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Hydrogen powered energy management system for sustainable industrant applications

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Abstract- Current high-temperature industrial systems still rely largely on fossil fuels, with hydrogen identified as a key vector for their decarbonization. In this paper, a methodology is developed for the development of an EMS based on hydrogen use in industry, namely in glass and ammonia manufacturing. The EMS will involve the use of renewable electricity, electrolysis for hydrogen generation, its storage, and fuel switching between natural gas and hydrogen in order to minimize the expenses and meet the restrictions related to load of furnaces and emission limits. Model Predictive Control is chosen as the EMS architecture with use of day-ahead forecasts of renewable power generation, electricity price and gas price. The proposed methodology includes the design of the system architecture, mathematical problem statement and constraints. Simulation experiments have shown that introduction of hydrogen improves the economics and increases the share of renewables. Comparison with the systems working only with fossil fuels has confirmed the potential of the proposed approach.
Key Word: Hydrogen Energy Management, Industrial Decar

bonization, Electrolysis, Model Predictive Control, Renewable Energy Integration, Glass Industry, Optimization

I. INTRODUCTION

The industrial sector contributes to a significant amount of the world's emissions of greenhouse gases, where high temperature processes such as glass melting, steel manufacturing, and ammonia production have proved to be more difficult to handle because of their need to use fossil fuels for combustion [1]. In Europe, natural gas, which mainly comprises methane, is still used as the main fuel for the industrial furnaces, making the shift towards greener alternatives more crucial and complicated. Hydrogen is seen as one of the solutions to these problems in that it can act as fuel, raw material, and an energy carrier at the same time [2].

However, implementation of hydrogen technology in the industrial environment encounters certain challenges. Intermittency of renewable energy sources and the cost of electrolyzer equipment and hydrogen storage facilities represent such obstacles [3]. Consequently, an efficient energy management system (EMS) is needed to manage generation, storage, and consumption of the fuel in an optimal way with regard to both economic benefits and reduction of emissions. It should be able to take into account the dynamic interactions between the price of electricity, renewable energy availability, hydrogen generation rate, and restrictions of the industrial process [4].

There exist a variety of EMS architectures developed for integrating hydrogen. The optimization approach proved to be efficient in terms of reducing operational cost in the case of grid-connected microgrids supplying industrial consumers [1]. The concept of model predictive control has been already implemented in the hydrogen storage systems coupled with wind farms to allow adaptation to forecast error [5]. However, further studies are needed to apply these approaches to particular industrial applications. The glass industry provides an illustrative example due to the continuous operation and constant thermal requirements of its furnaces [10].

The problem of lack of a structured EMS approach to integrate hydrogen for industrial purposes is solved in this paper by introducing a structured EMS approach to achieve a more efficient use of renewable energy for such applications. There are three objectives to achieve: first,

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designing the architecture of the system taking into account the process of generation of renewable energy, electrolysis, hydrogen storage, and use of hybrid fuels; second, formulating an optimization model which will minimize operating costs while satisfying process constraints; and third, analyzing the performance of the introduced EMS via simulation approach. This paper is focused only on grid-connected industrial processes, capable of purchasing renewable electricity and using natural gas infrastructure.

The significance of the research consists in taking into account the process constraints while formulating EMS, in considering the flexibility of switching from natural gas to hydrogen, and in providing quantitative analysis of the potential of such systems. The paper is organized as follows: literature survey gives an insight into related prior work, methodology describes the architecture and formulation of EMS, analysis provides quantitative results with comparative analysis, and conclusions summarize the findings and give directions for further work.

II. LITERATURE SURVEY

There have been many advancements made in the field of hydrogen energy management systems used for industrial applications during recent times, owing to the increasing interest in decarbonization strategies for hard-to-abate industries. In this context, Bruno et al. [1] developed an EMS for hydrogen use in a microgrid connected to the grid for supplying power to an industry glass furnace using optimization strategy. In their methodology, they focused on cost minimization on an hourly time step basis, by including forecast information of glass production, renewable energy production, and energy price. This study showed the potentiality of hydrogen integration, although it was performed only in one industrial case over a short duration of time. Kourougianni et al. [2] gave a detailed review of green hydrogen energy systems, comprising generation, storage, and application subsystems.

