TOBE

OPTIMIZING HYDROGEN PRODUCTION:

A COMPREHENSIVE EFFICIENCY TESTING FRAMEWORK

TECHNICAL REPORT

DISCOVER HOW TOBE ENERGY IS REDEFINING HYDROGEN PRODUCTION THROUGH RIGOROUS EFFICIENCY TESTING AND CUTTING-EDGE INSTRUMENTATION.

This document provides a detailed analysis of Tobe Energy's methodology for measuring and enhancing the efficiency of its novel hydrogen production system. Through advanced instrumentation, real-time data acquisition, and robust validation techniques, we ensure precision, transparency, and repeatability in efficiency calculations. By showcasing our results and scaling plans, this report highlights Tobe Energy's commitment to delivering economically viable and environmentally sustainable hydrogen solutions.

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Optimizing Hydrogen Production: A Comprehensive Efficiency Testing Framework

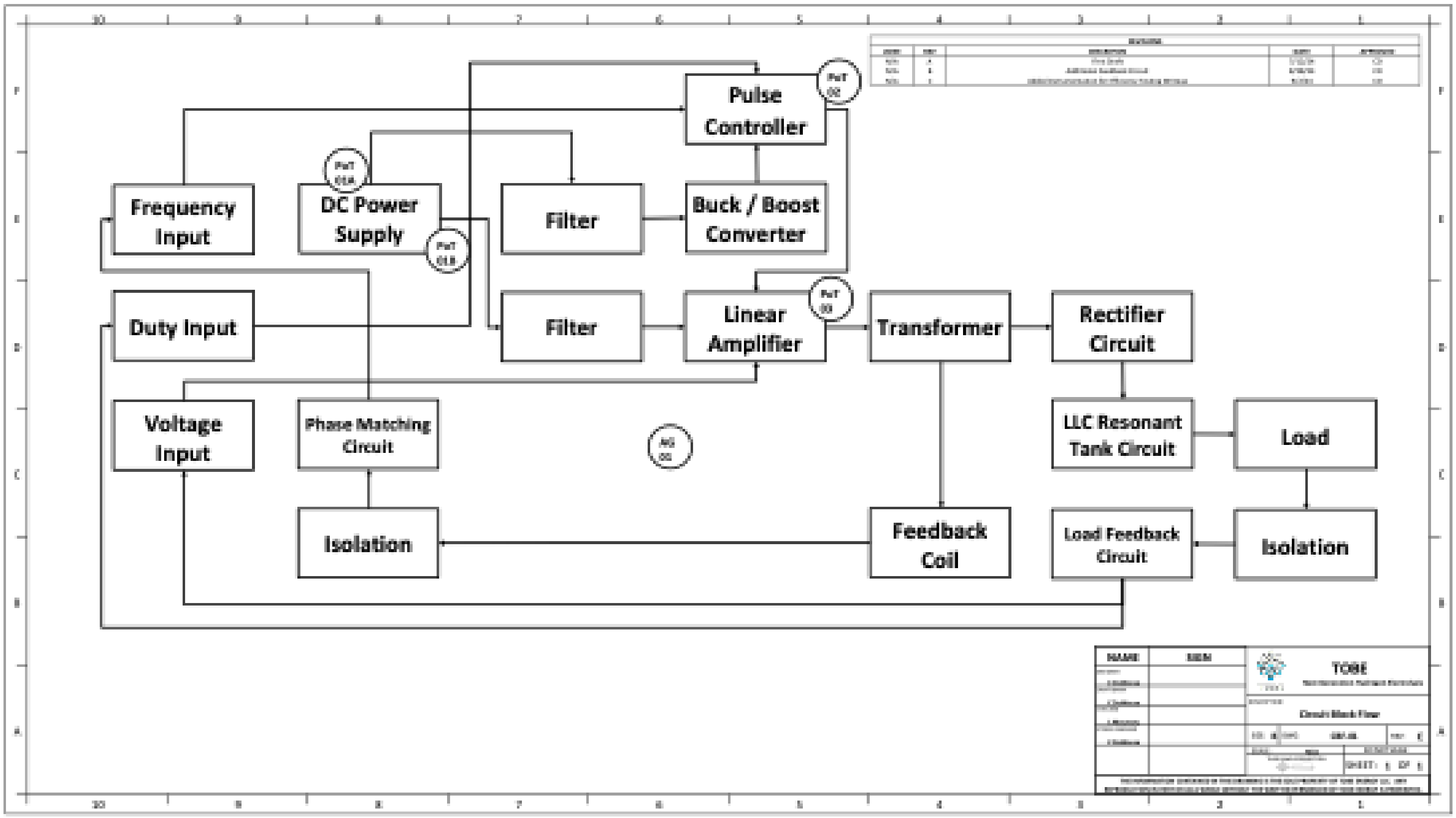
In the evolving landscape of renewable energy, hydrogen production plays a pivotal role in providing a clean, sustainable alternative to fossil fuels. The efficiency of hydrogen production systems is critical, as it directly impacts both the economic viability and environmental sustainability of hydrogen as a fuel source. At Tobe Energy, we have developed a novel electrolysis-based hydrogen production system designed to maximize efficiency by reducing energy losses, improving operational reliability, and minimizing waste.

