^{RT}, Q^{RT}	Provided power by RT market (MW, MVar)
P^{EZ}	Consumed power in EZ (MW)
P^{E}	Produced power in ESS (MW)
$P^{E,ch}$, $P^{E,dch}$	Charging/discharging power in ESS (MW)
P^{W}	Output of WT (MW)
P^{DU}, Q^{DU}	Output power of DU (MW, MVar)
P^{C}, Q^{C}	The unintentional curtailed load (MW, MVar)
p^{loss}, q^{loss}	Loss of line (MW, MVar)
P^{L}, Q^{L}	Electrical consumption (MW, MVar)
$P^{L,DR}$, $Q^{L,DR}$	Electrical consumption after using DR (MW, MVar)
Δ^{+}, Δ^{-}	Increased/reduced active demand in TOU-DR (MW)
Δ^{++}, Δ^{--}	Increased/reduced reactive demand in TOU-DR (MVar)
LOP^{TA}	Level of pressure in storage tank for HVS (bar)
SOC	State of charge for ESS (MWh)
E	HVs' consumption (kg)
F^{EZ}, F^{EZ*}	Produced hydrogen in EZ (inflow), outflow hydrogen (kg)
ΔF^{TA}	Hydrogen flow in the tank (kg)
ΔF^{EZ}	Hydrogen flow in EZ (kg)
T^{ch}, T^{dch}	Successive charging/discharging hours of ESS (h)
T^{on}, T^{off}	Successive on/off hours of DU (h)
V^{EZ}	Drop voltage in EZ (Volt)
I	Commitment indicator for DU
y	Charging indicator for ESS
x	Discharging Indicator for ESS
un	Availability Indicator of main grid

Parameters

UT, DT	Minimum up/down time of DU (h)
UR, DR	Ramp up/down value of DU (MW/h)
MC, MD	Minimum charging/discharging time in ESS (h)
c, cc	DA and RT market prices ($/MWh)
k	Hydrogen price in station ($/kg)
$VOLL$	Value of lost load ($/MWh)
Λ	Demand response incentive ($/MWh)
u	The allowed portion of shiftable load
∂	Dissipation parameter of HVS
μ	Unit conversion in LOP
ηEZ	Conversion efficiency in EZ
ηE	Operation efficiency for ESS
ρ	Scenario's probability
Δt	Time interval (h)
R	Gas constant (J/mol K)
J	Current density (A)
LHV	Lower heating value of hydrogen (kWh/kg)
Ms	Mass molar of hydrogen (kg/mol)
τ	Mean temperature inside the storage tank/EZ (K)
Z	Volume of the tank (m^3)
g	Faraday constant (C/mol)

Indexes

t, z	Index for the time and scenario
d,h,e,w	Index for DU, HVSs, ESS and WT

II. INTRODUCTION

A) Motivation and background: One of the recent strategies worldwide have been deployed in order to decrease their dependence on fossil fuels is the deployment of eco-friendly vehicles. While the penetration of electric vehicles is increasing in communities, hydrogen vehicles (HVs) are also attracting attention as being a way for organizations to reduce the urban greenhouse gas emissions [1].

J.P.S. Catalão acknowledges the support by FEDER funds through COMPETE 2020 and by Portuguese funds through FCT, under POCI-01-0145-FEDER-029803 (02/SAICT/2017).

The HV experience is rather similar to that of a fossil fuel-powered vehicle in terms of driving range and fueling time [2]. As more renewable energy sources are deployed, the opportunity for producing more hydrogen gas to power HVs increases. Hydrogen is produced by using an electrolyzer (EZ) by converting electrical energy into hydrogen. Hydrogen can either be produced on a large scale far away from hydrogen vehicle stations (HVSs), where it can then be transferred to the HVSs, or on a small scale at the HVSs [3]. The transportation of hydrogen requires sophisticated distribution infrastructures and specialized services. [4]. The utilization of the renewable energy resources (RESs) and other flexible units such as energy storage systems (ESSs) and demand response (DR) within power systems leads to a serious need for developing an optimal scheduling mechanism for the operation of these resources.

