Theoretical Research Paper



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HAYTHAM X ONE: A Reliable Energy Nexus

ABSTRACT

Bangladesh is currently dealing with energy production problems characterized by recurrent load shedding and total reliance on foreign fossil fuel imports. In order to ensure a consistent and dependable supply of electricity constantly, the **HAYTHAM X ONE** project offers the idea of using an innovative integrated approach that combines cutting-edge **Concentrating Solar Power** (**CSP**) technology with effective energy storage systems supervised by **Artificial Intelligence** (**AI**) driven management while utilizing Bangladesh's geographic and environmental potential. This approach optimizes operational efficiency and minimizes energy loss, positioning Bangladesh as a green energy leader in the region. The effectiveness of renewable energy sources is largely dependent on favorable weather. To counter this issue, our proposed framework combines **CSP**, various redundant independent energy storage systems such as **Reverse Electrodialysis** (**RED**) batteries, sand thermal storage etc. in response to Bangladesh's energy needs and climate. Additionally, this paper explores the production of hydrogen as a renewable fuel source.

1. INTRODUCTION

Bangladesh's energy infrastructure is under immense pressure due to rapid industrialization and a population exceeding 174 million (Worldometer, 2024). According to the Bangladesh Power Development Board (BPDB), peak electricity demand in 2023 reached over 15 GW, but the country's production capacity is often insufficient which leads to frequent power outages and load shedding. In 2022, the country faced an estimated shortfall of up to 2,000 MW daily during peak hours that severely impacted businesses and households (The Business Post, 2022). Additionally, Bangladesh is heavily dependent on fossil fuel imports, with approximately 40% of electricity generated from imported liquefied natural gas (LNG) and coal (Dialogue Earth, 2023; IRENA, 2021). This dependency led to the country spending over $4.5 billion on energy imports in 2022 (IEEFA, 2023).

While Bangladesh has the potential to generate up to 50 GW of renewable energy, particularly from solar power (National Bureau of Asian Research, 2023), only about 1.183 GW has been harnessed as of June 2023 due to infrastructure challenges and inconsistent weather patterns (pv magazine International, 2020). The country's monsoon season and subtropical climate, which account for around 40% of the year, further complicate the reliable use of solar energy, particularly for technologies that require direct sunlight (USAID, 2021).

In response to these challenges, the **HAYTHAM X ONE** project proposes a comprehensive approach that integrates **Heliostats**, **Concentrated Solar Power** (**CSP**), **Helio-Thermal Brine Separation** (**HTBS**), and the **Thermo-Chemical Water Splitting Process** (**TCWSP**) alongside efficient energy storage systems and hydrogen production. Heliostats concentrate solar beams onto a receiver atop a solar power tower that generates superheated steam to power a turbine and generate electricity. Seawater is purified and desalinated through filtration and **HTBS** and supplies water for this process, while the **TCWSP** harnesses heat to split water and produce hydrogen. To ensure uninterrupted energy production, sand storage batteries store excess thermal energy for use during periods of low solar irradiation. Additionally, AI-driven systems will optimize the flow of energy and maintain the components of the power plant.

This paper outlines the theoretical framework of this project, exploring its conceptual design, projected energy output, economic viability, environmental sustainability, and potential for hydrogen production. By utilizing advanced renewable energy technologies, **HAYTHAM X ONE** proposes to provide Bangladesh with energy independence, while positioning the country as a major participant in the green energy usage and export market. However, the paper only provides a brief description of the theoretical framework based on a thorough analysis of previous research conducted in this area; thus, some modification and deviation will be required in the practical application.

2. TECHNOLOGICAL FRAMEWORK

2.1 Heliostat, Parabolic Trough Reflector and Concentrating Solar Power (CSP)

A potential replacement for traditional photovoltaic (PV) cells is concentrating solar power (**CSP**), particularly for integrating with traditional thermal steam generators. **CSP** exists in four optical types, namely parabolic trough, dish, concentrating linear Fresnel reflector, and solar power tower. By directing sunlight through reflective surfaces onto a receiver, **CSP** captures heat from the sun and uses it to produce steam that drives a turbine to generate energy .Large-scale power generation projects benefit greatly from **CSP** systems since they can store excess heat for use later on, producing electricity even in absence of **Direct Normal Irradiation** (**DNI**) [1].

Figure 1: Heliostats

A vital part of **CSP** tower systems are heliostats, which are mirrors that track the sun and converge sunlight onto a central receiver. By concentrating sunlight, these mirrors effectively create a high temperature, which improves the power generation effectiveness. Heliostats are especially useful in areas with high **DNI**, but their usefulness can be increased with the help of cutting-edge AI and energy storage technologies that lessen the effects of unpredictable solar availability.

