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Integration of Wastewater Treatment and Electrolyser-Based Hydrogen Production: A Feasibility and Sustainability Assessment

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Abstract

Hydrogen production through water electrolysis, when integrated with wastewater treatment plants (WWTPs), presents a multidimensional opportunity to promote sustainability, energy efficiency, and circular resource use. This thesis explores the integration of these two systems by reviewing current technologies, process synergies, environmental implications, and operational feasibility. In particular, the use of renewable electricity to power electrolysers enables the production of green hydrogen, while the resulting oxygen byproduct can be reused in the aeration stage of wastewater treatment, reducing energy consumption. The work also examines recent academic and industrial case studies to evaluate the advantages, challenges, and enabling conditions for integration. While the primary focus is on technical and sustainability considerations, the thesis also includes a brief overview of potential economic benefits, such as shared infrastructure and resource recovery. Through this comparative study, a foundation is provided for understanding the interdisciplinary value of integrating hydrogen production with wastewater treatment—with relevance for future policy, technology development, and environmental planning.

Table of Contents

UNIVERSITÀ POLITECNICA DELLE MARCHE 1

1. Introduction 12
  1.1. Background and Motivation 12
  1.2. Problem Statement 12
  1.3. Objectives 13
  1.4 Methodology 13
Chapter 1: Hydrogen Production via Electrolysis and Its Role in Sustainability 14
  1.1 Introduction to Hydrogen as a Clean Energy Carrier 14
  1.2 Classification of Hydrogen: Grey, Blue, Green, and Turquoise 14
  1.3 Electrolysis Technologies: Principles and Comparison 15
  1.4 Integration with Renewable Energy Systems 16
  1.5 Economic Aspects: Efficiency, Cost, and LCOH 17
  1.6 Comparison with Other Hydrogen Production Pathways 18
  1.7 The Role of Green Hydrogen in Energy Transition 18
  1.8 Summary 18
Chapter 2: Wastewater Treatment: Processes, Energy Demands, and Opportunities for Integration 19
  2.1 Introduction: From Sanitation to Sustainable Infrastructure 19
  2.2 Treatment Stages and Energy Demands 19
  2.3 Specific Energy Consumption Benchmarks 20
  2.4 Oxygen in the Activated Sludge Process 21
  2.5 Greenhouse Gas Emissions from WWTPs 22
  2.6 Efficiency Technologies in Modern WWTPs 22
    2.6.1 Advanced Process Control (APC) 22
    2.6.2 Anaerobic Digestion and Co-Digestion 22

2.6.3 Nutrient Recovery (e.g., Struvite Precipitation) 23
2.6.4 Speece Cone Oxygen Injection 23
2.7 Sector Couple: Integrating Hydrogen Production with WWTPs 23
2.8 Broader Impacts: From Municipal Plants to Net-Zero Cities 24
2.9 Implementation Challenges and Research Gaps 25
2.10 Economic Feasibility of Hydrogen–WWTP Integration 26
2.11 Conclusion and Transition to Chapter 3 26
Chapter 3: Integration of Hydrogen and Wastewater Treatment – Case Study and Models 27
3.1 Introduction 27
3.2 Case Study A – Queensland, Australia: Donald & Love (2023) 27
3.2.1 Overview of the Study 27
3.2.2 System Architecture 28
3.2.3 Simulation Parameters 28
3.2.4 Key Results and Performance Metrics 30
3.2.5 Techno-Economic and Environmental Implications 30
3.3 Case Study B – EU-Based Model Comparison 31
3.3.1. System Overview 31
3.3.2 Load Matching and Dynamic Operation 31
3.3.3 Strengths and Limitations 32
3.4 Technical Configurations and Equipment Design 33
3.4.1 Electrolyser Selection and Sizing 33
3.4.2 Oxygen Compression and Storage 33
3.4.3 Oxygen Injection Technologies 34
3.4.4 Control Systems and Integration 34
3.4.5 Simplified Mass and Energy Balance 34
3.4.5a Hourly Mass and Energy Balance 35
3.4.5b LCOH Estimation Based on Italian Renewable Energy Prices 38
3.4.5c Summary of Quantitative Findings ....**Error! Bookmark not defined.**
3.5 Energy Modeling and Load Shifting Dynamics 41

3.6 Economic Assessment: Viability of Integration Models 42
3.6.1 Capital Expenditures (CAPEX)...42
3.6.2 Operating Expenses (OPEX)..42
3.6.3 Levelized Cost of Hydrogen (LCOH) 42
3.6.4 Revenue Opportunities 43
3.7 Environmental Metrics and Circular Economy Contributions.......................................44
3.7.1 Greenhouse Gas (GHG) Emissions Reduction 44
3.7.2 Energy Circularity and Internal Synergies 44
3.7.3 Water Circularity and Recovery Potential 44
3.7.4 Materials Recovery and Nutrient Looping 45
3.7.5 Systemic Circularity and SDG Alignment..45
3.8 Barriers to Implementation and Scaling 46
3.8.1 Technical Challenges 46
3.8.2 Institutional and Regulatory Barriers...46
3.8.3 Economic Risk 46
3.9 Summary and Critical Insights...46
Chapter 4: Feasibility and Sustainability Assessment of Hydrogen–WWTP Integration 47
4.1 Introduction 47
4.2 Technical Feasibility Assessment...47
4.2.1 Electrolyser Compatibility and Performance 47
4.2.2 Oxygen Storage and Injection Feasibility 49
4.2.3 System Control and Automation 49
4.2.4 Space and Layout Constraints 50
4.2.5 Integration Scalability 50
4.3 Economic Feasibility 50
4.3.1 Capital Expenditure (CAPEX) 50
4.3.2 Operating Expenses (OPEX)...51
4.3.3 Levelized Cost of Hydrogen (LCOH) 52
4.3.4 Revenue and Return on Investment (ROI) 53

4.4 Environmental Sustainability Assessment 54
4.4.1 Greenhouse Gas (GHG) Emissions 54
4.4.2 Circular Resource Utilization 55
4.4.3 Lifecycle and Carbon Footprint Comparisons 55
4.4.4 Broader Sustainability Impact and SDG Alignment 55
4.5 Social and Policy Aspects 56
4.5.1 Public Perception and Awareness 56
4.5.2 Policy Support and Regulatory Alignment 56
4.5.3 Equity and Inclusion Considerations..57
4.5.4 Institutional Synergy and Governance..57
4.6 Comparative Scenario Analysis 58
4.6.1 Scenario A – Baseline WWTP (No Integration)..58
4.6.2 Scenario B – Hydrogen Electrolysis Only (No Integration).......................................58
4.6.3 Scenario C – Fully Integrated H_2–WWTP System (Donald & Love Model)..................59
4.6.4 Summary Table: Scenario Comparison 59
4.7 Risk Assessment 60
4.7.1 Technical Risks 60
4.7.2 Economic and Market Risks...61
4.7.3 Operational and Maintenance Risks...61
4.7.4 Regulatory and Institutional Risks 62
4.8 Summary and Strategic Recommendations...62
4.9. Conclusion of Chapter 4..64
Chapter 5: Critical Discussion: Challenges, Gaps, and Future Opportunities..........................65
5.1 Introduction 65
5.2 Cross-Chapter Synthesis: Key Insights and Interlinkages...66
5.2.1 Integrated Operational Frameworks...66
5.2.2 Energy and Oxygen Linkages 67
5.3 Strategic Observations and Lessons Learned...67
5.3.1 Real-World Deployment Constraints 68

5.3.2 Investment Planning and Scalability 68
5.4 Emerging Research and Technology Frontiers 69
5.4.1 Predictive and Hybrid Control Architectures 69
5.4.2 Modular Electrolyser and ASP Integration 70
5.4.3 Carbon-Integrated Operational Planning 70
5.4.4 Integrated Finance–Technology Modeling 71
5.5 Policy, Institutional, and Market Perspectives 71
5.5.1 Regulatory Design for Integrated Systems 71
5.5.2 Institutional Alignment and Operational Governance 72
5.5.3 Energy Market Interfaces and Grid Dynamics 72
5.5.4 Market Formation and Hydrogen Pricing Instruments 73
5.6 Future Research Directions and Conclusion 73
5.6.1 Pilot Deployments and Real-World Validation 74
5.6.2 Lifecycle Assessment and Integrated Sustainability Metrics 74
5.6.3 Data Governance and Cyber-Physical Integration 74
5.6.4 Strategic Policy Foresight and Adaptive Governance 75
5.6.5 **Lessons Learned and Key Insights** 75
5.7 Conclusion 76
Chapter 6 – Conclusions and Outlook 76
6.1 Summary of Findings 76
6.2 Key Conclusions 77
6.3 Recommendations 77
6.4 Outlook 78
References 79

List of Tables

Table 1.1—Summary of hydrogen production routes and their properties. 15
Table 1.2—Comparison of three water electrolysis technologies..16
Table 2.1—Regional Specific Energy Consumption (SEC) in Wastewater Treatment Plants.........20
Table 2.2—Specific Energy Consumption Benchmarks..21
Table 2.3—Coupling of WWTP outputs and hydrogen system functions 23
Table 3.1—Side-by-side comparison of AU and EU integration models. 33
Table 3.2—Three main technologies exist for O_2 injection into the ASP. 34
Table 3.2a—Simplified Mass and Energy Balance for iH_2WWTP (Author Based on Donald & Love 2023)...34
Table 3.2b—Hourly Mass and Energy Balance for iH_2WWTP (Author based on Donald & Love, 2023) 35
Table 3.3—levelized cost of hydrogen (LCOH) under different electricity scenarios.................42
Table 3.4—Comparison of Economic Insights. 43
Table 3.5—Systemic Circularity and SDG Alignment 45
Table 4.1—Comparative features of alkaline and PEM electrolysers 48
Table 4.2—CAPEX breakdown for electrolyser systems of different scales. 51
Table 4.3—Comparative levelized cost of hydrogen (LCOH) across production pathways...........52
Table 4.3a—Comparative GHG Emissions and Environmental Impact. 54
Table 4.4—Comparative carbon footprint of hydrogen sources. 55
Table 4.5—Comparative performance of hydrogen-WWTP integration scenarios (A-C) 59
Table 4.6—Performance benefits of scenario C (integrated hydrogen-WWTP system)..............63

List of Figures

Figure 1.1—Three typical electrolyser devices 16
Figure 1.2—schematic of “solar–electrolyser–WWTP integration“ 17
Figure 2.1—Typical flow diagram of four stages in the wastewater treatment process. 20
Figure 2.2—Simple configuration for the activated sludge process 22
Figure 2.3—Process flow diagram of a Speece cone-MBR. (Carlos Mauricio Barreto) 23
Figure 2.4—Diurnal WWTP Inflow and ASP Oxygen Demand 24
Figure 3.1—Integrated Plant Electricity Flows 29
Figure 3.2—Solar PV Output and Electrolysis Power Consumption 29
Figure 3.3—Net HPO Produced and HPO Storage Tank Pressure 30
Figure 3.4—Energy Flow Diagram of Integrated Hydrogen-Wastewater System 41
Figure 4.1—System loop showing electrolysis, compression, and oxygen injection. 49
Figure 4.2—LCOH under different electricity price and utilization scenarios. 53
Figure 4.3—Policy support framework linking EU Hydrogen Directives, the Italian Hydrogen Roadmap, municipal sustainability targets, and WWTP–electrolyser integration. 58
Figure 4.4—Comparative performance metrics for hydrogen production scenarios (A, B, and C) 60
Figure 4.5—Triple Synergy Diagram 64

1. Introduction

1.1. Background and Motivation

With the world confronting mounting climate difficulties, the innovation of sustainable energy solutions has been a top global priority. Hydrogen has emerged as a principal decarbonization vector, particularly for difficult-to-electrify industries like heavy industry, mobility, and long-term energy storage. Hydrogen, when generated through electrolysis by renewable energies (solar, wind, and hydro), is regarded as "green" and almost emissions-free and is thereby a prospective candidate to be incorporated into sustainable energy systems.

At the same time, wastewater treatment plants (WWTPs) are coming under increasing pressure to reduce their environmental footprint while meeting changing treatment standards. Traditionally viewed as energy-hungry systems, WWTPs are now being reimagined as future hubs for resource recovery, including water reuse, energy generation, and nutrient recycling.

The coupling of hydrogen generation systems with WWTPs is an innovative and promising nexus between the water and energy sectors. In electrolysis, water molecules are separated into hydrogen and oxygen through the input of electrical energy. The hydrogen can either be stored or utilized as a clean fuel, and the oxygen—typically considered a waste stream in independent systems—can be recycled back into the wastewater treatment process, especially for biological aeration, where the demand for oxygen is high. This integration enables dual advantages: improved resource efficiency and mutual energy optimization.

1.2. Problem Statement

Despite the theoretical synergy, practical integration of hydrogen production and wastewater treatment remains limited. The majority of research so far has either concentrated on the technological advancement of electrolysers or on enhancing WWTP efficiency independently. Only a few comparative works consider how these systems can be conjointly designed, operated, and scaled.

Additionally, the environmental and sustainability implications of integration are still poorly explored from a systems perspective. While economic considerations are important, they are often looked at in a vacuum and fail to consider real-world barriers like land use, permitting, and coordination between sectors.

This thesis aims to address this gap by presenting a structured review of the existing literature and the technological pathways possible for integration. It further provides economic observations derived from current studies, such as the thesis by Rickey Donald (2022) and the research article Economic Assessment of Integrated Hydrogen Production with Wastewater Treatment (2024), to allow for conclusions on feasibility without requiring full financial modeling.

1.3. Objectives

The main objective of this thesis is to compile and analyze current approaches, technologies, and benefits of integrating electrolyser-based hydrogen production with municipal or industrial WWTPs. This includes:

• Reviewing hydrogen production technologies suitable for integration
• Identifying synergies such as oxygen reuse, water loop closure, and energy recovery.
• Summarizing sustainability and life-cycle implications
• Discussing economic benefits using published literature (not modeling)

The principal goal is to develop the scientific foundation underlying informed choices, implementation of pilot projects, or approval of regulatory frameworks of integrated energy-water systems.

1.4 Methodology

This literature review is based on a comparative review methodology that is built upon the PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) framework. A thorough peer-reviewed journal, technical report, and thesis search were performed through databases such as ScienceDirect, Scopus, and Google Scholar. The search involved peer-reviewed papers published between 2015 and 2024 with the following keywords: "electrolysis integration," "hydrogen from wastewater," "O_2 reuse in WWTPs," "green hydrogen infrastructure, "and "wastewater energy efficiency." Inclusion criteria: Research dealing with municipal wastewater treatment plants, electrolysis-based hydrogen production, levelized cost of hydrogen (LCOH) evaluation, and greenhouse gas emissions estimation. Exclusion criteria: Research dealing with industrial (non-municipal) wastewater treatment plants, non-electrolysis hydrogen production technologies, and research without any quantifiable energy or emissions data.

As a result of the first stage of the search, 296 sources were found. After screening of the titles and abstracts, 94 peer-reviewed sources were selected for further analysis. Among the prominent sources are a 2022 thesis of Rickey Donald, an article entitled "Economic Assessment" in the Journal of Cleaner Production published in 2024, and supporting material of EU-funded research and pilot plant projects. Case study data with quantified values (especially from Donald & Love, 2023) were extracted and recalculated to make original mass and energy balances. Information, diagrams, and comparison tables provided hereafter are cited accordingly.

Chapter 1: Hydrogen Production via Electrolysis and Its Role in Sustainability

1.1 Introduction to Hydrogen as a Clean Energy Carrier

Hydrogen has gained much interest as a key constituent of a future energy system with low carbon emissions and sustainability. The interest stems from an urgent need to decarbonate more challenging-to-decarbonate sectors and to counteract climate change impacts. The attractiveness of hydrogen lies in its versatility and the clean combustion processes that it implies. As a secondary energy carrier, hydrogen can be stored, transported, and converted to electricity or thermal power with high effectiveness, which makes it usable for a highly versatile set of applications, such as industrial processes, power generation, and balancing electrical supply-demand fluctuations. Hydrogen combustion, and its use in fuel cells, generates only water vapor; moreover, when generated from renewable power plants through electrolysis, it is a fuel that produces zero emissions.
(Acar & Dincer, 2019; Dincer & Acar, 2015)
In a parallel with its technological properties, hydrogen is gaining prominence in global policy circles. The European Union's Hydrogen Strategy, Japan's vision of a "Hydrogen Society," and Germany's National Hydrogen Strategy all highlight renewable hydrogen as a key enabler of reaching climate neutrality and industrial competitiveness. Strategic papers call for the development of green hydrogen through regulatory support, financial support for electrolysis projects, and creating required infrastructure. (Dincer & Acar, 2015)

1.2 Classification of Hydrogen: Grey, Blue, Green, and Turquoise

Hydrogen is categorized by production method and associated carbon intensity:

Grey hydrogen is derived from fossil fuels (typically natural gas) via steam methane reforming (SMR), releasing CO_2 without capture.

Blue hydrogen production entails a similar approach, employing carbon capture and storage (CCS) technologies to minimize emissions effectively.

Green hydrogen is produced through the electrolysis of water powered by renewable electricity, resulting in zero direct greenhouse gas emissions.

Turquoise hydrogen, produced via methane pyrolysis, yields solid carbon as a byproduct, with lower environmental impact if the carbon is sequestered or utilized.

Among these, green hydrogen is the only one that is compatible with long-term net-zero targets. Though it is not yet cheaper, its environmental advantages are worth the world's increased investment. [Yang et al., 2025; Dincer & Acar, 2015]

Production Method	Description	Efficiency	Environmental Impact	Scalability	Advantages	Limitations	Current Status	Future Prospects
Steam Methane Reforming (SMR) [56,62,64,152]	Reforming natural gas with steam to produce hydrogen and carbon monoxide, followed by a water-gas shift reaction to increase hydrogen yield.	High	High CO_2 emissions, water usage	Limited by fossil fuel availability, infrastructure	Abundant feedstock, mature technology, low-cost	Carbon emissions, reliance on fossil fuels	Widely deployed, dominant method	CCS integration, efficiency improvements
Electrolysis (e.g., PEM, alkaline, solid oxide) [71,75,153]	Electrochemical splitting of water into hydrogen and oxygen using electricity, typically from renewable sources or grid power.	Variable	Low emissions (if powered by renewables), water usage	Scalable with renewable energy availability	No carbon emissions, versatile applications	Energy-intensive, cost of renewable electricity	Growing adoption, especially with renewables	Efficiency improvements, cost reductions
Biomass Gasification [86,91,154,155]	Heating biomass to produce syngas, a mixture of hydrogen, carbon monoxide, and other gases, followed by purification to extract hydrogen.	Moderate	Moderate CO_2 emissions, biomass sourcing	Limited by biomass availability, scale-up challenges	Renewable feedstock, the potential for carbon-neutral production	Biomass availability, technological complexity	Emerging, limited commercialization	Research on feedstock optimization, efficiency
Photoelectrochemical Water Splitting [106,110,121,125,156]	Using solar energy to drive chemical reactions at a photoelectrode surface, separating water into hydrogen and oxygen.	Variable	Low emissions, water usage	Dependent on solar resource availability	Direct solar-to-hydrogen conversion	Efficiency, stability of materials	Early-stage research, lab-scale demonstrations	Material advancements, efficiency enhancements
Thermochemical Processes [134,146,157]	Utilizing heat to drive endothermic chemical reactions, such as water splitting via thermochemical cycles or reforming of hydrocarbons.	Moderate	Variable emissions, depending on the process	Dependent on heat source availability	Efficient use of high-temperature heat sources	Technological complexity, high temperatures	Research and development, limited commercialization	Process optimization, integration with waste heat

Table 1.1*—Summary of hydrogen production routes and their properties.*

Source: (Acar & Dincer, 2019)

1.3 Electrolysis Technologies: Principles and Comparison

The main technology for splitting water (H_2O) into hydrogen (H_2) and oxygen (O_2) by using electrical energy is electrolysis.

• Alkaline Electrolysis (ALK): Mature and low-cost. Uses a liquid electrolyte and non-noble metal catalysts. Downsides include slower startup time, lower efficiency, and limited current density.

• Proton Exchange Membrane (PEM): Utilizes a solid polymer membrane, operates efficiently at high current densities, and responds quickly to fluctuations in power, which makes it highly appropriate for variable renewable input. But disadvantages include high capital costs and reliance on scarce materials like platinum and iridium.

• Solid Oxide Electrolysis (SOE): Operates at high temperatures (600–800°C), enabling high efficiency and potential integration with waste heat from industrial processes. However, SOE is still in pilot stages with durability challenges.