B) Relevant literatures: In recent years, several studies have been conducted to optimize the scheduling of energy systems for attaining various goals. In [5], non-linear stochastic scheduling of integrated wind and hydrogen production is proposed to reduce the wind generation curtailment and operation cost. The robust optimization technique used in [6] schedules the hydrogen productions and renewables. However, physical constraints of network are not considered in this work. In [7], the authors propose a multi-objective model for optimal management of renewables and storage considering DR. The objective of the study is to investigate how DR impacts the overall economic aspects of the operation. Hydrogen production for the transportation sector is neglected in the same study. In [8], a cooperative day-ahead operation HVSs and wind generation for supplying hydrogen vehicles (HVs) is presented, in which the Nash bargaining approach is implemented to deal with the power trading and benefit sharing between the resources. Nevertheless, the AC network constraints are not added to the problem. A centralized scheduling of HVSs is studied in [9], through which the dependency on electricity market reduces, and the HVSs ensure enough capacity for the DR program. The uncertainty and linear problem are not modeled in [9]. In [10], stochastic scheduling of an isolated hybrid electric/hydrogen refueling station is investigated while market trading and DR program are not taken into account.
Reference [11] proposes a model for MG operation, including the HVSs without considering the coordination of ESSs and DR. In this study, the AC power flow formulation is modelled.

C) Contributions and organization: Implementing MGs can provide a reliable solution to integrate the hydrogen production for HVSs using different types of generation units. This is because the penetration of HVSs for providing HVs on the power network is increasing, leading to the necessity to power the HVS continuously and safely, which can be satisfied by MG. To the best of our knowledge, there exist a very limited number of studies that focus on MGs incorporating HVSs for the urban transportation sector. Furthermore, previous researches have not considered the coordination of the DR and ESS with the HVS using a comprehensive linear ACOPF model. MG operators face many uncertainties, including electrical loads, HVs and renewables; therefore, effective managing of these uncertain sources is necessary. The goal of this study is to fill in these gaps with MG stochastic scheduling, guaranteeing optimal coordination of HVSs with flexible load and generation resources in the presence of various uncertainties.

The rest of the paper is organized as follows. Section III reviews the preliminaries and methodology. Section IV presents the problem formulation. Section V presents numerical analysis, and the last section concludes the study.

III. METHODOLOGY

Operation of HVSs: Fig. 1 shows the process of hydrogen production in an HVS. In HVSs, EZ consumes power to produce hydrogen and oxygen, as depicted in chemical reactions (1a) and (1b) [6]. Hydrogen in EZ is described by (2a). The difference between hydrogen inflow and hydrogen outflow in EZ is defined as (2b). According to the flow differences in EZ, the level of pressure (LOP) is defined as (2c) [12]. However, hydrogen inlet and outlet flow rate must be equal to make the pressure constant in EZ in steady state mode, as shown in (3). EZ only consumes power relevant to its demand since the current density and temperature are fixed. As depicted in (4a)-(4b), storage tank pressure levels are also influenced by integrals of the net gas flow, or the difference between gas flowing into and out of the tank. 'E' stands for hydrogen consumed by HVs in the HVS. Considering the equations, k is a constant factor that is dependent on the volume, temperature and other properties of the tank and EZ [8]. The linear form of these equations will be used in our problem.