This paper outlines the methodology used to measure the efficiency of our hydrogen production system, detailing the instrumentation and calculations employed, and reviews results of some of our efficiency testing. By carefully selecting and integrating sensors, we have developed a comprehensive testing framework that accurately captures the key parameters affecting system performance. This approach ensures that the data collected is not only precise but also easily replicable, allowing for consistent monitoring and improvement over time.

The goal of this white paper is to provide a clear, step-by-step guide on how our system's efficiency is calculated, from measuring power input to quantifying hydrogen output. Each piece of instrumentation used, along with its unique tag number, will be detailed in the following sections, along with how the collected data feeds into the overall efficiency calculation. This methodology is designed to ensure transparency and repeatability, making it a valuable tool for internal testing, external validation, and future system optimization.

By laying out this process, we aim to showcase the rigorous testing and validation procedures that underpin the performance of our hydrogen production system. As efficiency remains one of the most important metrics in evaluating any energy system, our methodology reflects our commitment to developing a solution that is both economically viable and environmentally responsible.

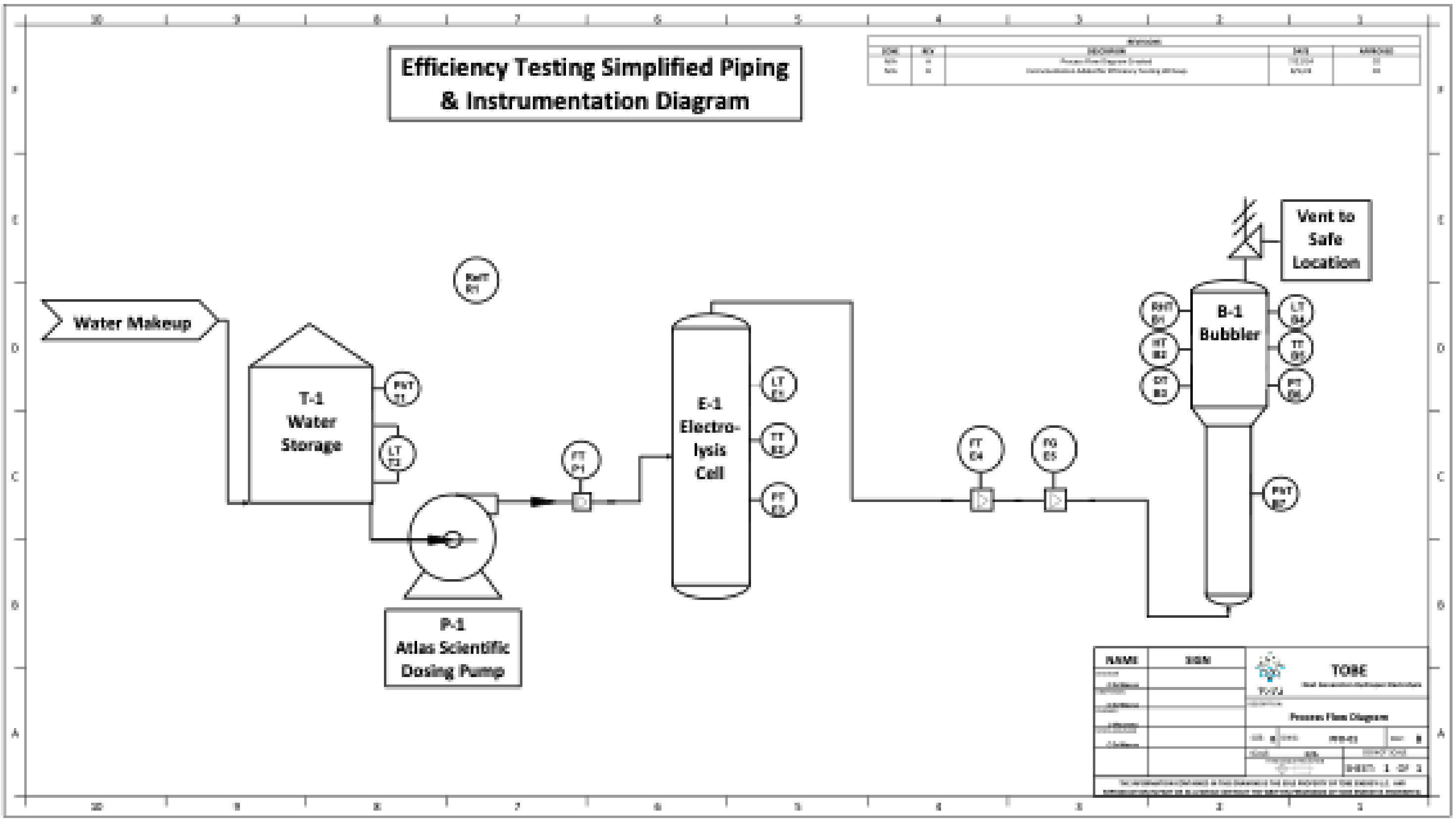
Circuit Block Flow Diagram Overview



The Circuit Block Flow Diagram provides a high-level representation of the electrical components in the hydrogen production system. This diagram outlines the flow of electrical power through the system, starting from the power supply and flowing through various sensors and circuits before reaching the electrolysis unit. Key elements such as power sensors (PoT-01A/B, PoT-02, PoT-03) and current clamps (AG-01) are annotated, allowing for real-time monitoring of power consumption and input levels.