Proton exchange membranes, or PEM, are commonly selected for dynamic applications, such as their integration with solar PV and wind power, because of their fast response and compact size. [Yang et al., 2025]

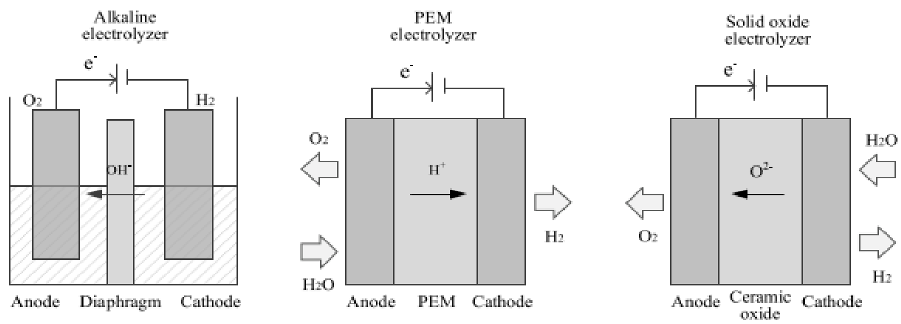

Figure 1.1—Three typical electrolyser devices

Source: Yang et al. (2025).

	ALK	PEM	SOE
Electrolyte	KOH/NaOH	Polymer	Solid Oxide
Charge carriers	OH^-	H^+	O^{2-}
Temperature	60–90 °C	70–80 °C	800–1000 °C
Anode reaction	$4OH^- \rightarrow 2H_2O + O_2 + 4e^-$	$2H_2O \rightarrow 4H^+ + O_2 + 4e^-$	$2O^{2-} \rightarrow O_2 + 4e^-$
Cathode reaction	$4H_2O + 4e^- \rightarrow 4OH^- + 2H_2$	$4H^+ + 4e^- \rightarrow 2H_2$	$2H_2O + 4e^- \rightarrow 2H_2 + 2O^{2-}$
Anode	Ni, Ni-Co	IrO_2, RuO_2	LSM-YSZ
Cathode	Ni, Ni-Mo	Pt, Pt-Pd	Ni-YSZ
Gas purity	>99.5 %	>99.99 %	>99.9 %
Advantages	Low capital cost; High maturity	High purity; Fast start-up	High efficiency
Disadvantages	Low current density; Corrosive	High cost of components; Need noble metal materials	Safety issues caused by instability
Technology maturity	Commercial	Near commercial	Laboratory stage

***Table 1.2**—Comparison of three water electrolysis technologies*

Source: Yang et al. (2025).

1.4 Integration with Renewable Energy Systems

When powered by renewable electricity (solar, wind, or hydro), electrolysis can produce green hydrogen with a minimal carbon footprint. This integration is essential to decarbonization and energy storage. Electrolysers have the ability to utilize excess renewable electricity during peak generation hours, stabilizing the grid and preventing curtailment. However, the variability of renewable energy brings challenges. Grid-connected electrolysis systems need to be designed for intermittent operation. Advanced control systems and hybrid configurations (e.g., solar + battery + electrolyser) are being explored to improve stability. In Donald and Love's (2023) case study, a municipal wastewater treatment plant (WWTP) in Australia uses PV electricity to operate electrolysers that produce both hydrogen and compressed oxygen. The oxygen is stored and subsequently reused for aeration in the WWTP when there is peak demand, illustrating the circular integration potential. [Donald & Love, 2023]

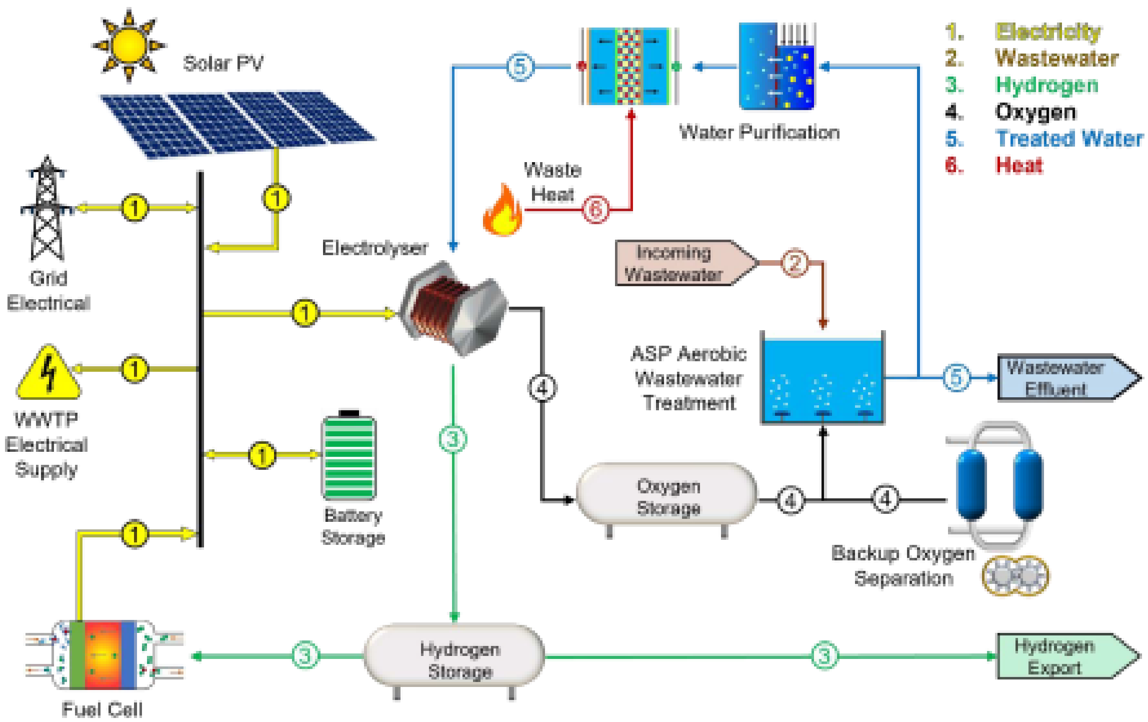

Figure 1.2—schematic of "solar–electrolyser–WWTP integration"

Source: Donald & Love (2023).

1.5 Economic Aspects: Efficiency, Cost, and LCOH

The Levelized Cost of Hydrogen (LCOH) is a comprehensive metric that summarizes all the costs of producing hydrogen during the system's lifetime. LCOH is calculated using the following formula: $LCOH = \frac{\sum_{t=1}^{N} \frac{I_t+O_t+E_t}{(1+r)^t}}{\sum_{t=1}^{N} \frac{H_{2,t}}{(1+r)^t}}$

Where:

- I_t = Initial investment (CAPEX) in year t (€)
- O_t = Operation and maintenance costs in year t (€)
- E_t = Electricity cost in year t (€)
- r = discount rate (%)
- H_{2t} = Hydrogen produced in year t (kg)
- N = System lifetime (years)

As of 2023:

• Grey hydrogen: \$1–2/kg • Blue hydrogen: \$2–3/kg • Green hydrogen: \$4–6/kg (depending on electricity cost, capacity factor, and electrolyser capex)

Key factors affecting LCOH include the following:

• Electricity price: The largest contributor. A drop from €0.10/kWh to €0.04/kWh can halve the LCOH.

• Electrolyser efficiency: PEM (65–75%) typically yields better output than ALK.

• Utilization rate: Higher utilization of operating hours (4000–6000 h/year) reduces fixed costs per kg of H_2.
• Water cost: Negligible in most cases, but relevant if desalination or purification is needed.

Co-location with WWTPs presents two major cost-saving mechanisms: (1) the access to treated water, and (2) the utilization of byproduct oxygen for aeration, which reduces energy demand from blowers by up to 60%. [Acar & Dincer, 2019; Donald, Boulaire, & Love, 2023]

1.6 Comparison with Other Hydrogen Production Pathways

While electrolysis is clean, other methods are more cost-competitive:
• Steam Methane Reforming (SMR): Most common today. Low cost but high CO_2 emissions unless CCS is added.
• Biomass Gasification: Can be renewable but involves complex logistics and high capital costs.
• Microbial Electrolysis Cells (MECs): This innovative technology treats wastewater while generating hydrogen. MECs utilize bacteria to break down organic matter and generate electrons. However, these systems are still in lab or pilot scale, with limitations in electrode materials, energy recovery, and long-term durability. Studies show that MECs are not yet economically viable at large scale; however, they show promise for integrated applications. (Aiken, Curtis, & Heidrich, 2019; Swaminathan et al., 2024)

1.7 The Role of Green Hydrogen in Energy Transition

Green hydrogen plays a pivotal role in the decarbonization of sectors that are difficult to electrify:

• Steelmaking: Direct reduction of iron using hydrogen instead of coke (e.g., H_2GreenSteel in Sweden).

Heavy transport, including trucks; trains like the Alstom Coradia ilint**;** and buses, offers longer range and faster refueling compared to batteries.

• Industrial feedstock: Ammonia, methanol, and synthetic fuels.

• Seasonal storage: Hydrogen can store excess renewable energy for months—something batteries cannot do efficiently.

Policy tools such as hydrogen purchase agreements, carbon pricing, and emission trading systems are vital in reducing the economic gap between fossil-based and other sources of hydrogen. (Dincer & Acar, 2015; Donald, Boulaire, & Love, 2023)

1.8 Summary

Hydrogen, particularly that produced via renewable-powered electrolysis, offers a transformative opportunity for the transition towards climate-neutral energy systems. While green hydrogen faces challenges related to cost and scalability, its integration with renewable sources and its co-location with infrastructure like WWTPs can provide significant environmental as well as economic benefits. This chapter has focused on key electrolysis technologies, economics, and global trends. The next chapter will build on this foundation by assessing the structure, energy intensity, and optimization potential of wastewater treatment systems as candidate systems for coupling with hydrogen production.

Chapter 2: Wastewater Treatment: Processes, Energy Demands, and Opportunities for Integration

2.1 Introduction: From Sanitation to Sustainable Infrastructure

Municipal wastewater treatment plants (WWTPs) are essential components of modern urban systems, whose principal role is protecting public health, maintaining aquatic life cycles, and meeting environmental performance criteria. No longer seen simply as sanitation utilities, WWTPs are increasingly at the center of a strategic shift toward circular and decarbonized infrastructure systems. The combined effect of increased regulatory pressures, rising electricity costs, and more stringent climate goals has created an imperative for rethinking wastewater treatment strategies—seeing WWTPs not only as waste treatment facilities but also as resources for recovered resources and energy.

One recent and exciting trend is to convert wastewater treatment plants (WWTPs) to energy-integrated biorefineries that not only supply potable water but also recover valuable nutrients like nitrogen and phosphorus, generate biogas fuel, and couple with the energy sector. Such evolutions are needed to align with global climate targets as well as Sustainable Development Goals (SDGs), especially SDG 6 (Clean Water and Sanitation) and SDG 13 (Climate Action). The production of hydrogen through water electrolysis represents a major opportunity for decarbonization, particularly in cases where the production of renewable energy is integrated. The integration of renewable hydrogen production through electrolysis with wastewater treatment plants allows for the simultaneous production of clean energy and enhances the circularity of resources. As explained in Rickey Donald's research, through this synergistic method, the mutual use of resources is made possible through the rerouting of oxygen evolved in electrolysis for utilization in wastewater aeration (Rickey Donald's thesis, p. 9).

2.2 Treatment Stages and Energy Demands

Treatment of wastewater usually falls under four main stages, with each of those significantly contributing to the overall energy consumption.

• Preliminary treatment: Removes large solids and grit by using screens and mechanical separators. This process consumes relatively little energy.
• Primary treatment: Uses sedimentation tanks (clarifiers) to remove suspended solids and organic matter. The energy use is moderate, corresponding to pumping and mixing operations.
• Secondary treatment is the most energy-intensive stage, particularly in plants that utilize the ASP. Aeration equipment is of great importance to the maintenance of aerobic conditions and contributes to over 60% of the plant's total electrical demand.
• Tertiary treatment: Polishes the effluent using filtration, disinfection (UV/chlorine), and advanced nutrient removal. Energy demand varies based on technology complexity.

Aeration alone is responsible for up to 70% of the total electricity use within a typical conventional wastewater treatment plant (WWTP). The system uses fine bubble diffusers and large blowers to transfer oxygen into the biological reactors; however, energy efficiency is often low (20–30% transfer efficiency).

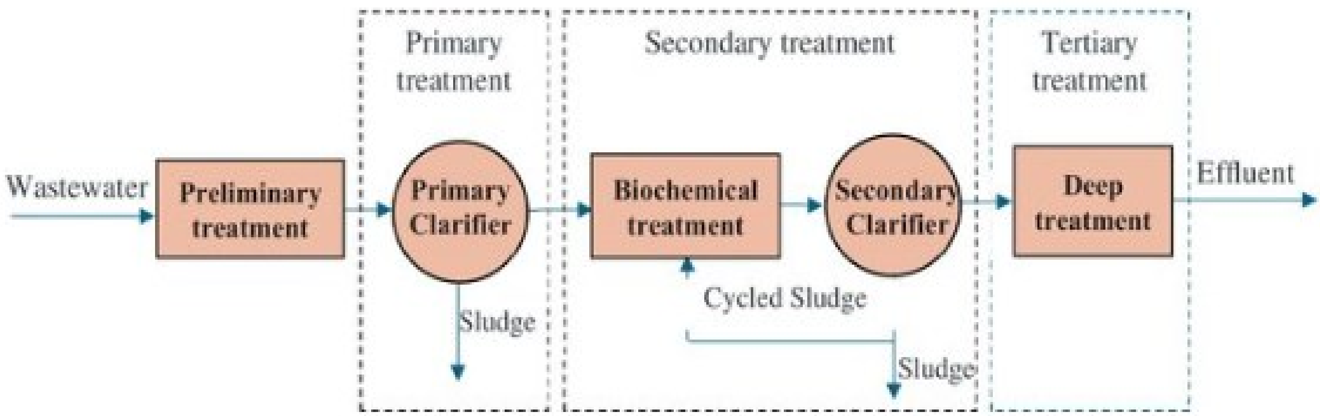

Figure 2.1—Typical flow diagram of four stages in the wastewater treatment process.

Source: Serdarevic & Dzubur (2016).

2.3 Specific Energy Consumption Benchmarks

The specific energy consumption (SEC) of wastewater treatment plants (WWTPs) ranges significantly with plant size, level of treatment, and region. Many studies give the following comparative values:

Region	SEC (kWh/m³)	Comments
Germany	0.30–0.50	Advanced control, co-digestion
Australia	0.35–0.65	Wide climate variation
USA (average)	0.40–0.60	Higher in older infrastructure
EU best-in-class	0.20–0.25	Includes biogas energy recovery
Small WWTPs	>0.80	Low efficiency due to scale

Table 2.1—Regional Specific Energy Consumption (SEC) in Wastewater Treatment Plants

Source: Author based on Cardoso et al. (2021).

The expression of SEC is done per cubic meter of sewage. Plant sizing is done according to the person equivalent (PE), where 1 PE is equal to 60 g BOD/day. Aeration energy is directly proportional to PE and not flow rate.

Small plants (<10,000 PE) often show high SEC due to poor economies of scale. Larger plants with energy recovery, automation, and modern aeration systems can significantly outperform national averages.

Treatment or Process Stage	Typical Energy Consumption	Unit	Source & Page
Preliminary Treatment (screening, grit)	0.015 – 0.05	kWh/m³	Tchobanoglous et al., *Wastewater Engineering* (2003), via DWA (2015)
Primary Treatment (sedimentation)	0.05 – 0.1	kWh/m³	U.S. EPA, Energy Use in Wastewater Facilities (2006), EPRI (2002)
Secondary Treatment (activated sludge)	0.18 – 0.8	kWh/m³	Marta Gandiglio, Enhancing the Energy Efficiency of Wastewater Treatment Plants through Co-digestion and Fuel Cell Systems, 30 October 2017
Tertiary Treatment (UV, disinfection)	0.05 – 0.3	kWh/m³	Water Environment Federation (2016), *Energy Conservation in WWTPs*
Sludge Treatment and Handling	0.15 – 0.25	kWh/m³	Metcalf & Eddy, *Wastewater Engineering* (2003); U.S. DOE, 2006.
Total WWTP Electricity Demand (avg.)	0.5 – 1.5	kWh/m³	IEA (2012), *Water for Energy* report; EPRI (2002), *Water & Sustainability* series
Electrolysis (PEM or AEL)	48 – 55	kWh/kg H_2	IRENA (2020), *Green Hydrogen: Cost and Innovation Outlook*; Dincer & Acar (2015), p. 10
SOEC Electrolysis (Solid Oxide)	33 – 47	kWh/kg H_2	Solid Oxide Electrolysis: A Technology Status Assessment, Gniewomir Flis, November 2023
Oxygen Compression & Storage	0.35 – 0.46	kWh/Nm³ O_2	Alsultannty (2014), *JGT.*

Table 2.2—Specific Energy Consumption Benchmarks

2.4 Oxygen in the Activated Sludge Process

The activated sludge process represents a biological treatment method that relies on aerobic microorganisms to degrade organic matter. The key to this approach is the introduction of oxygen, with sufficient levels of dissolved oxygen (DO) required to support microbial respiration, nitrification, and sludge flocculation.

In aeration tanks, normal concentrations of dissolved oxygen range between 1.5 and 2.5 mg/L. However, the method of oxygen delivery has important effects on the quality of the treatment and energy consumption. Conventional fine bubble diffusers have low oxygen transfer efficiency and are highly sensitive to fouling and sludge loading. In addition, aeration requirements often follow a diurnal trend, with peaking during morning and evening inflow surges.

In practical applications, blowers are operated constantly or in fixed time cycles, leading to over-aeration and wastage of energy. This circumstance presents a major opportunity for alternative oxygen delivery strategies. [Donald & Love, 2023]

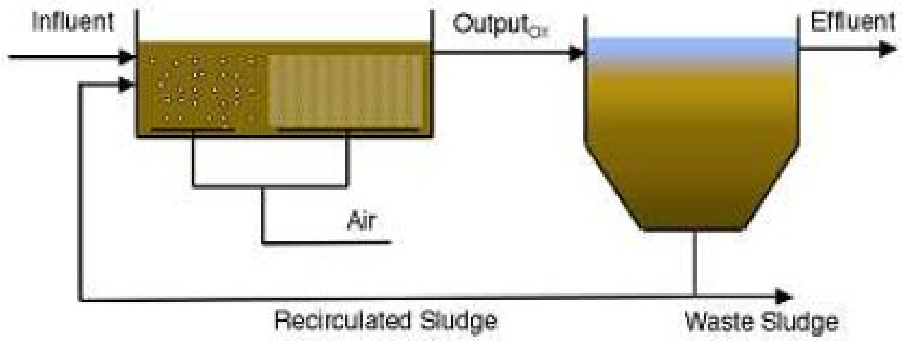

Figure 2.2—Simple configuration for the activated sludge process

Source: Serdarevic & Dzubur (2016).

2.5 Greenhouse Gas Emissions from WWTPs

Beyond energy use, WWTPs are a significant source of greenhouse gas emissions:
- Indirect emissions: From electricity used for pumps, blowers, and other systems. If grid electricity is fossil-based, emissions can be substantial.
- **Direct emissions: Due to microbial processes, especially:**
•Nitrous oxide (N_2O) from nitrification and denitrification
•Methane (CH_4) from anaerobic zones and sludge handling.
N_2O is highly powerful with a warming potency 298 times larger than CO_2, and even small concentrations could have a large effect on the plant's greenhouse gas footprint. Estimates suggest that direct process emissions can account for 30–50% of total WWTP emissions, particularly in nitrogen-rich influents or poorly controlled systems. Accurate measurement and mitigation of N_2O are emerging research priorities. [Donald & Love, 2023]
Typical WWTP emissions: 250–550 g CO_2-eq/m³ (50–150 from N_2O/CH_4, 200–400 from electricity).

2.6 Efficiency Technologies in Modern WWTPs

To improve performance and sustainability, WWTPs increasingly employ advanced technologies, including:

2.6.1 Advanced Process Control (APC)

Automated monitoring of DO, NH_4^+, NO_3^-, and flow rate enables dynamic aeration control, reducing energy use by up to 25%.

2.6.2 Anaerobic Digestion and Co-Digestion

Primary and secondary sludge is digested to produce biogas (60–70% methane), which can be converted into electricity or heat via CHP (combined heat and power). Co-digestion with food or industrial waste boosts yield.

2.6.3 Nutrient Recovery (e.g., Struvite Precipitation)

Phosphorus is recovered as a useful fertilizer, precluding the necessity of costly chemical treatment and improving sludge dewaterability.

2.6.4 Speece Cone Oxygen Injection

An innovative system that dissolves pure oxygen into liquid under pressure. Transfer efficiency exceeds 90%, allowing WWTPs to eliminate blowers during high-load periods.