Regarding industrial clusters, the development of an EMS model using the GreenLab Skive system ensured that operational costs were reduced and the production of green hydrogen was increased [3]. The study involved the use of demand response flexibility from the electrolysis, hydrogen storage, and electric batteries which showed how operational costs could be minimized through the use of optimal scheduling. The inclusion of the ammonia plant in this study was used to show the broad uses of hydrogen beyond its use as a fuel. Nonetheless, the study focused on a particular industrial cluster configuration.

The management of hydrogen systems has been enhanced through the use of model predictive control. This is because a two stage MPC was developed in order to manage the hydrogen system storage and a wind farm in respect to the allocation of hydrogen as fuel cells for the transport vehicles and market transactions within a day [5]. It was the first time that a hydrogen system had been modeled by taking into consideration the degradation in the electrolyzers and fuel cells using mixed logical dynamic model.

From the perspective of techno-economics, Ramsebner et al. [4] analyzed options for hydrogen production from renewables for industrial applications, where particular attention was paid to storage issues and to variability management. In doing so, the authors pointed out the importance of hydrogen production and industrial demand profile compatibility. The combination of several energy storage systems, such as batteries and hydrogen, in terms of demand response has been examined with hybrid storage having complementary properties at different time horizons [5].

The impacts of green hydrogen on the entire value chain have been studied by some researchers. Production, transportation, storage, and usage of hydrogen are among the aspects being analyzed in terms of research gaps related to grid integration and operation strategies [6]. The life-cycle assessments of hydrogen production technologies allow comparing technologies in terms of environmental performance [7], [8]. Concerning the industrial application of hydrogen, its use as a replacement for natural gas, e.g., for aluminum recycling, has been examined and found profitable in some cases [9].

However, despite these significant contributions, certain aspects are missing in the body of knowledge in this area. Very few works have considered the operational restrictions that arise due to the nature of continuous industrial processes such as maintaining furnace temperature and ensuring minimal load conditions within the EMS design. Additionally, the interaction between hydrogen and natural gas co-firing, which is one of the pathways through which hydrogen can be integrated into current systems, has not been studied quantitatively. Moreover, there are few comparative studies evaluating hydrogen-enabled EMS versus fossil fuel-only EMS.

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III. PROPOSED METHODOLOGY

1.System Architecture

The design of the energy management system involves an industrial plant that needs electrical power and heat. The architecture consists of five major components including renewable electricity production (solar PV and wind), electrical grid connection, proton exchange membrane (PEM) electrolyzer for hydrogen production, hydrogen storage (compressed gas), and a combustion system that can use natural gas, hydrogen or mixtures of them for furnace heating. The electric battery acts as an intermediary component in case of transient mismatch between renewable electricity generation and electrolyzer consumption.

The system architecture is depicted in Figure 1 below. In this design, the EMS control center acts as the coordinator unit. It gets forecast information and limitations and sends out setpoints to all subsystems. The electrical demand of the furnace auxiliaries and electrolyzer is supplied by either renewable production, battery discharge or from the electrical grid. Thermal demand is supplied by combustion of natural gas, hydrogen or their mixture.