$$Cathode:\ 2H_2O(l) + 2e^- \rightarrow H_2(g) + 2OH^-(aq) \quad (1a)$$

$$Anode:\ 2OH^-(aq) \rightarrow 0.5O_2(g) + H_2O(l) + 2e^- \quad (1b)$$

$$F_t^{EZ*} = \frac{\mathbb{P}^{EZ}(\tau^{EZ}, J^{EZ}) \times P_t^{EZ}}{V_t^{EZ} \times 2g} \quad (2a)$$

$$\Delta F_t{}^{EZ} = F_t{}^{EZ*} - F_t{}^{EZ} \quad (2b)$$

$$LOP_t{}^{EZ} = k^{EZ} \int \Delta F_t{}^{EZ} dt \quad (2c)$$

$$F_t^{EZ} = F_t^{EZ*} = \eta^{EZ} \frac{P_t^{EZ}}{LHV} \quad (3)$$

$$LOP_t{}^{TA} = k^{TA} \int \Delta F_t{}^{TA} dt \quad (4a)$$

$$\Delta F_t{}^{TA} = F_t{}^{EZ} - E_t \quad (4b)$$

Methodology: Fig. 2 describes in detail the proposed stochastic scheduling framework applicable to the MG. The goal of this scheduling procedure is to achieve the minimum operation cost. Data of historical demands and WTs are collected before using the simulation tool to generate scenarios. Using this data set, stochastic data analysis occurs for scenario generation and reduction, as shown in the figure, respectively. In addition to the deterministic and stochastic inputs, the optimal scheduling module is used to manage the resources. The results of this optimal scheduling are categorized into two stages as shown in the output variables box.

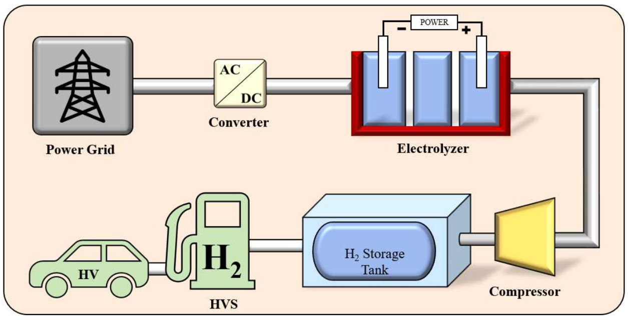


Fig. 1. The process of hydrogen production for HVS

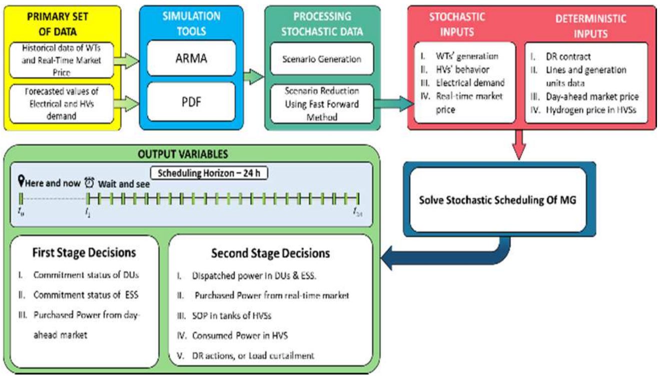


Fig. 2. Presented model for stochastic scheduling

A determination of the commitment status of DUs and ESS is made in the first stage of decisions, as well as the amount of purchasing power from the DA market. The second stage is where the purchasing power from the RT market, dispatched power by DUs and ESS, consumed power by HVSs for hydrogen production, regulating security constraints, DR participation and load curtailment (if required) are determined. In the following section, the mathematical formulations of the proposed model are introduced.

IV. Problem Formulations

Equations (5a)–(5C) show the objective function of minimizing the expected operation cost over the scheduling window. In general, there are two main components of expected operation costs. As shown in (5b), the first term represents the expected cost of acquiring power from the DA market. Moreover, the second term of expected costs includes the cost of purchasing energy from RA markets, the cost of DUs, the profit from selling hydrogen in HVSs, the TOU-DR incentive cost, and the load curtailment cost, as shown in (5c).

