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INDUSTRIAL WASTEWATER AS A FEEDSTOCK FOR GREEN HYDROGEN PRODUCTION: TOWARDS CIRCULAR ECONOMY AND SUSTAINABILITY

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ABSTRACT
This article aims to achieve environmental sustainability and economic benefits by exploring the possibility of integrating a green hydrogen production unit with a wastewater treatment plant in the Gems & Jewellery and Electronics industrial sectors present in Santacruz Electronics and Export Processing Zone, Special Economic Zone (SEEPZ SEZ). Conventional wastewater treatment frequently results in Treated Effluent (TE), which is disposed of or occasionally reused for cooling or irrigation. By adopting creative reuse strategies, such as using treated wastewater as a source for green hydrogen generation, enterprises can reduce carbon emissions, conserve fresh water, and implement a circular economy concept. This study assessed the technical and financial feasibility of integrating a green hydrogen production unit with the SEEPZ sewage treatment plant in Mumbai, Maharashtra, India. This research reveals a significant potential revenue stream and economic advantages over traditional wastewater treatment methods. The use of Proton Exchange Membrane (PEM) electrolyser systems might result in revenues of Rs. 303.3 million for capacities of 120 kg H_2/day and Rs. 1,737.2 million for capacities of 1,200 kg H_2/day. This integration of green hydrogen production units with wastewater management in industrial sectors like SEEPZ results in significant prospects for both revenue generation and environmental stewardship, aligning with Sustainable Development Goals (SDG) 6 (Clean Water and Sanitation) and 7 (Affordable and Clean Energy).
Keywords: Hydrogen from Waste, Electrolysis of Water, Green Hydrogen, Treated Effluent, STP, Sustainable Waste Treatment.
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INTRODUCTION

Natural resources like the sun, water, minerals, and flora have helped humans over the ages by enabling them to survive and establish societies. The primary resources needed to build civilisations and the industrial revolutions are energy and water. In recent decades, natural resources have come under increasing strain due to overuse and mismanagement. The overuse of non-renewable energy resources and the use of vast quantities of freshwater resources are depleting them, causing several detrimental effects that eventually led to climate change and global warming. Thus, necessary steps must be taken to shift global attention to a more sustainable and green future. Similarly, water resources in SEEPZ have been valued since 1973 and are valuable for industries situated inside the zone that must be preserved to prioritise export production. In order to preserve SEEPZ's natural water resources, the proper management of water and wastewater is needed. As the commercial hub of India, SEEPZ is heavily dependent on desalination and municipal supplied water as resources to supply both potable and non-potable water. Hence, connecting to one of the main ideas underlying India's 2030 vision is the introduction of water reclamation prospects for sustainable growth, taking governance, social, and economic performance into account. The state gets its potable and non-potable water via desalination and municipal supplied water as a natural resource. In order to assist in generating clean treated water, the used water is sent to wastewater treatment plants where contaminants are removed. Despite having a wastewater treatment system in place, SEEPZ has not yet fully utilised the processed effluent of that system. Currently, the treated wastewater is either disposed of in the sea or used solely for limited purposes such as cooling or landscape irrigation. By offering a more practical water reclamation technique, there are additional reuse concepts that might be more advantageous. Huge volumes of high-quality reusable water can be used for a variety of purposes, potentially yielding huge profits and quick payback times in the fields of energy production, groundwater recharging, industrial uses,

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and potable water. As a result, an economy can be generated in addition to helping to meet the water demand, which is currently endangered by the problem of clean water scarcity from recoverable sources. The introduction of water reclamation prospects for sustainable growth in the three primary pillars of Economic, Social, and Governance (ESG) performance is one of the factors propelling India's 2030 aim. The vision focuses primarily on the 6^{th} and 7^{th} goals, which are to ensure that water and sanitation are available and managed for everyone with a cleaner energy production (SDG-Sustainable Development Goals- Index 2.0), in line with the UNSDGs (United Nations Sustainable Development Groups) as it strives to achieve SDGs. Beyond the desire to establish a circular economy, there are several motivators and demands for resource recovery. Water reclamation can help address environmental problems such as ecosystem losses, seawater intrusion into groundwater, and short-term water shortages to fulfil the SDGs. In addition to facilitating green hydrogen energy recovery, this technique can lessen the demand on the industry to cut greenhouse gas emissions.[1,2] For example, Sonal et al. (2014) conducted a cost-benefit analysis of eight different technologies using the classic Analytic Hierarchy Process (AHP) and the fuzzy AHP. The technologies used in this study included steam methane reforming, coal gasification, biomass gasification, photovoltaic-based electrolysis, wind-based electrolysis, hydro-based electrolysis, and chemical looping water splitting. It also included partial oxidation of hydrocarbons. The study was assessed based on five criteria: air emissions, energy efficiency, scalability, waste disposal, raw material and utility consumption, and greenhouse gas emissions. The study found that although fossil fuels were more affordable, they had fewer advantages and more negative effects on the environment. Another Hui *et al.* (2021) study examined the life cycle sustainability from economic, environmental, social, energy-based, and technical aspects, emphasising the pressing need for sustainable Hydrogen Production Technology (HPT). The study's findings indicate that the most environmentally friendly technological choice for producing hydrogen is copper-chlorine (Cu - Cl) thermochemical water-splitting, which is followed by natural gas steam reforming and wind-powered water electrolysis. The least environmentally friendly choice is to employ coal gasification. In another study, Barghash H. *et al.* (2022) carried out a life cycle assessment study for the production of bio-hydrogen gas from sewage treatment plants using solar PVs. In this work, a reactor with a capacity of 0.96 Litres of H_2 per Litre of medium was used to generate hydrogen gas from 1 Litre of sludge and treated effluent utilising a variety of techniques. Additionally, resource depletion, environmental impacts, and human impacts were studied using the Life Cycle Impact Assessment (LCIA) process, and attempts were made to mitigate the negative effects through the implementation of various remedies. The Eco-invent database was utilised in conjunction with the OpenLCA software to calculate the consequences. The study also included a comparison of the LCIA with and without solar energy utilisation. The outcomes showed that combining a solar energy system with hydrogen gas will assist in finding the best ways to reduce carbon footprints. The literature describes several methods for creating hydrogen, including biological processes that use biomass as energy.[3,4,5&6] While the idea of splitting water molecules electrically has been around for 260 years, the idea of using electrolysis to produce renewable energy just came up in the 1990s. Growing concern about finding solutions to environmental issues led to the introduction of this notion. This study introduces a new way to reduce the industry's reliance on non-renewable energy by using treated wastewater from a key sector to produce hydrogen. The focus is on generating green hydrogen from treated effluent at the SEEPZ Sewage Treatment Plant (STP) in Mumbai, Maharashtra, which is operated by the SEEPZ SEZ Authority (SSA). The research examines the feasibility of producing hydrogen with a Proton Exchange Membrane (PEM) electrolyser system in two scenarios: one with a capacity of 120 kg of hydrogen per day and another with 1,200 kg per day. By using treated effluent as a resource, this study aims to promote a sustainable circular economy. It also provides useful insights for decision-makers and stakeholders in the wastewater sector, helping them to create a sustainable path towards decarbonization and economic generation techniques.