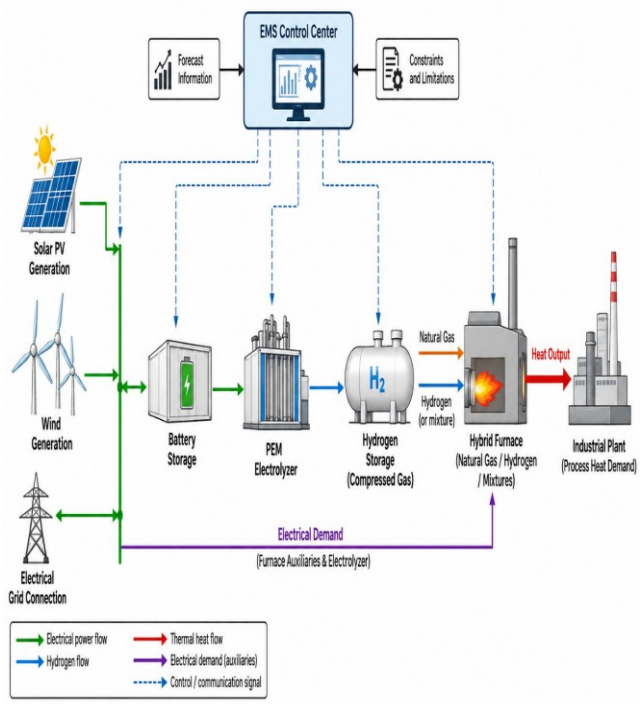


Figure 1: System architecture of the hydrogen-powered EMS

2.Optimization Formulation

EMS utilizes a rolling horizon approach with an optimization period of 24 hours and hourly time-step. The objective function is to minimize total cost which includes the grid electricity purchase cost, natural gas cost, and cost due to renewable energy curtailment. The decision variables include grid import power, electrolyzer power set point, battery power flow, hydrogen tank inventory, and fueling composition between hydrogen and natural gas for the furnace.

This optimization can be solved using Mixed Integer Linear Programming (MILP). Binary variables indicate the operational status of the electrolyzer and fuel type used by the furnace. Continuous variables correspond to power, storage state, and fuel quantity. Constraints are defined such that:

- Power balance at each time step,
- Thermal balance satisfying the furnace demand,
- Hydrogen tank inventory dynamics with constraints on hydrogen tank inventory,
- Battery state of charge constraints,
- Electrolyzer operational constraints (minimum load and ramp rates), and
- Furnace operational constraints (maximum hydrogen blending ratio and minimum thermal load stability)

This particular constraint is important in case of an industrial furnace that may have some kind of compatibility issue with the materials used or need stability in combustion, thus limiting the amount of hydrogen that can be added in the mixture in terms of volume percentage. It is depicted in the form of an upper limit on the hydrogen percentage of total thermal input.

Figure 2 depicts the control loop structure of the EMS, from forecast to optimization to setpoints dispatching. The rolling horizon approach enables the system to revise its decision-making process based on discrepancies between forecasts and reality, making it resilient against uncertainties.

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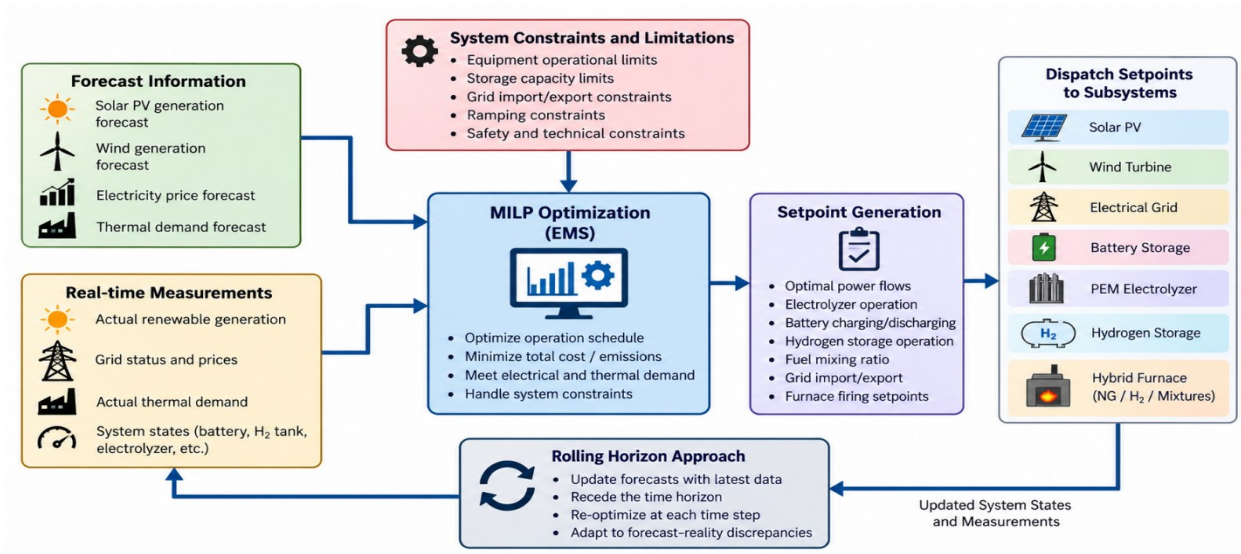