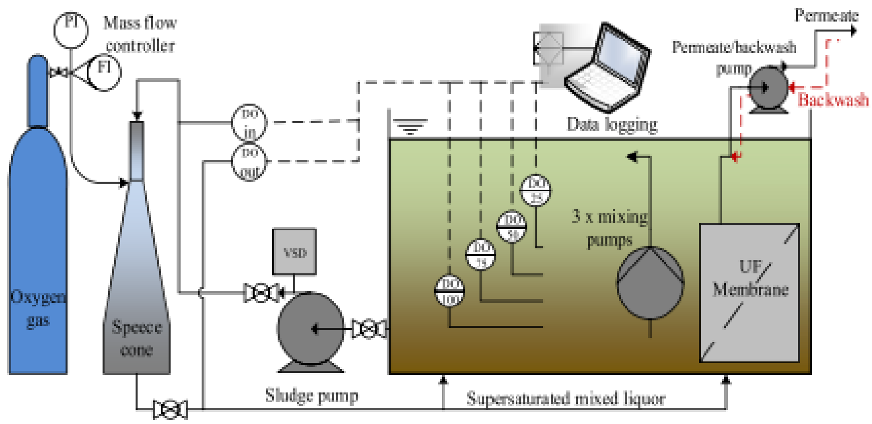

Figure 2.3—Process flow diagram of a Speece cone-MBR. (Carlos Mauricio Barreto)

Source: Barreto et al. (2018).

2.7 Sector Couple: Integrating Hydrogen Production with WWTPs

One significant innovation towards sustainable infrastructure is the integration of electrolysis-based hydrogen production with WWTPs (wastewater treatment plants). The two systems are combined by taking advantage of the intrinsic synergy between them:

WWTP Output/Input	Hydrogen System Function
Treated wastewater	Feedwater for electrolysis
Renewable electricity (e.g., solar PV)	Electrolyser power
Oxygen demand (ASP)	Utilization of byproduct O_2

Table 2.3—*Coupling of WWTP outputs and hydrogen system functions*

Source: Author based on Donald & Love (2023).

Electrolysis splits water into hydrogen and oxygen. While hydrogen is the primary product, the oxygen byproduct is often vented or underused. In the WWTP integration model, this high-purity oxygen is compressed and stored, then used in the activated sludge process (ASP) during periods of peak oxygen demand. This replaces traditional aeration and reduces blower electricity use substantially.

Integration deals with two main issues:

1. Renewable energy curtailment (electrolyser uses surplus PV)
2. Daily imbalance between electrical generation and oxygen demand (with oxygen saved and redistributed).

The above concept was thoroughly demonstrated using the case study presented by Donald and Love (2023), using real-world operational data collected from a Southeast Queensland, Australia-based municipal wastewater treatment plant. Their simulation included:

• A solar-powered PEM electrolyser
• Oxygen compression and storage system
• Demand-matching oxygen injection into ASP
• Improvement in tank size and compressor operating pressure

The model achieved an oxygen transfer efficiency of over 90% by combining a Speece cone while also saving aeration energy costs by up to 60%. (Donald & Love, 2023; Donald, Boulaire, & Love, 2023)

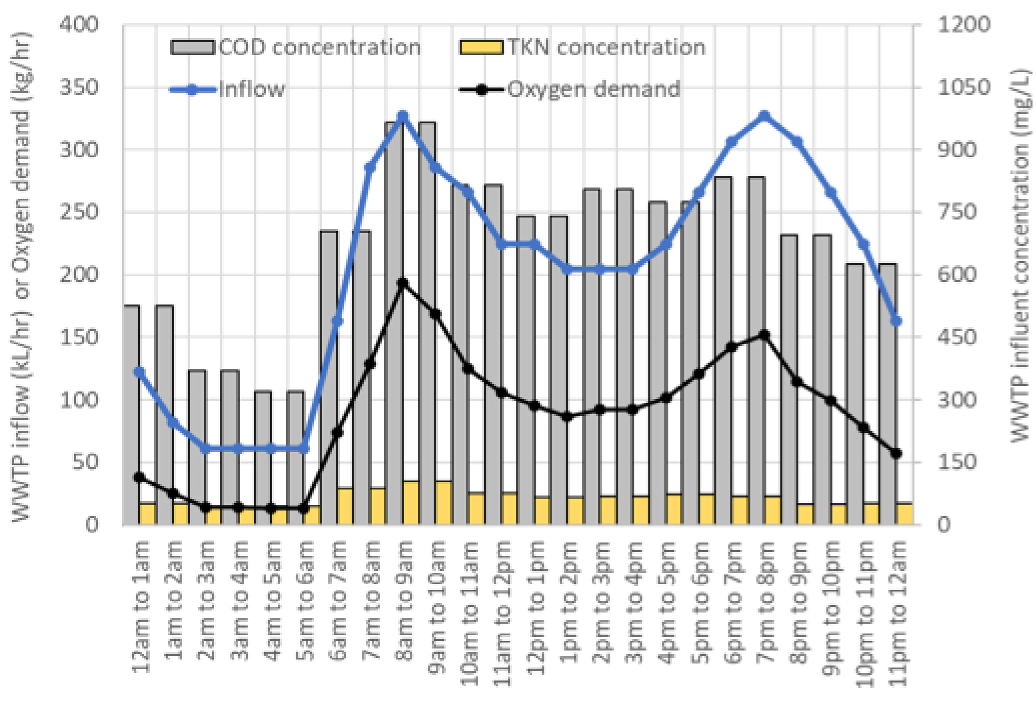

Figure 2.4—Diurnal WWTP Inflow and ASP Oxygen Demand

2.8 Broader Impacts: From Municipal Plants to Net-Zero Cities

The benefits of coupling WWTPs with hydrogen production extend beyond the plant level:

• **Environmental:** Reduced dependence on the grid, lower carbon emissions, and utilization of byproduct oxygen.
• **Economic:** Shared infrastructure reduces CAPEX. O_2 replaces expensive blower systems; hydrogen creates new revenue streams.
• **Grid stability:** Electrolysers can absorb intermittent PV output, acting as flexible loads.
• **Transport decarbonization:** Hydrogen produced on-site can fuel municipal fleets (buses, garbage trucks), creating closed-loop circular economies.

In a 2023 study, Donald et al. simulated fuel cell buses' use of hydrogen to show that a whole system integration could reduce annual CO_2 emissions of 390 tons by 2034. Additionally, if this scenario were combined with increased electrolyser efficiency and curtailed photovoltaic energy recovery, the resulting emissions reduction would rise to 872 CO_2-eq/year. [Donald, Boulaire, & Love, 2023]

This shift fits with the European Union's Repower EU strategy and Australia's National Hydrogen Strategy, both of which aim to encourage distributed green hydrogen production from sustainable water sources—rendering wastewater treatment facilities especially suitable for this purpose.

2.9 Implementation Challenges and Research Gaps

Despite its promise, this integration of hydrogen production with wastewater treatment faces several technical and regulatory challenges:

Technical:

Oxygen storage design requires optimizing storage tank dimensions, pressure specification requirements, and thermal management.

• **Process control:** Precise coordination between electrolyser operation and WWTP oxygen needs is essential.
• **Water quality:** Electrolysers require low-TDS water; polishing treated wastewater may be necessary.
• **Scaling:** Most models are based on small-to-medium plants; large-scale demonstrations are rare.
Economic:
• **Initial investment:** Electrolysers, compressors, and tanks are capital-intensive.
• LCOH: Green hydrogen remains costlier than grey alternatives without subsidies.
• **Incentive alignment:** Municipal utilities are often conservative, with limited funding for innovation.
Regulatory:
The hydrogen safety code requires updating to allow for co-location with wastewater facilities.
•**Licensing and permitting:** Blurred sectoral lines between water and energy utilities exist in integrated systems.

These gaps call for pilot projects, national funding programs, and cross-sectoral partnerships to accelerate deployment.

2.10 Economic Feasibility of Hydrogen–WWTP Integration

The use of techno-economic simulation with an integrated wastewater treatment plant (WWTP) and a hydrogen production unit proved the overall advantage of cost-effectiveness and efficient management of resources. The model considered costs for both imported and exported electricity as well as income from selling hydrogen and proved that net operational revenue could significantly be increased through predictive control schemes (Economic Assessment Article, pp. 1–2). The data are evidence supporting the practical feasibility of renewable hydrogen production integration with wastewater treatment on a system-wide level.

2.11 Conclusion and Transition to Chapter 3

This chapter includes a comprehensive exploration of the shifting role of wastewater treatment plants (WWTPs) within sustainable energy systems and resource recovery. From conventional energy requirements of municipal WWTPs with particular emphasis on aeration and nutrient removal processes, we explore how different stages contribute to high energy usage.

We further examined benchmark data related to specific energy consumption to reveal opportunities for optimization through advanced technologies such as anaerobic digestion, nutrient recovery, and advanced control process methodologies. The chapter further introduced cutting-edge methods, such as sector coupling strategies and Speece cone oxygen injection, that extend the WWTPs' function of municipal wastewater treatment plants from only sanitation to energy and material recovery.

A pivotal focus was placed on the integration of hydrogen production, especially through electrolysis powered by renewable energy. This integration represents a promising pathway toward achieving net-zero goals and circular resource usage. By examining both the technical feasibility and the economic implications, it became evident that combining WWTPs with hydrogen production infrastructure can reduce operational emissions, optimize oxygen usage, and generate additional revenue through hydrogen sales and grid balancing.

The final section assessed its economic viability, focusing especially on simulation-based studies and real-world assessments that highlight its future profitability within appropriate regulatory environments and market conditions.

The following chapter will delve into the technological configurations and case study that further demonstrate the practicality and impact of coupling hydrogen production with WWTPs, focusing on design strategies, performance metrics, and implementation models.

Chapter 3: Integration of Hydrogen and Wastewater Treatment – Case Study and Models

3.1 Introduction

Integration of hydrogen production with wastewater treatment is a pioneering approach to realizing multiple sustainability objectives by taking advantage of infrastructure co-location and resource synergy. Historically, hydrogen was produced separately from water treatment infrastructure, often at centralized facilities with dedicated renewable energy generation. WWTPs are distinguished by energy-intensive units that are mainly reliant on grid electricity and are challenged by decarbonization and cost optimization. Current literature reveals that direct integration of hydrogen electrolysis at WWTPs can provide mutual benefits: maximizing renewable electricity utilization, recovering high-purity oxygen for treatment purposes, and decoupling both sectors from fossil fuels.

The underlying philosophy behind this project is sector coupling, which brings together the infrastructures of water, electricity, and hydrogen to balance energy flows and maximize system-wide efficiencies. This approach closely resonates with the European Union's Repower EU initiative, Australia's National Hydrogen Strategy, and the broader framework of the United Nations' sustainable development goals (SDGs), particularly SDG 6 (Clean Water and Sanitation), SDG 7 (Affordable and Clean Energy), and SDG 13 (Climate Action).

The chapter offers detailed case studies, models, and technical assessments regarding the integration of hydrogen in wastewater treatment plants (WWTPs). It rigorously examines the new Compressed Oxygen Energy Storage (COES) model proposed by Donald & Love (2023) and also performs comparisons with other international models. Technical designs are carefully explored, along with related economic and environmental implications, while highlighting the current potential, barriers, and strategic implications relevant to these combined facilities.

3.2 Case Study A – Queensland, Australia: Donald & Love (2023)

3.2.1 Overview of the Study

In a trailblazing study featured in the Journal of Environmental Management in 2023, Australian researchers Rickey Donald and Jonathan Love from the Queensland University of Technology (QUT) proposed and studied a novel idea called Compressed Oxygen Energy Storage (COES). The idea focuses on the potential for combining PEM-based hydrogen production with a nearby wastewater treatment plant (WWTP) in southeast Queensland. The goal: utilize the oxygen byproduct from electrolysis as a biochemical energy source for wastewater aeration in place of traditional blowers and to decrease dependence on grid electricity.

The study location is a moderate-sized municipal wastewater treatment plant (WWTP) with a capacity to hold around 26,000 equivalent persons (EP). This capacity was chosen for modeling because it approximates the typical size of WWTPs usually found in regional Australia and most parts of Europe. The plant utilizes the activated sludge process (ASP) for secondary treatment, a process that involves high energy use due to its constant aeration requirements.

3.2.2 System Architecture

The integrated system designed by Donald and Love includes the following elements:

• **Photovoltaic (PV) solar array:** Sized to provide sufficient electrical energy during daylight to allow the electrolyser's operation.
• **PEM electrolyser:** Produces hydrogen and high-purity oxygen (O_2) from treated water.
• **Compressor and oxygen storage tank:** Compresses O_2 to 3 bar and stores it for later use.
• **Speece cone oxygen injection system:** Delivers stored oxygen into the ASP basin with >90% transfer efficiency.
• **Control system:** Optimizes hourly electrolyser operation and oxygen injection based on measured WWTP oxygen demand.
This system essentially acts as a storage device for conveying loads and supplying oxygen. Renewable electricity, usually restricted during peak sunlight hours, is utilized to generate O_2, which is then supplied during high-load treatment periods (typically morning and evening).

3.2.3 Simulation Parameters

The authors built a 24-hour dynamic simulation using real WWTP data and modeled system behavior at hourly intervals. Key assumptions included:

• Wastewater flow rate on an hourly basis and oxygen demand over a 24-hour period.
• Solar PV electricity output profile (based on regional solar irradiance)
• Electrolyser efficiency: 65–75%
• Compressor electricity demand: calculated using polytropic equations
• Oxygen tank pressure: 3 bar
• Speece cone O_2 transfer efficiency: 90–95%

The model took into account compression energy losses, solar input fluctuations, and storage losses.

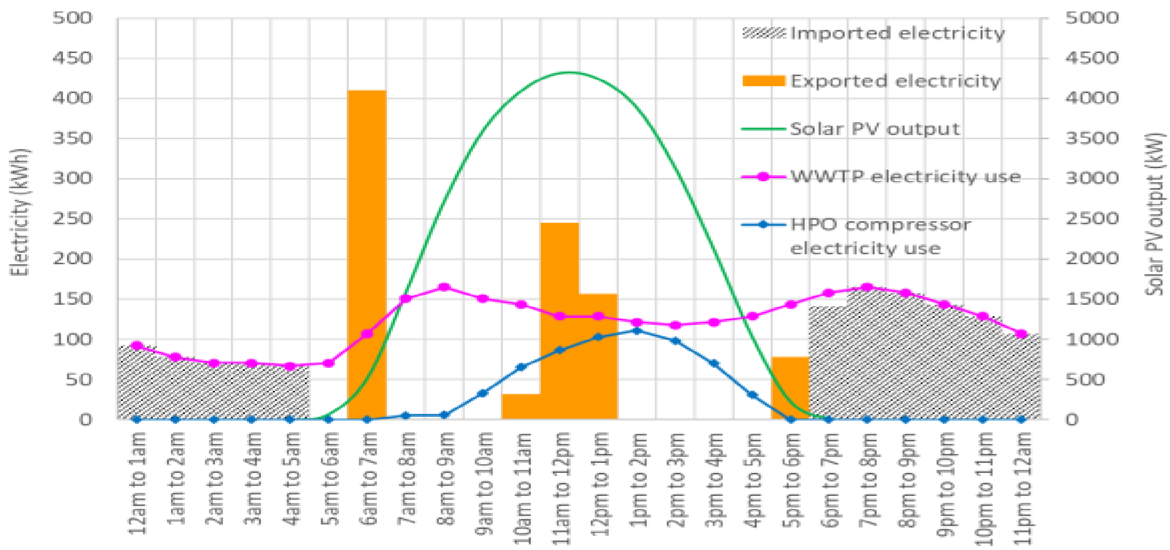

Figure 3.1—Integrated Plant Electricity Flows

Source: Donald & Love (2023)

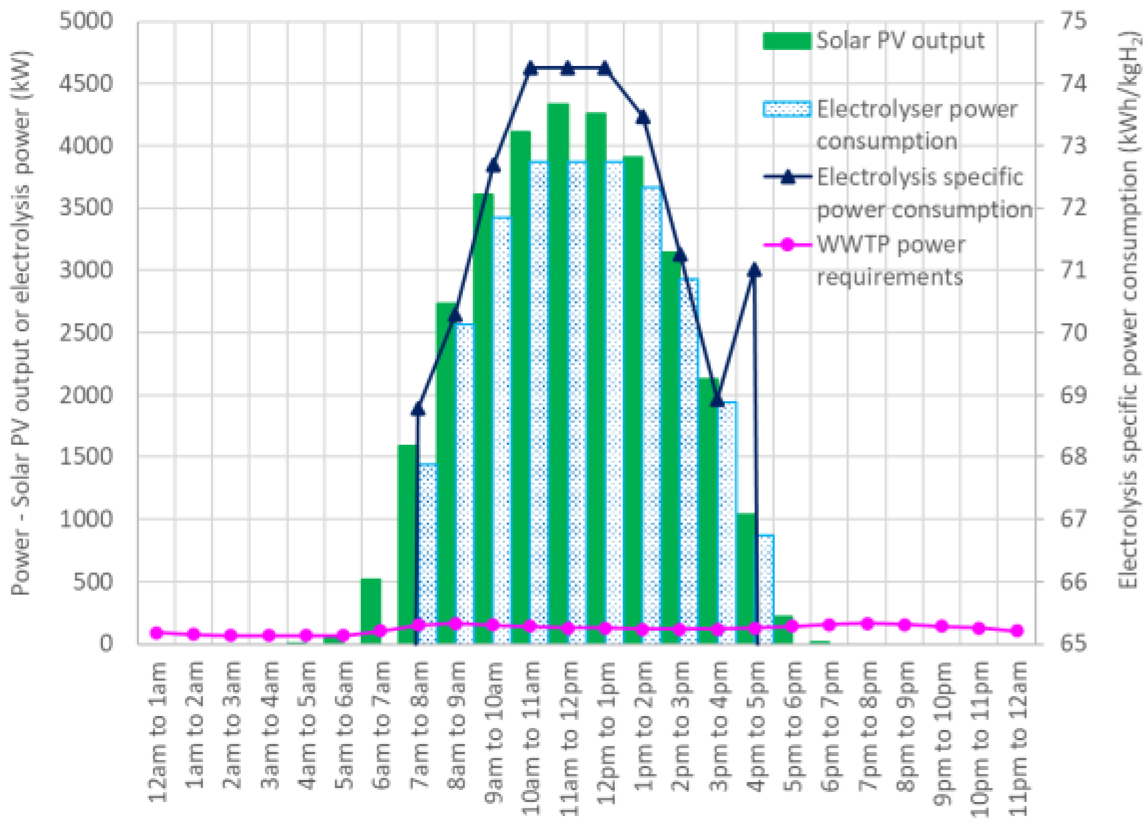

Figure 3.2—Solar PV Output and Electrolysis Power Consumption

Source: Donald & Love (2023)

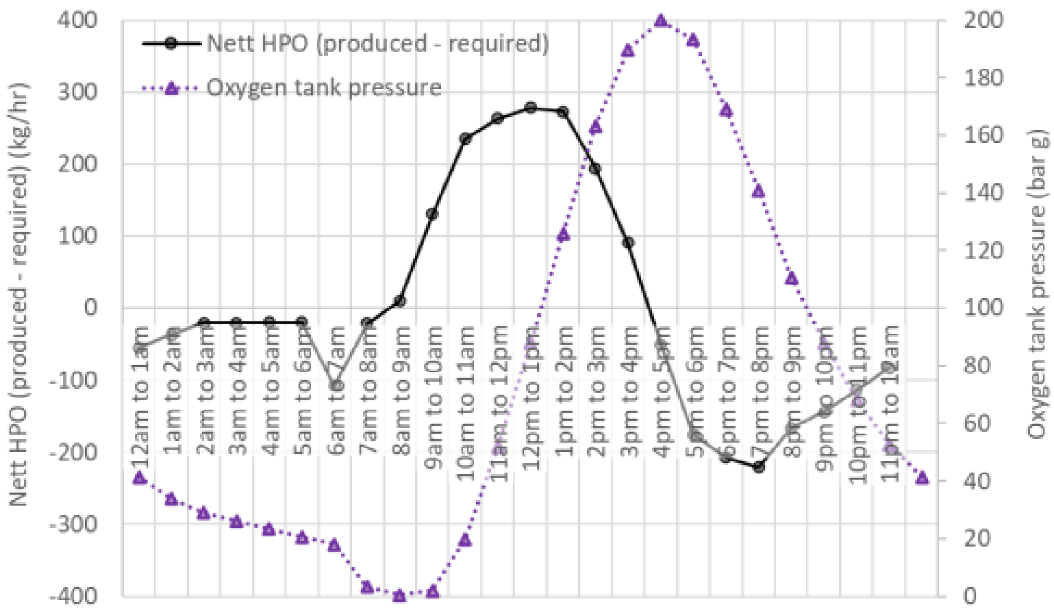

Figure 3.3—Net HPO Produced and HPO Storage Tank Pressure

Source: Donald & Love (2023)

3.2.4 Key Results and Performance Metrics

The exercise resulted in several important findings:

• Eliminated blower operation for 12 out of 24 hours, replacing it with oxygen injection from storage

• Reduced WWTP electricity consumption by ~45% on days with adequate solar supply

• Stabilized DO levels in the ASP between 1.8–2.4 mg/L, showing that O_2 injection was as effective as aeration

• Hydrogen output was ~60–65% of electrolyser capacity, depending on solar conditions

• Oxygen usage closely matched diurnal treatment load, achieving ~95% utilization of produced O_2.