Apart from heliostats, **Parabolic Trough Reflectors** (**PTR**) are yet another widely used innovation in systems utilizing **CSP**. PTRs are made up of curved reflectors that direct sunlight onto a linear receiver, which is usually a tube, filled with oil or another heat-transfer fluid. After the fluid reaches high temperatures, it can be utilized to produce steam, which is needed to produce electricity. PTR systems have been widely used because of their high thermal efficiency, less expensive initial investment, and comparatively straightforward design [2]. PTR systems work particularly well with thermal energy storage systems and are especially well-suited for utility-scale solar power plants [3]. This allows for extended power output during cloudy days or nocturnal hours.

Figure 2: Parabolic Trough Reflector (PTR)

However, in sub-tropical regions such as Bangladesh, persistent high levels of DNI are essential for **CSP** performance. Due to this constraint, backup energy storage devices are essential for maintaining a continuous power production.

2.2 Thermal Energy Storage System

Thermal energy storage (TES) is essential for the successful deployment of **CSP** technologies, allowing energy to be stored during peak sunlight hours and dispatched when solar irradiance is low. Traditionally, molten salt has been the preferred medium for thermal storage due to its high heat capacity and ability to maintain thermal stability at high temperatures. However, molten salt systems can be costly, particularly in terms of materials, maintenance, and the infrastructure needed to keep the salt in a molten state.

Sand has become an ideal alternative for thermal storage as it is inexpensive, readily available, and has a relatively high specific heat capacity of 830 J/kg°C. While the heat capacity is not as high as specialized materials like molten salts (which have a specific heat capacity around 1500 J/kg°C), sand is still quite efficient for storing and releasing heat in large-scale applications. In addition, non-construction grade sand can be effectively used as thermal storage which is an ideal choice for use in developing nations like Bangladesh. According to recent research, sand can be heated to high degrees and can hold thermal energy for an extended amount of time [4]. Sand storage batteries offer a reliable and efficient energy storage option, and their usage in **CSP** systems may result in cheaper capital and operating costs [5].

2.3 Reverse Electrodialysis (RED)

Utilizing the salinity gradient between freshwater and saltwater, **Reverse Electrodialysis (RED)** is an emerging method for producing and storing energy. Ions traverse through selective ion exchange membranes during the process which generates an electric potential that can be turned into energy. RED technology has been analyzed for its potential in combining with renewable energy sources including solar and wind to provide a stable and efficient energy storage solution.

New developments in membrane technology have enhanced the reliability and effectiveness of RED systems, suggesting that combining them with **CSP** and other renewable energy sources is a reasonable choice. For example, storing extra electrical energy (50 watt in a study in Spain) as ionic potential and utilizing it to power CSP systems during periods of low solar irradiation is made possible by employing RED as a backup [6]. Bangladesh has a distinct geographic advantage for RED technology implementation as part of an integrated energy strategy due to its proximity to both freshwater and saline water bodies.

2.4 Thermo-Chemical Water Splitting Process (TCWSP)

The Thermochemical Water Splitting Process (TCWSP) uses high temperatures and chemical catalysts in a periodic manner to break down water into hydrogen and oxygen. This method is very effective for producing hydrogen because it uses chemical cycles that permit reactant reuse and typically operates at temperatures between 800°C and 1,200°C [7]. As a scalable technique for creating hydrogen without emitting greenhouse gasses, TCWSP has proven a great deal of potential.

As the Thermo-Chemical Water Splitting Process (TCWSP) requires high conversion efficiencies to withstand extremely high temperatures, recent advances have concentrated on creating high-performance materials like refractory metals and advanced ceramic composites [8], as well as extremely resilient catalysts like cerium oxide ($CeO2$) and cobalt ferrite ($CoFe2O4$). At temperatures above 1200°C, these materials exhibit exceptional thermal stability, chemical resistance, and oxidation tolerance. TCWSP is dependent on these materials for maintaining the efficiency of hydrogen production through multi-step redox reactions. The ability to directly use extra thermal energy from the solar field to drive the thermochemical reactions is one benefit of integrating TCWSP with CSP systems. TCWSP provides a sustainable way to produce significant amounts of hydrogen fuel that may be exported or utilized locally in fuel cells or other energy systems.