Overview of Sewage Treatment Plant

The process of purging waterborne contaminants from influent to create clean effluent that can be recycled or used again is known as sewage/wastewater treatment.[8] A concentrated by-product of the contaminants eliminated during wastewater treatment procedures is sludge. Wastewater is polluted water it has strong smells, dark colours, and high turbidity. Moreover, it has been contaminated by various pollutants. It is important to identify both chemical and biological characteristics, which include Total Organic Carbon (TOC), Nitrogen (N), Phosphorus (P), Microbial Organisms, and Biological Oxygen Demand (BOD) of the wastewater. Depending on the origin of the wastewater *e.g.* domestic, commercial, industrial, agricultural, or collected stormwater, the characteristics vary. The quality of the treated effluent and wastewater directly depends on the design and operational condition of the sewage treatment plant.

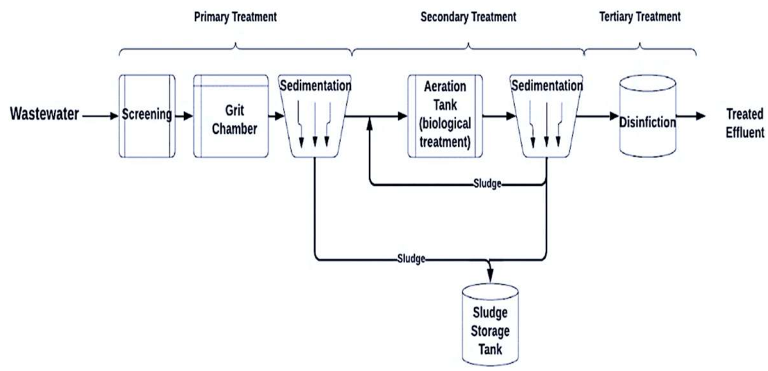

Fig.-1: Schematic Diagram of a Sewage Treatment Plant

Figure-1 illustrates a schematic representation of the different operational stages of a sewage treatment plant. Grit removal and screening are used to eliminate larger-sized physical pollutants from wastewater before it enters the primary treatment stage. The first sedimentation tank is used to remove oils and grease.[9] After that, the water goes through a secondary or biochemical treatment procedure in the aeration tank. In order for the bacteria to develop and obtain food from biological contaminants, it is crucial to keep the interactions between nutrients and microorganisms in the effluent in a controlled environment. This is accomplished by oxidising dissolved organic matter using activated sludge, which is subsequently removed from the process when the water reaches the second sedimentation tank.[10] The sludge is put into a storage tank so it can be used again, maybe to make compost, after it has been dried off. Even after going through primary and secondary treatment, the water does not reach a quality that makes it suitable for reuse in industrial, agricultural, or household settings. Thus, tertiary treatment is required to get the desired quality of water. In this process, advanced treatment stages are used, which vary depending on the intended treated effluent quality and reuse objectives. For instance, desalination techniques like Ion Exchange (IX), Electrodialysis (ED), and Reverse Osmosis (RO) can be used to provide demineralized water.[11] Building wastewater treatment plants and treating wastewater have two goals. First, by stopping the release of tainted water into the environment, it is essential to preserve city sanitation. Second, the produced treated effluent can be utilised again in various applications and is regarded as a reclaimed water source.[8]

Overview of Green Hydrogen Production

Despite producing treated effluent from water resources and providing a rich supply of microorganisms from the feed wastewater that creates sludge, wastewater treatment plants can be regarded as producers of new energy sources. Therefore, combining the elements that can yield hydrogen will turn the wastewater treatment plant into a clean energy generation plant.