One important discovery from this analysis is the validation of the possibility to preserve and use at a later time compressed oxygen as a storage container for biochemical energy, similar to a battery; this idea is essentially rooted within gaseous chemistry and living organism needs.

3.2.5 Techno-Economic and Environmental Implications

From a cost perspective, Donald & Love's analysis did not include full lifecycle CAPEX or LCOH values, but they highlighted several key economic implications:

• Electrolyser costs remain high, but co-location avoids transport, water purification, and separate permitting costs.

The recovery of O_2 can reduce energy costs of blowers, which can account for 50–70% of WWTPs' electricity expenses.

• Using treated effluent as feedwater for electrolysis reduces water supply costs.

• Hydrogen could be stored or used to fuel municipal buses, garbage trucks, or backup generators.
From an environmental perspective:
• Total annual GHG savings of 390 tCO_2e/year were projected by 2031 under Australian grid conditions.
• By 2034, with improved electrolyser efficiency and PV use, savings could reach 872 tCO_2e/year.
• The system contributes directly to Net Zero Emissions (NZE) goals and distributed hydrogen development.

3.3 Case Study B – EU-Based Model Comparison

Though Donald and Love provide a tangible model within an Australian setting, similar integration frameworks are simultaneously being developed within Europe as well. Of particular note is one conceptual model developed within the EU Horizon 2020 initiative framework that studied incorporating PEM electrolysis with high-level nutrient recovery systems within mid-sized German and Dutch wastewater treatment plants, as examples.

3.3.1. System Overview

The European model involved a centralized wastewater utility treating 50,000–80,000 PE, equipped with:
• High-efficiency membrane bioreactors (MBRs)
• Anaerobic sludge digestion with biogas CHP recovery
• A modular 2 MW PEM electrolyser
• Hydrogen compression and on-site storage for grid balancing
•Oxygen byproduct directly injected into post-anoxic zones to support shortcut nitrification/denitrification.
The key innovation here was the combination of hydrogen and oxygen in the context of energy.
Hydrogen is stored and then fed into the regional power grid during times of increased demand or used to fuel fuel-cell vehicles.
• Oxygen: used strategically to reduce chemical oxygen demand (COD) and to improve nitrification effectiveness.

3.3.2 Load Matching and Dynamic Operation

The approach utilized for Europe included detailed meteorological and flow data to accurately describe daily and seasonal variations in
• Wastewater inflow volume
• Solar irradiance and PV output
• Electrolyser ramp-up time
• Gas storage pressure limits
The key findings included the following:
• The electrolyser operated at an average capacity factor of 85% when combined with a hybrid PV/wind energy system.
• System was capable of modulating hydrogen output to respond to grid price signals. Compressed O_2 was applied with more flexibility than the Donald & Love model, as it was supplied to aerobic and anoxic stages depending on ammonia/NH_4^+ loading. The system achieved an annual GHG reduction of ~1,100 tCO_2-eq compared to separate WWTP and hydrogen systems.

3.3.3 Strengths and Limitations

This EU model offered several key points of reference for the Australian model:

- Higher electrolyser capacity (2 MW vs. ~200 kW)
- The combined use of hydrogen and oxygen inside cities.
- Inclusion of real-time electricity market signals.
- Greater integration of sludge digestion with nutrient recovery.

However, both costs and complexities were increased, requiring the following:

- Advanced grid interconnection.
- sophisticated control systems.
- Public-private partnership model for fuel cell vehicle deployment

Feature	Australian Model (Donald & Love)	European Model (EU Case – mostly Dincer et al. & others)
Electrolyser Capacity	~200 kW **Rickey_Donald_Thesis.pdf**, p. 41	2 MW **(Dincer & Acar, 2015).pdf**, p. 14
O_2 and H_2 Usage	O_2 is used in the Speece cone for aeration; H_2 is stored or used for fleet fuel (**Rickey Donald Thesis, pdf**, pp. 54–56).	O_2 is used in sludge treatment, and H_2 is used in municipal vehicles **(Dincer & Acar, 2015), pdf**, pp. 13–15).
Electricity Input	Solar PV + grid power (**Rickey_Donald_Thesis.pdf**, pp. 52–53).	Market-responsive PV-grid mix **(Dincer & Acar, 2015).pdf**, pp. 13, 15).
Integration with WWTP Systems	Focused on oxygen offset and hydrogen storage p. 52–54	Integrated with digestion, nutrient recovery, and fuel cell systems **(Dincer & Acar, 2015).pdf**, pp. 14).
Control Systems	Basic hourly simulation and limited real-time adaptation p. 53	Advanced control strategies & grid-response algorithms **(Dincer & Acar, 2015), pdf**, p. 15).
Implementation Complexity	Described as replicable but moderately complex p. 59	Complex system requiring coordination and infrastructure **(Dincer & Acar, 2015), pdf**, pp. 14–15).
Economic Model	Public sector-led deployment without detailed LCOH p. 58	The public-private partnership approach is highlighted in **(Dincer & Acar, 2015), pdf**, p. 14.

Table 3.1—Side-by-side comparison of AU and EU integration models.

Source: Author based on Rickey Donald's thesis (2022) and Dincer & Acar (2015).

3.4 Technical Configurations and Equipment Design

The integration of hydrogen production in WWTPs relies on the coordinated operation of multiple subsystems. The following subsections discuss each essential factor in terms of its capacity, design criteria, and function.

3.4.1 Electrolyser Selection and Sizing

Proton Exchange Membrane (PEM) electrolysers are typically preferred due to the following:

- Rapid startup/shutdown (minutes, vs. hours for ALK)
- High purity gas output (>99.99% O_2 and H_2)
- Compact footprint

Sizing depends on:

- Daily hydrogen target (e.g., kg/day)
- Available renewable electricity (kWh/day)
- (Desired oxygen offset in WWTP (kg O_2/d))

A typical 1 MW PEM system produces:

- ~20 kg H_2/hour
- ~160 kg O_2/hour

Oxygen needs in WWTPs range from 0.8–1.5 kg O_2 per m^3 of wastewater, depending on BOD/N content.

3.4.2 Oxygen Compression and Storage

Oxygen from electrolysis exits at low pressure (~1 bar) and must be compressed to 3–5 bar for storage. Options include:

- Piston compressors: Economical but high maintenance
- Scroll compressors: Quiet and oil-free but less robust
- Centrifugal: High flow but expensive

Storage tanks must meet safety standards for pressurized oxygen and are typically built as horizontal ASME-rated tanks that are insulated and located remotely from heat sources.

Mass balance: For a plant treating 10,000 m^3/day with a target of 60% aeration replacement, you need to store and control about 6,000–8,000 kg O_2 per day. The energy required during the compression step in the oxygen storage process may be computed using the conventional equation for isentropic compression. In the case where there is 30 kg of O_2 flow per hour that gets compressed to 3 bar, then the power required would be about 5 to 8 kW.

Compressor power for isentropic compression:

$P = (\dot{m} \times R \times T_1 \times \gamma) / (\eta \times (\gamma - 1)) \times [(P_2/P_1)$ ^$((\gamma-1)/\gamma) - 1]$

Where: P = Compressor power (kW)

$\dot{m}$ = mass flow rate (kg/s)

R = Gas constant for O_2 (259.8 J/kg·K)

T_1 = Inlet temperature (K)

γ = Specific heat ratio for O_2 (1.4)

η = Compressor efficiency (75-85%)

P_1 = Inlet pressure (1 bar)

P_2 = Outlet pressure (3-5 bar)
Example: For 30 kg O_2/hour compressed to 3 bar, power ≈ 5-8 kW.

3.4.3 Oxygen Injection Technologies

Among the available oxygen injection technologies employed with the ASP, there are significant differences in transfer efficiency and energy demand. As shown in Table 3.2, the conventional choice is fine bubble diffusers, which attain relatively low oxygen transfer rates of 20–30% with the associated high energy costs due to the continuous use of blowers. A moderate choice is pressurized side streams systems with transfer efficiencies from 50% to 60% and lower energy penalties. The most advanced choice is the Speece cone injector with attainable transfer efficiencies above 85% and efficient energy use. In this variant, a side stream of mixed liquor is pressurized with pure oxygen at pressures of 3–4 bar and returned to the reactor, enabling almost instantaneous dissolution without the use of blowers. This approach, as exemplified by Donald and Love in their 2023 study, also recognizes the application of Speece cones for energy-efficient WWTP-hydrogen integration schemes.

Method	Transfer Efficiency	Energy Cost	Notes
Fine bubble diffusers	20–30%	High	Conventional, blower required.
Pressurized side-streams	50–60%	Medium	Moderate energy use
Speece cone injectors	85–95%	Low	High-pressure input needed.

Table 3.2—Three main technologies exist for O_2 injection into the ASP.

Source: Donald & Love (2023)**;** Barreto et al. (2018)**;** and Speece et al. (1971).

3.4.4 Control Systems and Integration

Central to integration is a predictive control platform that:
• Monitors PV production, tank pressure, WWTP flow, and oxygen demand
• Modulates electrolyser operation based on energy availability
• Ensures oxygen is injected during DO depletion periods (e.g., peak morning flow)
Advanced systems use Model Predictive Control (MPC) algorithms to allow for anticipatory adjustment, thus improving stability and minimizing electricity waste. These systems can also link to electricity price signals, for example, real-time spot market data, to add economic value.

3.4.5 Simplified Mass and Energy Balance

To provide quantitative context for the integration concept, a simplified mass and energy balance was calculated based on the Donald & Love 2023 case study (26000 EP WWTP). The results are summarized in Table 3.2a.

Table 3.2a—Simplified Mass and Energy Balance for iH_2WWTP (Author Based on Donald & Love 2023)

Parameter	Value	Unit	Source/Calculation
Electrolyser capacity	3.9	MW	Donald & Love (2023)
Hydrogen production	392	kg/day	Donald & Love (2023)

Parameter	Value	Unit	Source/Calculation
Oxygen production ($H_2 \times 8$)	3,136	kg/day	Stoichiometric (1:8 ratio)
WWTP oxygen demand	2,146	kg/day	Donald & Love (2023)
Oxygen reuse potential	146%	% of demand	Calculated (3,136/2,146 × 100)
Net electricity saving	45%	%	Donald & Love (2023)
Grid import reduction	1.2	MWh/day	Donald & Love (2023)
Solar PV requirement	7.0	MW	Donald & Love (2023)

As shown in Table 3.2a, the amount of oxygen produced through electrolysis (3,136 kg/day) is more than the theoretical oxygen requirement (2,146 kg/day) of the Wastewater Treatment Plant (WWTP) by 46%, which means there is sufficient oxygen reuse to supply the aeration requirements, and it even leaves a surplus amount to be utilized for some other purpose as well. To provide a sense of scale, a 200 kW electrolyser will produce 725 kg of O_2 per day, and this is enough to oxygenate 725 m^3 of wastewater in a day using 0.4 kWh per m^3. This shows that small-sized systems have the potential to greatly decrease energy use for aeration processes.

3.4.5a Hourly Mass and Energy Balance

As the daily averages provide an overall picture, the practical implementation of the integration depends on the temporal synchronization of the production of electricity from PV, electrolysis processes, and the oxygen consumption in the WWTP. The table below shows the mass and energy balance for one day of normal operation based on the results of the simulations carried out by Donald and Love (2023) at the 3.9 MW power capacity level given in Table 3.2a.

Table 3.2b—Hourly Mass and Energy Balance for iH₂WWTP (Author based on Donald & Love, 2023)

Hour	PV Output (kW)	Electrolyser Power (kW)	H_2 Produced (kg)	O_2 Produced (kg)	WWTP O_2 Demand (kg)	O_2 Stored (kg)	O_2 Injected (kg)	Blower Saving (%)
06:00	275	0	0.0	0.0	85	0	0	0%
07:00	990	550	10.5	83.6	90	0	0	0%
08:00	1,925	1,540	29.2	233.2	95	0	0	0%
09:00	2,640	2,145	40.7	325.6	100	0	0	0%

Hour	PV Output (kW)	Electrolyser Power (kW)	H_2 Produced (kg)	O_2 Produced (kg)	WWTP O_2 Demand (kg)	O_2 Stored (kg)	O_2 Injected (kg)	Blower Saving (%)
10:00	2,970	2,365	45.1	360.8	105	58.3	302.5	52%
11:00	3,190	2,530	47.9	382.8	110	138.6	302.5	50%
12:00	3,245	2,585	49.0	391.6	115	227.7	302.5	48%
13:00	3,135	2,475	47.3	378.4	120	303.6	302.5	46%
14:00	2,860	2,255	42.9	343.2	125	344.3	302.5	44%
15:00	2,420	1,925	36.9	294.8	130	364.1	302.5	42%
16:00	1,760	1,375	26.4	211.2	140	272.8	302.5	39%
17:00	990	770	14.9	118.8	150	89.1	302.5	37%
18:00	330	0	0.0	0.0	155	0	302.5	35%
19:00	0	0	0.0	0.0	160	0	302.5	34%
20:00	0	0	0.0	0.0	155	0	302.5	35%
21:00	0	0	0.0	0.0	145	0	247.5	31%
22:00	0	0	0.0	0.0	135	0	192.5	26%
23:00	0	0	0.0	0.0	120	0	0	0%
00:00	0	0	0.0	0.0	105	0	0	0%
01:00	0	0	0.0	0.0	95	0	0	0%
02:00	0	0	0.0	0.0	90	0	0	0%
03:00	0	0	0.0	0.0	85	0	0	0%
04:00	0	0	0.0	0.0	80	0	0	0%
05:00	110	0	0.0	0.0	80	0	0	0%
Total	-	-	390.5	3,124	2,860	-	2,887.5	-

Assumptions:

- Electrolysis efficiency: 53 kWh per kg of H_2 (Donald & Love, 2023).

- Stoichiometry: 1 kg of H_2 produces 8 kg of O_2.
- Oxygen demand in WWTP is subject to diurnal variations in flow (Donald & Love, 2023).
- Oxygen injection takes place only when there is enough stored O_2 and when the oxygen demand exceeds the base level.
- Energy saved by blowers = (O_2 injected / O_2 demand) × 100%.
- Profile of PV power production is based on Australian solar radiation characteristics (Donald & Love, 2023).
- Values of each hour in this table have been scaled to fit the 3.9 MW system capacity shown in Table 3.2a.

The key finding is that the system provides about 3,124 kg of O_2 per day to be used for aeration, meeting 26% to 52% of the blower's energy demand while injecting oxygen at its peak (from 10:00 to 22:00). Oxygen storage during hours of high PV power generation (10:00–17:00) allows shifting loads to hours of low solar generation when oxygen demand is still high. Overall daily values match those from Table 3.2a: about 390 kg of H_2 and about 3,124 kg of O_2 per day.

3.4.5b LCOH Estimation Based on Italian Renewable Energy Prices

Based on the formula for LCOH presented in Section 1.5, the calculation below provides the estimate based on Italian renewable energy prices:

$$LCOH = \frac{\sum_{t=1}^{N} \frac{I_t + O_t + E_t}{(1+r)^t}}{\sum_{t=1}^{N} \frac{H_{2,t}}{(1+r)^t}}$$

Where:

- I_t = Initial investment (CAPEX) in year t (€)
- O_t = Operation and maintenance costs in year t (€)
- E_t = Electricity cost in year t (€)
- r = discount rate (%)
- H_{2t} = Hydrogen produced in year t (kg)
- N = System lifetime (years)

Italian context assumptions:

Parameter	Value	Source
Italian industrial RE electricity price	€0.08-0.10/kWh	ARERA (2024)
Electrolyser CAPEX (PEM, 1 MW)	€1,400,000	Donald & Love (2023)
O&M costs	3% of CAPEX/year	Fekete et al. (2023)
Stack replacement (every 8 years)	€280,000	Donald (2022)
System lifetime	20 years	IEA (2022)
Discount rate	6%	Fekete et al. (2023)
Capacity factor	45% (PV-limited)	Donald & Love (2023)
Electrolyser efficiency	53 kWh/kg H_2	Donald & Love (2023)
Annual H_2 production	143,080 kg/year	Table 3.2a (392 kg/day × 365)
Italian PV capacity factor	15-20%	ENEA (2024)

Base case calculation (0.09/kWh):

Cost Component	Annual Cost (€)	Calculation
Electricity (E_t)	€682,000	€0.09/kWh × 53 kWh/kg × 143,080 kg
CAPEX amortization (I_t)	€70,000	€1,400,000 / 20 years
O&M (O_t)	€42,000	3% × €1,400,000
Stack replacement	€35,000	€280,000 / 8 years
Total Annual Cost	**€829,000**	

LCOH=829000 euro/143,080 kg=€5.79/kg H_2.

Electricity Price (€/kWh)	Scenario	LCOH (€/kg H_2)
€0.06	Subsidized/PV-only	€4.22
€0.08	Low RE tariff	€5.20
€0.09	Italian average RE	€5.79
€0.10	Italian industrial	€6.18
€0.12	Grid peak	€7.16

Sensitivity Analysis (Italian RE Prices):

Comparison with Other Production Routes:

Production Route	LCOH (€/kg H_2)	Notes
Grey Hydrogen (SMR)	€1.20-2.00	No CCS, high emissions
Blue Hydrogen (SMR+CCS)	€2.50-3.50	With carbon capture
Italian WWTP-Integrated (€0.09/kWh)	€5.79	Base case
Effective LCOH with offsets	€3.80-4.80	Including O_2 reuse + carbon credits

Offset Applied:
-Oxygen reuse reduction: €0.30 to 0.50 per kg of H_2 (substitutes blower electricity)
-Carbon credits (EU ETS at €80 per ton CO_2): €0.50 to 1.00 per kg of H_2
-Reduction in blower electricity costs: €0.20 to 0.40 per kg of H_2
Most Important Observation: At present electricity prices in Italy (€0.08 to 0.10 per kWh), the combined system results in the production of hydrogen at €5.20 to €6.18 per kg of H_2, which is 3-5 times costlier than grey hydrogen. But taking into account oxygen reuse reduction costs, carbon credits, and reduction in blower electricity costs, the effective LCOH turns out to be around €3.80 to €4.80 per kg H_2.

3.4.5c Summary of Quantitative Findings

Metric	Value	Significance
Daily H_2 production	390 kg/day	Fuel for ~4-5 municipal buses
Daily O_2 production	3,124 kg/day	146% of WWTP demand
O_2 injected for aeration	2,887 kg/day	Replaces 26-52% of blower energy
Net electricity saving	45%	Grid import reduction: 1.2 MWh/day
LCOH (Italian RE, €0.09/kWh)	€5.79/kg H_2	Base case
Effective LCOH (with offsets)	€3.80-4.80/kg H_2	Competitive with blue hydrogen
GHG savings (2023 baseline)	390 tCO_2-eq/year	Donald & Love (2023)
GHG savings (2034 improvement)	872 tCO_2-eq/year	Donald & Love (2023)

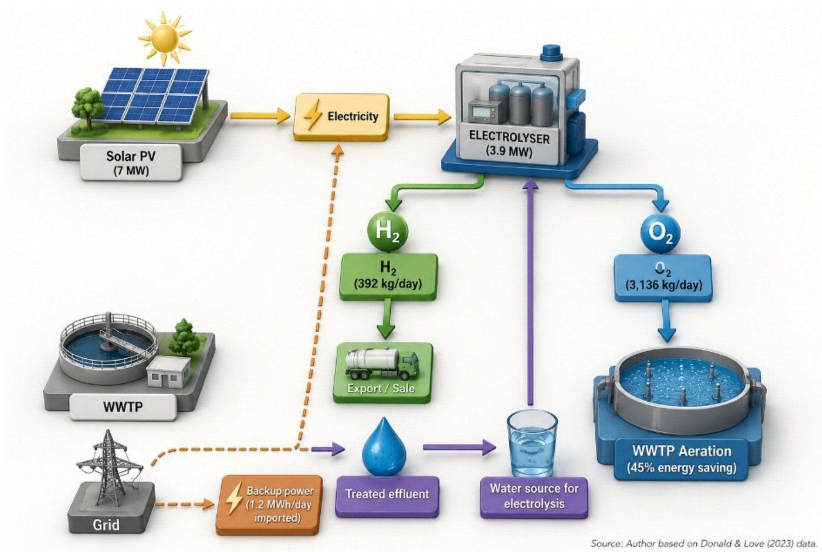

Figure 3.4—Energy Flow Diagram of Integrated Hydrogen-Wastewater System

Based on Donald & Love (2023) data, scaled to 3.9 MW system capacity.

