Adaptive Demand-Side Management Algorithm for Grid-Integrated PV-Wind-Battery-Hydrogen Systems Using Model Predictive Control

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ABSTRACT

Systems for producing green hydrogen will be essential in the move away from fossil fuels and towards technology that produces no carbon emissions. In order to undertake PV-Wind-H₂ design for various hybrid configurations, this study provides a novel model for an off-grid hydrogen plant coupled with wind power, solar photovoltaic, and a battery energy storage system. This model makes use of meteorological information as well as component electrical variables. The objectives are to size and operate the systems properly in order to reach production targets while reducing H₂ expenses. The direct connection of a PV-Wind-Electrolyser optimises component sizes and hydrogen generation, with the Electrolyser curves determined by the area and number of Electrolyser cells linked to photovoltaic modules. The coupling factor is increased when maximum power point (MPP) tracking is used. However, when compared to optimal PV-Wind-Electrolyser coupling, this gain is minimal. The advantage of battery-assisted electrolysis is that it minimises the size of the electrolyzer, illustrating how easy it is to run it at part loads. As a result, the photovoltaic-Wind and Electrolyzer are bigger to allow H₂ generation, but the batteries work much better.

Keywords: Battery storage, Energy management system, Hydrogen production, Model Predictive Control.

1. Introduction

The Paris and United Nations Agreements seek to restrict the rise in the worldwide temperature to less than 1.5 degrees Celsius above the time before industrialisation by the end of this century. CO₂ emissions must be eliminated entirely in order to achieve this goal. This can be accomplished by either drastically reducing emissions of carbon from energy-related enterprises and procedures or by offsetting the residual emissions using carbon dioxide-removing machinery [1]. Additionally, amid changes in the international political landscape, a region’s high reliance on fossil fuels could be perceived as a financial threat for those with little fossil fuel resources. Many sectors, including long-distance transportation, steelmaking, and chemistry have hurdles as they transition away from fossil fuels. Since they are heavily dependent on natural gas and oil, they are challenging to directly electrify. It will be crucial to find solutions as the globe moves closer to net-zero emissions. Furthermore, because renewable energy output is intermittent, energy storage technologies are required to decrease energy curtailment and enhance the security of the power supply. One of the most potential possibilities is hydrogen created from renewable energy sources. It makes it possible to decarbonize industries that cannot be directly electrified or heavily rely on fossil fuels [2]. The method of producing hydrogen by a renewable energy source and water electrolysis is the most environmentally friendly. The high cost of green hydrogen compared to alternatives centred on fossil raw resources or additional low-carbon expertise is one of the biggest problems it now faces. Due to technological advancements, green hydrogen is anticipated to match the price of fossil derived hydrogen over the next ten years. It entails both the construction of electrolyser facilities with increased capacity and the on-going decrease in the price of producing renewable energy. This is the main factor affecting water electrolysis costs [3], [4].

Design engineers employ simulation and modelling as important tools to further the understanding, creation, and forecast of hydrogen tools. They comprise a wide range of techniques, from multi-system research to component level research. Validated blocks and references that
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They do not incur the expenditure of inverters or suffer from their energy loss. Even though their main issue is that none of the projects have generalizable topologies, much as with other DC technologies like batteries [12]–[16]. Inverters, transformers, and rectifiers are not needed for a grid-connected system with PV-EL coupling with MPPT since all that is needed is a DC-DC converter. Despite being the simplest connection, straight photovoltaic-EL connecting without any power electronics requires careful planning to prevent energy losses.