Hydrogen can be produced from renewable resources and used as an energy carrier; this has attracted a lot of attention recently. Since it is environmentally benign and doesn't release any greenhouse gases (carbon, nitrogen, or sulfur) during combustion, it may be used as a substitute for fossil fuels. It can be used to produce both heat and power in fuel cells.[12] Furthermore, natural gas has a calorific value of just 44.2 GJ/ton, but molecular hydrogen has the highest calorific value of any known gaseous fuel at 143 GJ/ton.[13,14]

Depending on the usage of the energy source, there are numerous ways to produce hydrogen. By heating and causing chemical reactions, thermochemical processes liberate hydrogen from organic fuels like coal and natural gas.

The water molecule (H_2O) can be split into hydrogen and oxygen using electricity in electrochemical processes such as electrolysis. Biological approaches generate biohydrogen by using photolysis and fermentation in the presence of microorganisms.[15]

Table-1: Electrolyser and their Operating Conditions[3]

Operating conditions	AWE	PEM	AEM	Solid oxide
Operating	70–90°C	50–80°C	40–60°C	700–850°C
Temperature				
Operating Pressure	1–30 bar	<70 bar	<35 bar	1 bar
Type of electrolyte	5–7 mol/L KOH	Membranes (PFSA)	KOH or $NaHCO_3$ 1 mol/L & DVB polymer	Yttria-stablized Zirconica (YSZ)
Separator	ZrO_2 stabilized with PPS mesh	Solid electrolyte (PFSA membrane)	Solid electrolyte (DVB polymer and KOH or $NaHCO_3$)	Solid electrolyte (YSZ)

Green Hydrogen Production using the Electrolysis Method

The benefit of treating wastewater is that treated effluent can be produced in any desired quality. Hence, treated wastewater might be used in an electrolysis unit of operation as a renewable water source for electrolysis. According to Equation 1, 1 mol of water needs 237.2 kJ of electricity in addition to 48.6 kJ/mol of heat to generate hydrogen and oxygen gases.

$$H_2O + Electricity\left(273.2\frac{kJ}{mol}\right) \rightarrow Heat\left(48.6\frac{kJ}{mol}\right) + H_2 + \frac{1}{2}O_2 \qquad (1)$$

There are three tiers to the electrolyser's technical features. The first phase is the cell, which is made up of two porous transport layers and where two electrodes (the anode and cathode) are submerged in a liquid electrolyte that is next to a solid electrolyte membrane and bipolar plates.[16] The stack, which is composed of several cells connected in series, represents the second level as shown in the layout of the hydrogen generation facility. The electrolyser contains operational equipment attached to it for hydrogen gas output, water input source and treatment, cooling, hydrogen processing, and power input source.[3] Depending on the kind of electrolyte utilised, the operating environment, and the particular ionic species (such O^{2-}, H^+, and OH^-) involved, there are various kinds of electrolysis methods that can be employed. Proton Exchange Membrane (PEM), Solid Oxide (SOE), Alkaline Water (AWE), and Anion Exchange Membrane (AEM) electrolysers are the four most often utilised types of electrolysers. Table-1 indicates the most suitable operational conditions for the above-mentioned electrolysers. It is noteworthy to mention that AEM and SOE are currently being researched at the lab scale, while AWE and PEM are now in use on a commercial basis. In AWE systems, liquid electrolytes are utilized, while PEM, AEM, and solid oxide electrolysers use solid electrolytes that insulate electrons but allow ion transport between the electrodes.[17] The most fundamental kind of electrolysis and the first to be developed commercially is alkaline electrolysis.[18] The scaled-up advanced system level, or third level, is composed of two electrodes (anode and cathode) operating at lower temperatures of 50 - 80°C in an alkaline electrolyte, like KOH or NaOH, as illustrated in Figure-2(A). The anode and cathode are separated by the membrane, a porous inorganic diaphragm that is positioned in the centre of the cell. The OH^- ions are also transported to the anode side using this layer. The reactions taking place at the anode and cathode are shown below (equations 2 and 3). It can be easily produced on a large scale and has a straightforward system architecture. The main disadvantage of this process is that the generated hydrogen and oxygen gases could mix as they move through the electrolyte solution.[17]

Anode: $4OH^- \rightarrow 2H_2O + O_2 + 4e^-$ (2)
Cathode: $4H_2O + 2e^- \rightarrow 2H_2 + 2OH^-$. (3)

A schematic representation of PEM is shown in Figure-2(B). By substituting a solid electrolyte that demands greater pressure values than an alkaline electrolyser, it is intended to address the problem of gas mixing in the electrolyte solution. An anode section and a cathode section, separated by a membrane, comprise the PEM electrolyser. Electrons are transferred from the anode section (positive) to the cathode section (negative) of the electrolyte solution as the current flows through the membrane. The anode and cathode reactions are shown in Equations 4 and 5. Hydrogen is liberated from the solution as bubbles when it releases its electrons to form positive ions (H^+) and move in the opposite direction[17].

$$\text{Anode: } 2H_2O \rightarrow 4H^+ + O_2 + 4e^- \quad (4)$$
$$\text{Cathode: } 4H^+ + 4e^- \rightarrow 2H_2 \quad (5)$$