Additionally, the diagram showcases the integration of the signal processing and amplification units, ensuring that electrical power is optimized for efficient hydrogen production. The layout of the circuit is designed to provide precise feedback on voltage, current, and power at each critical stage, enabling accurate calculations of the total energy input into the system. By incorporating both real-time monitoring and secondary validation points, the Circuit Block Flow Diagram ensures transparency in the measurement of power consumption.

Simplified Piping & Instrumentation Diagram



The Piping & Instrumentation Diagram (P&ID) outlines the physical and chemical processes involved in the hydrogen production system. It provides a detailed look at the flow of fluids, gases, and electrolytes throughout the system, from the water supply tank to the electrolysis cell and the gas storage units. Critical instrumentation, such as flow transmitters (FT-E4, FT-P1), pressure sensors (PT-E3, PT-B6), and level sensors (LT-T2, LT-E1, LT-B4), are strategically placed to ensure continuous monitoring of the system’s operational conditions.

The diagram also illustrates the flow of oxygen and hydrogen gases through the system, highlighting key components like the bubbler, where the oxygen concentration is measured (OT-B3), and the hydrogen sensor (HT-B2), which ensures safe operation and efficient gas separation. Each measurement point is designed to feed real-time data into the control system, enabling the precise tracking of gas production and water consumption. The Process Flow Diagram ensures that the overall system remains balanced and that gas production rates can be optimized for maximum efficiency.