Figure 2: EMS control flow diagram

Operational Constraints and Assumptions

The operation of the industrial plant is continuous, while the thermal profile resembles that of a glass-melting furnace, which is rather steady baseload with small fluctuations. Electrolyzer capacity is selected so as to ensure that its hydrogen production rate allows for a significant share of the thermal demand to be met by the renewable power surplus. Grid electricity pricing is based on a time-of-use tariff with peaks and off-peak hours. Prices of natural gas are assumed to be predictable within the 24-hour horizon.

The emissions limit is introduced via a constraint on the maximum CO_2 equivalent of fuel emissions in a day, which should correspond to the company's sustainability standards or government regulations. The emissions constraint creates an incentive to consume hydrogen during peak emission hours, since marginal emissions of hydrogen generated by renewable energy sources are almost negligible.

The model is implemented in a commercial software solution and run on a rolling hourly basis. Forecasting errors are not accounted for explicitly in this approach; however, rolling horizon adds certain robustness. The following chapter contains simulation results and analysis.

IV. ANALYSIS

Simulation Setup and Scenarios

The suggested EMS system was simulated for a period of 14 days with synthetic data, which can be considered representative of a European industrial plant. There were three cases analyzed: (S1) base case scenario without hydrogen technology, where thermal load is provided by natural gas, and electricity by the grid supply and renewable production without electrolysis; (S2) hydrogen-enabled scenario with conservative blending limit of hydrogen equal to 20% of thermal input; and (S3) hydrogen-enabled scenario with increased blending limit of hydrogen equal to 40%.

Figure 3 shows profiles of renewable energy production and electricity load for one week. Diurnal profile of solar power production and stochastic nature of wind can be noticed. Furnace electricity load is quite stable as the processes in industrial plant are steady.

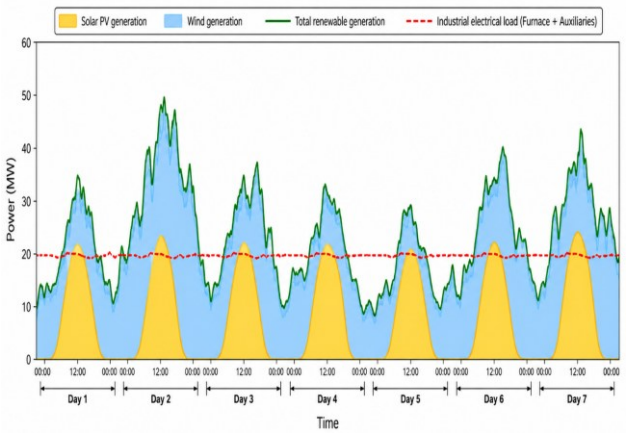


Figure 3: Renewable generation and electrical demand profiles

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Operational Results

Figure 4 shows the behavior of hydrogen tanks' inventories and the operation of the electrolyzer during the simulation horizon for scenario S2. The electrolyzer works mainly at times when there is a large amount of renewable production and low cost of electricity, generating hydrogen that is used at times of high heat demand or high natural gas prices in the furnace. The hydrogen tank inventory shows a cyclic pattern with periods of stockage and depletion of the tanks.