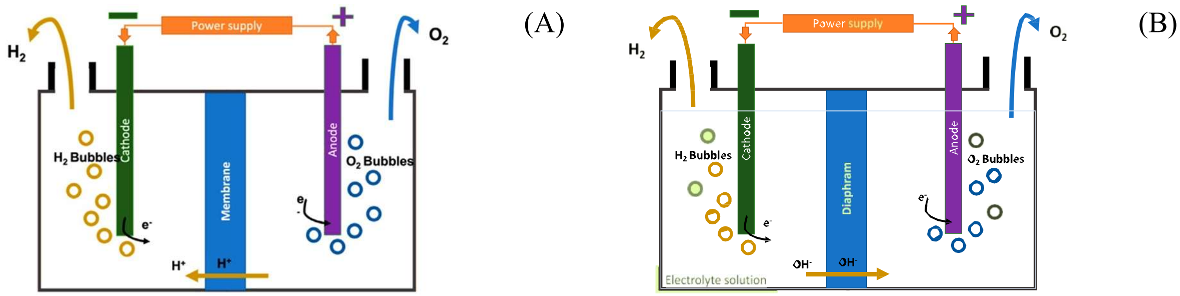

Fig.-2: (A) Showing the Process of an Alkaline Electrolyser, (B) Showing the Process of Proton Exchange Electrolyser[17]

The sustainability of the electrolysis process, which creates green hydrogen using renewable energy sources like solar, wind, or biomass, depends on the availability of electricity. As a consequence, it produces oxygen as a byproduct, leading to a zero-emission facility that will help the wastewater treatment sector decarbonise. To confirm that the treated effluent should reach a certain quality, which is suitable for the electrolysis process, the wastewater treatment facility must be equipped with an additional advanced treatment, like a reverse osmosis unit. Nonetheless, some concerns have been brought up about the release of hydrogen and its transportation and storage.[17]

EXPERIMENTAL

Feasibility Study Based on SEEPZ Sewage Treatment Plant

The SEEPZ STP hosted the feasibility study, which was managed by the SEEPZ SEZ Authority (SSA). It is located in Mumbai, the capital of Maharashtra. The facility was operational in 1975 and was run by AR Envirotech, a third-party service provider approved by the SEEPZ SEZ Authority, during the research.

In the past, the plant used a Membrane Bioreactor (MBR) with the Conventional Activated Sludge (CAS) technology to increase treated effluent quality, improve operational efficiency, and reduce carbon emissions. The factory has a 2,000 m^3/day capacity. However, because of the water pumping system, it is an energy-intensive process, and there is a chance of membrane fouling, which can lead to an increase in operational cost and maintenance expenditures.[19] The head works area, treated effluent area, biological treatment process area, and sludge dewatering unit are the four primary components of an MBR system. The plant produces clean Treated Effluent (TE) and sludge by treating home and industrial wastewater. The authorities auctioned off the produced sludge regularly to earn money. The schematic diagram of the SEEPZ STP operating modules is shown in Figure-3. The plant generates 1,800 m^3/day of Treated Effluent (TE) and receives 2,000 m^3/day of wastewater. Currently, 1,000 m^3/day of the treated effluent produced is used for irrigation, while the remaining 800 m^3/day is released into the groundwater or sea.[20]

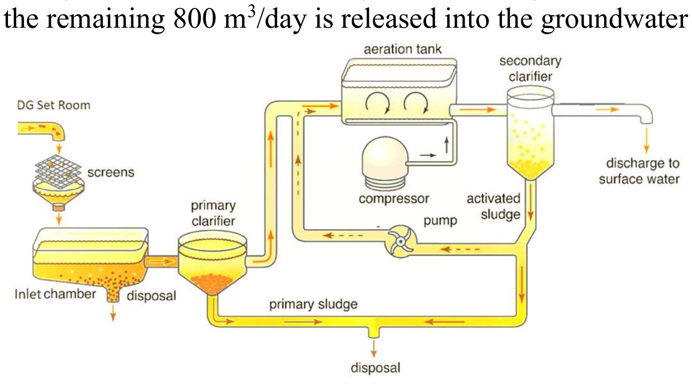

Fig.-3: Schematic Diagram of the SEEPZ Sewage Treatment Plant

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To make use of the treated wastewater in a more sustainable way, a new proposal is suggested, which is discussed below. The suggested scenarios for resource recovery are shown in Figure-4. Electrolysis is used in Case 1 to produce green hydrogen.

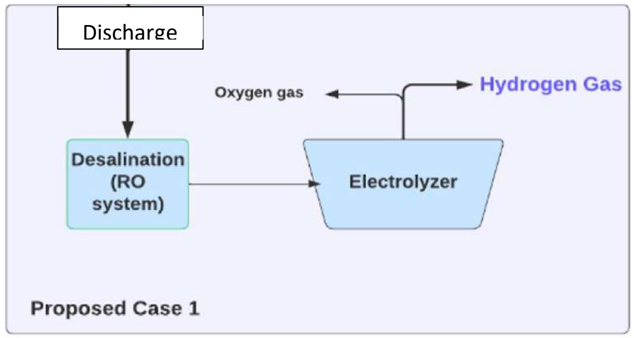

Fig.-4: Schematic Diagram for the Proposed Case 1

Market Analysis for Green Hydrogen Production

The world's goals for producing energy have changed from relying on non-renewable resources like fossil fuels to adopting greener solutions like solar and wind energy. Figure-5 shows the consistent rise in renewable energy resource production from 1947 to 1990 and from 2012, published by PIB (Press Information Bureau) on 9th Sept. 2022.