$$\mathcal{H} = Min \sum_{t\epsilon T} f_I(t)\Delta t + \sum_{t\epsilon T}\sum_{z\epsilon Z} \rho_s\, f_{II}(t,z)\Delta t \tag{5a}$$

$$f_I(t) = c_t P_t^{DA} \tag{5b}$$

$$f_{II}(t,z) = cc_{t,z}P_{t,z}^{RT} + \sum_{n\in N}\sum_{d\epsilon D} c(P_{n,d,t,z}^{D}) - \sum_{n\in N}\sum_{h\epsilon H} kG_{n,h,t,z} + \sum_{n\in N} \Lambda_{t,z}\Delta_{n,t,z}^{+} + \sum_{n\in N} VOLLP_{n,t,z}^{C} \tag{5c}$$

The technical and economical constraints of the proposed model are represented as bellow:

Constraints (6a)–(6b) determine the limits for imported power from the electricity markets. The binary variable $un_{t,z}$ is the state of main grid availability. Also, constraints (6c)-(6d) dignify the purchasing power from both DA and RT markets.

$$P^{MG,min}un_{t,z} \le P_{t,z}^{MG} \le P^{MG,max}un_{t,z} \tag{6a}$$

$$Q^{MG,min}un_{t,z} \le Q_{t,z}^{MG} \le Q^{MG,max}un_{t,z} \tag{6b}$$

$$P_{t,z}^{MG} = P_t^{DA} + P_{t,z}^{RT} \tag{6c}$$

$$Q_{t,z}^{MG} = Q_t^{DA} + Q_{t,z}^{RT} \tag{6d}$$

The linearized operational constraints for HVS are defined by (7a)-(7e). As shown by (7a), the consumed power of EZ is bounded by its minimum and maximum power consumption. The produced hydrogen flow (F) in EZ, which is an input flow of the storage tanks for charging HVs (E), is defined as (7b). Constraint (7c) represents the self-efficacy of the tank, reflected in the LOP, input and output hydrogen flow rates, and hydrogen dissipation [9]. Furthermore, (7d) restrains the LOP to consider the limitations of the storage tank. Constraint (7e) makes sure that the LOP at the beginning and end of the scheduling period remains the same for ease of scheduling the following day.

$$P_h^{EZ,min} \le P_{h,t,z}^{EZ} \le P_h^{EZ,max} \tag{7a}$$

$$F_{h,t,s} = \eta_h^{EZ}\frac{P_{h,t,z}^{EZ}}{LHV_h} \tag{7b}$$

$$LOP_{h,t,z}^{TA} = LOP_{h,t-1,z}^{TA} + \mu\frac{R\tau^{TA}}{Z^{TA}Ms}(F_{h,t,z} - E_{h,t,z})\Delta t - \partial_h LOP_{h,t,z}^{TA} \tag{7c}$$

$$LOP_h^{TA,min} \le LOP_{h,t,z}^{TA} \le LOP_h^{TA,max} \tag{7d}$$

$$LOP_{h,1,z}^{TA} = LOP_{h,T,z}^{TA} \tag{7e}$$

Constraint (8a) defines the amount of stored energy, acquired when charging/discharging in ESS. Constraints (8b)-(8c) define the boundaries of charging-discharging power. As constrained by (8d), the charging-discharging procedure cannot occur concurrently. State of charge (SOC) referring to the relationship between stored energy during a charging-discharging procedure, is ensured by (8e). In (8f), the SOC should be kept between the maximum and minimum ranges. Constraints (8g)-(8h) keep charging and discharging for the assigned following hours [13].

$$P_{e,t,z}^{E} = P_{e,t,z}^{E,dch} - P_{e,t,z}^{E,ch} \tag{8a}$$

$$P_e^{E,ch,min} y_t \le P_{e,t,z}^{E,ch} \le P_e^{E,ch,max} y_t \tag{8b}$$

$$P_e^{E,dch,min} x_t \le P_{e,t,z}^{E,dch} \le P_e^{E,dch,max} x_t \tag{8c}$$

$$x_t + y_t \le 1 \tag{8d}$$

$$SOC_{e,t,z} = SOC_{e,t-1,z} - (1/\eta_e^E) P_{e,t,z}^{E,dch} \Delta t + \eta_e^E P_{e,t,z}^{E,ch} \Delta t \tag{8e}$$

