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Distributed Telemetry and Dynamic Allocation across Renewable-Fed Multi-Cell Hydrogen Plants

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Abstract

The electricity supply is also variable at renewable power plants and uneven distribution of energy across several cells makes it difficult and often impractical to maintain optimal hydrogen output and energy use efficiency from the renewable energy. Existing allocation methods are mainly based on the distribution of fixed or equal power levels, irrespective of real-time operating conditions of cells. This paper presents a newly proposed Telemetry Based Dynamic Power Allocation (TDPA) method which allocates the renewable power dynamically based on the cell efficiency and temperature simulation data received from the distributed telemetry. The proposed framework was tested in a MATLAB simulation model of a 4-cell hydrogen plant with a renewable power range of 20-80 kW, an operating time of 24 hours and a simulation interval of 1 minute. The proposed approach increased the hydrogen production by 5.3% while maintaining a target of 21.9 kg/day, while raising the share of RE from 88.5% to 93.1% and decreasing the maximum cell temperature from 64.2°C to 61.8°C, and the renewable curtailment from 11.5% to 6.9% was further reduced. As can be seen from these results, the suggested TDPA framework can be considered as an effective and low-cost solution for the operation of a multi-cell hydrogen plant based on renewables.

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1. Introduction

Enhanced penetration of renewable energy has given rise to the need to consider green hydrogen production as a sustainable alternative for long-term energy storage and decarbonization. Clean hydrogen generation by water electrolysis using solar and wind energy is an important technology in the future energy landscape, because it allows carbon-free hydrogen production. However, renewable energy is inherently variable in nature, so there is constant fluctuations in electrical power provided to the electrolyzer plants. Variable conditions may decrease the efficiency of hydrogen production and cause unequal usage of the electrolysis cells.

Multi-cell electrolyzer plants have been gaining much attention as they offer greater flexibility in operation than single-cell. Running the plant with multiple cells allows for flexibility in the operation of the plant when the renewable energy source is intermittent, while assuring hydrogen production at all times. However, at high rates of renewable energy fluctuation, it is difficult to coordinate effectively between the cells. Traditional equal power allocation methods are based on equal power sharing among all cells, regardless of individual cell operating conditions, which can lead to over thermalization, sub-optimal power use efficiency and lower hydrogen yield.

Distributed telemetry is a good solution to monitor an electrolyzer cell's operating status continuously. The telemetry allows the allocation controller to determine the power distribution decision based on the actual operating state of each cell as it collects essential data including cell temperature and efficiency of conversion. Combining telemetry and dynamic allocation can then enhance plant performance without the complexity of adding dynamic allocation.

A novel Telemetry Based Dynamic Power Allocation (TDPA) approach for renewable energy sources (RES) fueled multi-cells hydrogen plants is proposed in this paper. The main findings of the work are threefold: (i) the strategy developed to continuously monitor the operating conditions of multiple electrolyzer cells is distributed; (ii) a lightweight dynamic power allocation strategy that allocates power to cells based on their efficiency and temperature is developed under different renewable energy conditions to improve the utilization of renewable energy compared with the conventional equal power, (iii) test and validation of the proposed framework through simulation and improvements gained in hydrogen production, renewable energy utilization, renewable power curtailment and thermal performance are demonstrated when compared with the equal power conventional strategy.

2. Related Work

Hydrogen generation using renewable energy has proven to be an exciting research field due to its potential role in low carbon energy systems and energy storage over longer time periods [8]. Some recent studies have considered the combination of pepm and alkaline electrolyzer with solar pv and wind energy to achieve high efficiency of hydrogen generation in the presence of variable renewable generation [2]. In recent years, several energy management strategies have been offered to make best use of renewable energy resources [4] but many of these strategies place emphasis on maximizing hydrogen production with little consideration for the coordinated operation of multiple electrolyzer cells subjected to constantly varying power input [7].

In order to increase operational flexibility, multi-cell or modular configurations of electrolyzers have been developed, where the available renewable power is split between multiple electrolyzer units [9]. Such studies have shown that modular operation can alleviate unnecessary shutting down requirements and offer more flexibility to variability in renewable power generation than single stack arrangements [6]. However, most of the traditional power management approaches use either fixed scheduling or equal power allocation approach where the power is equally distributed among the cells irrespective of their instantaneous operation [3]. Consequently, the variability among cells in terms of their efficiency and thermal characteristics is often ignored, resulting in an energy inefficiency and variation in operating conditions [11].