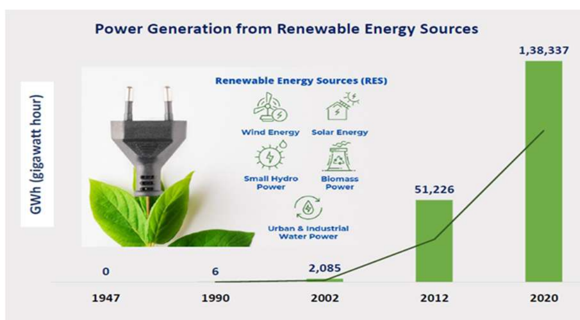

Fig.-5: Showing Renewable Energy Production from 1947 to 2020

In the energy sector, hydrogen gas has the potential to be a clean energy source in the future. Decarbonisation has become more necessary recently in a number of areas. It can be applied to numerous industries, including transportation and chemical refineries, which struggle mightily to cut emissions; green hydrogen could be the solution. One noteworthy aspect of hydrogen gas production is its ability to be combined with natural gas and fed into the natural gas grid, thus aiding in the worldwide decarbonisation of gas networks.[21] Furthermore, the energy industry is not the only one with a need for hydrogen. The Public Sector Units in India (SAIL, BHEL, etc.) require hydrogen for the production of steel, iron, glass, and electronic parts, while the chemical industry uses it to produce ammonia. Furthermore, fuel cells can be a viable option for a continuous power source or backup that may be applied to various systems to achieve the hydrogen-to-power idea.[22]

India has gradually separated its economic expansion from its production of greenhouse gases. For instance, Indian Railways alone would cut emissions by 60 million tonnes a year by achieving its Net Zero Emissions target by 2030. In a similar vein, India's vast UJALA Light Emitting Diode (LED) bulb initiative is saving 40 million tonnes of pollution every year. India established the National Hydrogen Mission in 2013 to become the largest hydrogen hub in the world to support these ongoing efforts. This suggests that the creation of hydrogen ought to be the top goal for each industrial zone in our nation. Nonetheless, the hydrogen business faces some obstacles. The fossil fuel industry supplies the hydrogen produced today, which contributes significantly to CO_2 emissions. The fact that all low-carbon hydrogen production methods are thought to be expensive is still another significant obstacle. However, the Ministry of New and Renewable Energy claims that by 2030, the cost of employing hydrogen generation for renewable energy might be reduced by 45%. Cost reduction may benefit from the mass manufacture of components used in hydrogen production[22].

General Procedure

Technical Feasibility for Green Hydrogen Production

This study uses technical analysis to assess the technical viability of implementing the suggested water reclamation ideas. It covers some of the resources and technology that can be used to create hydrogen from the products and wastewater that the SEEPZ STP generates (as indicated in Table-2).

Table-2: Concentration and Loading Rate of SEEPZ STP Effluent

Parameters	Load (kg/day)		Concentration(mg/L)
	Average annual	k Value (Max. month)	
BOD	189	203	3
TSS	428	434	4
Total N	360	1,000	4
ORG - N	0	0	0
NH_3 - N	69	125	1
COD	226	249	2
Total Alkalinity	—	—	200

Based on SEEPZ STP effluent data, two PEM electrolysis scenarios (120 kg/day and 1,200 kg/day) were assessed for feasibility using cost-benefit analysis and NPV modelling over 10 years. The processes involved are described below.

Electrolysis Technology

In order to produce green hydrogen through electrolysis technology, system-level design and balance must be adhered to. Its four main parts are the oxygen gas separator, the power supply system, the hydrogen processing and storage facility, the feed-water, and the electrolysis stack.[3] The usual system design for producing hydrogen from an intake of purified water is shown in Figure-6. Using Treated Effluent (TE) as a source of water that is carried to the electrolysis system, Table-2 also shows the loading and concentration of the TE based on data provided by the SEEPZ SEZ Authority. The TE is regarded as a dependable water source for electrolysis, which can be used for producing hydrogen. According to a study that used the Sustainable Value Methodology (SVM) to assess the sustainability of various water sources as a supply to the electrolysis process. Where treated urban wastewater is available for reuse with minimal cost and is regarded as reliable for long-term availability against the effects of climate change, as well as for short-term availability despite weather and drought.[23]