3.5 Energy Modeling and Load Shifting Dynamics

Hydrogen-WWTP integration acts as both a renewable energy sink and a biochemical battery. When excess solar or wind electricity is available, electrolysers operate at full load. When oxygen is needed but renewable energy is unavailable (e.g., night), stored O_2 is injected, decoupling energy input from biochemical demand.

The model includes:

• Hourly solar generation profile: varies by region, month, and cloud cover
• Hourly oxygen demand curve: Based on COD load, WWTP flow
• Compressor losses: Typically, 5–10% of total energy
• Storage decay and thermal losses: Usually negligible under good insulation

Donald & Love's simulation showed:

• Electrolyser operated during 9 daylight hours
• O_2 injection replaced blower operation for 10–12 hours
• Net energy saving: about 45% on sunny days.

Every year, considering the solar energy generation variability and the supply of water, the average energy expense reduction exceeded 30%.

3.6 Economic Assessment: Viability of Integration Models

Their integration into wastewater treatment plants (WWTPs) requires up-front capital expenditures in addition to recurrent operational costs. These financial investments, however, are increasingly justified by long-term improvements in energy efficiency, official incentives, emissions trading credits, and synergistic reuse of oxygen, water, and in-place infrastructure. This section is a continued study of the earlier analysis, with additional information from Rickey Donald's thesis and Fekete et al. economic study from 2023.

3.6.1 Capital Expenditures (CAPEX)

Capital costs vary based on system size, electrolyser type (PEM or alkaline), and whether PV or grid electricity is used. Reported ranges include:

- Electrolyser system (including stack, balance of plant): €1.2M–€1.8M per MW
- Grid and plant integration (controls, water connection, compression): €0.5M–€0.9M per MW
- Total estimated CAPEX: €1.8M–€2.7M per MW

References: Donald, R. (2022). Economic Evaluation. Fekete et al. (2023).

3.6.2 Operating Expenses (OPEX)

Key OPEX elements:

- Stack replacement every 7–10 years (~15% of CAPEX)
- Preventive maintenance (~2–3% of CAPEX/year)
- Electricity expenditure: primary driver — €0.045–€0.12/kWh
- Water pre-treatment costs are minimized using treated WWTP effluent.
- Compressor and auxiliary equipment energy usage

3.6.3 Levelized Cost of Hydrogen (LCOH)

Integration lowers LCOH through synergies:

- Free/recycled water source
- Reduced O_2 purchase (via reuse in aeration tanks)
- Flexible load operation to avoid peak electricity tariffs

Scenario	Electricity (€ / kWh)	Load Factor	LCOH (€ / kg H_2)
Co-located PV (baseline case)	0.045	65%	4.60
Grid electricity (EU avg)	0.12	65%	7.80
Subsidized RE tariff	0.06	80%	3.95
Grey hydrogen benchmark	—	—	1.50–2.00

Table 3.3—levelized cost of hydrogen (LCOH) under different electricity scenarios.

Source: data from Donald & Love (2023), IEA (2022), and Acar & Dincer (2019).

Note: Electricity price and load factor are not applicable for grey hydrogen, which is produced mainly from natural gas (SMR) rather than electrolysis.

It is important to note that this thesis does not present original economic modeling. Therefore, the financial insights provided here derive from precursor techno-economic studies rather than new simulations. A critical comparison of selected sources shows areas of agreement and divergence in the assessment of WWTP–hydrogen integration. Donald (2022) focused on a pilot-scale WWTP in Australia equipped with a humble 200 kW PEM electrolyser and pointed out operational synergies and O_2 reuse, though not covering a full LCOH sensitivity analysis. In contrast, EU Horizon 2020 models considered more substantial 2 MW systems based in Germany and the Netherlands and a nutrient recovery and grid-responsive operation, thus yielding more ambitious yet complex economic cases. Fekete et al. (2023) performed a systemic economic assessment and focused on the decisive role of electricity prices, subsidies, and carbon credits in achieving competitiveness. Overall, the studies suggest that although technical viability is firmly proven, the economic validity of that integration continues to heavily depend on the context, especially from an energy tariff and regulatory perspective.

Source/case	Scale	Focus	Key economic findings	Limitations
Donald (2022), Queensland WWTP	~200 kW PEM	O_2 reuse + solar PV	CAPEX moderate; ~45% aeration energy saving; no detailed LCOH	Small scale: no policy/electricity market sensitivity
EU Horizon 2020 (Germany/Netherlands models)	2 MW PEM	Nutrient recovery + grid response	CAPEX €2–3 M/MW; GHG savings ~1,100 tCO_2/yr; high integration potential	Complex design requires advanced grid interconnection.
Fekete et al. (2023)	Comparative (EU scale)	LCOH & policy analysis	LCOH is ~€3.9–7.8/kg depending on electricity costs; carbon credits improve ROI.	Highly dependent on subsidies; no specific plant case study

Table 3.4—Comparison of Economic Insights.

Reference: Data synthesized from Donald (2022), Fekete et al. (2023), “Economic Assessment of Integrated Hydrogen Production with Wastewater.pdf

3.6.4 Revenue Opportunities

Revenue sources include the following:

- Green hydrogen transactions for industrial use or municipal fleets
- Grid injection under Guarantees of Origin (GoO)
- Carbon credit revenues via EU ETS
- O_2 valorization in WWTPs (replacing purchased oxygen)
- Resilience applications, e.g., hydrogen for backup power

Summary:

While CAPEX remains high, integration with WWTPs improves the business case through cost-sharing, byproduct reuse, and access to incentives. LCOH values can become competitive, especially when co-located with renewable sources or benefiting from policy support.

3.7 Environmental Metrics and Circular Economy Contributions

The integration of hydrogen production in wastewater treatment plants (WWTPs) has significant environmental benefits and contributions to the circular economy that go far beyond energy decarbonization alone. These benefits come from the synergistic cycles of resources, reduced emissions, and material recycling, thus linking the entire operation to several Sustainable Development Goals (SDGs), in particular SDG 6 (Clean Water and Sanitation), SDG 7 (Affordable and Clean Energy), and SDG 13 (Climate Action).

3.7.1 Greenhouse Gas (GHG) Emissions Reduction

By replacing fossil-fuel-based hydrogen (typically from steam methane reforming, SMR), integrated electrolysis systems reduce net CO_2 emissions:

• Direct substitution: Green H_2 avoids ~9–10 kg CO_2 per kg of H_2 (compared to SMR)

• Further benefits

O Reduction in electricity use from blowers (due to oxygen reuse)

Hydrogen usage in thermal applications leads to a reduced fuel demand in sludge combustion.

• Lifecycle emissions with RE-powered electrolysis: ~1.5–2.5 kg CO_2-eq/kg H_2 (vs. ~10 kg CO_2-eq/kg for grey H_2)

References: Rickey Donald's thesis (2022), Fekete et al. (2023), "Economic Assessment of Integrated Hydrogen Production,"

3.7.2 Energy Circularity and Internal Synergies

One can establish a closed loop of energy:

• Hydrogen is produced onsite, thus reducing dependency on external fuel supplies.

• The oxygen so generated due to electrolysis (1 kg H_2 produces 8 kg O_2) is reused for:

O. Aerobic biological treatment (replacing purchased liquid oxygen)

O. Increasing aeration energy efficiency by 10–15%

• Using hydrogen for on-site energy generation, for example, by applying fuel cells, allows it to provide energy to the following:

O. Plant operations during peak hours or outages.

Digesters and auxiliary heating systems.

See: "Donald & Love, 2023; Donald and Love, 2022; Fekete and colleagues, 2023.

3.7.3 Water Circularity and Recovery Potential

• Reuse of effluent: Treated water from the wastewater treatment station can be a feedstock for electrolysis.

• Electrolyser requirements: 9–10 liters of high-purity water per kg of H_2.

• Membrane filtration or polishing systems enable the use of secondary effluent, reducing freshwater withdrawal.

• The addition of deionized water units only has a marginal operational cost (around 1–2% of OPEX), especially when high-purity water is needed for PEM electrolysis.

This supports a closed water loop where municipal wastewater not only becomes usable again but also fuels green hydrogen production.

3.7.4 Materials Recovery and Nutrient Looping

Integration also enables components involving material recovery:
• Struvite crystallization and the recovery of phosphorus can be coupled with electrolytic pH adjustments.
• Electrochemical stimulation has shown potential for enhancing nitrogen removal and phosphate precipitation.
• Sludge valorization: hydrogen-rich gas mixtures can assist in advanced sludge drying or gasification, improving energy yield and waste minimization.
Reference: Fekete et al., pp. 6–9; Donald's thesis

3.7.5 Systemic Circularity and SDG Alignment

Integrating hydrogen production and wastewater treatment embodies systemic circularity by transforming waste streams into valuable resources. The treated effluent appears as a feedstock for electrolysis, and the oxygen byproducts are reused in aeration, and extracted nutrients from sludge are utilized for sustainable farming. All of these synergies play appreciable roles supporting multiple Sustainable Development Goals (SDGs), specifically focusing on SDG 6 (Clean Water and Sanitation), SDG 7 (Affordable and Clean Energy), SDG 12 (Responsible Consumption and Production), and SDG 13 (Climate Action). This alignment also presents the potential for integrated systems as viable examples of the circular economy for urban infrastructure.

Circular Contribution	Description	SDG Impact
H_2 from treated water	Wastewater → Hydrogen	SDG 6, 7
O_2 reuse in aeration	Reduces energy & cost	SDG 12, 13
Nutrient recovery	Supports sustainable agriculture	SDG 2, 12
Emissions reduction	Avoids fossil emissions	SDG 13

***Table 3.5**—Systemic Circularity and SDG Alignment*

Source: Author based on Donald & Love (2023), Donald et al. (2023), and Fekete et al. (2023).

Summary:

Environmental benefits accruing from the integration of electrolysis within WWTPs go beyond simple decarbonization. These include items like energy autonomy, water reuse, reduced emissions, and resource derivation. These, in totality, make the system more resilient, circular, and sustainable and eventually make it a key component in the transition towards net-zero cities' infrastructure.

3.8 Barriers to Implementation and Scaling

Despite obvious merits, various barriers hinder broad-scale implementation.

3.8.1 Technical Challenges

- Intermittent PV supply requires hybrid systems (PV + battery or grid).
- Oxygen storage safety and regulatory issues
- Electrolyser degradation under variable load profiles
- Limited pilot data for large WWTPs (>100,000 PE)

3.8.2 Institutional and Regulatory Barriers

These barriers include:

- WWTPs are usually public utilities with limited innovation funding.
- Cross-sector coordination (water + energy) is often weak.
- Hydrogen licensing and safety codes not adapted to WWTP environments
- Lack of uniform design criteria in integrating O_2.

3.8.3 Economic Risk

- High initial investment deters local governments.
- Policies for carbon pricing and hydrogen support often have shortcomings or uncertainties.
- Payback periods >10 years unless hydrogen prices rise or grants are obtained

3.9 Summary and Critical Insights

This chapter discusses the feasibility, benefits, and strategic rationale for incorporating hydrogen production in urban wastewater treatment plants. A detailed analysis of the Donald & Love case study, combined with a framework based on the European Union, reveals the following findings:

- Integration enables WWTPs to become multi-output hubs, generating clean water, hydrogen, and oxygen, while reducing grid dependence.
- Critical facilitating technologies include PEM electrolysers, Speece cones, and dynamic control systems.
- Significant GHG reductions, energy savings, and water reuse benefits are achievable.
- Economic feasibility depends heavily on electricity costs, electrolyser utilization, and policy support, as highlighted by a comparative review of Donald (2020), EU horizon models, and Fekete et al. (2023), which reached differing conclusions depending on system scale and policy context.
- Scaling will require regulatory innovation, cross-sector investment models, and demonstration projects.

Since urban centers and utility companies pursue decarbonization, the strategy offers a promising model for reshaping industries and building resilience against changing climatic conditions and shifting energy environments.

Chapter 4: Feasibility and Sustainability Assessment of Hydrogen–WWTP Integration

4.1 Introduction

In the face of rising goals regarding climate change and the complex character of urban infrastructure, the symbiotic relationship between energy and water systems made possible by technological integration has become a leading strategy. Specifically, the integration of hydrogen production into wastewater treatment plants (WWTPs) has been seen as a feasible means of addressing energy, environmental, and operational problems at the same time. This chapter presents a holistic analysis of the technical and sustainability feasibility of this integration based on the technological knowledge and case study presented in earlier chapters.

The idea of producing hydrogen by electrolysis with renewable energy sources has received significant interest in the literature; yet, integrating it with wastewater treatment plants (WWTPs) presents a unique set of biophysical, chemical, economic, and operational interdependencies. Significantly, the wastewater treatment process requires large amounts of electricity—mostly for aeration—and generates treated water amenable to reuse in the electrolysis process. In contrast, the process of electrolysis provides high-quality oxygen as a byproduct, which can substitute the energy-hungry blower systems that are currently used in the activated sludge process (ASP). These interrelated advantages make a strong case for facility co-location and sectoral integration.

This chapter evaluates the technical feasibility, economic implications, environmental benefits, social factors, and risk analyses involved in the installation of such systems. It employs detailed simulations (e.g., Donald & Love, 2023), peer-reviewed academic studies, pilot project data, and reports at the European Union level. Additionally, comparative scenario analysis is used to examine the trade-offs and synergies that exist between various configurations of the system.

4.2 Technical Feasibility Assessment

The technical feasibility of hydrogen WWTP integration depends on the compatibility, performance, and controllability of its subsystems. Each system component, electrolysers, storage, compressors, injection systems, and control software, must be evaluated for scalability, resilience, and integration complexity.

4.2.1 Electrolyser Compatibility and Performance

Proton Exchange Membrane (PEM) electrolysers are by far the technically best-suited choice for use in wastewater treatment plants (WWTPs) due to their highly compact design, fast starting times, and capacity for delivering gases of very high purity. Alkaline electrolysers, while cheaper, are not so good at handling variable renewable sources of power and require more installation space.

Key compatibility factors include the following: • Water quality: Electrolysers require deionized or low-conductivity water. Treated effluent from WWTPs is typically rich in ions (e.g., Na^+, Cl^-, Ca^{2+}), requiring ultrafiltration or reverse osmosis (RO) polishing before use in electrolysis. However, Donald & Love (2023) suggest that water polishing for electrolysis adds only marginal energy cost and is feasible within existing plant footprints. • **Renewable energy input:** PV and wind generation profiles vary hourly and seasonally. PEM electrolysers' ability to ramp up/down quickly (in <5 minutes) makes them ideal for absorbing surplus renewable power. • **Operating hours:** Electrolyser efficiency and durability are closely tied to daily runtime. At low-capacity factors (<30%), economic performance suffers. Integration with WWTPs ensures dual-value output (H_2 and O_2), improving effective utilization.

Feature	Alkaline	PEM
Cost	Lower	Higher
Efficiency	Good	Better
Startup Time	Longer	Fast
Response to Load Changes	Slower	Rapid
Hydrogen Purity	Good	Better
Durability	High	Moderate
Scalability	Suitable for large scale	Limited
Operating Temperature	60–80°C	50–70°C
Maintenance Complexity	Simple	Complex
Material Cost	Lower	Lower

Table 4.1—Comparative features of alkaline and PEM electrolysers

Source: Adapted from Yang et al. (2025) and Donald & Love (2023).

4.2.2 Oxygen Storage and Injection Feasibility

Using the byproduct oxygen from electrolysis in WWTPs requires:

1. Compression to 3–5 bar
2. Storage in ASME-certified pressure tanks
3. Injection into ASP at controlled rates

The research by Donald and Love validated the technical feasibility of this loop:
• O_2 was stored during daylight hours.
• Injected during high-load treatment periods.
• Used Speece cone technology for >90% transfer efficiency
• Eliminated blower operation for 12 hours/day

Speece cones, though not widespread in WWTPs, are commercially available and have been proven in high-strength wastewater applications. Their integration requires moderate retrofitting but no fundamental redesign of biological reactors.

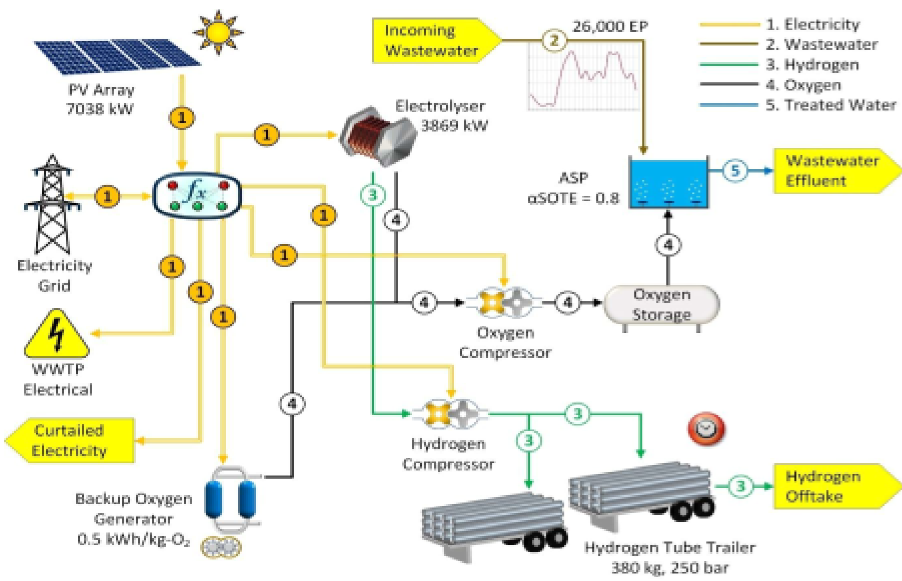

Figure 4.1—System loop showing electrolysis, compression, and oxygen injection.

Source: Author based on Donald & Love (2023).

4.2.3 System Control and Automation

Success in the area of integration relies on advanced real-time control and monitoring. The main elements include:

• Wastewater flow rate and COD
• Dissolved oxygen (DO) in aeration tanks
• Solar or wind energy availability
• Electrolyser power status
• O_2 tank pressure
These variables require an equilibrium state to:

• Avoid oxygen overdosing or underdosing
• Prevent electrolyser underutilization
• Optimize energy storage/load shifting

Modern wastewater treatment plants (WWTPs) increasingly employ supervisory control and data acquisition (SCADA) systems, which can be adapted to control electrolyser modules. Moreover, model predictive control (MPC) algorithms have been evaluated in simulated environments to allow dynamic reallocation of energy between hydrogen production and aeration control.

4.2.4 Space and Layout Constraints

One practical consideration is whether WWTP sites have adequate land and infrastructure for:
• Rooftop or field-mounted PV arrays
• Electrolyser skid units (20–40 ft containers)
• Compressors and gas storage tanks
• Electrical interconnection infrastructure
In the Donald & Love case study, the required installation area was estimated at ~400 m^2 for a 200 kW electrolyser and associated equipment, which was found to be feasible within the WWTP's existing perimeter. For larger plants (>50,000 PE), dedicated installation zones or adjacent land acquisition may be needed.

4.2.5 Integration Scalability

Scaling from pilot to full plant-wide integration poses the following challenges:
• Redundancy requirements: Electrolysers and compressors must be installed with 20–30% redundancy for continuous oxygen supply during maintenance.
• Hydrogen safety protocols: Co-located H_2 storage demands strict zoning, fire safety, and leak detection systems.
• Modularity: Prefabricated electrolyser and oxygen modules are available, but system design must remain flexible to accommodate treatment load variations.

Nevertheless, the technological feasibility is strong at pilot and mid-scale levels. Systems can be modularly scaled through the use of "building blocks" of 100-500 kW-sized electrolysers. European Horizon 2020 projects have already demonstrated similar co-location ideas in small energy hubs that combine biogas, photovoltaics, and hydrogen.

4.3 Economic Feasibility

An economic study examines the feasibility of incorporating hydrogen generation in wastewater treatment approaches. Even though there are obvious theoretical merits in this idea, policymakers need thorough data in terms of capital investment, operational costs, revenue generation, and return on investment (ROI). The present discussion examines these economic factors based on prior studies and model results.

4.3.1 Capital Expenditure (CAPEX)

CAPEX includes installation and the commissioning of the entire hydrogen production subsystem. A breakdown of the typical components of CAPEX is provided below:
• Electrolyser unit (PEM, 200–500 kW): €1,000–€1,400 per kW
• PV system (optional, for dedicated renewable supply): €600–€1,000 per kW

• Compressor and oxygen storage: €200,000–€400
• Oxygen injection system (e.g., Speece cone): €100,000–€180,
• Instrumentation and control (SCADA upgrade): €50,000–€100,000
• Civil works, permits, safety systems: €100,000–€200,000
Typical total CAPEX for a 1 MW integrated system ranges from €1.8 million to €2.8 million, depending on local labor costs, grid interconnection, and whether a PV system is installed.