New developments in telemetry and digital monitoring now allow real-time monitoring of the operating parameters in renewable energy systems [1]. Alternately, distributed telemetry enables many parts of the plant to send operating data, like electrical power, temperature and conversion efficiency, to be used in centralized decision-making [5]. In parallel, there have been studies on dynamic power allocation techniques that aim at optimizing energy distribution based on varying system conditions [10]. While the performance of individual techniques has been satisfactory, there has been limited research on the combined use of these techniques in a multi-cell hydrogen plant powered by renewable sources [12]. There is a lack of research that combines distributed telemetry with an approach to dynamically allocate resources which was particularly developed for the case of modular electrolyzer coordination in the presence of renewable power sources that experience fluctuations.Existing research does not consider distributed telemetry combined with a lightweight dynamic allocation strategy, specifically designed for cases of fluctuating renewable power and modular electrolyzer coordination.

Hence, this study will tackle this research gap by proposing a Telemetry-Based Dynamic Power Allocation (TDPA) framework using simulated telemetry information for the adjustment of the allocation of renewable power among multiple electrolyzer cells. The adaptive simulation-based allocation strategy is proposed to improve hydrogen production rate, utilize renewable power more, minimize renewable power curtailment, and keep the operating temperature lower.

3. Proposed Distributed Telemetry And Dynamic Allocation Framework

3.1 Overall System Concept

The proposed Renewable-Fed Multi-Cell Hydrogen Plant will utilize distributed telemetry and adaptive power allocation to improve renewable energy use. The system consists of a renewable energy source, a distributed telemetry unit, a Telemetry Based Dynamic Power Allocation (TDPA) controller, four electrolyzer cells and a hydrogen production unit as illustrated in Figure 1. The architecture allows for monitoring of cell operating conditions and dynamically distributing renewable power among the electrolyzer cells.

The renewable energy source is a sum of power generated by Solar PV and wind. As renewable energy sources are intermittent, the available power that is supplied to the hydrogen plant varies over time. This renewable energy is the key resource to the proposed allocation framework.

The distributed telemetry unit is able to continuously measure the operating condition data for each electrolysis cell, such as the operating temperature and conversion efficiency data, and to transmit the data to the TDPA controller. With these telemetry data, the controller can distribute more power to the cells with higher efficiency and lower cell temperature, while the lower efficiency cells with higher temperatures will receive less power, thus maintaining balanced plant operation.

Four parallel electrolyzer cells are used to convert electrical energy to hydrogen using the allocated renewable power. Hydrogen from all the cells is merged to get the overall output of the plant. The proposed architecture offers a simple and effective design that delivers adaptive renewable power allocation, multi-cell power balancing and enhanced hydrogen production under variable renewable energy (VRE) condition as shown in Figure 1.