Introduction to Efficiency Calculation

The efficiency of our hydrogen production system is determined by comparing the total energy input to the system with the energy content of the hydrogen produced. Accurately measuring these values requires a comprehensive instrumentation setup, ensuring that every relevant parameter—from electrical power to gas flow and composition—is captured in real-time. By leveraging a combination of sensors and validation instruments, we are able to achieve precise control over the data collection process, allowing for reliable and reproducible efficiency calculations.

The key components contributing to the calculation include:

1. Total Power Input
2. Gas Production Measurement
3. Gas Production & Composition Validation

When demonstrating calculations throughout this paper, the tag numbers of each instrument will be referenced as variables. This approach streamlines the calculations, making it easier to trace how each measurement is integrated into the efficiency formula, while maintaining consistency with the system's instrumentation and diagrams.

The calculations outlined in the following sections detail how each of these measurements is used to compute the overall efficiency of the system. Our approach accounts for both electrical and gas-related variables, allowing us to present a complete picture of the system's energy conversion effectiveness.

Total Power Input

Measured using high-precision power sensors, the total electrical energy supplied to the electrolysis system is carefully monitored. We also use secondary verification tools, such as current clamps and analog meters, to validate these readings.

Put very simply, the total power input to the system is as follows:

$$P_{total} = PoT_{01A} + PoT_{01B}$$

To calculate the switching losses, it is very simply:

$$P_{switching} = P_{total} - PoT_{02} - PoT_{03}$$

Both values are in watts.

Gas Production Measurement

The volumetric flow rate of the gas produced, primarily hydrogen, is tracked through flow sensors, and corrections are made for relative humidity and water vapor content. By accounting for these factors, we ensure the measured gas volumes accurately reflect the dry gas output of hydrogen and oxygen.

Flow Rate Measurement

The volumetric flow rate of the gas produced, primarily hydrogen, is tracked through flow sensors, and corrections are made for relative humidity and water vapor content. By accounting for these factors, we ensure the measured gas volumes accurately reflect the dry gas output of hydrogen and oxygen.

Relative Humidity Correction

Given that the gas exiting the electrolysis cell is typically somewhat saturated with water vapor, we must correct the measured gas flow for relative humidity. We use a temperature corrected humidity sensor, RHT-B1, positioned in the bubbler, provides real-time data on the relative humidity of the gas. This allows us to determine the fraction of the gas flow that is water vapor, which is subtracted from the total flow to yield the dry gas flow rate.

To mitigate the possibility of air present in the bubbler prior to system testing, it is important to note that we do start the bubbler water full and manually drain to reduce the level once gas production has begun.

In the following formulas, the variable P represents pressure, unlike P representing power in the previous formulas. First, we have the partial pressure of water vapor.

$$P_{H2O} = RH \times P_{SAT}$$

Where,
PH20 is the partial pressure of the water vapor
RH (RHT-B1) is the measure of the relative humidity (values of 0.0-1.0) measured by the sensor.
PSAT is the saturation vapor pressure of water at the gas temperature (from a reference table or more preferably a reference table built into an excel macro).

After we have obtained the partial pressure of the water vapor. We are able to correct the volumetric gas flow measurement.

$$Q_{DRY} = Q_{MEASURED} \times \frac{P_{TOTAL} - P_{H2O}}{P_{TOTAL}}$$

Where,
QMEASURED (FT-E4) the volumetric flow measurement
PTOTAL (PT-E3) is the pressure of the gas produced in the electrolysis cell
PH2O was calculated above

Finally, the QDRY value, according the stoichiometric ratio, is hydrogen by volume.
So, the volumetric quantity of hydrogen gas produced, corrected for relative humidity is:

$$Q_{H2} = \frac{2}{3} \times Q_{DRY}$$

In liters per minute of hydrogen produced.

Gas Production & Composition Validation

While the above calculations are straightforward and easily verifiable through literature, and the sensors are robust with analog gauges and meters to double-check and verify, we have implemented several additional layers of validation.