2.5 Hydrogen Fuel Cells (HFC)

Hydrogen fuel cells are gaining attention for their ability to generate clean electricity, producing only water as a byproduct. The most common type, Proton Exchange Membrane Fuel Cells (PEMFC), operates at low temperatures and is used in transportation, portable power, and stationary systems (Barbir, 2005). These cells are highly efficient, often surpassing 60% in electricity generation, and can be integrated with renewable energy sources like solar and wind (Bessarabov et al., 2016). Despite their benefits, challenges such as high material costs (e.g., platinum catalysts), hydrogen storage issues, and limited infrastructure for hydrogen production remain (Momirlan & Veziroglu, 2005). Research continues to focus on cost reduction and increasing hydrogen production efficiency via renewable sources, positioning hydrogen fuel cells as key contributors to a sustainable energy future.

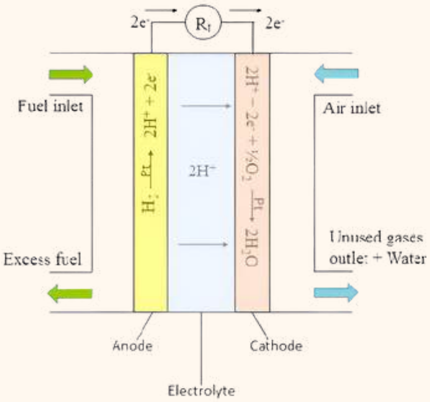


Figure 3: Hydrogen Fuel Cell (HFC)

2.6 Artificial Intelligence in Energy Management

Artificial Intelligence (AI) is proving to be a key factor for the optimization of renewable energy systems, particularly in terms of cost reduction and increased operational effectiveness. The inherent unpredictability and discontinuous nature of renewable energy sources are greatly minimized by AI. Deep Neural Networks (DNN), Predictive Analytics, and Reinforcement Learning (RL) are three AI methods employed in energy management that have demonstrated a great deal of promise for optimization of system performance.

Reinforcement Learning (RL) is particularly well-suited for managing complex, dynamic systems that energy grids face everyday. RL algorithms can continuously learn from real-time data to optimize processes such as the positioning of solar panels or heliostats, the regulation of turbine operations, and the management of energy storage systems. By analyzing variables like solar irradiance, ambient temperature, and electricity demand, RL can adjust system components in real time, leading to more efficient energy capture and storage. Studies have shown that RL-based optimizations can increase energy efficiency by up to 15%, especially in systems subject to variable environmental conditions.

Deep Neural Networks (DNN) is widely used for forecasting energy production and consumption. These models can analyze historical and real-time data to predict periods of high or low renewable energy output, enabling more efficient resource allocation. For example, DNNs can predict energy demand and help determine when stored energy from thermal batteries or other storage systems should be used to meet peak demand. This predictive capability allows for more stable integration of renewable energy into the grid, minimizing the need for backup fossil fuels and reducing overall carbon emissions.

Predictive Analytics in energy management focuses on improving system reliability and reducing downtime through proactive maintenance strategies. By analyzing historical data on equipment performance, failure rates, and environmental conditions, AI-driven predictive maintenance can anticipate when critical components like turbines or storage systems require servicing. This reduces the likelihood of unexpected breakdowns, improving system reliability and cutting maintenance costs. In renewable energy systems, predictive analytics can reduce downtime by 30-50%, significantly extending the lifespan of key infrastructure components.

The combination of these AI models allows for more efficient and reliable renewable energy systems, enables real-time adjustments to optimize energy generation, improves storage utilization, and ensures predictive maintenance, thus enhancing the overall resilience and sustainability of energy infrastructure.