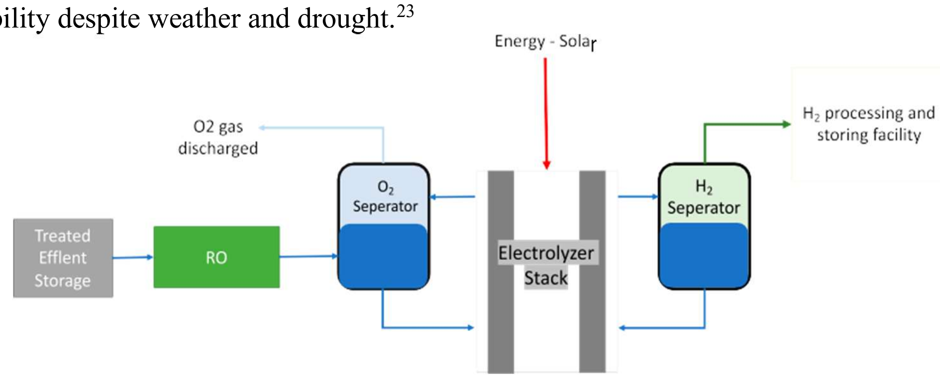

Fig.-6: Schematic Diagram of the Green Hydrogen Generator

As the final TE produced by the SEEPZ STP has a reasonably higher value of BOD, COD, and total N content. Therefore, it is suitable to use in an electrolyser. In order to maximise the electrolysis process's efficiency, the input water must be extremely pure. The efficiency of producing hydrogen increases with its level of purification. Any dissolved materials that are added to the water degrade the quality of the water and increase the risk of scaling or fouling the electrolysis membranes as seen in cases explained by Sudhir & Prasanna (2023), where untreated automobile effluents caused membrane inefficiency before natural adsorbent filtration, which shortens their lifespan and speeds up their disintegration. It is said that 9 kg of water must be supplied for every kilogram of hydrogen produced. The amount of water needed is even higher, 18 - 24 kg for the less efficient electrolysis processes.[3] The American Society for Testing and Materials (ASTM) states that the makers of electrolyzers have an impact on the quality of the water. It was determined that deionized water Type I or II, or less pure, with a conductivity of less than 5 μS/cm, would be an appropriate electrolyser input. Furthermore, the majority of electrolyzers on the market come with a demineralization step.[23] Therefore, to purify the water utilising membrane technology with a high-pressure flow, desalination technology such as Reverse Osmosis (RO) or an Ultrafiltration (UF) unit must be installed. The type of electrolyser and its technical characteristics determine the level of treatment. By using more pressure to counteract the osmotic pressure, partially permeable membranes in RO technology eliminate undesirable molecules and ions from water. It needs a high-pressure pumping system and a high energy consumption of 3 - 6 kWh/m^3. Ultrafiltration (UF), on the other hand, has a more compact membrane design that is less expensive, requires less maintenance, uses only 0.025-0.1 kWh/m^3 of energy, and generates 7% less waste from the water feed, saving operating expenses. Even though UF is less expensive and energy-efficient, a RO system is thought to be the best choice for producing water quality appropriate for industrial uses and removing any potential for scale formation, fouling, and equipment corrosion, particularly in high-pressure systems like electrolysers.[24] Nevertheless, electrolyzers that are used for commercial purposes, like Siemens PEM Silyser electrolyzer units, come with an integrated water purifying system.[25] The type of electrolysis utilised determines the differences in the stack system. Since PEM is the most recent commercial technique and has more characteristics than alkaline electrolysis, it was chosen. The PEM stack is thought to have a simpler design with less equipment than an alkaline electrolyser system, although it is more sophisticated than the conventional design. Additionally, it is a more adaptable system with a quicker response time that can be used in a wider range of operating conditions. PEM requires extra unit operations on the anode and cathode sides because of its greater operating pressure of about 30 bar. On the anode side are circulation pumps, heat exchangers, and pressure control and monitoring devices. On the cathode side, there is also a hydrogen processing unit with a gas separator. De-oxygenation is used to eliminate any surplus oxygen from the compressor, gas drier, and hydrogen output. Figure-7 displays the PEM system design with the equipment.[21] The two products are hydrogen, which is processed and stored, and oxygen, which is vented outside the system.

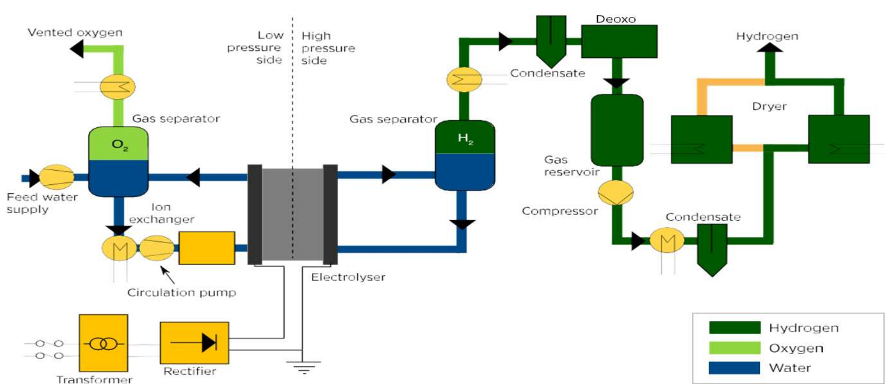

Fig.-7: System Design of PEM-WE (Proton Exchange Membrane Water Electrolyser)

Thirdly, in order to qualify as a green hydrogen production system, the power system that powers the electrolyser needs to be powered by renewable energy sources. The ideal choice in the case of the SEEPZ STP is solar energy, which may be used as a source of electricity because SEEPZ is located in an area that receives daily daylight. To convert AC to DC, solar panels are connected to a transformer, which is then connected to a rectifier. As shown in the schematic flow in Figure-8, electrochemical storage (battery) must be provided to store the generated power and supply the power to the electrolyser. The electrolyser's efficiency and the system's adaptability to solar energy changes, when direct sunlight is unavailable due to clouds, shadows, or darkness, determine the best power system design.[15]

An analysis of the potential economics of solar-to-hydrogen production using PEM electrolysis for SEEPZ was carried out. Given that the SEEPZ STP is situated in Mumbai, the estimated annual solar PV energy production within the STP grounds is 62.96 MWh (Source: SSA), and can result a significant yield of H_2/year.[26] This can attest to the possibility of producing hydrogen in the SEEPZ STP utilising the PV system and PEM technology. One disadvantage of using this technique is that it requires larger spaces for solar panels to be installed, and the amount of land needed for the electrolyser depends on the plant's capacity.[27] A two-story structure plan or smaller container units that accommodate several stacks of electrolysers can minimise the area of the PEM electrolyser. One Giga Watt (GW) PEM plant needs a maximum area of 0.08 km^2 (8 ha), according to a study done by the Institute for Sustainable Process Technology (ISPT) in 2020.