In order to change the voltages in PV module I-V curves, the power supplied from Photovoltaic-variable sources of renewable energy to EL with DC-DC (Maximum Power Point Tracking) relies on this dual function. It is used to sustain the maximum power point at the regulator’s input under any irradiation-temperature condition and transform it into an I-V output that is optimal for EL requirements. In other words, under the assumption of 100% conversion efficiency, the Maximum Power Point Tracking modifies the photovoltaic voltage to maximum power point, and the regulator changes it to the same power point on the EL curve. This would result in more VRE adaptability and flexibility for a variety of systems, even while the controller would need to follow photovoltaic power to EL safe working thresholds [17], [18]. The photovoltaic and EL curves’ crossings serve as the operational sites for direct connection. Compared to an ideal MPPT, this causes some power losses over time and lowers design flexibility (sizing). That is due to the requirement that the EL’s voltage range be compatible with any conceivable PV voltages. Existing designs frequently oversize the solar field in comparison to the inverters and the EL because PV module production at peak power occurs infrequently across several geographical regions. Systems powered by the electric grid and/or batteries can be installed to enhance EL use. It is crucial to take into account the market price and environmental effect of energy because only a small portion of the power mix will be sustainable in the first scenario, making the resultant H2 “green.” It may be exciting to utilise energy with origin and price assurances. The size of the components in systems with electric storage (batteries) must be determined based on how well they work and how much they cost; bigger battery capacity improves utilisation and lowers EL costs but at the risk of higher storage costs and losses. Grid-assisted and battery-assisted PV-EL systems both offer more reliable generation of H2 based on demand. Utilising them concurrently would be inefficient since the intermediate storing of hydrogen created by the EL is more effective than that of energy produced by the photovoltaic field [19]–[22].

The electrolysis plant’s output capacity and the fluctuating green power supply must be matched. This will need energy storage technologies. There is several energy storage systems developed on different platforms, and any one of them typically excels at a certain role. For instance, by constructing a hydrogen energy storage system, the hydrogen output from an off-grid facility may be connected to a need for hydrogen or a certain base load. On the other side, a battery energy storage system may be used to regulate the supply of electricity to the electrolyzer utilising electrochemical storage technology.
In a recent study, we found that [23] a BESS used as a temporary store could balance the power distribution to the electrolyzer. It might lessen the requirement for excessive power production capability and end brief shutdowns. On the other side, using a hydrogen energy storage system can help reduce the required capacity for renewable installation [24]. A solar photovoltaic-wind hybrid energy structure with a battery energy storage system and a HESS was simulated by Marchenko and Solomin [25] to power two loads with maximum power ratings of ten kilowatts and one hundred kilowatt respectively. They optimised their design to show the benefits of using a hybrid energy structure. It shows that using a battery energy storage system to store energy is more affordable than using hydrogen storage for short periods of time. A HESS and BESS are also required, according to Puranen et al. [26], to offer an off the grid green energy solution for a Finnish family. Even from a purely technical perspective, they found that a HESS is better for long time storage of energy while a BESS is preferable for short-term usage. Göökçek and Kale conducted an economic and technological evaluation of an off the grid hydrogen fuelling station powered by wind energy and solar photovoltaic [27]. The system was developed with the use of commercial software and tuned to come across 125 kilogram daily H2 consumption. Commercial software can be used to provide a computational foundation for modelling plant operation. But this way could make simulating the systems more difficult and make it harder to understand how the techniques were applied. Water electrolysis system utilising solar-wind hybrid energy structures were evaluated by Nasser et al. [28]. The systems under study were largely concentrated on hydrogen synthesis as an energy storing structure for later fuel cell-based power production. The price of H2 with a solar photovoltaic structure and hybrid solar Photovoltaic-wind structure on its own is comparable, the review finds. However, it is important to remember that the weather in the definite geographic areas where the plant is situated affects the cost of manufacturing hydrogen from renewable sources. To lower energy prices, Xu et al. [29] created a multi-optimization for standalone solar photovoltaic-wind H2 systems. Additionally, it supported lowering the power abandonment percentage, or the percentage of energy production that is decreased, as well as the energy supply possibility, or the percentage of energy demand that is not met by generation. A study scenario including hydrogen storage tanks and fuel cells was used to evaluate the suggested approach. The optimization's findings showed the appropriate component capacities to meet a power peak and certain energy demand. Yet, neither battery energy storage nor system control were incorporated in the optimisations. In order to attain net-zero energy buildings, Izadi et al. [30] looked into merging solar PV-wind hydrogen systems. Commercial software was used to simulate the system. An artificial neural network-based model was built, and it was afterwards tuned using a genetic algorithm (GA) for system optimisation. To reduce total expenses, emissions of CO2, and the possibility of a power outage, the optimal number of wind turbines and solar photovoltaic panels was found. For renewable hybrid energy systems, Eriksson and Gray [31] presented a multi-optimization algorithm that takes into account environmental, economic, technical, and socio-political factors. The Particle Swarm Optimisation (PSO) technique was used to optimise a normalised weighted restricted function with the technical aim of reducing the likelihood of energy supply failure. Economic objectives include the total present value and the levelized price of energy. Energy's carbon footprint is measured for environmental reasons. The numerical characterization of quantitative and qualitative criteria, such as public acceptance or employment chances, determines the socio-political aim in the end. For solar PV systems, wind farms, electrolyser, H2 storage, fuel cells, and batteries, the recommended optimisation strategy can provide the optimum capabilities. However, system control is not a component of the optimisation.