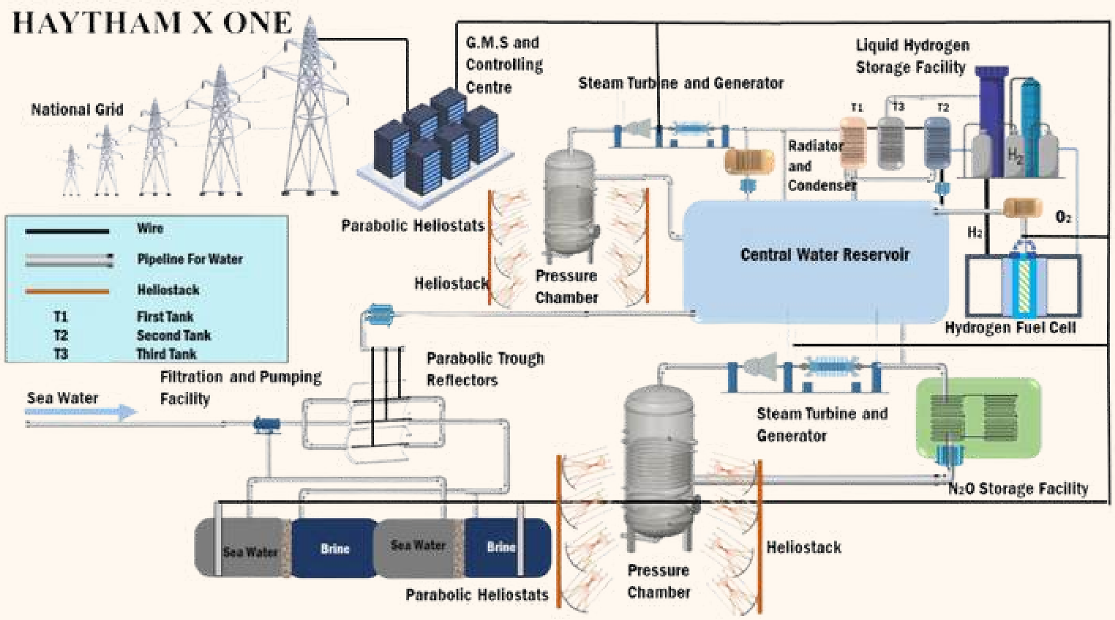


Figure 4: Schematic Representation

3. METHODOLOGY

3.1 Conceptual Synopsis

The goal of the HAYTHAM X ONE is to combine CSP and efficient storage monitored by artificial intelligence (AI)-based management systems into a unified structure that can aid the current grid of Bangladesh. Coastal regions of the country will be the system's primary implementation sites because they receive more solar radiation than the country's interior, supply of sea water and required area needed for installment. The proposed strategy, which combines Parabolic Trough Reflector (PTR) and CSP systems with sand storage and production of hydrogen, ensures that electricity may be produced during unfavorable times, which are frequent in tropical regions, as well as during the hours of greatest sunlight.

Initially, the filtration facility will receive seawater through the pumping facility and get filtered. The water will pass through the PTRs and undergo HTBS process. The RED battery will receive concreted brine and fresh water separately. Freshwater serves as the primary power plant driving source, while RED is one of the backup storage systems. A heat transfer fluid of molten salt is used in the solar receiver. Here mainly CSP aided by modified heliostats will generate electricity in steam turbines at 1500° Celsius. Around 800° Celsius of the byproduct-heated water will be used in the TCWSP and sand storage system. Sand storage is the primary storage method in adverse weather conditions. The RED and Hydrogen Fuel Cell combined will work as a secondary backup battery. Additionally, the hydrogen produced via TCWSP is stored in Hydrogen Storage and supplied to a Hydrogen Fuel Cell (HFC) at the time of need.

3.2 Parabolic Trough Reflector (PTR) and Helio Thermal Brine Separation (HTBS)

Sea water flows through the filtration and pumping facility and the macro debris will be separated from the main water stream. For 1 MW of energy generation, approximately 1.8 to 2 liters of water per second are required. Based on this, the total water requirement for the 1000 MW operation amounts to roughly 129600 m^3/day of freshwater, while around 288,000 m^3/day of seawater is needed for desalination to produce the necessary freshwater. The entire water intake will be done from the sea .This filtrate now goes through a pipe which is set at the focus point of required length and appropriate focal point of a Parabolic Trough Reflector. Though PTR is a CSP technology for electricity generation, in our proposed system the function of PTR in HTBS is separation of water and Brine. This method of CSP is only used for HTBS, not power generation in our system. This long Parabolic Trough Reflector will converge the solar radiation at its focus and the converging beam heats the water up to at least 400° Celsius. The steam is collected in gravitational separator valves and goes through a radiator and condenser to lose the heat and will be directed to the Central Water Reservoir. And there will be brine left at the bottom of the pipe. There will be a controlled valve at the starting of a bypass line to separate the brine and direct it to the RED battery storage.

3.3 Heliostats: The Key Component

The heliostat is the primary device employed for solar power concentration, consisting of hexagonal, concave mirrors designed to focus solar radiation onto a central receiver. The efficiency of the entire Concentrated Solar Power (CSP) plant is largely dependent on the performance of individual heliostats. To ensure maximal operational efficiency, we propose a centralized control system for synchronizing all heliostats and maintaining optimal alignment throughout the day.