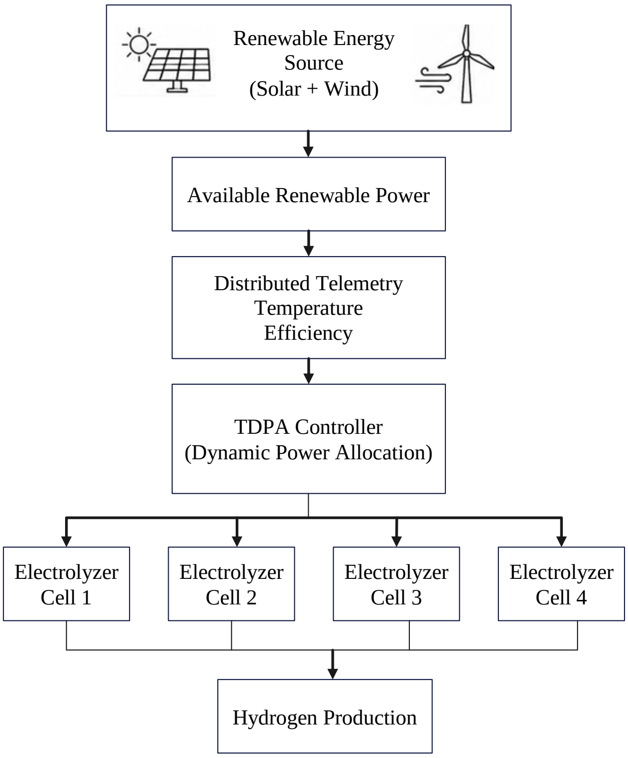

Fig. 1. Architecture of the Proposed Renewable-Fed Multi-Cell Hydrogen Plant

3.2 Telemetry-Based Dynamic Allocation

The proposed Telemetry Based Dynamic Power Allocation (TDPA) method will continuously collect the telemetry data from each electrolyzer cell and distribute the total available renewable power based on the operating status of the electrolyzer cells. The telemetry unit records the conversion efficiency and temperature for each of the four required temperature zones of the electrolyzer, and sends this data to the TDPA controller every simulation time step. Telemetry data received from the cells allows the controller to take a look at the condition of each cell by calculating a priority score. Renewable energy can be used effectively with lower temperature cells, and hence higher temperature cells are of lower priority. The available renewable energy is then distributed in the same proportion as the calculated priority score, and the same procedure is followed during the simulation, adapting the power distribution as new operating conditions of the cells and renewable energy are encountered. The priority score of i-th electrolyzer cell is computed by Equation (1).

$$S_i(t) = 0.6\eta_i^n + 0.4[1 - T_i^n(t)], \_\_\_\_\_\_\_\_\_ (1)$$

InEquation (1), $S_i(t)$ denotes the priority score of the i-th electrolyzer cell at simulation time$t$, η_i^n represents the normalized conversion efficiency of the i-th cell, and $T_i^n(t)$ denotes its normalized operating temperature. . The weighting factors 0.6 and 0.4 represent the relative importance given to the conversion efficiency and operating temperature, respectively. The priority score is higher, as a result of increased conversion efficiency and reduced operating temperature, so that the TDPA controller can allocate renewable power in a flexible way to maintain a balanced operation and optimize the hydrogen production performances.

3.3 Dynamic Renewable Power Allocation

This proposed Telemetry-Based Dynamic Power Allocation (TDPA) method distributes the available renewable power amongst four electrolyzer cells based on a priority score derived from them, rather than distributing power equally.Once the priority scores determined by equation (1) are received by the controller, the controller assigns more renewable energy to the cells with higher conversion efficiency, lower operating temperature, and less to the hotter cells to minimize thermal stress.This adaptive strategy optimizes the use of renewable sources, ensures the cell is operating within its optimum range and generates more hydrogen.

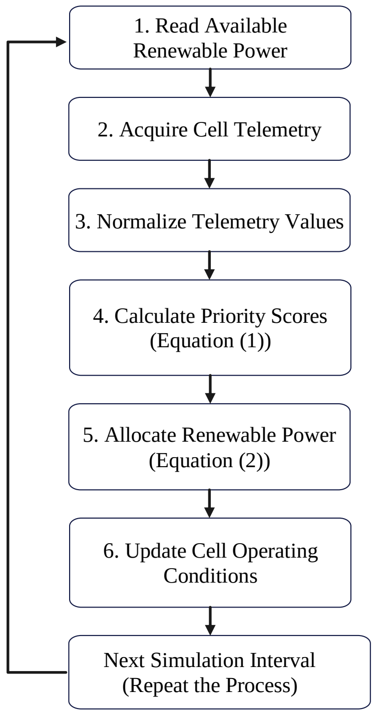

Fig. 2. Workflow of the Proposed Telemetry-Based Dynamic Power Allocation Method

Figure 2 shows the overall allocation process. All of these tasks are performed continually by the controller, which then uses the resulting priorities to schedule the allocation of renewable power, adjusting operating conditions of the electrolyzer cells, and then repeats this process for the next simulation interval. This feedback mechanism allows adaptation to varying renewable power and cell operating conditions. The renewable power for the i-th electrolyzer cell is calculated as in Equation (2).

$$P_i(t) = P_{ren}(t)\frac{S_i(t)}{\sum_{j=1}^{4} S_j(t)}, \quad (2)$$

In Equation (2), $\boldsymbol{P_i(t)}$ is the renewable power allocated to the $\boldsymbol{i}$-th electrolyzer cell at time $\boldsymbol{t}$, $P_{ren}(t)$is the total available renewable power, and $S_i(t)$ is the priority score obtained from Equation (1). The denominator, $\sum_{j=1}^{4} S_j(t)$, represents the sum of the priority scores of all four cells, while i denotes the cell index (1-4)and t is the simulation time. The distributed renewable energy is proportional to the priority score, as stated in Equation (2), which guarantees a balance operation, greater use of renewables and higher hydrogen production.