$$SOC_e^{min} \le SOC_{e,t,z} \le SOC_e^{max} \tag{8f}$$

$$MC_e(y_t - y_{t-1}) \le T_{e,t}^{ch} \tag{8g}$$

$$MD_e(x_t - x_{t-1}) \le T_{e,t}^{dch} \tag{8h}$$

The maximum and minimum generation of DUs follows constraints (9a)–(9b) [18]. The binary variable represents the commitment status of the DUs.

The ramp-up/down rate boundaries obey (9c)–(9d), showing that the generated power cannot surpass these rates in two consecutive hours. Also, minimum up/down hours are confined by (9e)–(9f). These constraints ensure the minimum on and off time limits.

$$P_d^{D,min} I_{d,t} \le P_{d,t,z}^{D} \le P_d^{D,max} I_{d,t} \tag{9a}$$

$$Q_d^{D,min} I_{d,t} \le Q_{d,t,z}^{D} \le Q_d^{D,max} I_{d,t} \tag{9b}$$

$$P_{d,t,z}^{D} - P_{d,t-1,z}^{D} \le UR_d \tag{9c}$$

$$P_{d,t-1,z}^{D} - P_{d,t,z}^{D} \le DR_d \tag{9d}$$

$$UT_d(I_{d,t} - I_{d,t-1}) \le T_{d,t}^{on} \tag{9e}$$

$$DT_d(I_{d,t-1} - I_{d,t}) \le T_{d,t}^{off} \tag{9f}$$

Residential consumers shift their demand into low-peak hours in the TOU-DR program, as previously mentioned. The amount of transferred load is $u \times 100\%$ of the main demand. To satisfy consumers properly, the sum of the reduced and increased demand in the operation horizon must be the same. The mathematical formulas of the TOU-DR application in the MG operation is as (10a)-(10h) [14].

$$P_{t,z}^{L,DR} = P_{t,z}^{L} + \Delta_{t,z}^{+} + \Delta_{t,z}^{-} \tag{10a}$$

$$Q_{t,z}^{L,DR} = Q_{t,z}^{L} + \Delta_{t,z}^{++} + \Delta_{t,z}^{--} \tag{10b}$$

$$-u \times P_{t,z}^{L} \le \Delta_{t,z}^{-} \le 0 \tag{10c}$$

$$0 \le \Delta_{t,z}^{+} \le u \times P_{t,z}^{L} \tag{10d}$$

$$-u \times Q_{t,z}^{L} \le \Delta_{t,z}^{--} \le 0 \tag{10e}$$

$$0 \le \Delta_{t,z}^{++} \le u \times Q_{t,z}^{L} \tag{10f}$$

$$\sum_{t \in T} \Delta_{t,z}^{-} + \sum_{t \in T} \Delta_{t,z}^{+} = 0 \tag{10g}$$

$$\sum_{t \in T} \Delta_{t,z}^{--} + \sum_{t \in T} \Delta_{t,z}^{++} = 0 \tag{10h}$$

The security constraints for voltage regulation, load curtailment, loss of lines and power flow of lines are also considered in this study, as presented in [13].

V. NUMERICAL ANALYSIS AND CASE STUDIES

A. System under study and data

In order to examine the proposed method, 21-bus MG [15] is used, as shown in Fig. 3. The technical parameters of HVSs in MG are used from [11]. The technical data related to other resources are borrowed from [13].

The data of the RT/DA markets, and WTs' generation is adopted from [16] for scenarios generation. Figure 4 also demonstrates the HV demands, which are approximated based on the profile represented in [11]. The price of produced hydrogen is 1.35 $/kg [11].