For gas composition, we utilize an oxygen sensor (OT-B3) capable of measuring the oxygen concentration in the bubbler with an accuracy of less than 1%, across a range of 0-100%. Additionally, we measure hydrogen concentration up to 10,000 ppm using a dedicated hydrogen sensor (HT-B2). To accurately track the buildup of hydrogen in the system, we begin with air in the bubbler and monitor hydrogen levels as they rise to 10,000 ppm. When this sensor is not used to verify hydrogen concentration in startup up systems, we utilize this sensor to provide a method of leak detection

Furthermore, by tracking the flow rate of water through the dosing pump and monitoring water levels in each of the vessels—ranging from the water tank to the electrolysis cell and the bubbler—we maintain a precise mass balance of the system. Temperature and pressure measurements in both the electrolysis cell and the bubbler are also factored into these calculations, ensuring that all "lost" mass matches the volume of gas produced.

Finally, we track the pH of the system, which is particularly important for efficiency tests where we simulate "sea brine." This is used as an additional verification check against an analog TDS meter, providing another layer of accuracy in our efficiency testing.

Published Results from SBIR Grant Testing

Our efficiency testing has been validated through a series of experiments conducted as part of our SBIR grant. These tests were carried out using both low and high TDS water, following the exact methodology outlined in this paper, with one notable exception: the total power input was measured using a wall outlet plug power meter, positioned between the 120VAC power source and our Siglent DC Power Supply.

The reported efficiency values inherently include the losses from the DC power supply, which is designed more for versatility than for efficiency. The Siglent power supply used in our tests operates with an efficiency of approximately 79.1% to 79.8%, as detailed in the manufacturer's efficiency report here. To account for this, when excluding the losses of the laboratory power supply, we add the average observed efficiency difference (20.2% to 20.9%) to the reported values, resulting in adjusted system efficiencies ranging from 89.6% to 92.8% on LHV.

Scaling of Hydrogen Production

Notably, our testing covered two system configurations:

- **1kW Unit: Designed specifically for high TDS contaminant testing.**
- **2.5kW Flagship Prototype: Capable of producing more than 5kg+ H2 / Day**

For the 2.5kW low TDS testing, the hydrogen mass produced, standardized over 24 hours of continuous operation at full capacity, amounted to 7.7kg. This demonstrates that as the size and power applied increase, our hydrogen production scales linearly with the power input and the anode+cathode surface area. Preliminary data indicate confidence in scaling this process to 25kg/day of hydrogen production with no significant loss of efficiency. Furthermore, we believe that the system can be scaled beyond this, given sufficient time and resources for further testing.

Summary of Testing	Total Power Input (Watts)	Test Duration (hours)	Avg. Volumetric Flow Measurement (LPM)	Calc Total Mass Produced during Test	Daily Production Rate (kg/day)	Calc. Eff. (%) LHV
1kW Low TDS	6,012	6	9.8	0.783	3.133	72.37%
1kW High TDS	6,143	6	9.7	0.775	3.100	70.11%
2.5kW Low TDS	14,972	6	24.3	1.942	7.768	72.06%
2.5kW High TDS	5,032	2	23.5	0.626	7.512	69.12%

Future Results and Battery-Powered Operation

In addition to the data published here, we have explored powering the flagship prototype using more efficient AC/DC conversion methods, batteries, and solar arrays. While the detailed data for these tests have not yet been released, we can report system efficiencies between 90% and 95% on an LHV basis for hydrogen production exceeding 5kg/day. These results will be included in a forthcoming report, which we plan to release in mid-October. We can currently confidently say we have observed an average efficiency in a 10-hour test duration of our flagship 5kg/day prototype of 94.7%.

Instrumentation and System Connectivity

Overview of Instrumentation

Accurate measurement is key to determining system efficiency, and to achieve this, we have carefully selected and integrated a range of sensors throughout our hydrogen production system. Each sensor is tagged and mapped to either the Process Diagram (P&ID) or the Circuit Diagram, ensuring clarity and traceability during testing. The primary role of these instruments is to capture real-time data related to power input, hydrogen output, and system conditions, all of which contribute to our efficiency calculations.