This study proposes a brand-new paradigm for integrated solar PV-powered hydrogen (H2) production systems. This improves current design applications and serves as an important tool for business and decision-makers to aid techno-economic evaluations. It makes it possible to model, simulate, and optimise PV-H2 systems within a specific application scenario, depending on differences in technology, operational conditions, and climatic variations. To estimate the power balances for various hybrid configurations, such as battery assisted electrolysis, power tracking, or direct coupling, the model takes into consideration meteorological data in addition to the electrical variables of the components (i.e., PV & EL). The major goals are to size and run the structures effectively in terms of coupling factors, H2 generation, and EL use in order to lower costs (V/kgH2). Finally, the problems brought on by oversizing the PV field are avoided as the solutions investigated in the research do not have inverters-rectifiers. Furthermore, it was found that the size of the EL is more dependent on the number and size of the electrolytic cells that make up the pile than on the nominal amount of power it generates.

2. THE PROPOSED GRID-CONNECTED PV-WIND-BATTERY-HYDROGEN PRODUCTION SYSTEM

The system under discussion includes wind installations, photovoltaic, a battery energy storage system, and an alkaline water electrolyzer for environmentally friendly power production. The electricity produced by the wind power (Pw) and solar PV (PPV) plants is combined. The system's electrical usage is controlled at each simulation time step using a finite-state machine controller. The energy supply for the alkaline water electrolyser (Pe) is used to calculate the generation of hydrogen. Economic modelling is used to calculate the levelized price of H2. The suggested grid-connected PV-Wind-Battery-Hydrogen Production System is shown in Fig. 1. The fixed nominal alkaline water electrolyzer power of 10 MW defines the nominal peak energy capabilities of wind installations and solar Photovoltaic as well as the energy storage capacities of the battery energy storage system. This technology allows the plant to be scaled up or down by simply increasing the nominal electrical output of the alkaline water electrolyzer and lowering the amount of variables.
Since power conversion losses account for a relatively minor part of operational power levels, the model does not include power electronics for converting energy between constituents. The size of the time step is determined by trade-offs between high-resolution simulation outcomes and processing duration, which is increased by the optimisation procedure. The electricity production information gathered from a wind turbine and a solar Photovoltaic system used in this research is interpolated from a 10 minute to five minutes of time resolution in order to match the photovoltaic energy measurement. With the same time step resolution, integrated wind and solar photovoltaic power generation is used in the simulation of the plant. In this study, a battery energy storage system is used to showcase the lithium iron phosphate battery system, a material that is suitable for applications that are stationary because of its low cost, protection, and extended lifespan. In stationary applications, the lithium iron phosphate battery’s decreased power density compared with other lithium battery chemistries wouldn’t be a concern. The future need for battery energy storage system capability cannot be predicted by technology. For maximum output in a short amount of time, the battery energy storage system’s rate of discharge is controlled at C/4 to stop exhausting the entire volume of stored energy. One C is considered to be a credible estimation for a utility-scale battery energy storage system; hence the charging rate is capped at one C. It is assumed that the BESS efficiency is constant, $\eta_b = 90\%$, for both charging and discharging. This includes the effectiveness of both cells and power electronics. The BESS model operates in two modes: charging and discharging. The charge status after the charging operation is computed as:

$$SOC_i = SOC_{i-1} + \frac{P_{b,i} \Delta t}{\eta_b C_b}$$  \hspace{1cm} (1)$$

The battery’s SOC after discharging is stated as:

$$SOC_i = SOC_{i-1} + \frac{P_{b,i} \Delta t}{\eta_b C_b}$$  \hspace{1cm} (2)$$

Lithium-ion batteries are known to lose power as a consequence of both how often they are used (cyclic ageing) and how long they are kept stored (calendar ageing). For a BESS user, degradation manifests as a reduction in battery life brought on by the depletion of lithium stock as well as a reduction in maximum power due to a rise in resistance within the battery over time. When loss of capacity contributes to twenty percent of the initial capacity, this is a common definition of a battery’s end of life.

Alkaline water electrolyzer (AWE) depends on a commercial Alkaline water electrolyzer with a nominal maximum power of $P_{e, \text{nom}} = 3 \text{ MW}$. During capacity optimisation, the electrolyzer’s performance is kept constant. Twenty percent of the nominal power is the commercial plant’s minimum power, or $P_{e, \text{min}}$. Gas crossovers rise at low current densities, making the operation dangerous. The AWE $P_{e, i}$ operating power is determined independently for each time step by first verifying that there is sufficient input power to start the system up and then figuring out the smallest difference between its nominal power and input power. When the water electrolyzer is in use, a progressive voltage rise is a sign of deterioration. Degradation may result from both temporary elements, such as bubble formation, and long-term physical changes to the electrolyzer’s parts. Because degradation processes are generally sluggish, voltage increases in alkaline electrolyzers are typically less than 3 $\mu \text{V h}^{-1}$. Degradation is included in the electrolyzer concept as a gradual loss of efficiency. The electrolyzer stack is changed when efficiency drops by 10%. The life of the electrolyzer stack is often indicated by this level of degradation.
3. SIMULATION RESULTS AND DISCUSSION

The optimum energy management strategy suggested in this study is put to the test using three different methodologies, which are then compared and analysed. Scheme No. 1: The model predictive controller is employed in the hydrogen integrated energy system instead of particle swarm optimisation. Scheme 2: the particle swarm optimization is used with a single objective function. Scheme 3: MOPSO is used with the model predictive controller. By contrasting Schemes 1 and 2, it is possible to see how the cogeneration features of the hydrogen integrated energy network affect how well demand side management operates in the energy network. Fig. 2a displays the electrical power outputs of Scheme 1. The photovoltaic power is nil between 00:00–06:00, and the wind supplies the majority of the electrical demand at that time. The PV power is greater between 10:00 and 14:00, and it meets the majority of the electric load demand; the wind turbine is mostly inactive during this time. The load demand rises between 17:00 and 22:00, and the electricity provided by PV steadily goes to zero. Wind and Hydrogen Fuel Cells are both key power suppliers during this time period. Because only the electrical output of the Hydrogen Fuel Cell is included in Scheme 1, the load demand is mostly met by Wind, Battery, and PV in Fig. 2b. Scheme 2’s electric power results are displayed in Figs. 2c and 2d. Scheme 2 compares to Scheme 1 and considers the cogeneration effects of the H₂ fuel cell. This is mostly shown in provision of heat loads, and the amount of wind is notably less. The wind turbine does not provide any electricity between 10:00 and 14:00 when the photovoltaic power is enough, and the battery output is drastically reduced. Power consumption is significantly reduced as a result, and a bigger share of the cost of operating the system is attributable to power consumption. This shows that taking into account the hydrogen fuel cell’s cogeneration effect has a more pronounced impact on lowering system operating expenses. Fig. 2c display the electrical energy testing outcomes for Scheme 3’s design. The photovoltaic