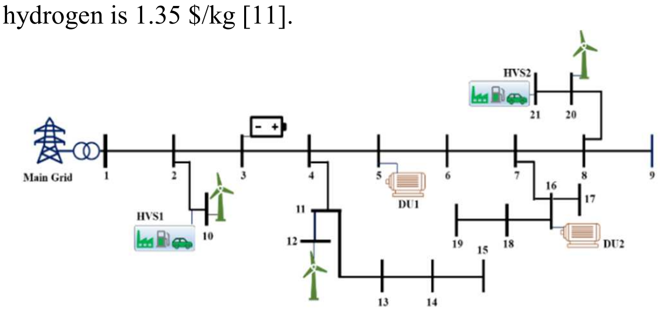
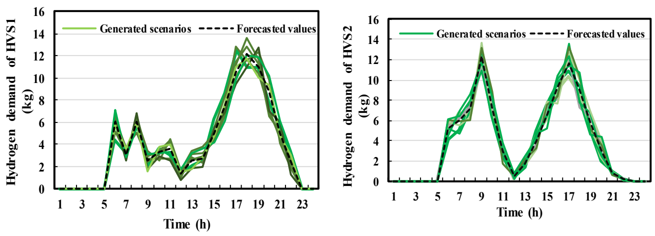


Fig. 3. Schematic of MG



a) HVS 1 b) HVS 2

Fig. 4. Demand of Hydrogen vehicles in different HVSs

B. Numerical analysis and discussion

Fig. 5 Illustrates the energy consumers that are provided by DUs, ESS, and the electricity market. ESS is charged between 2-6 in the low electricity price period. Once the market price is higher, it starts discharging about 16 to 21 when the load increases. Even though DUs are set up to supply power at all times, they generate most of their power during high-price periods (i.e., 20-21).

However, the share of the electricity markets' power is significant in supplying demand at the beginning of the day as the market price is much lower than DUs' generation cost. The purchased market power decreases to the minimum level in 20 as the market price is very high.

In addition, HVSs receive power for producing hydrogen for use by HVs. As can be seen in Fig. 6, aggregated power consumed in HVS1 and HVS2 has risen partly in hours 3-6 and significantly in 16-19. In these hours, the consumption levels of HVs are at their highest, and the hydrogen generated in the HVSs is sold to HVs at the stipulated price.

Fig. 7 shows how much hydrogen is produced and consumed at both stations. Indications of demand for HVs are exhibited by the yellow line, but supply of hydrogen is displayed by the green line. To ensure a sufficient supply of hydrogen during peak demand hours, hydrogen production starts before HVs reach the station. In this process, the HVs do not utilize the entire amount of hydrogen produced by the converted power. In the storage tank, there is still some hydrogen.

The pressure of the stored gas never reaches zero as shown in the illustration Fig. 8. In Fig. 8 for time periods such as 4-8 and 12-17, LOP increases in the hydrogen storage tank in the morning and afternoon so that the HVSs are ready for fueling HVs. Additionally, the pressure at the end of the scheduling horizon needs to be maintained at its original level, as shown in Fig. 8. The operation cost of MG is 1952.92$ using these resources.