Integration and Monitoring with Arduino Instrumentation

The entire instrumentation setup is connected via an Arduino-based system, which acts as the central hub for sensor data collection. The sensors are programmed to interface with the Arduino platform, allowing for seamless data acquisition. To enable remote monitoring and enhance system visibility, we have built a custom dashboard using the Arduino Cloud platform. This dashboard allows real-time monitoring of system parameters such as voltage, current, temperature, and hydrogen flow rate, making the efficiency testing process highly accessible and transparent.

List of Instruments and Specifications

For each instrument, we provide its specifications, its corresponding tag number from either the Process Diagram or Circuit Diagram, and a brief description of what it measures.

Power Sensor

- Tag Numbers: PoT-01A/B, PoT-02, PoT-03 (Block Flow Circuit Diagram)
- Sensor Model Number: INA260
- Specifications:
  - o Voltage Range: 0-36V DC
  - o Current Range: ±15A
  - o Power Range: Up to 540W (calculated based on voltage and current ranges)
  - o Accuracy: ±0.02% for voltage, ±0.1% for current
- Measurement: Monitors voltage, current, and power in real-time.
- Purpose: The INA260 sensor is used to monitor the total electrical power input into the electrolysis system. This sensor combines voltage and current readings to calculate the power, ensuring accurate tracking of the energy supplied to the system.
- Integration: I2C interface for real-time data acquisition
- Note: Since the voltages at PoT-03 exceed the measurement limits of the INA260 sensor, a voltage divider circuit is used to step down the voltage. The Arduino code references the characteristics of the divider to return the correct voltage values, ensuring safe and accurate measurement of high-voltage signals.

Temperature Sensor

- Tag Numbers: TT-E2, TT-B5 (Simplified Piping & Instrumentation Diagram)
- Sensor Model Number: DS18B20
- Specifications:
  - o Temperature Range: -55°C to +125°C
  - o Accuracy: ±0.5°C from -10°C to +85°C
  - o Resolution: Programmable (9 to 12-bit)
- Measurement: Measures the temperature of the electrolyte within the electrolysis cell.
- Purpose: This sensor is used to monitor the electrolyte temperature to track heat losses and thermal behavior, which are important for analyzing system efficiency.
- Integration: The DS18B20 is connected to the Arduino via a One-Wire interface, allowing multiple sensors to be connected on the same data line for temperature monitoring across the system.

Environmental Reference Sensor

- Tag Number: RefT-R1 (Simplified Piping & Instrumentation Diagram)
- Sensor Model Number: BME280
- Specifications:
  - Temperature Range: -40°C to +85°C
  - Humidity Range: 0% to 100% RH
  - Pressure Range: 300 hPa to 1100 hPa
- Accuracy:
  - Temperature: ±1.0°C
  - Humidity: ±3%
  - Pressure: ±1 hPa
- Measurement: Measures ambient temperature, humidity, and barometric pressure.
- Purpose: The BME280 is used as a reference transmitter to capture the environmental conditions during testing. Ambient temperature, pressure, and humidity can affect hydrogen production, and this data helps in adjusting and contextualizing efficiency calculations.
- Integration: Connected to the Arduino via the I2C interface.
- Note: The BME280 provides critical environmental data that can be used for correlating system performance with external conditions.

Pressure Sensor

- Tag Number: PT-E3 and PT-B6 (Simplified Piping & Instrumentation Diagram)
- Sensor Model Number: DFRobot Sen0257
- Specifications:
  - Pressure Range: 0-232 psig (16 bar)
  - Accuracy: ±0.5% of full scale
  - Interface: Analog (0.5V to 4.5V output)
- Measurement: Measures the pressure of gases or liquids in the system.
- Purpose:
  - PT-E3: Monitors the pressure at the electrolysis cell to ensure stable operating conditions.
  - PT-B6: Monitors the pressure at the bubbler to verify safe and consistent gas flow.
- Integration: Connected to the Arduino via analog input pins, where the voltage output is converted to pressure using a calibration curve.