To further enhance performance, two specific engineering advancements are recommended:

1. Advanced Sun-Tracking Mechanism: For continuous and precise solar energy capture, an automated sun-tracking system is essential. Tracking the sun's azimuth and elevation throughout the day ensures the heliostats maintain the solar flux on the receiver, thereby maximizing the conversion of solar energy into heat.
2. Aerodynamic and Structural Resilience: Designing heliostats with an optimized aerodynamic profile can significantly reduce wind loads, enhancing structural stability in high-wind environments. Constructing the mirrors from composite materials with high tensile strength allows them to endure adverse weather conditions, including extreme winds and storms, thereby minimizing mechanical failure rates.

The sun-tracking mechanism is augmented with **Light Dependent Resistors** (**LDRs**), providing real-time feedback on solar irradiance to continuously adjust the heliostat's angular position. These sensors are responsive to variations in solar intensity caused by environmental factors such as cloud cover, allowing for dynamic recalibration to maintain optimal energy capture. The heliostat tracking system will incorporate multiple Degrees of Freedom (DOFs) to allow for precise orientation:

- **Azimuth rotation:** Enables horizontal movement to follow the sun's east-to-west trajectory.
- **Elevation tilt**: Adjusts the vertical angle of the mirrors to capture solar radiation optimally during different times of the day.
- **Axial rotation of the mirror**: Facilitates minor corrections to ensure optimal reflection alignment onto the receiver.

This dual-stage tracking system operates as follows:

- A coarse adjustment phase, driven by a coordinate-based calculation algorithm, initially aligns the heliostats based on the solar azimuth and elevation angles.
- A fine adjustment phase is then implemented using LDRs distributed along the edges of the heliostat to detect differential solar intensity. By comparing resistance values across these sensors, the system can determine the precise angular adjustments needed to optimize reflection accuracy.

Following the fine adjustment, a predictive control model is engaged. This model uses the sun's trajectory data to anticipate future positional changes, reducing the need for continuous recalibration. By employing this approach, the system achieves a higher degree of precision, ensuring that solar flux remains concentrated on the receiver despite fluctuations in environmental conditions. Glass Fiber Reinforced Polymer (GFRP) is a lightweight, strong, and corrosion-resistant material that can handle various environmental conditions. For maximum efficiency and cost-effectiveness, a hybrid approach using GFRP for the frame and Aluminum Honeycomb Panels for the reflective backing can balance cost, strength, and weight.

The incremental cost associated with these enhancements—improved aerodynamic design and precision tracking systems—is offset by a significant increase in heliostat and plant efficiency, resulting in higher overall energy output and operational longevity.

3.4 Reverse Electrodialysis (RED)

It is a membrane-based technology that generates electricity via the "controlled mixing" of solutions at different salt concentrations. **Ion-exchange membranes** (**IEMs**) enable the production of renewable energy by converting the salinity gradient, which would be dissipated during a spontaneous (i.e., uncontrolled) mixing process, into an ionic current and, later, into electricity at the electrodes. We present a formation where Brine and less concreted sea water is pumped alternatively divided by IEM. It is to be noted RED is not a regular energy storage system but a backup for extreme conditions as it can be stored for a long time. As the brine has more charged ions than seawater, positive ions will go to the sea water as osmosis as it has fewer amounts of ions. So, the amount of negative ions will be more in brine and a potential difference is created. By connecting the respective chambers electricity can be produced for replenishing the battery during daytime the HTBS will supply brine and seawater.

3.5 Concentrated Solar Power (CSP) Electricity Production and Hydrogen Production

At first 21500 heliostats will converge sunlight to their focus point on the pressure chamber with the precision of one tenth or one twentieth of a degree which will make the temperature to 1500° Celsius. The 1000MW facility is divided into 4 solar towers each producing 250 MW of electricity .The solar receiver will be filled with molten salt (40% Sodium Nitrate and 60% Potassium Nitrate) as heat transfer fluid which is designed to maintain the temperature. Within the chamber, an oscillatory pipeline submerged within that liquid will help liquid water coming from the central reservoir to turn into superheated high-pressure steam close to 1500° Celsius. Now the process is splitted in two ways, the steam turbine will produce electricity with the help of a generator connected to it via conventional thermal energy cycle. The Siemens SST-700/900 Series is a high-efficiency steam turbine with up to 45% thermal efficiency, widely used in solar thermal power plants for its flexibility and adaptability to various **CSP**. According to our calculation around 1000 Mega Watt of electricity each is estimated to be produced in four separate units and the electricity will be sent to the Central Power Station which will supply the electricity to the National Grid. On the other side, the heated water will be channeled to the Hydrogen Production Tank (HPT) for the generation of Hydrogen following the process of Thermochemical Water Splitting Process (TCWSP). In the first tank H_2SO_4 will be present and the following reactions will occur: $H_2SO_4 \rightarrow SO_2 + H_2O + [O]$. And to keep the temperature at 850° Celsius the cold water from the central water reservoir will be pumped to be mixed with the hot steam with the appropriate ratio instantly calculated by AI after collecting data from sensors. Then in the third tank, following reaction will occur: $I_2 + SO_2 + 2H_2O \rightarrow 2HI + H_2SO_4$. And in second tank, the following reaction will occur: $2HI \rightarrow I_2 + H_2$.