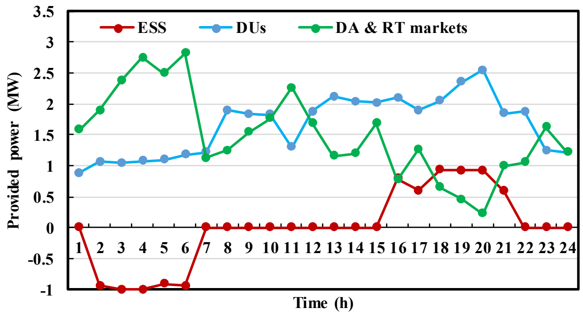


Fig. 5. Provided electrical energy by DUs, ESS, and electricity markets

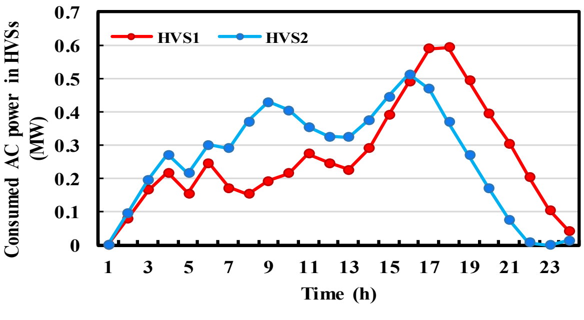


Fig. 6. Consumed AC power in HVSs for hydrogen production

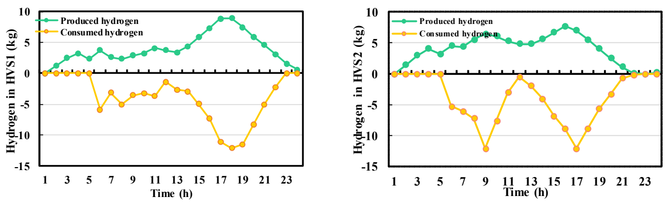


Fig. 7. Produced/consumed hydrogen in HVSs

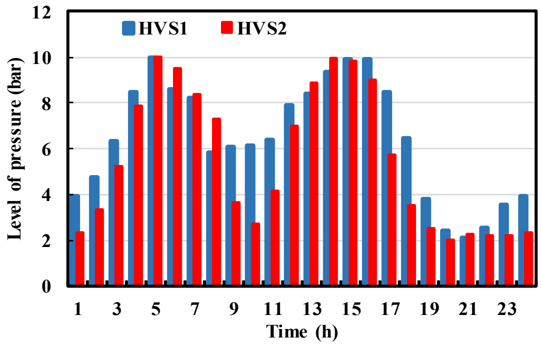


Fig. 8. LOP of storage tank in HVSs

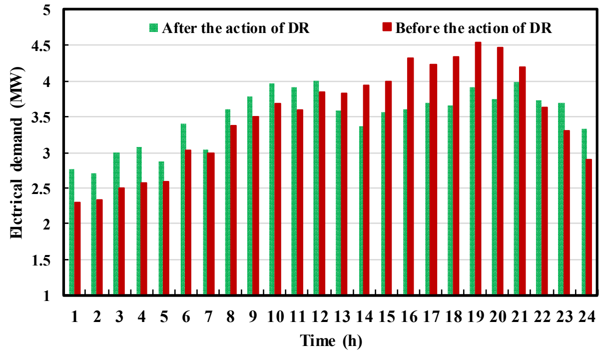


Fig. 9. Influence of TOU-DR on load profile

This scheduling also investigates the TOU-DR program's influence. In this case, up to 20% of consumers can participate in the TOU-DR program. Fig. 9 illustrates how the loading profile changes when this program is used. According to this profile, some portion of demand in peak hours (i.e., 13-21) is shifted to the low demand and price hours. The operation cost in MG reduces 2.23%, compared to the operation without DR actions. Not only is the operation cost reduced, but also the risk of load shedding in critical situations is mitigated.

VI. Conclusion

Integrating HVs at large-scale into the future grids requires the adoption of HVSs to provide the necessary infrastructure. The HVS should be provided with reliable and consistent power to operate properly. The HVs' demand can be safely met by MGs that use flexible units, especially clean ones like renewable energy resources, ESS, and DR. Therefore, an efficient stochastic model was proposed for MGs to schedule HVSs and flexible resources optimally. This problem modelled the uncertainties of HV, electrical load, WTs, and RT market prices. In addition, we presented a linearized model that confirmed the accuracy and fast convergence in our mathematical analysis. Further, we examined how to coordinate ESS, alongside TOU-DR, so that electric consumers and HVs could benefit from more economical, flexible, and reliable operations. Additionally, simulation results demonstrated the effectiveness and application of the proposed method while adequately addressing research gaps in the area of MG operation studies considering HVSs, uncertain behaviour of HVs, and flexible resources such as ESSs and DRs.

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