4. Simulation Setup

The proposed Telemetry Based Dynamic Power Allocation (TDPA) framework was tested using a MATLAB/Python based simulation. The simulation is a hydrogen production plant fed by renewables, with four parallel electrolyzer cells where renewable power is dynamically allocated depending on the priority as ranked by the telemetry based priority scores. The solar and wind energy is intermittent and a synthetic renewable power profile, ranging from 20kW to 80kW was employed over a 24 hour operating period. The simulation time step used was 1 min, enabling the real-time monitoring of the behavior of the cells and the allocation of the power needed in the adaptive way within the study time horizon.

For this simulation the following assumptions are made: All electrolyzer cells have the same rated capacity of 20 kW and they operate independently with control by the proposed TDPA controller. The controller collects the temperature and efficiency of each cell at each time step of the simulation, calculates the priority scores (see Equation (1)), and distributes the available renewable power with Equation (2) at every time step. Various parameters used for the simulation in the present study are reported in Table 1.

Table 1. Simulation Parameters

Parameter	Value
Number of cells	4
Rated power per cell	20 kW
Renewable power	20-80 kW
Simulation duration	24 h
Time step	1 min

4.1 Hydrogen Production Model

The hydrogen production capacity of the proposed multi-cell renewable fueled electrolyzer system is estimated by using contribution of the renewable power and the conversion efficiency of each cell of this electrolyzer. The total hydrogen production is the sum of the hydrogen produced by all four cells for each simulation interval. The hydrogen production model is written in Equation (3).

$$M_{H_2} = \sum_{i=1}^{4} \frac{\eta_i P_i \Delta t}{33.33}, \quad (3)$$

In Equation (3), M_{H_2}represents the total hydrogen produced during the simulation (kg), η_i denotes the conversion efficiency of the $\boldsymbol{i}$-th electrolyzer cell, P_i is the renewable power allocated to the $\boldsymbol{i}$-th cell (kW), andΔt represents the simulation time step (h). The value 33.33 kWh/kg is the energy needed to generate 1 kg of hydrogen. Overall hydrogen production can be enhanced by having the highest possible cell efficiency and a maximum allocation of renewable power; the proposed TDPA framework can achieve this by maximizing renewable energy use and optimizing hydrogen production.

4.2 Renewable Energy Utilization

Evaluating the effectiveness of available renewable power sources for hydrogen production is called Renewable Energy Utilization (REU). It is the percentage of renewable energy that is used for the electrolyzer cells to the total renewable energy available in the simulation. The higher the REU, the greater the efficiency in using renewable resources and the less energy wastage. The calculation of the renewable energy utilisation is shown in Equation (4).

$$REU = \frac{Energy\ \ Used}{Available\ \ Renewable\ \ Energy}, \quad (4)$$

REU in Equation (4) represents the percentage of renewable energy used from the renewable source in the four electrolyzer cells in this simulation and is equal to the total renewable energy supplied by the synthetic renewable source (Available Renewable Energy) divided by the total renewable energy used by the four electrolyzer cells (Energy Used). When more renewable energy is effectively allocated for hydrogen production, its utilization increases as is made clear from Equation (4).

Renewable energy utilization is directly correlated with renewables energy curtailment. The more that renewable energy is used, the less is curtailed. The lower it is used, the less renewable energy is curtailed. Hence, the proposed TDPA framework will maximize REU which will also reduce the wastage of the RE in hydrogen production.

The synthetic renewable power profile used for the simulation is shown in Figure 3. The profile is a periodic output of renewable energy, ranging from 20kW to 80kW, to simulate actual solar and wind conditions. The daily increase of the renewable power continues throughout the day, and peaks at 12 h at 80 kW, as depicted in Figure 3, before decreasing towards the end of the simulation. This time-varying renewable input can be used as the power input in the proposed TDPA framework and as a realistic operating scenario for the evaluation of adaptive renewable power allocation and hydrogen production.