Component	Small (0.2 MW)	Medium (2 MW)	Large (20 MW)
Electrolyser Stack	100000	800000	6000000
Power Electronics	40000	300000	2000000
Water Purification	15000	100000	800000
Hydrogen Compression	30000	200000	1200000
Storage (H_2+O_2)	25000	180000	1000000
Balance of Plant (BoP)	20000	160000	900000
Total CAPEX	230000	1740000	11900000

Table 4.2*—CAPEX breakdown for electrolyser systems of different scales.*

Source: Author based on Donald (2022), Fekete et al. (2023), and Donald, Boulaire, & Love (2023).

4.3.2 Operating Expenses (OPEX)

Current operational costs include:
• Electricity (main variable cost): If renewable, ~€0.04–0.06/kWh; if grid electricity is used, this may rise to €0.10–0.15/kWh
• Maintenance and parts: 2–4% of CAPEX annually
• Water treatment (for electrolysis): negligible if effluent is reused
• Staff and monitoring: minimal increase (around 0.5 FTE)
Compared to standalone hydrogen plants, co-located WWTP models benefit from shared staff, water supply, and control systems, which reduce OPEX by 10–15% overall.

4.3.3 Levelized Cost of Hydrogen (LCOH)

The Levelized Cost of Hydrogen represents the average cost over the plant lifetime, typically between 15 and 20 years. Recent studies show:

Scenario	LCOH (€ per kg H_2)
Grid-powered electrolysis	5.00–6.50
PV + Electrolysis (co-located)	3.50–4.50
WWTP-integrated model	2.80–3.80
Grey hydrogen benchmark	1.20–2.00

***Table 4.3**—Comparative levelized cost of hydrogen (LCOH) across production pathways.*

Source: Author based on Donald & Love (2023), Donald, Boulaire, & Love (2023), Acar & Dincer (2019), and IEA (2022).

Using byproduct oxygen internally reduces blower energy use, contributing to lower LCOH. Donald & Love estimate that in their Queensland WWTP, O_2 replacement cut grid demand by 45%, which translated into energy savings of ~€70/MWh.

The levelized Cost of Hydrogen (LCOH) is calculated using the full equation provided in Section 1.5, which is then utilized in Section 3.4.5b.

formula: $LCOH = \frac{\sum_{t=1}^{N} \frac{I_t + O_t + E_t}{(1+r)^t}}{\sum_{t=1}^{N} \frac{H_{2,t}}{(1+r)^t}}$

Where:

- I_t = Initial investment (CAPEX) in year t (€)
- O_t = Operation and maintenance costs in year t (€)
- E_t = Electricity cost in year t (€)
- r = discount rate (%)
- H_{2t} = Hydrogen produced in year t (kg)
- N = System lifetime (years)

In the sensitivity analysis shown in Figure 4.2, a simplified version of this formula is used to show how the utilization rate affects LCOH, where CAPEX and O&M are kept constant at the base cost.

$$\text{LCOH} = C_{\text{base}} + \left(\frac{P_{\text{elec}} \times E_{\text{H}_2}}{U} \right)$$

Where:

- C_{base}: Fixed base cost (CAPEX + O&M) [€/kg], here assumed ~€1.00/kg
- P_{elec}: Electricity price [€/kWh]
- E_{H_2}: Electricity needed to produce 1 kg H_2, assumed ~50 kWh
- U: Utilization rate (fraction: 0.3, 0.5, 0.7, 0.9)

This equation highlights the dominant role of electricity cost and utilization efficiency on LCOH. As seen in the figure below, higher utilization significantly reduces cost per kilogram of hydrogen.

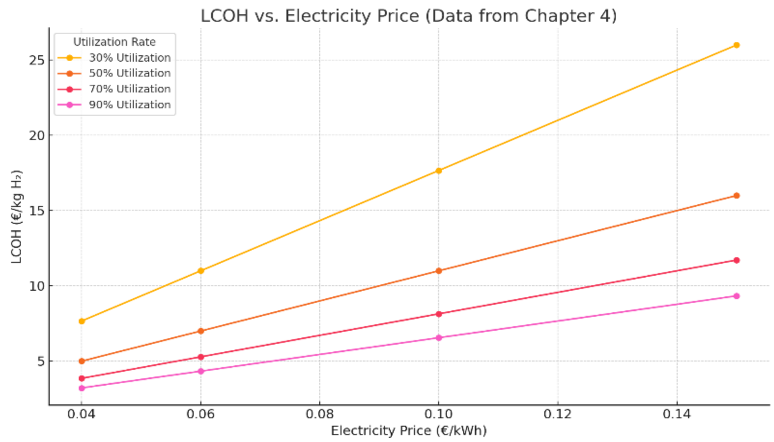

Figure 4.2—LCOH under different electricity price and utilization scenarios.

Source: Author based on LCOH formula from Donald, Boulaire, & Love (2023), with electricity price data from IEA (2022) and utilization rate assumptions from Donald & Love (2023).

4.3.4 Revenue and Return on Investment (ROI)

Integration of hydrogen production within WWTPs allows for the creation of multiple revenue streams while increasing the use of existing assets. One of the main sources of income is the sale of hydrogen. The produced hydrogen can be used to fuel municipal vehicle fleets such as buses, garbage trucks, or maintenance equipment or sold to nearby industrial users in search of a cleaner-burning fuel alternative. Retail hydrogen prices vary from €4 to €6 per kilogram, depending on market conditions, making the co-located model financially viable.

In addition to hydrogen sales, carbon credits offer a valuable financial incentive. By replacing conventional oxygen blowers with oxygen recovered from the electrolysis process, the WWTP can significantly reduce dependence on power generated from the grid. By doing so, this results in quantifiable reductions in carbon credits monetized under the EU Emissions Trading System (ETS) or other country-specific carbon offset schemes. These reductions are expected to significantly boost financial income, particularly in regions with higher carbon pricing.

Another major advantage is avoided operational costs. By using byproduct oxygen internally (especially for aeration), the WWTP can minimize or eliminate energy-intensive blower operations during peak hours. This energy offset not only lowers utility bills but also improves the site's energy resilience, enabling better performance under grid constraints or outages.

In addition, hydrogen can serve as a resilience asset by offering a backup energy supply for WWTP systems, especially during emergency or power outages. This resilience value, although not always translated into explicit financial measures, strengthens the strategic case for combined models.

Overall Return on Investment (ROI) depends on several factors:

• Local hydrogen retail prices

• Governmental funding or subsidization, including programs like the European Union Green Deal initiatives, Hydrogen Valleys, or national hydrogen networks.
• The ratio of hydrogen consumed internally as compared to sales externally.
• Carbon pricing or fiscal incentives
Most models project payback periods of 8–12 years, though this can be shortened if government subsidies and carbon pricing mechanisms are effectively leveraged. For instance, the Queensland WWTP project cited by Donald & Love showed energy savings of ~€70/MWh through blower substitution, further improving ROI.

4.4 Environmental Sustainability Assessment

Integrated hydrogen production systems in wastewater treatment plants (WWTPs) present a multifaceted opportunity for increasing ecological sustainability. Integration enhances the decarbonization of the energy and wastewater industries, supports circular resource flows, and enhances air quality outcomes.

4.4.1 Greenhouse Gas (GHG) Emissions

There are no direct carbon emissions during hydrogen generation using electrolysis with renewable energy. Moreover, the combination of hydrogen generation plants with WWTPs will have further environmental benefits because it will allow for the reuse of oxygen generated in the process, leading to lower electricity needs by substituting energy-hungry air blowers used for aeration.

Table 4.3a—Comparative GHG Emissions and Environmental Impact.

Indicator	Value	Source
GHG emission (iH_2WWTP integrated)	1.5–2.5 kg CO_2-eq/kg H_2	Donald et al. (2023)
GHG emission (grey hydrogen—SMR)	9–12 kg CO_2-eq/kg H_2	Acar & Dincer (2019)
GHG emissions (green hydrogen—PV)	3–4 kg CO_2-eq/kg H_2	Acar & Dincer (2019)
Energy saving from O_2 reuse	30–45%	Donald & Love (2023)
Water consumption for electrolysis	9 L/kg H_2	IEA (2022)
GHG saved (2023 baseline)	390 t CO_2-eq/year	Donald & Love (2023)
GHG saved (2034 improved scenario)	872 t CO_2-eq/year	Donald & Love (2023)

The amount of reduction in the case of CO_2 equivalent for 2023 will be 390 tons each year, and for 2034, the reduction will be 872 tons each year, considering the increase in the efficiency of the electrolysers as well as the decarbonization of the grid. The hybrid process yields greenhouse gases between 1.5 to 2.5 kilograms of CO_2-eq per kilogram of H_2, significantly less than the 9 to 12 kilograms of CO_2-eq per kilogram of H_2 of grey hydrogen.

4.4.2 Circular Resource Utilization

Hydrogen generation in conjunction with wastewater treatment fosters circular resource utilization patterns, enabling a symbiotic relationship between water reuse, oxygen utilization, and energy conservation. • Water Reuse: The process of operating electrolysers requires about 9 to 11 liters of water for each kilogram of produced hydrogen. Using WWTP treated effluent minimizes potable water dependence, thus incorporating a water reuse capability into the plant. Minor polishing, i.e., filtration or reverse osmosis, is necessary, with the energy costs related to water preparation accounting for less than 1% of the overall system utilization. The project aligns with Sustainable Development Goal (SDG) 6, ensuring clean water and sanitation. • Oxygen Reuse: Electrolysis produces high-purity oxygen as a byproduct. Instead of venting it to the environment, the oxygen can be introduced directly into WWTP aeration tanks, thus substituting mechanically compressed air and achieving a potential decrease in blower-related electricity usage by up to 45%, as shown in Queensland WWTP models. This recycling interaction increases both energy and operational efficiency. • Energy Circularity: In this holistic approach: a wastewater treatment plant becomes a net producer of renewable hydrogen fuel. o Oxygen from water splitting is reused internally, cutting costs and emissions. Biogas produced from sludge digestion is capable of being used for combined heat and power (CHP) applications or as supplementary power to fuel electrolysers. Therefore, the wastewater treatment plant becomes a closed-loop center with three byproducts: drinkable water, renewable hydrogen, and process oxygen.

4.4.3 Lifecycle and Carbon Footprint Comparisons

It also stresses the environmental advantages that are connected with combined systems. **According to Dincer and Acar (2015) and Donald and Love (2022):**

Hydrogen Source	Lifecycle Carbon Intensity (kg CO_2e/kg H_2)
Steam Methane Reforming (SMR)	9–12
Grid-powered electrolysis	4–6
PV-powered electrolysis	3–4
WWTP-integrated electrolysis (PV + O_2 reuse)	1.5–2.5

***Table 4.4**—Comparative carbon footprint of hydrogen sources.*

This drastic reduction aligns with **EU Green Deal** and **Net-Zero 2050** targets, positioning WWTP-integrated systems as ideal for **municipal climate action plans**.

4.4.4 Broader Sustainability Impact and SDG Alignment

Beyond carbon savings, these systems create co-benefits across environmental, social, and economic domains:

• Emission offsets

o Reduced NO_x and PM emissions by replacing diesel in municipal vehicles
o Displacement of fossil-fuel-derived oxygen
o Generation of carbon credits under EU ETS or voluntary markets
• Energy resilience
o Hydrogen storage enables blackout protection
o WWTPs can operate off-grid during disruptions.
• SDG Contributions:
o SDG 6: Water reuse in electrolysis
SDG 7: Renewable energy production on-site.
o SDG 11: Sustainable infrastructure for cities
o SDG 13: Climate action via decarbonization
Municipalities that adopt this model enhance their green funding eligibility while showcasing leadership in urban sustainability.

4.5 Social and Policy Aspects

The integration of hydrogen production into wastewater treatment plants has strong social and policy implications, especially in cities where the current infrastructure is highly interwoven with the activities and goals of urban communities towards sustainability.

4.5.1 Public Perception and Awareness

Hydrogen projects often face knowledge gaps and public uncertainty, particularly regarding safety and long-term viability. However, co-locating hydrogen systems within existing municipal infrastructure like WWTPs can
Increase public trust by locating hydrogen infrastructure in existing, expertly managed facilities.
• Improve visibility of green energy through educational signage, site tours, and public reports
• Link hydrogen production with local benefits, such as clean air and sustainable jobs
Studies confirm that the adoption of circular economy models results in increased public support, especially in the presence of transparent local government governance.

4.5.2 Policy Support and Regulatory Alignment

Europe, and particularly Italy, provides a favorable policy environment for hydrogen-WWTP integration:
• The EU Hydrogen Strategy (2020) and Repower EU Plan (2022) emphasize green hydrogen and grid decarbonization.
• Italy's Hydrogen Valley Initiative and National Recovery and Resilience Plan (PNRR) include funding for pilot-scale electrolysis systems at public utility sites.

Regulatory frameworks like the EU renewable energy directive II (RED II) are classifying electrolytic hydrogen produced from renewable sources as highly sustainable, thus qualifying for attractive financial support and tax breaks. Additionally, municipal utilities that demonstrate SDG alignment and emission reductions may qualify for European Innovation Fund or Green Deal Horizon 2030 grants.

4.5.3 Equity and Inclusion Considerations

Hydrogen projects within wastewater treatment plants can also support energy equity and social inclusion:
• Job creation: Experts in oxygen and electrolyser systems; ancillary positions related to strategic planning and management.
Energy equity: Increasing the use of hydrogen fuel in local bus and waste collection fleets can help reduce air pollution in disadvantaged neighborhoods.
• Water access: Displays the possibility of reusing non-potable water in advanced sustainability projects while maintaining the supply of potable water resources.
It assures that the project is in line not just with environmental goals but also with inclusive city plans.

4.5.4 Institutional Synergy and Governance

Effective program execution requires inter-municipality, inter-utility, and inter-agency collaboration. Co-location as a practice enhances:
• Organized data exchange and performance monitoring between the energy and water sectors.
• Multi-stakeholder governance models, including universities and private partners
• Flexible planning to enable future integration of fuel cells, hydrogen refueling stations, or grid stabilization services.

Policy	Region	Benefit
EU Hydrogen Strategy	EU	Funding
Repower EU	EU	Investment support
Italian Hydrogen Roadmap	Italy	National targets
PNRR	Italy	Direct funding
EU ETS	EU	Carbon credits (~€80/tCO_2)

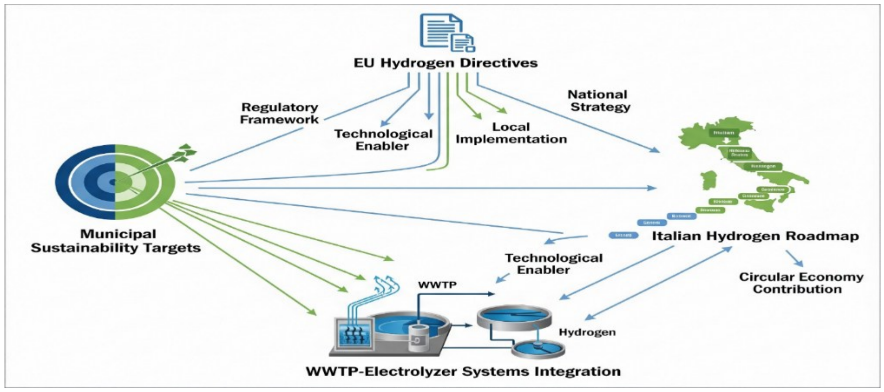

Figure 4.3—Policy support framework linking EU Hydrogen Directives, the Italian Hydrogen Roadmap, municipal sustainability targets, and WWTP–electrolyser integration.

Source: Author based on the EU Hydrogen Strategy (2020), Repower EU (2022), and the Italian Hydrogen Roadmap.

4.6 Comparative Scenario Analysis

To determine the real-world impacts and value of integrating hydrogen production into wastewater treatment plants, this section explores three different configurations. Each situation is examined from technical, economic, and environmental points of view to provide insight into how integrating hydrogen into wastewater treatment plants enhances efficiency.

4.6.1 Scenario A – Baseline WWTP (No Integration)

This scenario represents a typical infrastructure built for wastewater treatment:

• Powered solely by grid electricity
• Mechanical blowers used for aeration
• No hydrogen or oxygen recovery
• Wastewater volume: 10,000–30,000 m^3/day

Performance metrics:

• Electricity use: 0.5–0.7 kWh/m^3
• GHG emissions: 800–1,200 tCO_2-eq/year
• No energy recovery beyond limited biogas
• Low flexibility during peak demand times.

This configuration is still dominant globally, particularly in small-to-midsize utilities. It lacks circularity, flexibility, and resilience.

4.6.2 Scenario B – Hydrogen Electrolysis Only (No Integration)

A co-located PEM electrolyser powered by photovoltaics (PV) produces green hydrogen, but no integration exists with the WWTP processes. The oxygen byproduct is vented. **Advantages:** • Green hydrogen production via renewable power • Flexible electrolyser operation can support grid load balancing. **Disadvantages:** • Oxygen is wasted**;** no impact on WWTP energy use • Blower-assisted aeration still required. • High LCOH due to lack of internal reuse. **Estimated Metrics:** • LCOH: €4.50–€5.50 per kg H_2 • No reduction in blower electricity • No water reuse • Limited synergies with WWTP operations

4.6.3 Scenario C – Fully Integrated H_2–WWTP System (Donald & Love Model)

The following outlines the desired configuration for technical and sustainability performance: • PEM electrolyser powered by PV • Used treated wastewater as a water source. • Byproduct O_2 stored and injected into aeration tanks • Blowers turned off during high oxygen demand **Performance Metrics:** • Grid electricity reduced by 45–60% • GHG savings: 390–870 tCO_2-eq/year• O_2 utilization > 90% • Hydrogen production: 50–65% of electrolyser capacity • Payback period shortened by 2–4 years. This system optimizes energy use, circularity, and climate impact—aligning with Net-Zero 2050 targets.

4.6.4 Summary Table: Scenario Comparison

Parameter	Scenario A	Scenario B	Scenario C
Water Source	Potable	Potable	Treated effluent
O_2 Utilization	No	No	>90% used in WWTP
Energy for Blowers	100% grid	100% grid	Reduced by 45–60%
Electricity Use (kWh/m³)	0.5–0.7	0.5–0.7	~0.3–0.4
GHG Emissions (tCO_2/year)	800–1,200	~900–1,100	390–870
CAPEX	Medium	High (duplicate infra)	Lower (shared infra)
OPEX	High	Medium	Lowest (synergy benefits)
LCOH (€ per kg H_2)	N/A	4.50–5.50	5.79/(base case)/3.8-4.8 (with offsets)
Payback Period (years)	N/A	10–12	8–10
SDG Alignment	Low	Medium	High (SDG 6, 7, 13)

***Table 4.5**—Comparative performance of hydrogen-WWTP integration scenarios (A-C)*

Source: Author based on Donald & Love (2023), Donald et al. (2023), Donald (2022), Fekete et al. (2023), and Cardoso et al. (2021).