Level Sensors

- Tag Numbers: LT-T2, LT-E1, LT-B4 (Simplified Piping & Instrumentation Diagram)
- Sensor Model Number: MaxBotix HRLV-EZ1
- Specifications:
  - Measurement Range: 1 mm to 500 cm
  - Accuracy: ±1% of the detected range
  - Resolution: 1 mm
  - Output Type: Pulse width, analog voltage, or serial output
  - Measurement: Measures the distance from the sensor to the liquid surface, which is converted into the liquid level.
- Purpose:
  - LT-T2: Monitors the liquid level in the water tank to ensure proper filling and avoid overflow.
  - LT-E1: Tracks the water level within the electrolysis cell for operational stability.
  - LT-B4: Monitors the bubbler water level to maintain safe operations.
- Integration: Connected to the Arduino using either the pulse width, analog, or serial output options, allowing for flexible and precise liquid level measurement in the system.
- Note: The MaxBotix HRLV-EZ1 provides enhanced accuracy and noise filtering, ensuring stable, continuous liquid level readings suitable for real-world operational environments.

Flow Transmitter

- Tag Number: FT-P1(Simplified Piping & Instrumentation Diagram)
- Sensor Model Number: DFRobot Gravity Liquid Flow Sensor
- Specifications:
  - Flow Range: 0.15-1.5 L/min
  - Accuracy: ±3%
  - Output Type: Digital pulse output
- Measurement: Measures the flow rate of liquid passing through the Atlas Scientific Dosing Pump.
- Purpose:
  - FT-P1: The flow transmitter monitors the real-time flow rate of the dosing pump, ensuring that the correct volume of liquid is delivered during operation. This data is crucial for maintaining accurate dosing and flow control in the system.
- Integration: Connected to the Arduino via a digital input pin, the sensor’s pulse output is used to calculate the flow rate by counting the pulses per liter. The Arduino code processes this data to provide real-time flow rate readings between 0.15 to 1.5 L/min.

Gas Flow Transmitter

- Tag Number: FT-E4 (Simplified Piping & Instrumentation Diagram)
- Sensor Model Number: FS1015
- Specifications:

o Flow Range: 0-50 L/min (air or non-corrosive gases)

o Accuracy: ±2%

o Output Type: Analog voltage output

- Measurement: Measures the flow rate of gas produced in the electrolysis cell.
- Purpose:

o FT-E4: The flow transmitter is used to monitor the flow of gas exiting the electrolysis cell, providing real-time data on gas flow rates.

- Integration: The FS1015 is connected to the Arduino via an analog input pin. The sensor's analog output corresponds to the gas flow rate, which is then converted into liters per minute (L/min) using calibration data in the Arduino code.

pH Transmitter

- Tag Number: PhT-T1, PhT-B7 (Simplified Piping & Instrumentation Diagram)
- Sensor Model Number: Atlas Scientific pH Meter
- Specifications:

o pH Range: 0-14

o Accuracy: ±0.002 pH

o Output Type: Analog or I2C (depending on the configuration)

- Measurement: Measures the pH level of the water in the system.
- Purpose:

o PhT-T1: Monitors the pH level of the water in the tank, ensuring it remains within the optimal range for efficient electrolysis.

o PhT-B7: Monitors the pH of bubbler to maintain stable operating conditions and detect any shifts in chemical balance.

- Integration: The Atlas Scientific pH sensors are connected to the Arduino via an I2C interface, allowing real-time data acquisition.

Humidity and Temperature Transmitter

- Tag Number: RHT-B1 (Simplified Piping & Instrumentation Diagram)
- Sensor Model Number: DHT22
- Specifications:

o Humidity Range: 0% to 100% RH

o Accuracy (Humidity): ±2% RH

o Temperature Range: -40°C to +80°C

o Accuracy (Temperature): ±0.5°C

o Output Type: Digital (single-wire)

- Measurement: Measures the relative humidity and ambient temperature in the system environment.
- Purpose:

o RHT-B1: Monitors the ambient humidity in the vapor space of the bubbler to ensure accurate hydrogen and oxygen production calculations.