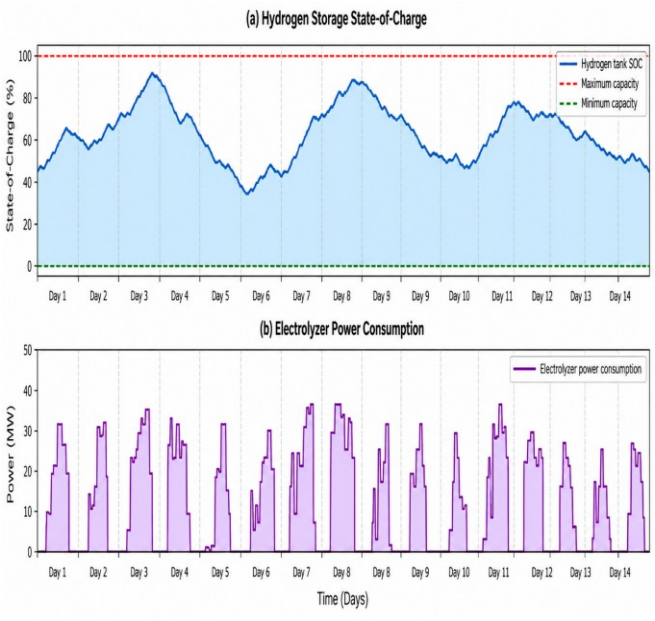


Figure 4: Hydrogen storage dynamics and electrolyzer operation

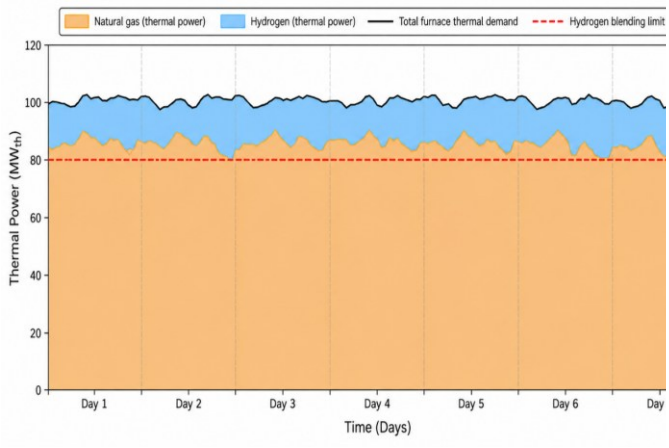


Figure 5: Thermal fuel mix under hydrogen-enabled operation

Fuel composition for thermal energy needs for scenario S2 is provided in Fig. 5. The percentage of hydrogen as a source of thermal energy varies according to its availability. In the case of abundant renewable energy, hydrogen reaches the limit of 20%, whereas it decreases during the period when the amount of renewables is low, and the stored hydrogen is used carefully. The rest is supplied by natural gas.

The trajectories for the total cost incurred by all three scenarios are compared in Figure 6. Both S2 and S3 have a reduced cumulative cost compared to S1, and the difference widens with the passage of time. This is due to two reasons; first, the use of natural gas when prices are high, and secondly, efficient usage of renewable sources which could be wasted otherwise. Scenario S3 incurs slightly reduced cost compared to S2; however, the marginal benefits become smaller as the blending limit rises.

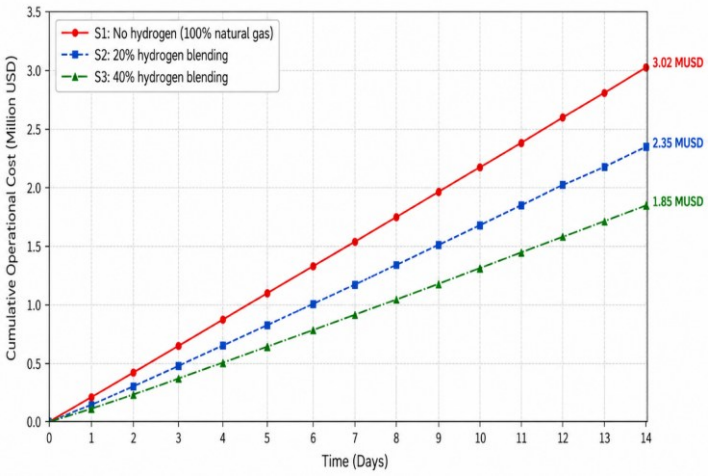


Figure 6: Cumulative operational cost comparison

Comparative Analysis

Table 1 highlights a comparison of the three scenarios based on various operational and financial metrics. For the hydrogen-based scenarios, there is evidence of savings in natural gas use and emission, as well as an increase in renewable energy production. However, the amount of improvement is constrained by the blending requirement that determines the maximum replacement of natural gas with hydrogen in the furnace.