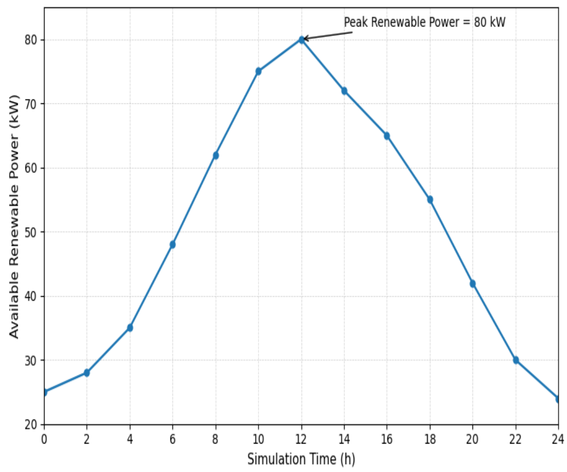

Fig. 3. Synthetic Renewable Power Profile Used in Simulation

5. Results And Discussion

5.1 Dynamic Allocation Behaviour

The proposed Telemetry-Based Dynamic Power Allocation (TDPA) framework dynamically allocates the total renewable power among the four electrolyte cells based on the actual operation conditions. The allocation is continuously adjusted by the controller, which uses the priority scores based on telemetry data, as the renewables change during the simulation. This Adaptive strategy allows efficient use of the renewable energy available and adapts to changes in the efficiency and operation temperature of the cells.

Figure 4 shows the power allocation for renewables that is acquired from the proposed framework. As depicted in the figure, the allocated power rises from 48 kW at 6 h to 80 kW at 12 h which is the peak of the renewable power availability. In this time, cell 1 gets 22 kW, which is the maximum possible, since it has the highest priority score out of all the cells, and the rest of the cells are allocated power in proportion to their operating conditions. The power of each of the four cells is proportionately decreased, as the available renewable power decreases in the later hours.

It can also be seen from Figure 4 that the proposed TDPA framework keeps the loading balance between the electrolyzer cells which provides less power to a single electrolyzer cell rather than utilizing all the power to a single cell. The allocation of power to cells is not much affected by the simulation, making this operation stable in multi-cells without too much loading of the individual electrolyzers. This adaptive and balanced allocation would help in improving the utilization of renewable energy sources, enable efficient production of hydrogen and also boost the overall performance of the multi-cell hydrogen plant with renewable energy.

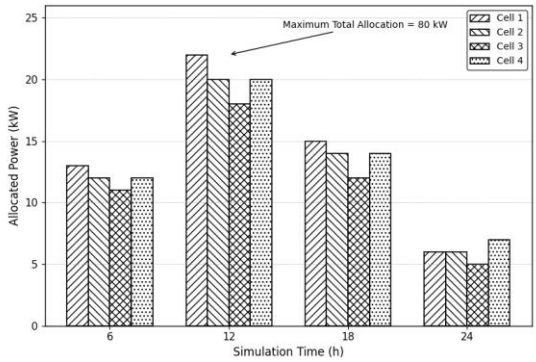

Fig. 4. Allocated Power for Four Electrolyzer Cells

5.2 Comparative Performance

The capability of the proposed Telemetry Based Dynamic Power Allocation (TDPA) strategy is presented and compared to the conventional Equal Allocation strategy. Four main performance metrics are compared - hydrogen production, renewable energy utilisation, renewable energy curtailment and maximum operating temperature. The summarised comparative results are shown in Table 2.

Table 2. Performance Comparison

Metric	Equal Allocation	Proposed TDPA
Hydrogen production	20.8 kg/day	21.9 kg/day
Renewable utilization	88.5%	93.1%
Renewable curtailment	11.5%	6.9%
Maximum temperature	64.2˚C	61.8˚C

As shown in Table 2, the proposed TDPA framework was successful at producing 21.9 kg/day of hydrogen while the Equal Allocation method had a hydrogen production yield of 20.8 kg/day. The improvement is said to be due to the adaptive distribution that is carried out based on the real time operating conditions of the electrolyzer cells, thus allowing more efficient conversion of renewable energy into hydrogen.

The proposed framework was also found to be efficient in the renewable energy utilization. The renewable utilization rose from 88.5% in 2018-19 to 93.1% in 2019-20, as indicated in Table 2, while the renewable energy curtailment fell from 11.5% to 6.9%. The results show that the strategy of TDPA uses more percentage of the available renewable energy than the others, thus reducing the amount of renewable power that is not harnessed and increasing the efficiency of the system.

The proposed TDPA framework also showed effective reduction in the maximum operating temperature of the electrolyzer cells, in addition to improving the energy utilization. Table 2 shows that the maximum temperature, which decreased due to Equal Allocation, rose back to 64.2°C with the proposed method. The reduced operating temperature represents a balanced power distribution among the cells that results in less thermal stress while ensuring a higher hydrogen production as well as efficient renewable energy utilization.