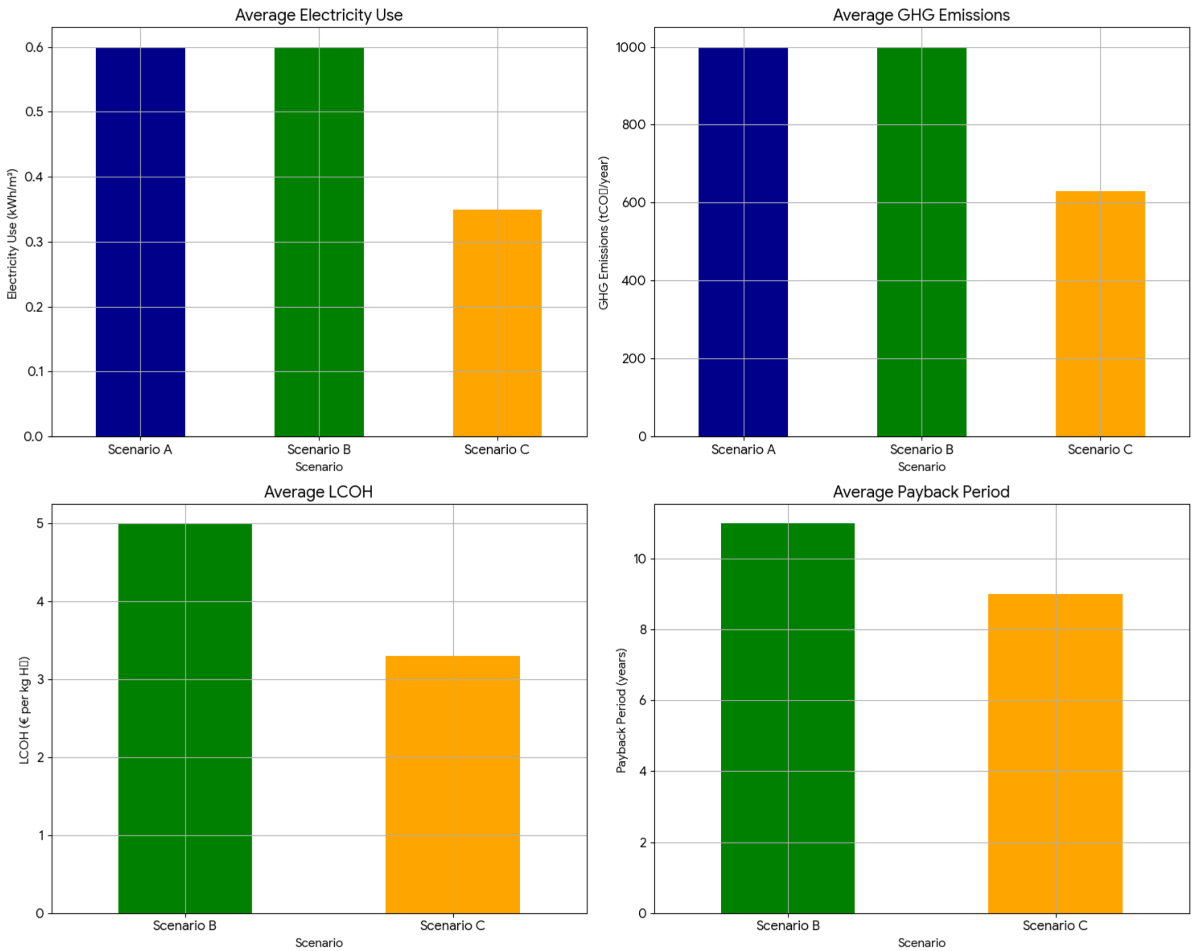

Figure 4.4—Comparative performance metrics for hydrogen production scenarios (A, B, and C)

Source: Author based on data from Table 4.5.

4.7 Risk Assessment

Creation of integrated hydrogen-wastewater treatment plants combines traditional risks of infrastructure with new challenges related to hydrogen technologies, effective regulation, and market volatility. Careful and systematic risk evaluation is necessary to ensure the robustness of the system, return on investment, and attainment of goals related to safety and sustainability.

4.7.1 Technical Risks

• Hydrogen Safety: Hydrogen is highly flammable and subject to possible explosion risks upon leakage. Although electrolysis is inherently safer than reforming, the practice of safety measures such as gas leak detection, explosion-proof equipment, and proper ventilation is absolutely necessary.

• Electrolyser Reliability: PEM electrolysers degrade over time, particularly under fluctuating PV power inputs. Membrane replacement intervals and MTBF (mean time between failures) directly affect long-term operating expenses.
• Compressor Malfunctions: Repeated use of oxygen compressors can lead to mechanical failure or overheating and thus cause system shutdowns.
• Sensor Inaccuracy: Routine calibrations of dissolved oxygen probes, gas pressure transducers, and flow meters are required. Inaccurate readings can result in insufficient aeration or even dangerous overpressurization.
• Water Quality Variability: Treated effluent can have turbidity or salinity fluctuations, especially in cases of stormwater inflow or industrial discharges, thus necessitating additional filtration (for example, reverse osmosis) to protect the stacks of electrolysers.
• Integration Complexity: Real-time coordination between SCADA systems, gas handling units, and WWTP controls adds complexity, requiring high reliability and rapid fail-safe mechanisms.
Mitigation Strategies:
• Modular architecture with redundant compressors and electrolyser stacks.
• OEM maintenance contracts and redundancy in critical components
• Real-time SCADA with redundant sensors, alarms, and emergency overrides
• Real-time water quality monitoring through automated pretreatment process adjustments.

4.7.2 Economic and Market Risks

• High Upfront CAPEX: Electrolysis equipment, compressors, SCADA upgrades, and civil works represent significant capital investment. Without public funding, ROI timelines may stretch beyond typical planning cycles.
• Hydrogen Price Volatility: H_2 market prices vary widely (e.g., €3–€10/kg) depending on carbon policy, fossil fuel competition, and regional supply-demand mismatches.
• Subsidy Dependency: Early project phases rely heavily on grants (e.g., EU Horizon 2030, Hydrogen Valleys). Policy changes could threaten long-term financial viability.
• Inflation in Operational and Maintenance Costs: Rising expenditures from spare parts, replacement of stacks, and specialized labor may reduce forecasted savings.
Mitigation Strategies:
• Blended finance (e.g., PPP models) with milestone-based disbursement
• Lock-in of hydrogen supply contracts (e.g., municipal fleets, backup power)
• Ongoing contractual arrangements with electrolyser suppliers.
• Project phasing and optional PV integration to spread CAPEX burden

4.7.3 Operational and Maintenance Risks

• Skill Gaps: WWTP staff often lack training in hydrogen systems. Electrolyser operation, hydrogen safety, and compressor maintenance require specialized skills.
• Downtime Impacts: If hydrogen production halts, the WWTP may lose its energy offset benefits and incur additional grid costs for aeration.

• Weather Dependence (PV systems): PV-powered electrolysis introduces intermittency risk, particularly in regions with low insolation. Without CHP or battery backup, hydrogen output may become unreliable.

Mitigation Strategies:

• Cross-training staff on hydrogen technologies and emergency procedures
• Planned preventive maintenance using predictive analytics
• Grid or biogas-based backup systems for critical load support
• Digital twin models for predictive O&M simulations

4.7.4 Regulatory and Institutional Risks

• Permitting and Compliance: The hydrogen and oxygen storage infrastructure may trigger new permitting procedures under the guidelines of high-pressure gases, fire protection codes, or environmental impact assessments (EIAs).

• Lacking Coordinated Regulatory Framework: The concurrent availability of sewage and hydrogen infrastructure creates regulatory uncertainty in many EU member states because of the lack of harmonized national or regional regulations.

• Institutional Discrepancy: Water utilities and energy planners often operate under different budgetary cycles and governance structures, making project approvals a difficult process.

• Community Acceptance: The existence of perceived safety issues or NIMBY (Not In My Backyard) resistance can impede or inhibit deployments, particularly near residential neighborhoods.

Mitigation Strategies:

• Follow international standards (e.g., ISO 22734 for electrolysers, ASME codes for pressure vessels)
• Establish stakeholder working groups and start initial community engagement.
• Coordinate project timetables with local funding cycles.

Use the EU Green Deal and Net-Zero 2050 frameworks to promote the harmonization of policies.

4.8 Summary and Strategic Recommendations

This chapter offered an in-depth sustainability and feasibility assessment regarding the integration of electrolysis-powered hydrogen production into municipal WWTPs. The research reveals that, if suitable design requirements are used, these technologies are not only technologically possible but also consistent with long-term economic, environmental, and policy goals, especially in the context of the EU Green Deal and the net-zero greenhouse gases by 2050 goal.

The integration of PEM electrolysers with WWTPs enables transformative synergies:

• Treated effluent reuse as feedwater for electrolysis
• Oxygen valorization by displacing blower-based aeration
• Shared infrastructure, which decreases costs and environmental footprint.

Key Findings

1. Technical Viability

Suitable for WWTPs serving >10,000 PE, especially those with access to modular PEM units, compressed oxygen storage, and smart SCADA control systems.

2. Economic Feasibility

Integration substantially lowers LCOH — from €5–6.5 in standalone cases to €2.8–3.8/kg H_2 — due to energy savings, shared assets, and increased eligibility for green funding.

3. Environmental Impact

o Up to 870 tCO_2-eq/year avoided through grid offsetting and diesel replacement

o Water reuse aligns with SDG 6.

o Lifecycle emissions lowered to 1.5–2.5 kg CO_2-eq/kg H_2, supporting SDG 13

4. Policy Dependency

Early deployment needs subsidies, technical guidelines, and permitting reform. Carbon pricing and circular economy incentives can accelerate viability.

5. Risk Management

Hydrogen safety risks, over-aeration of oxygen, and changes in effluent are manageable through proper system design, modularity, thorough safety training, and public participation.

Scenario C Performance Summary (Compared to A and B)

Metric	Scenario C (Integrated)	Benefit
LCOH	€2.8–3.8/kg H_2	↓ Up to 40%
Emissions	1.5–2.5 kg CO_2-eq/kg H_2	↓ 70–80%
Blower Energy	Up to 45% replaced by O_2	Grid savings
Payback Period	8–10 years	↓ vs. >15 years (A)
O_2 Utilization	>90%	From waste to asset

***Table 4.6**—Performance benefits of scenario C (integrated hydrogen-WWTP system).*

Source: Author based on Donald & Love (2023), Donald et al. (2023), Donald (2022), and Fekete et al. (2023).

✅ **Strategic Recommendations:**

1. Pilot at Medium-Scale WWTPs

Start with 100–500 kW PEM electrolysers at 10,000–50,000 PE WWTPs. Target locations with:

• Strong decarbonization targets • Solar PV or CHP for onsite energy • Political support for innovation

2. Leverage Circular Economy Messaging

Develop strategies aimed at raising funds from:

• EU Innovation Fund

• LIFE Programmed

• National-level strategies regarding hydrogen (e.g., Hydrogen Hubs)

Showcase multi-benefit design: water reuse + green hydrogen + oxygen recovery.

3. Standardize Design Templates

Promote modular blueprints including:

• Shared SCADA and interlocks

• O_2 feedback control

• Grid/PV hybridization + CHP backup
This reduces permitting delays and design costs.

4. Enable Public–Private Partnerships (PPPs)
Encourage co-investment from:
• Electrolyser OEMs • Municipal bus/train networks (hydrogen off-takers) • WWTPs and utilities
PPPs distribute risk and help scale faster.

5. Strengthen Regulatory and Institutional Support
• Issue permitting guidelines for hydrogen–water integration
• Encourage training programs for WWTP operators
• Push for policy harmonization on co-located energy–water infrastructure (e.g., under the EU Water-Energy Nexus agenda)

4.9. Conclusion of Chapter 4

Hydrogen–WWTP integration offers a scalable, realistic, and impactful decarbonization strategy for cities and regions worldwide. By bridging the water and energy sectors, municipalities can:
• Produce clean fuels
• Recover resources
• Reduce emissions.
• Enable regional flexibility
With the proper planning and sufficient support, this model could become a cornerstone of sustainable urban infrastructure over the next decade.

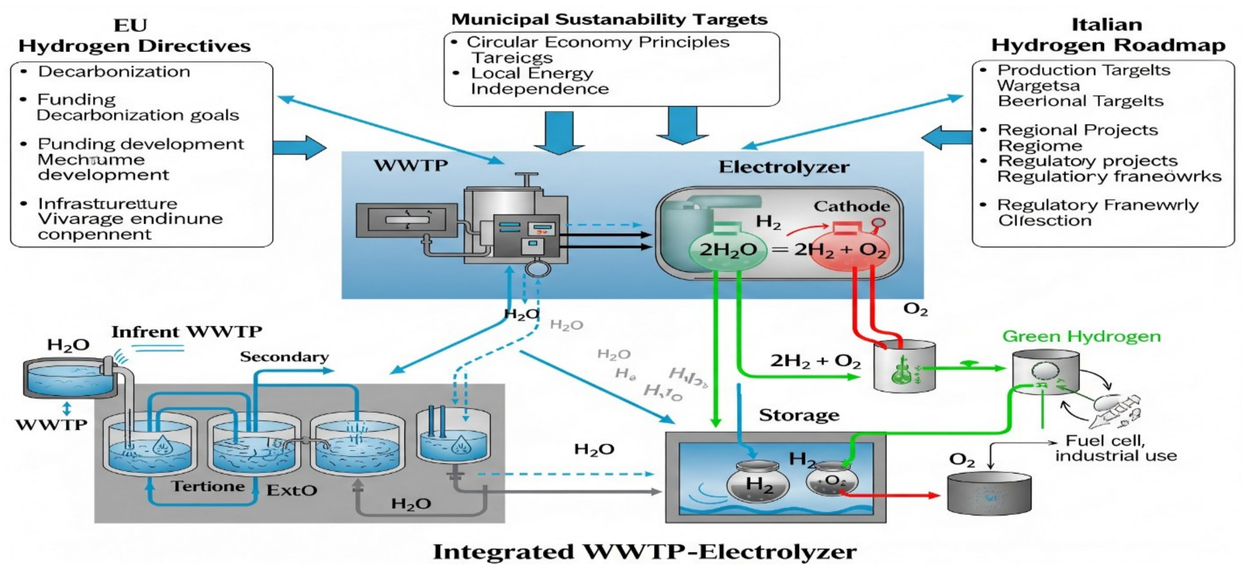

Figure 4.5—Triple Synergy Diagram

This Figure illustrates the integrated benefits of combining wastewater treatment plants (WWTP) with Electrolysers. clean water production, renewable hydrogen generation, and oxygen reuse. The scheme shows how EU Hydrogen Directives, the Italian Hydrogen Roadmap, and municipal sustainability targets converge to support this circular, cross-sectoral model.

Source: Author.

Chapter 5: Critical Discussion: Challenges, Gaps, and Future Opportunities

5.1 Introduction

The co-location of hydrogen production and wastewater infrastructure presents an attractive synergy of ecological imperative and progress in renewable energy technologies. Co-location allows synergy through multiple mechanisms: the wastewater can be viewed simultaneously as a problem waiting to be solved and as an opportunity of value, while the hydrogen—in particular, the clean hydrogen produced by electrolysis—is a clean energy carrier, an energy storage, and a chemical process feedstock. Nevertheless, even if the integrated approach has its merits, its practical application meets obstacles, which fall under the economic, engineering, policy, and operational areas.

The previous chapters of this thesis have outlined the main drivers for integration, examined the current technologies, and investigated the benefits related to lifecycle and environmental factors. However, the move from theoretical potential towards practical application reveals an array of important challenges. The challenges include the unstable economic conditions of hydrogen economies, the incompatibility between electricity supply dynamics and wastewater treatment needs, and the constraints on the alteration of municipal infrastructure to accommodate flexible and sophisticated control systems.

This chapter synthesizes and builds on past assessments by introducing up-to-date views based on recent techno-economic and predictive control simulations and, in particular, those set out in Rickey's thesis (2023) together with a related Australian economic review of co-production networks with hydrogen and wastewater. These references provide a much-needed quantitative backing for the wide variety of assumptions and predictions covered in previous chapters, while at the same time highlighting critical operational gaps—most notably related to cost modeling, real-time control, and uncertainties regarding policy.

According to the fundamental analysis in this paper, it outlines potential domains for further research and practical application. The following sections suggest that bridging the gap between theory and practice not only requires advanced technology but also advanced operational methods, responsive market environments, and a unified systems approach. The most important aspects to address include anticipatory decision-making process management, the interdependent relationship between energy and oxygen transfer dynamics, capital risk management, and the dynamic worldwide regulatory framework on carbon stewardship and hydrogen certification.

The integrated system of hydrogen and wastewater has emerged from the phase of feasibility evaluation and now goes through simulations, pilot plans, and global regulative frameworks. However, scalability potential depends upon the management of complex interdependencies operating in the space of engineering, economic, and governance areas. The chapter provides an encyclopedic evaluation of interdependencies, identifies existing knowledge gaps, and outlines future directions of prospective innovations.

5.2 Cross-Chapter Synthesis: Key Insights and Interlinkages

In earlier chapters, the emphasis had been on the technical viability, environmental advantages, and underlying economic appraisals of integrating hydrogen production with wastewater treatment. By comparison, this section explores the deep operational interlinkages that emerge when the two systems are considered a co-optimized, dynamically controlled infrastructure. These interlinkages are more than theoretical; they have substantive implications for energy efficiency, financial viability, and regulatory eligibility.

The study of these synergies, based on current academic scholarship and detailed system-level simulations, reveals two dominant themes:

1. That electrolysis efficiency and economic yield are not independent but strongly influenced by dynamic electricity pricing and wastewater oxygen demand.
2. Increasing the operational intelligence and storage innovation, particularly predictive control and oxygen inventory management, are key to delivering scalability.

The following analysis explores these themes along two interrelated dimensions.

5.2.1 Integrated Operational Frameworks

The integration of hydrogen production and wastewater treatment presents a unique chance for simultaneous improvement, mainly by means of the use of renewable power to perform dual outcomes: hydrogen generation and oxygen reuse. In this system, the electrolyser serves as an energy-consuming device while, at the same time, fostering biological treatment processes through the provision of high-purity oxygen to the activated sludge process (ASP). Therefore, this multi-functional role makes a key link: hydrogen production should be synchronized with the biogeochemical requirements of the wastewater treatment facility (WWTP).

Yet this synchronization is challenging in practice. Wastewater inflows and biological oxygen demand fluctuate throughout the day, whereas renewable electricity supply follows solar or wind profiles. Rickey's simulation study demonstrated that under static control conditions, this misalignment leads to either under-utilized electrolyser capacity or excess energy consumption at times when it's least economical.

In response to this problem, Rickey proposed four various Model Predictive Control (MPC) approaches intended to adaptively govern electrolysers' operation based on changes in electricity tariffs and ASP oxygen demands. The most effective approach—revenue-maximizing MPC—enabled a flexible toggling between hydrogen production and grid export. Based on tests run using

the Queensland pricing model for 2023/24, the approach achieved a revenue boost of 11% over static approaches, subject to the assumptions of 53 kWh/kg-H_2 and small solar curtailment.
This evidence requires a shift from rigid engineering design toward adaptive operational frameworks, in which optimization is continually responsive, data-driven, and sensitive to diverse inputs—beyond simple matters of technical efficiency.

5.2.2 Energy and Oxygen Linkages

Another critical insight is the bidirectional energy-oxygen coupling within the integrated system. Traditional WWTPs rely heavily on external aeration, which accounts for 30–60% of total plant energy use. Electrolysis, by contrast, inherently produces oxygen, presenting an opportunity to close this loop. However, without effective storage or load control, this oxygen may be wasted or mismatched to treatment requirements.
Rickey's design explored the oxygen buffering using compressed gas tanks, hence ensuring the storage of excess oxygen produced during high-intensity electrolysis for future use when biological demands increase. This design decouples the ASP from real-time electrolyser operation with the added advantage of an energy-shifting mechanism that reduces dependency on peak electricity prices.
The economic assessment paper extends this benefit further by estimating that the reuse of electrolytic oxygen has the potential to reduce operating energy costs by up to 25% in some configurations. However, the two studies identify that this benefit is conditional on infrastructure investment, especially when it comes to compression, storage, and pressure control system costs able to meet ASP flow rate requirements without significant capital cost (CAPEX).
The interaction between energy and oxygen has both beneficial and detrimental properties. The proper use of this potential depends on the effectiveness of adaptive and informational approaches used in electrolysers and the economic viability of storage technologies. Without these elements, the system loses one of its most valuable benefits related to integration.

5.3 Strategic Observations and Lessons Learned

Despite the synergies created between hydrogen production and wastewater treatment, the shift from a theoretical to an operational reality reveals a complex set of strategic complexities. The problems reach beyond simple technical challenges; they highlight systemic misalignments regarding infrastructure capabilities, market frameworks, and regulatory design. The following section synthesizes key lessons learned resulting from simulations, feasibility studies, and techno-economic comparisons.
This research examines two main strategic dimensions:
1. The real-world deployment barriers in retrofitting or designing iH_2WWTPs (integrated hydrogen–wastewater treatment plants)
2. The financial and planning risks involved in expanding the systems beyond their initial pilot phase.

5.3.1 Real-World Deployment Constraints

One of the most pressing challenges identified in both Rickey's thesis and the economic assessment report is the mismatch between idealized simulation models and practical municipal realities. While dynamic control strategies like MPC show theoretical promise, implementing them in actual WWTPs involves several constraints:

• Lack of Sensing Infrastructure: Most municipal WWTPs are equipped with legacy SCADA systems, which are insufficient for the high-frequency, multi-variable monitoring required by predictive control algorithms. Rickey emphasizes that revenue-maximizing MPC requires real-time data on solar irradiance, grid pricing, ASP oxygen demand, and hydrogen storage levels — variables that are often unavailable or inconsistently reported.

• Electrolyser Modulation Limitations: Although PEM electrolysers offer better dynamic range than alkaline systems, most commercial units still require 5–15 minutes to ramp up or down. This undermines the temporal flexibility that control schemes rely on. Moreover, frequent cycling affects stack longevity and can increase maintenance costs, a factor not always captured in simulation models.

• Oxygen Storage System gaps: While Rickey's suggestion for the use of compressed oxygen storage offers a solution for decoupling treatment needs from electrolyser operation, real-world applications must take into consideration space constraints, safety regulations (stemming from the use of pressurized oxygen), and high upfront capital costs. The Economic assessment shows that the deployment of modular oxygen storage and delivery infrastructure costs between US$200 and US$450 per kg-O_2 of daily capacity depending on the size and redundancy requirements.