In both the reactors the reactants are recycled. So, only water needs to be supplied. And the produced hydrogen will be compressed in liquid state and stored in the Liquid Hydrogen Storage. And the required temperature will be maintained like it was done for tank 1. The produced H_2 will be converted into liquid hydrogen, stored in safe tanks and will be used to produce heat at night to continue producing electricity even when the sun is not present as well as be exported to other industries. The hot water coming from tank 3 has now lost most of the heat so it will go to the Central Water Reservoir. If required it will pass through a condenser to convert it into room temperature liquid. The Hydrogen will also be used for making Hydrogen Fuel Cells which will be used to produce electricity at night safely and efficiently.

3.6 Hydrogen Fuel Cell (HFC)

At the hydrogen fuel cell facility, multiple fuel cells are configured to utilize oxygen from Tank 2 of the **Thermo-Chemical Water Splitting Process** (**TCWSP**) system and hydrogen sourced from TCWSP. Oxygen is supplied to the cathode while hydrogen is introduced at the anode. A platinum catalyst at the anode facilitates the dissociation of hydrogen molecules into protons and electrons according to the principle of **Proton Exchange Membrane Fuel Cells** (**PEMFC**). The electrons are directed through an external circuit, generating an electric current and dissipating excess heat, while the protons migrate through a porous electrolyte membrane to the cathode. At the cathode, protons, electrons, and oxygen recombine to form water molecules as the sole byproduct. This design ensures high reliability and quiet operation due to the absence of moving parts. The resultant water is directed to a heat exchanger and subsequently stored in a central reservoir. Utilizing hydrogen fuel cells as a storage mechanism for Concentrated Solar Power (CSP) plants enhances energy stability and efficiency. Hydrogen effectively stores excess solar energy, facilitating load balancing and enabling long-duration storage with conversion efficiencies exceeding 60% when reconverted to electricity.

3.7 Sand Thermal Storage Battery and Reverse Electrodialysis (RED) Battery Storage

One of the key features of the **HAYTHAM X ONE** system is the replacement of conventional energy storage methods with sand-based thermal storage. The specific method used here is called **Single-Tank Thermocline System** for the simplicity and reliable design. The water in the pipeline will reach 1500 degrees Celsius during operating hours and will cool to 800 degrees Celsius after producing power via steam turbine. The heated water in this system will transfer heat to the sand storage mechanism. Our project's primary storage facility is sand. Results from experimental **CSP** plants using sand as a storage medium point to an 80% thermal efficiency for sand storage [9]. Minimal energy is lost during the storing and retrieval procedure attributed to this high level of efficiency. Single-tank thermocline systems store thermal energy in a solid medium, typically silica sand, within a single tank. During operation, this medium features a temperature gradient, with regions of high and low temperature. High-temperature heat-transfer fluid enters at the top and exits at the bottom, driving the thermocline downward and storing thermal energy. Reversing the flow moves the thermocline upward, releasing energy to generate steam and electricity. Buoyancy effects promote thermal stratification, stabilizing the thermocline. Using a solid medium and a single tank reduces costs compared to two-tank systems. This technology was demonstrated at the Solar One power tower, where steam served as the heat-transfer fluid and molten salt (40% Sodium Nitrate and 60% Potassium Nitrate) as the storage fluid.