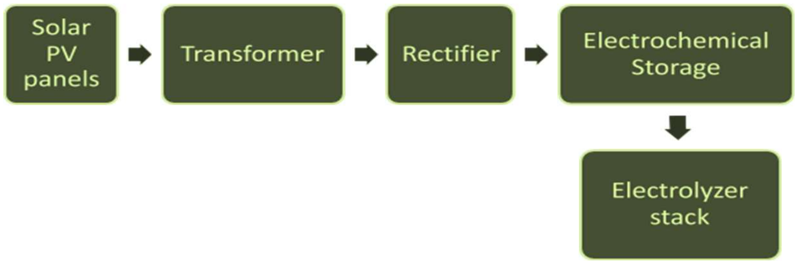

Fig.-8: Flow Diagram for Power Supply System of the Electolyser

Detection Method

Economic Feasibility of the Study

Considered to be the most crucial component of the feasibility study is the economic analysis. Equation 6 illustrates how the cash flows were determined using the Net Present Value (NPV) approach and a Cost-Benefit Analysis (CBA). The interest rate, or discount rate, is denoted by r in Equation 6, time is denoted by t, and the number of periods, or study years, is indicated by n. With a 5% discount rate, the estimated lifetime for this water reclamation process is ten years.[24] Net profit, or NP, is calculated by deducting the overall benefits from the total costs of a given year, as illustrated in Equation 7. Additionally, by information released at PIB in 2024 by the Ministry of Statistics & Programme Implementation, Government of India, an annual inflation rate based on the Consumer Price Index (CPI) for all of India of 4.83% was chosen.

$$NPV = \sum_{t=0}^{n} \frac{NP_t}{(1+r)^t} \quad (6)$$

$$NP = \sum B_i - \sum C_i \quad (7)$$

To ascertain their viability, a comparison is made between the two suggested hydrogen production systems and the traditional instance of the SEEPZ STP. Figure-9 shows the capital expenses (CAPEX), operating expenses (OPEX), and revenue CBA aspects. The capital expenditures for equipment costs are referred to as CAPEX. Operational expenses, or OPEX, can change over time. Energy, chemicals, labour, replacement, maintenance, waste management, and any other expenses are included in these expenditures. Plant operators operating under the SEEPZ SEZ Authority (SSA) contributed to the costs used for the SEEPZ STP's conventional case. The difference between the revenue from the proposed cases and the usual cases is used to compute the net savings. Table-3 summarizes similar CBA studies conducted for hydrogen production using various AWE, PEM, and SOE technologies.

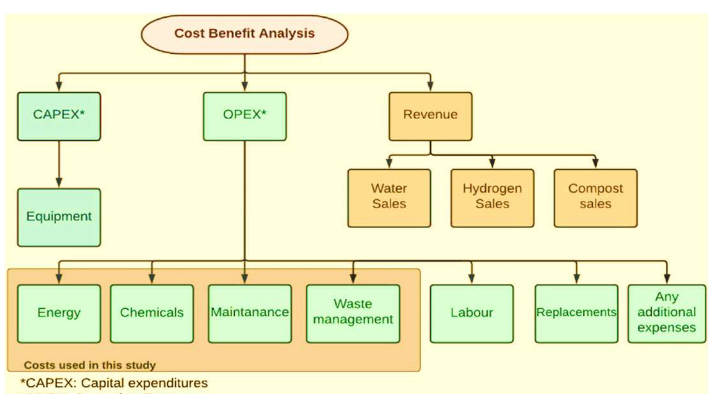

Fig.-9: Depicting the Parameters of Cost-Benefit Analysis

Table-3: Comparative Cost and Conversion Efficiency of Green Hydrogen (GH) Technologies

Fiscal Year	GH Technology	CAPEX costs, Dollar conversion -efficiency	References
2015	AWE	1,150 $/KW, 70%	GLENK AND REICHELSTEIN (2019)
	PEM	1,322 $/kW, 60%	GLENK AND REICHELSTEIN (2019)
	SOE	8,571 $/KW, 80%	WINKLER-GOLDSTEIN AND RASTETTER (2013)
2025	AWE	1,065 $/KW, 70%	GLENK AND REICHELSTEIN (2019)
	PEM	1,065$/KW, 60%	GLENK AND REICHELSTEIN (2019)
	SOE	1,057 $/kw, 80%	
2030	AWE	737 $/KW, 70%	JÜLCH (2016)
	PEM	737 $/KW, 60%	
	SOE	737 $/KW, 80%	

RESULTS AND DISCUSSION

Technical Results

The technical data that were acquired and used for this study are displayed in Figure-10. There were two electrolysis systems in use: Case A, which had a daily capacity of 120 kg of H_2, and Case B, which had a daily capacity of 1,200 kg of H_2. By comparing two capacities, as is typically done in an H_2A study (hydrogen utilising an electrolyser) with technical factors, this helped illustrate the system's robustness.