5.3 Overall Performance Improvement

The overall effectiveness and efficiency of the proposed Telemetry Based Dynamic Power Allocation (TDPA) was evaluated in comparison to the traditional Equal Allocation method. The comparison shows that the proposed framework always improves hydrogen production, renewable energy utilisation, renewable energy curtailment and thermal performance in every case due to adaptive renewable power allocation.

Results of the overall normalized performance comparison are presented in Figure 5. The results of the proposed TDPA framework are compared with the Equal Allocation strategy in the figure and it can be seen that TDPA outperform the Equal Allocation strategy on all the evaluation metrics. The greatest gains are seen in renewable curtailment reduction, with small gains in hydrogen production, renewable energy utilization and temperature management. The radar chart helps to visualize in a convenient way the enhancements made in a balanced way by the proposed framework.

Results of these quantitative improvements are summarized in Table 3. As seen in table 3, the proposed TDPA framework is able to boost hydrogen output by 5.3% and advance renewable energy use by 4.6 percentage points. Moreover, the renewable energy curtailment is decreased by 40.0%, which suggests that better utilization of the available renewable energy source, in terms of the reduction in the power curtailment. The adaptive allocation strategy also reduces the peak operating temperature by 2.4°C, which helps to achieve better thermal management and load balancing across the electrolyzer cells. The results show that the proposed framework supports the optimization of both efficiency of final production and utilization of renewable energy while increasing the reliability of operation.

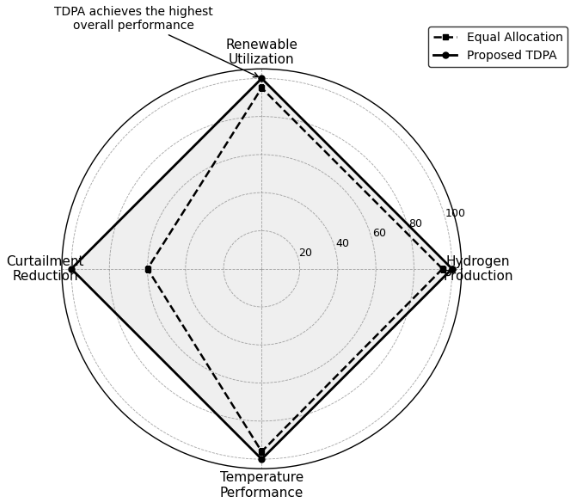

Fig. 5. Overall Performance Improvement

Table 3. Overall Improvement Summary

Metric	Improvement
Hydrogen production	5.3%
Renewable utilization	4.6 percentage points
Renewable curtailment	40.0% reduction
Maximum temperature	2.4°C reduction

6. Conclusion

In this paper, a Telemetry-Based Dynamic Power Allocation (TDPA) was proposed for renewable powered hydrogen plants composed of multiple cells. The proposed scheme consists of a distributed telemetry-based approach with adaptive renewable power allocation that dynamically allocates available renewable energy into 4 different electrolyzer cells based on efficiency and temperature. The framework continuously monitors the cell conditions and adjusts the distribution of power among cells, which facilitates the multi-cell operation as well as the use of intermittent renewable energy sources.

The proposed method was shown to be effective and efficient under a synthetic renewable energy profile in the simulation results. The TDPA framework raised the hydrogen production from 20.8 kg/day to 21.9 kg/day compared to the conventional Equal Allocation strategy, raised renewable energy utilization from 88.5% to 93.1%, lowered renewable energy curtailment from 11.5% to 6.9%, and lowered maximum operating temperature to 61.8°C from 64.2°C. The improvements offer the possibility of simultaneously improving production efficiencies, renewable energy use and thermal management by adaptive power allocation based on telemetry.

The proposed framework is both feasible and computation-efficient solution for hydrogen production plant based on renewable energy resources for ensuring reliable operation in variable renewable energy (VRE) scenario for reducing waste of energy and thermal stress. The framework can be applied flexibly and makes decisions according to changes and can be useful for energy management in future sustainable hydrogen production systems. In future, the proposed TDPA framework, real distributed telemetry networks, physical multi-cell electrolyzer systems, and real renewable-generation data sets will be integrated. When used under actual operating conditions, the framework can be further validated to gain a detailed understanding of its suitability, resilience and scalability, focusing on how well it can be adapted to large-scale H2 production plants powered by renewables.

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