3.8 AI-Based Management System

The **HAYTHAM X ONE** project utilizes an AI-based management system to optimize the operation of its integrated renewable energy framework, ensuring efficient energy production and storage. The AI system will rely on data from multiple sources and sensors to monitor the environment, the energy system, and infrastructure health. It will include: Solar Irradiance, Data on the intensity of sunlight, both direct and diffuse, Ambient Temperature: Temperature affects the efficiency of **CSP** and hydrogen production processes, Thermal Energy Storage Levels: The AI needs to monitor the thermal energy stored in the sand-based storage system and other energy storage devices as sand thermal batteries and Reverse Electrodialysis (RED) batteries and also Weather Conditions [(Wind speed (m/s), humidity (%), cloud cover (%)]

By employing **Reinforcement Learning (RL)** algorithms, the system adjusts the positioning of heliostats in real time to maximize solar energy capture. The heliostats' angle and rotation are controlled based on solar position and cloud cover, optimizing the concentration of solar beams onto the receiver. Studies show that RL-based optimizations can improve energy capture efficiency by up to 15%, especially under variable environmental conditions.

In addition to optimizing energy generation, the system uses Predictive Maintenance algorithms to monitor key components such as turbines and heat exchangers. By analyzing past performance data and real-time metrics, the system can predict when maintenance is required, thus reducing the likelihood of unexpected failures and minimizing downtime.

Furthermore, the AI system leverages **Deep Neural Networks (DNNs)** for energy forecasting. These models analyze past usage data and real-time energy consumption patterns to predict periods of high or low renewable energy output. This enables the AI system to efficiently allocate resources, particularly during periods of excess energy generation. For instance, when excess energy is produced, the AI directs this surplus toward hydrogen production via the **Thermo-Chemical Water Splitting Process (TCWSP)**, ensuring that both electricity demands and hydrogen production targets are met.

4. THEORETICAL ANALYSIS AND DISCUSSION

4.1 Energy Output Projections

Based on current research and future prediction, **HAYTHAM X ONE** is anticipated to produce about 1000 MW of power from its **CSP** system. Reliable power generation is ensured by this hybrid method when sufficient solar irradiation is available. The system's ability to store excess heat for up to several days through the incorporation of sand and hydrogen storage enables the ongoing production of energy even after sunset [10].

Calculation of number of heliostats in each Solar Towers

Formula for CSP Power Output from a Single Tower (Assuming 65% efficiency for CSP systems)

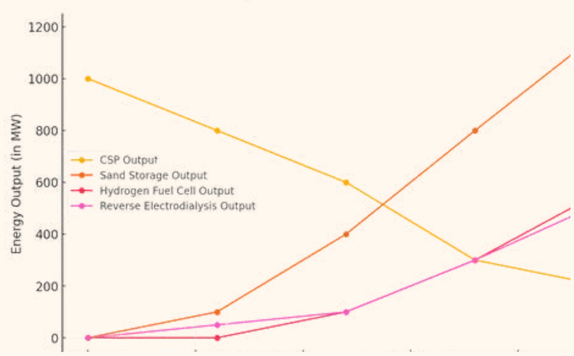
$P_{tower} = \eta_{sys} \times A_{heliostats} \times DNI \times N_{heliostats}$

Where: P_{tower} = Power output from a single tower (in Watts)

η_{sys} = System efficiency (typically around 60%)

$A_{heliostats}$ = Area of one heliostat (in square meters)=Assume each heliostat has an area of 20 m².

DNI= Direct Normal Irradiance (in W/m²) = In coastal regions (Bangladesh), the DNI is about 3600 W/m² on average (Solargis, n.d.).



Graph 1: Energy output over time for different systems

$$N_{heliostats} = \frac{P_{tower}}{\eta_{sys} \times A_{heliostats} \times DNI} = \frac{250 \times 10^6}{0.65 \times 5 \times 3600}$$

$= 21367.52 \approx 21400$

To generate 250 MW from a single tower approximately 21400 heliostats will be required.

Category	Description	Value/Formula	Result (MW)
Hydrogen Fuel Cell (PHFC)	Efficiency (ηHFC)	60%	568.8 MW
	Hydrogen Flow (ṅH2)	4000 mol/s	
	Gibbs Free Energy (ΔG)	237,000 J/mol	
	Power Output	PHFC = ηHFC · ṅH2 · ΔG	
Sand Storage System (PSAND)	Efficiency (ηSAND)	80%	1,190.6 MW
	Stored Energy (Qstored_current)	1,200 MW	
	Power Output	PSAND = ηSAND · Qstored_current	
Reverse Electrodialysis Battery (PRED)	Efficiency (ηRED)	35%	525 MW
	Membrane Area (Amembrane)	100 m²	
	Salinity Gradient (ΔS)	1,500	
	Number of Membranes (Nmembranes)	10,000	
	Power Output	PRED = ηRED · Amembrane · ΔS · Nmembranes	
Total Power Output	Primary Storage (Sand)	-	1,190.6 MW
	Backup Storage (HFC + RED)	-	1,093.8 MW