![Fig. 2. Electrical power outputs (a) Scheme 1: In the hydrogen integrated energy system, the model predictive controller is used without the particle swarm optimization. (b) Scheme 2: the particle swarm optimization is used with a single objective function. (c) Scheme 3: the multi objective particle swarm optimization MOPSO is used with the model predictive controller.](image)
generated electricity correction curve and prediction curve show that the expected result is slightly greater than the corrected outcome. Even if its mistake number is less and its effect on the system is less, the system will still be affected to some extent. The power outputs of Schemes 2 and 3 show that the load supply capacity is insufficient and that when the photovoltaic production declines, the electrical energy output of the hydrogen fuel cell also declines. The apparatus for supplying electric load will be affected in some way by this. When compared to Scheme 2, the modification in equipment production under Scheme 3 is less noticeable because of the PV output's minor prediction error. But because there is a forecast mistake, the gas turbine's operating period is longer. This will unquestionably shorten the wind turbine's useful life and somewhat reduce the impact of forecast inaccuracy on each piece of equipment's production. As a result, the operational dependability of multi-type energy systems is decreased.
and instability is enhanced. The energy production of the wind, the photovoltaic battery production curve, and the hydrogen fuel cell's total output are all shown in Fig. 3. The findings demonstrate that the change of the projected photovoltaic power curve by study of light strength uncertainty has a little impact on the power generated from wind turbines and H₂ fuel cells but little to no impact on the output of batteries. In the time range of 10:00–18:00, the adjusted curve is less favourable than the predicted outcome. The electric output of the wind turbine rises as the hydrogen fuel cell's overall output decreases. It suggests that optimising the electrical and thermal production power of H₂ fuel cells can enhance the system’s efficiency in using energy. It lowers operational costs, cuts back on the consumption of fossil fuels, and lowers carbon emissions. Scheme 3 differs from Scheme 2 in that it takes into account the unpredictable nature of PV output. Based on the solar irradiance density’s stochastic characteristic, the PV production forecast curve is adjusted. By improving the precision of solar power production prediction, the detrimental effects on the network of equipment’s financial dispatch may be successfully reduced, notwithstanding the minor rise in daily operating costs. As a result, the integrated hydrogen energy system’s operating dependability may be improved.

4. Conclusion

A 10 MW wind farm, solar PV installation, a battery energy storage system (BESS), and alkaline water electrolyzer (AWE) and for energy production made up the off-grid green hydrogen production system that was the subject of the investigation. A novel model for integrated H₂ generation structures using solar photovoltaic power is presented in this paper. This enhances already-existing design applications and serves as a useful tool for decision-makers and industry to facilitate technoeconomic analyses. It enables modelling, modelling, and optimisation of photovoltaic-hydrogen projects within a specified application environment, i.e., in accordance with the changes in technological capabilities, usage circumstances, and weather. The methodologies required to concurrently optimising component capabilities, system control, and levelized hydrogen cost were supplied by the developed simulation approach. The model considers the meteorological data as well as the electrical parameters of the components (i.e., PV & EL) to calculate the energy balances for different hybrid configurations, such as battery aided electrolysis, power tracking (MPPT), or direct connection. The major goals are to size and run the systems as efficiently as possible in terms of EL use, H₂ generation, and coupling factors, as well as to reduce costs (V/kg H₂). Finally, the negative effects of oversizing the photovoltaic field are prevented. As the study’s schemes don’t include inverter-rectifiers and EL size isn’t determined by nominal power. Rather than the quantity and dimensions of electrolytic cells that make up the Pile. The majority of the overall investment expenses are related to the production of wind energy. The total full-load hours of hydrogen production and the electrolyzer are greatly increased with the accumulation of solar photovoltaic and BESS in the plant. The BESS is used as a temporary storing option to maintain the electrolyzer working at its lowest load when solar PV and wind energy output are insufficient. The enhanced system management shows that hydrogen production is increased when operating at reduced loads.

References