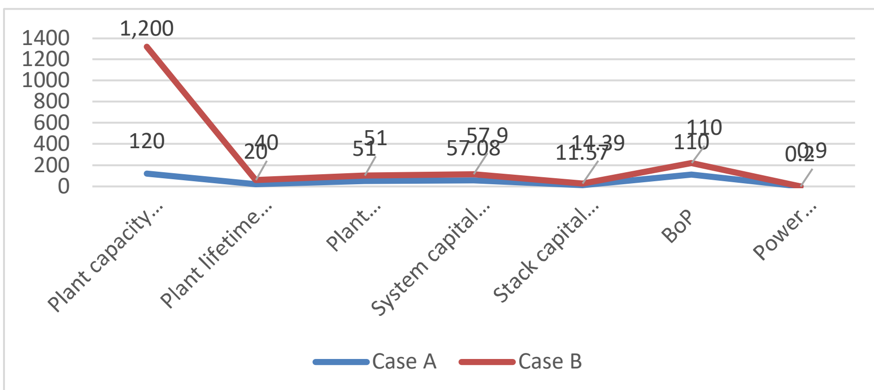

Fig.-10: Showing the Technical Data Used in the Study

Economic Results

Microsoft Excel was used to create cash flow tables that verified the results of the NPV and CBA computations. Selling sludge is typically how wastewater treatment facilities make money. Therefore, sludge with precious metal chips is being sold by SEEPZ SEZ Authority (SSA) for an average of 13.6 Rs/Kg. The expenses and income received by SEEPZ SEZ Authority (SSA) last year from the SEEPZ STP are shown in Table-4.

The cost of producing green hydrogen varies depending on the technique employed. One of the suggested technologies was a PEM electrolysis system, which generated extra income by selling the hydrogen gas that was created. Since it is currently impossible to determine the price of hydrogen in SEEPZ/Maharashtra, reports on the price of hydrogen published by the US Department of Energy were used. These reports were based on the cost of producing hydrogen from a PEM electrolyser using solar energy (photovoltaic cell) as a source of energy. According to Vickers et al. (2020), there were 6$/kg of H_2, which is equivalent to 498.35 Rs./kg of H_2. Table-4 displays the results of the site-collected CAPEX, OPEX, revenue, and NPV calculations, which were made by several articles.[28,29] Two potential solutions were examined for PEM: Case A, which had a lesser capacity of 120 kg H_2/day, and Case B, which had a higher capacity of 1,200 kg H_2/day. Such systems would consume 1.2 m³/day and 11 m³/day of water, respectively, based on James *et al.* (2013). Integrating with the prevailing SEEPZ Sewage Treatment Plant, hydrogen sales were estimated to command a significant contribution to revenues, Rs. 303.3 million for Case A and Rs. 1,737.2 million for Case B.

Table-4: Capex, Opex, and Benefits of the SEEPZ STP

Parameters	Amount In Rupees
Capex	
Equipment (initial investment) – Including parts replaced	6,00,00,000
Opex	
Labour	12,00,000
Energy	8,00,000
Chemicals	1,20,000
Waste management	80,000
Maintenance	1,00,000
Total OPEX	23,00,000
Benefits	
Sludge Selling	1,85,00,000
Total Benefit (total profit)	1,85,00,000
NPV for 10-year study period (Rs. In million)	83.3

In addition, NPV analysis was done on every instance during the course of the 10-year research period, as indicated in Table-5. All the examples had positive Net Present Values (NPVs), indicating the investment expenses were offset by the estimated earned benefits from the sales of hydrogen, compost, and treated water. Due to the huge plant capacity of 1,200 kg H_2/day, Case B for the PEM Electrolyser system has the largest net present value (NPV). Nevertheless, because the PEM stacks have relatively high capital costs and require higher energy expenses, a good NPV may also indicate higher CAPEX and OPEX costs to generate legitimate revenue. Thus, Case A illustrates that lower-capacity systems may offer more cost-effective pathways for hydrogen production under constrained capital expenditure scenarios (supporting SDG 6 and 7).

Table-5: Cost-Benefit Analysis and Net Present Value

Optical Mark Recognition (Annual Values)	SEEPZ STP conventional	SEEPZ STP + electrolysis system (Case A)	SEEPZ STP + electrolysis system (Case B)
Total - CAPEX	6,00,00,000	22,50,830.00	47,00,000.00
Total - OPEX	23,00,000	11,00,000.00	23,00,000.00
Total - Revenue. Year 1	1,85,00,000 (without H_2)	4,03,28,168	23,67,81,680
Year 10	14,33,49,623.35 (without H_2)	30,35,61,270.38	1,73,71,41,928.49
NPV for 10-year study period (Rs. In million)	83.3	303.3	1,737.2

Despite using less water than the SEEPZ STP's reclaimed water of 1800 m^3/day, Cases A and B generated a respectable amount of money. On the other hand, it may be assumed that 2,000 m^3 of water per day entering the electrolyser system will produce around 2,22,222.22 kg of H_2/day and generate about Rs. 363.5 billion in revenue.

CONCLUSION

This study demonstrates the technical and economic viability of producing green hydrogen from treated effluent at the SEEPZ sewage treatment plant in Mumbai. Using two PEM electrolysis scenarios (120 kg/day and 1,200 kg/day), the analysis revealed strong revenue potential and efficient water utilisation compared to existing plant output. Despite the capital investment required, the revenue from hydrogen sales presents a strong return on investment. This integrated approach supports Sustainable Development Goals (SDG) 6 (Clean Water and Sanitation) and 7 (Affordable and Clean Energy) by advancing both water reuse and clean energy initiatives. The treated effluent, often underutilised, can serve as a valuable input for sustainable hydrogen production, especially in water-intensive industrial sectors. Future research should focus on pilot-scale implementation, long-term economic modelling, and environmental impact assessment across varied industrial zones.

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CONFLICT OF INTERESTS

The authors declare that there is no conflict of interest.

AUTHOR CONTRIBUTIONS

The present work is related to *SDG-6: Clean Water and Sanitation* and *SDG-7: Affordable and Clean Energy*. All the authors contributed significantly to this manuscript, participated in reviewing/editing, and approved the final draft for publication. The research profile of the authors can be verified from their ORCID IDs, given below:

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