Table 1: Power Output from Hydrogen Fuel Cell, Sand Storage, and Reverse Electrodialysis Systems

4.2 Bangladesh: A Suitable Candidate

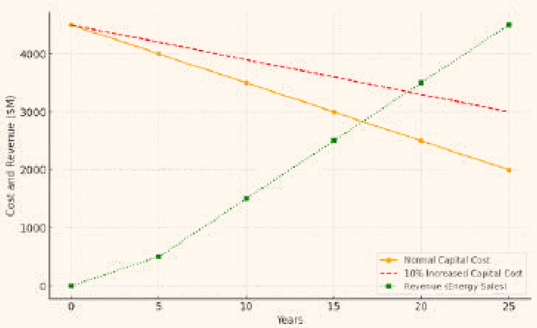
By harnessing its renewable energy potential through **CSP** hybrid systems, Bangladesh can meet its growing energy demand sustainably. Moreover, the production of green hydrogen creates opportunities for economic growth, providing a valuable export commodity in the growing global hydrogen market. **CSP** can significantly enhance the country's energy landscape by providing efficient, sustainable energy solutions. The project aligns with Bangladesh's national renewable energy goals, which aim for 10% renewable energy generation by 2030 [11].

- **CSP** operates three times more efficiently in tropical regions, benefiting from Bangladesh's high sunlight exposure (215 W/m² in the north-west to 235 W/m² in the south-west per day). While the average DNI in the coastal region is about 3600 W/m² on average (Solargis, n.d.).
- The country's favorable weather and abundant seawater make it ideal for **CSP** production, while materials for construction are readily available without reliance on rare resources.

CSP has proven financial viability in countries like Spain, Morocco, and the USA [12], and can enhance the existing grid's efficiency through AI-driven management systems.

4.3 Economic Viability and Environmental Analysis

The capital cost for a **CSP** plant with sand storage is estimated to be $4,500 per kW, which includes the cost of sand storage infrastructure and AI systems [13]. Operating costs are projected at $50 per MWh, making it competitive with other renewable energy sources (from existing facilities). A sensitivity analysis was performed to assess the financial impact of fluctuating energy prices and capital costs. A 10% increase in capital costs would extend the payback period by approximately two years, but the project's long-term profitability remains intact due to the growing global demand for hydrogen [14]. The plant is expected to reduce CO_2 emissions by approximately 1 million metric tons per year [15], contributing to global efforts to combat climate change.



Graph 2: Economic Viability and Cost Sensitivity Analysis

Furthermore, the project will create numerous jobs during both the construction and operational phases, with significant opportunities for local employment and skills development.

4.4 Future Research Directions and Scalability

Future research should focus on further improving the thermal efficiency of sand storage systems and exploring additional renewable energy sources that could be integrated into the plant. The scalability of **HAYTHAM X ONE** is significant, with the potential for future expansion to meet increasing domestic energy demand and provide additional capacity for hydrogen production. Stirling engine is a candidate to be experimented with instead of steam turbine to improve the efficiency further. Long term Hydrogen storage is a challenge which also needs to be addressed. Integration with Bangladesh's national grid will further enhance energy distribution, potentially reducing load shedding across the country [16]. In addition, further research could be done to open the door for our nation to utilize hydrogen as an automotive fuel.

5. CONCLUSION

The **HAYTHAM X ONE** project offers an innovative and comprehensive approach to addressing Bangladesh's energy challenges by leveraging Concentrated Solar Power (**CSP**) technology, efficient energy storage systems, and AI-driven management. The project's methodology integrates **CSP** with Parabolic Trough Reflectors (PTR) for water desalination and heliostat arrays to concentrate sunlight for electricity generation. Excess thermal energy is stored using advanced sand thermal storage systems, while hydrogen production via the Thermo-Chemical Water Splitting Process (TCWSP) ensures energy availability even after sunset. Furthermore, the inclusion of Reverse Electrodialysis (RED) and hydrogen fuel cells adds reliable backup power.

Through this multifaceted framework, **HAYTHAM X ONE** can provide continuous power generation while supporting the production of green hydrogen as a valuable export commodity. This combination of cutting-edge technologies and renewable energy systems positions Bangladesh to achieve both energy independence and environmental sustainability. With its capacity to reduce CO_2 emissions, create employment opportunities, and contribute to the global hydrogen market, this project is a crucial step toward transforming the country's energy landscape and achieving its renewable energy goals.

6. ACKNOWLEDGEMENTS

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