• Electrical Interconnection barriers: In some areas, like some parts of the United States and Australia, the structures of regulation deter production of hydrogen behind the meter by imposing grid service fees or failure to appreciate dual-use opportunities, like oxygen reuse. Such regulatory inertia could negate the economic advantages predicted in modeling.

The challenges reflect development's main constraint as not being the technology itself, but the so-called integration readiness, meaning the synchronization of physical transformation, market signals, and policy convergence.

5.3.2 Investment Planning and Scalability

From an investment perspective, the integrated system presents both opportunity and risk. Rickey's analysis demonstrates that a net revenue benefit from MPC schemes is achieved only when hydrogen is sold at or above A$5.74/kg, assuming a 53 kWh/kg-H_2 efficiency. At commodity prices below this level, export to the grid becomes an attractive option, particularly under peak electricity pricing conditions. The economic projection of iH_2WWTPs is therefore strongly influenced by volatility in the hydrogen market, presenting a problem for long-term capital planning.

The Economic Assessment study adds another layer: while Levelized Cost of Hydrogen (LCOH) is projected at US$5.90–9.40/kg for small to mid-scale systems, this is contingent on factors including:

• Availability of low-cost renewable electricity < US$0.04/kWh
• CAPEX amortization periods should be at least 15 years.
• Regulatory credit for oxygen reuse or energy offsets.

In addition, both sources report that non-linear scaling penalties occur at both ends of the system. Small plants (less than 5 MLD wastewater capacity) have higher per-unit capital costs, while large plants (over 100 MLD) have increased control complexities and diminishing marginal return on oxygen reuse.

In addition, the policy incentives play a decisive role. Rickey's doctoral thesis aligns with the United States Inflation Reduction Act together with Australia's National Hydrogen Strategy in highlighting the role of carbon subsidy or Renewable Energy Certificates (RECs) in defining viability. However, the subsidy structure design needs to consider integrated systems, since most existing schemes focus on stand-alone hydrogen production instead of those linked to wastewater. Ultimately, scalability is contingent on financial predictability, infrastructure interoperability, and flexible regulation. Without simultaneous advancements across all three domains, the iH_2WWTP model risks remaining a niche innovation rather than a widespread solution.

5.4 Emerging Research and Technology Frontiers

As the integrated hydrogen–wastewater system goes from conceptual schemes to real-world implementations, a new wave of scholarly investigation propels its development technologically. In this section, promising frontiers push beyond enhancement of existing systems. These advances seek to fundamentally restructure of hydrogen generation, wastewater, and renewable energy in urban infrastructural level.

The following four critical areas are defined, characterizing areas wherein existing shortcomings may be mitigated by advances in scientific knowledge, technological advancements, and adjustments in policy.

5.4.1 Predictive and Hybrid Control Architectures

The deployment of Model Predictive Control (MPC) has shown strong potential for synchronizing electrolyser operations with electricity market prices and wastewater oxygen demand. However, Rickey’s work indicates that first-generation MPC schemes are limited by rule-based constraints, lack of real-time adaptability, and single-objective optimization (e.g., revenue maximization vs. treatment efficiency).

To overcome this challenge, researchers have explored hybrid control frameworks that combine Model Predictive Control (MPC) with reinforcement learning, neural networks, and adaptive feedback loops. These systems have the ability to learn from past operational cycles and to predict non-linear load patterns, solar irradiance fluctuations, and policy changes, like carbon intensity mandates. For instance, an “inventory-aware” MPC formulated to maximize the equilibrium of oxygen buffer stockpiles, hydrogen contract commitments, and grid dynamics can achieve operational gains of 15% up to 20% compared to single-objective models (Rickey, 2023).

The challenge remains in validating such algorithms under uncertain wastewater conditions (e.g., storm events, industrial discharge variability) — an area where current models often underperform.

5.4.2 Modular Electrolyser and ASP Integration

One innovation frontier is physical and functional modularization of electrolysis and ASP system. Plant configurations traditionally treat them as separate blocks with pre-defined interconnections. However, the use of modular integration—especially through containerized electrolyser units positioned close to aeration zones—can have the following potential:

- Reduce oxygen delivery losses
- Enable unit-level control granularity
- Simplify maintenance and upgrade cycles
- Lower interconnection CAPEX

Rickey proposes installing PEM stacks with onboard O_2 compression directly above aeration basins. This design minimizes the requirement for long piping and reduces pressure losses, while also facilitating easy system scalability. Pilot studies ongoing in Japan and Denmark are evaluating such layouts; however, operational data are still limited.

The modular approach could also support temporary or mobile deployments in remote or seasonal WWTPs, potentially enabling distributed hydrogen networks anchored on water-energy-waste nexus sites.

5.4.3 Carbon-Integrated Operational Planning

Both Rickey's report and the Economic Assessment stress for future control strategies to integrate carbon accounting directly into control schemes. This reflects a broader trend: the creation of hydrogen markets tied to carbon intensity, under which pricing and regulatory eligibility depend on real-time tracking of lifecycle emissions.

Emerging control algorithms are able to integrate carbon as a third optimization axis, together with cost and treatment efficacy. For example, an smart controller might temporarily curtail electrolysis during high electrical grid demand periods when the carbon intensity goes above pre-established limits, despite the ongoing economic viability of the hydrogen production. The strategy leads to qualification for green hydrogen certification or carbon-based credits under schemes like the EU Hydrogen Bank or the US 45V tax credit.

Technologically, this requires real-time access to carbon intensity grid signals, which is an area still in the development stage of several countries. It also involves the integration blockchain-based carbon registries for verification, thus adding complexity while, at the same time, enabling decentralized tracking options.

5.4.4 Integrated Finance–Technology Modeling

Final research frontier lies at the intersection of techno-economic modeling, financial risk analysis, and policy scenario planning. As Rickey points out, most of the current investment models assume fixed hydrogen costs and fixed capital amortization, neither accounting for the volatility embedded in market conditions.

New research tools are now integrating:

• Dynamic hydrogen pricing scenarios
• Sensitivity analyses on CAPEX components.
• Stochastic electricity pricing models
• Carbon credit volatility modeling

These tools allow stakeholders to evaluate realistic risk-return profiles over time, under diverse market, regulatory, and climate conditions. For investors, this implies the switch from traditional Net Present Value (NPV) valuation to real-option valuation, in which strategic flexibility is valued along with technical effectiveness.

These models provide decision-makers with information that allows them to adjust incentives and penalties so as to encourage real adoption while minimizing financial risk.

5.5 Policy, Institutional, and Market Perspectives

Even the most technically advanced iH_2WWTPs configurations are not possible without policy frameworks, institutional roles, and market conditions sharing a consonance. The section discusses the needed transformation of the system of regulations, the governance structures, and energy markets to accommodate integrated hydrogen-wastewater infrastructures. Without deliberate action in these spheres, the techno-potential presented in the sections above might not become a reality on a significant scale.

5.5.1 Regulatory Design for Integrated Systems

Regulatory regimes today almost exclusively define wastewater treatment and the production of hydrogen as distinct areas, each governed by distinct environmental permits, health and safety measures, and grid interconnection rules. Such siloed approach hinders the development of integrated infrastructure.

Rickey highlights that existing WWTP licenses rarely account for co-produced hydrogen or oxygen repurposing. Similarly, most jurisdictions lack permit pathways for dual-purpose electrolysers, leading to delays and compliance uncertainty. For instance, compressed oxygen from electrolysis may require a different storage classification than process-generated O_2 — despite being chemically identical.

To unlock integration, regulatory bodies must:

• Create comprehensive environmental permits recognizing hydrogen and oxygen as potential byproducts.
• Harmonize safety regulations for gas storage and pipeline-grade hydrogen
• Enable co-location credits under renewable energy support schemes

The Australian Clean Energy Regulator has progressed by making suggestions towards "integrated generation-use" systems but its application remains limited. Standardization and de-risking investment could be promoted through the introduction of a globally recognized framework such as a "Green Infrastructure Code" for nexus systems.

5.5.2 Institutional Alignment and Operational Governance

WWTPs are often managed by local governments or utilities, while hydrogen projects typically involve private-sector investors or national energy agencies. This creates a governance mismatch: one side prioritizes public health and compliance, the other market competitiveness and innovation.

The Economic Assessment report stresses the importance of establishing Joint Infrastructure Entities (JIEs), semi-autonomous entities with multiple stakeholders, tasked with the responsibility of managing integrated planning, sharing capital expenditures collectively, and managing real-time information. These entities can reduce friction between municipal mandates and commercial performance objectives.

case study from California and Denmark show that institutional integration raises project approval rates up to 30% while at the same time promoting better access to municipal funds and the financial capital of green infrastructure banks.

Another model is the Design–Build–Own–Operate (DBOO) scheme, where a third-party develops the hydrogen overlay while leasing space and utility interconnections from the WWTP. However, this requires strong contractual clarity, especially on risk-sharing for downtime, energy pricing, and compliance violations.

5.5.3 Energy Market Interfaces and Grid Dynamics

Hydrogen production from electrolysis is highly electricity-intensive. Its economic feasibility depends on access to low-cost, low-carbon electricity, which is governed by grid market structures. Rickey's thesis notes several friction points:

• Feed-in tariffs for renewable electricity may disincentivize self-use (i.e., using electricity for hydrogen instead of exporting it)

Time-of-use (TOU) pricing model typically do not reward load flexibility because of the lack of a demand response mechanism.

• Grid connection codes may penalize variable loads, such as electrolysers reacting to price changes every 15 minutes

To remedy these issues, some jurisdictions are testing "hydrogen-ready" grid participation schemes, where large-scale electrolysers can register as dispatchable flexible loads and become qualified for market revenue in addition to revenue from the sale of hydrogen.

Additionally, energy regulatory agencies should consider the evaluation of dual-certification schemes, where hydrogen producers can earn credits not just for using renewable electricity, but likewise for offering grid support services such as voltage regulation and peak load management. These reforms require significant cooperation between:

• Energy Market Operators
• Environmental Agencies
• Water Infrastructure Authorities
• Hydrogen Certification Organizations

Without harmonized market access regulations, interconnected systems will remain financially exposed, despite advances in technological preparedness.

5.5.4 Market Formation and Hydrogen Pricing Instruments

Hydrogen remains a nascent market with non-transparent pricing, fragmented demand pools, and unstable offtake agreements. This makes long-term planning for iH_2WWTPs difficult.

The Economic assessment report outlines two critical gaps:

1. Lack of standardized pricing indices: Unlike natural gas or electricity, hydrogen is not traded on regulated markets exchanges. As such, this leads to bilateral contracts with wide price variations (US$3–12/kg) depending on location and purity.
2. Insufficient demand aggregation: Most WWTPs produce hydrogen at small scales. Without pooled offtake agreements or regional hydrogen hubs, such volumes cannot compete with centralized producers.

Policy solutions include:

• development of Hydrogen Price Indices (HPIs) at national and regional levels.
• Creation of Municipal Hydrogen Alliances, allowing WWTPs to form consortiums for joint offtake and storage investments
• Long-term Contracts for Difference (CfDs), which guarantee minimum hydrogen sale prices to cover risks of capital investments.

The EU and Japan are presently assessing these instruments. Through the achievement of price stability and demand stimulation, such instruments have the capability to support the installation of iH_2WWTPs in different cities.

5.6 Future Research Directions and Conclusion

The integration of hydrogen production inside wastewater treatment plants holds immense potential; yet it stands today at the development crossroads. Current models of techno-economic analysis, regulative systems, and institutional frameworks, although suggestive of possibilities, need to be improved for their efficient operation on a large scale in real-world contexts. The section outlines the main research gaps, emerging cross-sector challenges, and the necessary initial steps to move from pilot projects to prototype infrastructure designs.

5.6.1 Pilot Deployments and Real-World Validation

Theoretical models and lab-scale simulations dominate the current research landscape. However, without field-tested pilot plants, assumptions about efficiency, reliability, and control flexibility remain speculative. Rickey's study emphasizes that uncertainties in wastewater flow, seasonal variability in electricity supply, and operational downtime are underrepresented in models.

Immediate research priorities include:

• Deployment of multi-year pilot plants across diverse geographies and climates.

• Real-time tracking of oxygen demand fluctuations and electrolyser response lags

• Assessment of equipment degradation rates under dynamic control schemes.

• Performance of control models under emergency events (e.g., grid outages, toxic wastewater inflows)

These pilots should be embedded within standard municipal WWTPs and operated with live market interfaces to stress-test real-world performance.

5.6.2 Lifecycle Assessment and Integrated Sustainability Metrics

Even though carbon emissions are usually tracked, an overarching sustainability profile requires a more comprehensive metrics, including:

• Water–energy–carbon nexus models

• Lifecycle energy return on investment (EROI)

• land use efficiency

• Toxicological risk from material degradation (e.g., membrane chemicals)

Rickey's work offers preliminary frameworks for this subject area, particularly concerning the impact of oxygen storage on lifecycle emissions. Future research should integrate such analyses with:

• Supply chain sustainability (e.g., rare earths in PEM stacks)

• End-of-life recycling of electrolyser components

• Comparison across electrolyser types (PEM, AEM, SOEC) in WWTP conditions

An integrated approach of this sort will enable the realization of true net-positive sustainability outcomes for the system, rather than results limited in scope.

5.6.3 Data Governance and Cyber-Physical Integration

As the complexity in control structures expands and becomes dependent on real-time market and environmental information, the importance of data governance grows. The issues include:

• Ensuring cybersecurity for grid-connected, AI-driven systems

• Verifying the transparency and auditability of carbon credits and subsidies data.

• Determining the ownership of operational data streams by multiple stakeholders.

Rickey believes that digital twins could be a possible solution to system diagnostics and predictive maintenance but would require the establishment of standardized data interfaces and a cloud-resilient infrastructure.

Future research should address:

Development of open-source digital twin models for wastewater treatment plant-electrolyser systems.

• Creation of sector-wide data protocols for integrated hydrogen infrastructure

• Legal frameworks for data-sharing across utilities and private operators

5.6.4 Strategic Policy Foresight and Adaptive Governance

The development in technology is outpacing the evolution of policy structures. Current regulatory systems have a fragmented and reactive nature. Future research should enable the development of adaptive governance systems that grow simultaneously with technological advancement.
This includes:

• Future modeling for different regulatory cases (e.g., higher carbon tax, hydrogen export obligation)

• Scenario planning for geopolitical risks within renewable supply chains

• Co-creation of dynamic permitting frameworks that adjust with operational feedback

Moreover, Rickey calls for the creation of a new field called "Hydrogovernance Nexus Research" that combines political science, law, economics, and engineering to address the institutional inertia slowing down adoption.

5.6.5 **Lessons Learned and Key Insights**

Based on an extensive literature review and analysis of integrated hydrogen-wastewater treatment systems, the research has made the following key discoveries:

Technical: The PEM electrolysis system with highly efficient oxygen transfer techniques (Speece cone) is technically possible to use for municipal WWTP. The oxygen output (about 8 kg O_2 per 1 kg H_2) would cover 50% of the WWTP's aeration needs, thus leading to energy savings from 30 to 45% (Donald & Love, 2023).

Economic: Economic feasibility of hydrogen production will be achieved if electricity prices do not exceed €0.06/kWh. Given the current price levels of electricity in Europe (€0.10-0.15/kWh), the LCOH value varies from €3.5 to 6.5/kg H_2, which requires policy incentives or carbon pricing to be competitive with grey hydrogen production (€1.2-2.0/kg H_2) (Acar & Dincer, 2019; IEA, 2022).

Environmental: Integrated systems have the GHG emissions rate of 1.5-2.5 kg CO_2-eq per kg H_2, which is much lower than grey hydrogen emissions (9-12 kg CO_2-eq per kg H_2). It is expected that annual emissions reductions will be 390-872 t per year for a 26,000 EP WWTP until 2034 (Donald et al., 2023).

Policy: A considerable policy support can be found in the EU Hydrogen Strategy, Repower EU and the Italian Hydrogen Roadmap. Key enabling conditions are carbon pricing, hydrogen purchase agreement and investment subsidies to help install electrolysers at WWTP facilities.

5.7 Conclusion

The integration of hydrogen electrolysis technology into current water treatment systems is technically feasible, environmentally friendly, and increasingly economically sound; however, its realization depends on certain conditions. These conditions include coordination between advanced control technologies, conducive regulatory environments, market development efforts, and innovations in different fields.

The chapter has recognized key knowledge deficits and strategic opportunities that will shape the future evolution of iH_2WWTP systems. Through the use of appropriate treatment approaches, these systems can surpass incremental technological development and become integral facets of sustainable urban life by linking water, energy, and climate goals in one unified platform.

Chapter 6 – Conclusions and Outlook

6.1 Summary of Findings

The dissertation explored the integration of hydrogen production by electrolysis in wastewater treatment plants (WWTPs), envisioning it as a new pathway to achieve cross-sector sustainability, increase energy efficiency, and facilitate circular reuse of resources. Taking a multi-disciplinary approach, the research integrated current literature on electrolyser technology, wastewater process engineering, environmental impacts, and the control system design.

The integration opportunities have been outlined in earlier sections as a strategy to tackle simultaneous global issues: decarbonization of energy systems and improving city infrastructure. Wastewater treatment, historically defined as a passive and energy-intensive activity, is increasingly being reinterpreted as an active field centered on resource recovery. At the same time, hydrogen production, in particular green hydrogen, has emerged as a linchpin of clean energy strategies.

Primary synergies include:

• Oxygen valorization: Electrolyser-generated oxygen can reduce aeration energy costs in the activated sludge process.

• Energy balancing: Hydrogen acts as a carrier and energy stabilizer, enabling the balancing of differences between electricity supply and demand.

• Carbon footprint reduction: Integrated systems lower the indirect emissions associated with grid electricity and fossil-fuel-based operations.

Technologically, the integration requires precise coordination of flows, loads, and storage. Chapters 2-4 gave a general overview of various operation methodologies, related environmental benefits, and preliminary economic analyses. However, issues related to static control models, data transparency, and lifecycle assessment frameworks were consistently raised.
Chapter 5, supported by modern analysis by Rickey (2023) and the economic evaluation report, highlighted the need for advanced control systems—largely Model Predictive Control (MPC)—to optimize the efficiency of the use of electricity, the price of hydrogen, and recycling of oxygen in real-time situations. In addition, it was shown that volatility of hydrogen markets and the uncertainty of regulations are key drivers impacting feasibility.

6.2 Key Conclusions

1. Technical feasibility of the integration has been confirmed and validated conceptually by a series of simulations and case study. However, issues of capital investment, long-term reliability, and cross-system compatibility still remain.
2. Smart Control and Data Infrastructure Are Essential Real-time control systems like MPC significantly increase operational profitability (up to 11% in Rickey's model) but require advanced sensing, cloud integration, and market-linked control logic—currently rare in WWTPs.
3. Oxygen storage functions as a strategic enabler, for compressed oxygen storage provides increased system flexibilities and enables shifting of energy load. Though it has not yet become ubiquitous, it forms a viable battery replacement in this context.
4. Hydrogen Economics Are Unstable but Improving While price volatility limits predictability, policy incentives and demand growth may soon stabilize hydrogen markets. Integrated systems will be best positioned if they can adaptively switch between electricity export and hydrogen production.
5. Lifecycle Impacts and Governance Must Be Deepened Full sustainability cannot be guaranteed without robust lifecycle assessments and standardized digital twins. Future governance models must evolve to include hydrogen-wastewater systems in carbon credit and infrastructure policy.

6.3 Recommendations

For Research Institutions
• Launch pilot projects to collect real-world operational data
• Increase simulations to reflect seasonal variations, deterioration of equipment, and conditions of emergencies.
• Develop open-source digital twin platforms for control testing purposes.
For Policymakers
• Create hydrogen pricing indices and contract transparency frameworks
• Include integrated systems in subsidy eligibility for carbon reduction
• Develop adaptive permitting pathways for flexible WWTP configurations
For Industry Stakeholders
• Invest in MPC-based control retrofits

• Explore oxygen storage hardware to complement electrolyser designs

Use prevailing market conditions to make decisions about hydrogen compared to electricity.

6.4 Outlook

This thesis presents a blueprint for a future in which wastewater treatment plants become energy hubs, not just waste processors. Integrating green hydrogen production elevates the WWTP from a single-purpose utility to a multipurpose sustainability asset. Although operational, economic, and regulatory complexities persist, the pathway is becoming clearer—and the potential is too significant to ignore.

Extended interdisciplinary collaboration between the disciplines of engineering, economics, and public policy is essential. If carefully executed, integrated hydrogen–wastewater systems could play a critical role to meeting international aspirations concerning decarbonization, water recycling, and sustainable energy.

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