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Table 1: Comparative analysis of operational scenarios

Indicator	S1 (No H_2)	S2 (20% blend)	S3 (40% blend)
Total operational cost (relative)	1.00	0.91	0.88
Natural gas consumption (relative)	1.00	0.84	0.71
Renewable curtailment (relative)	1.00	0.62	0.48
Hydrogen production (MWh thermal equivalent)	0	142	238
Grid electricity import (relative)	1.00	1.07	1.12
Thermal supply reliability	1.00	1.00	1.00

This means there is a relationship between natural gas substitution and electricity imported from the grid. There is an increase in electrical demand as a result of hydrogen production and this will in part be achieved by importing more from the grid due to low renewable energy production. One can see this through the higher grid import of S3 as compared to S2. Net emission savings will depend on the carbon intensity of the grid electricity since this will keep on falling over time in Europe.

The reliability measure shows that all scenarios have continued with uninterrupted operation of the furnace showing the effectiveness of the EMS constraint formulation.

V. DISCUSSION

Results of this paper are in agreement with results obtained by prior studies showing that hydrogen introduction into industrial applications is economically feasible. Decreases in costs noted in this paper are in line with the direction of costs decreases obtained for glass industry applications; however, the quantitative comparison is somewhat complicated because of the differences in system setup and boundary conditions. Reduction of renewable energy curtailment becomes an additional advantage which is sometimes not accounted for in previous papers, and which shows the usefulness of hydrogen storage as an element of system flexibility.

It turned out that the limitation on the hydrogen fraction blending becomes a crucial one and limits the possible benefits. In reality, operators of industrial furnaces might not be ready to use higher values of this parameter because of the necessity of testing and changing burners. Cost-wise, benefit from increasing this fraction from 20% to 40% turns out to be relatively small.

However, higher imports of grid electricity in the case of hydrogen-enabled operations need special attention because if grid electricity carbon intensity is high, then some emissions reduction can be reduced due to the emissions from increased electricity consumption. Thus, the connection of hydrogen production with the use of renewable energy sources needs to be emphasized.

There are some limitations that need to be considered. First, the simulation was based on the synthetic data and did not take into account the forecast errors. Moreover, optimization was carried out with perfect forecasting in each of the 24-hour periods. In the future, stochastic optimization and robust control should be taken into account for dealing with forecast errors. Furthermore, only the operating costs were considered while the investment costs needed for building an electrolyzer, storage system, and furnace modifications were not taken into account.

VI. CONCLUSION

The hydrogen-based energy management system described in this paper has been designed to manage energy consumption in industries sustainably and in particular, in those involving high temperature operations which need continuous supply of thermal energy. In this EMS, the integration of renewable power generation, PEM electrolysis, hydrogen storage, and hybrid fuel use is done under model predictive control approach that aims at minimizing cost while meeting process constraints.

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The simulation analysis conducted over 14 days produced four primary insights. First, there were cost savings through hydrogen integration, which was less expensive compared to natural gas alone, with savings becoming more pronounced as optimization occurred over time through fuel switching. Second, there was a reduction in the use of natural gas, along with emission reductions proportional to the amount of hydrogen being used, subject to the blending constraint. Third, there were significant reductions in renewable energy curtailment, underscoring the potential benefits of hydrogen storage as a flexible solution for industries with renewable energy sources. Fourth, the value added from increasing the blending constraint to 40% was marginal.

The results showed a trade-off between the reduction in natural gas and the import of grid electricity. There is an increase in the electrical load for the production of hydrogen and the net emission reduction relies upon the carbon content of the marginal electricity production. This is a clear indication of the need for hydrogen use to be coupled with renewable energy acquisition.

The contributions of this study are the inclusion of process constraints in an EMS optimization model and a systematic comparison with the base case operations. The approach may be extended to industries with analogous features such as ammonia production and some steel plants with minor adjustments in the process constraints.

Areas for future research could include some shortcomings of the current research. The inclusion of the stochastic optimization for dealing with forecasting uncertainty will make the research more practically relevant. Extending the research to account for capital costs and life cycle emissions will contribute to better understanding of economic and environmental feasibility. Validation of the research on a pilot plant will allow to examine the EMS in a real world environment and collect empirical data for building models. Also, analyzing different hydrogen storage options such as liquid hydrogen or metal hydrides will allow to explore additional areas for further research. With the growth of industrial decarbonization process, hydrogen EMS will become even more relevant in the context of sustainability.

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