- Integration: The DHT22 sensor is connected to the Arduino using a single-wire digital interface, allowing real-time humidity and temperature monitoring.

Hydrogen Leak Detection Sensor

- Tag Number: HT-B2 (Simplified Piping & Instrumentation Diagram)
- Sensor Model Number: Figaro TGS821
- Specifications:

o Hydrogen Detection Range: 500-10,000 ppm

o Accuracy: ±30% at 1,000 ppm H_2

o Output Type: Analog voltage

- Measurement: Detects the presence of hydrogen in the air to monitor potential leaks.
- Purpose:

o HT-B2: Primarily used to detect hydrogen leaks and ensure that the system achieves a hydrogen capture rate of greater than 99%. The sensor will provide an alert if hydrogen levels exceed safe thresholds, enabling immediate action to prevent potential hazards.

- Integration: Connected to the Arduino via an analog input pin, the sensor’s voltage output is monitored continuously to detect even small hydrogen leaks in the system.

Oxygen Sensor

- Tag Number: OT-B3 (Simplified Piping & Instrumentation Diagram)
- Sensor Model Number: Figaro KE-25
- Specifications:

o Oxygen Concentration Range: 0% to 100% O_2

o Accuracy: ±1% O_2

o Output Type: Analog voltage output

- Measurement: Measures the concentration of oxygen in the bubbler.
- Purpose:

o OT-B3: The sensor monitors the oxygen concentration in the bubbler, which allows us to determine the remaining concentration of hydrogen (since what is not oxygen is hydrogen). This data, along with the readings from the hydrogen sensor (HT-B2), ensures that the system maintains the desired hydrogen concentration and validates the efficiency of gas separation.

- Integration: The KE-25 is connected to the Arduino via an analog input pin, providing real-time oxygen concentration data to continuously monitor the gas composition in the bubbler.
- Note: The sensor plays a crucial role in validating the hydrogen capture rate and ensuring safe and efficient operation by measuring oxygen levels as a proxy for hydrogen concentration.

Additional Verification Instruments

While the primary data acquisition for efficiency calculations is handled through Arduino-compatible sensors, several standalone instruments are employed to double-check and verify key measurements. These instruments serve as secondary verification points, ensuring that all data collected is accurate and consistent.

AC Current Measurement

- Location: AG-01 (Circuit Block Flow Diagram)
- Instruments:

o AstroAI CM2KOR AC Clamp Meter: A standalone clamp meter used to measure alternating current in the power supply lines.

o Hantek CC-65 AC/DC Current Clamp: An oscilloscope probe capable of measuring both AC and DC currents, providing detailed waveform data.

- Purpose: These tools are used to cross-check current measurements collected by the system's Arduino sensors, ensuring precision in power calculations.

Gas Flow Measurement

- Location: FG-E5 (Simplified Piping & Instrumentation Diagram)
- Instrument: Welding Gas Acrylic Flowmeter
- Range: 0-50 L/min
- Purpose: This flowmeter is used to verify the flow rates of gases in the system, particularly hydrogen and non-corrosive gases. It provides an additional manual check to ensure the accuracy of the Arduino-monitored flow rates.

Power Supply Analog Gauges

- Location: Resonant Tank Circuit
- Instruments: Analog voltage and current gauges mounted on the power supply cases.

o These gauges provide real-time visual feedback of voltage and current levels within the Resonant Tank Circuit. They are used primarily for operational monitoring and can be toggled on or off, as their presence may affect system performance.

- Purpose: The analog gauges offer a quick, manual reference for voltage and current conditions, serving as a secondary validation tool alongside the digital measurements captured by the Arduino system.

About Us

Tobe Energy is a pioneering clean technology company dedicated to accelerating the global adoption of green hydrogen. Combining cutting-edge engineering with a fresh approach to electrolysis, we've developed a breakthrough, novel approach to electrolysis that eliminates waste heat and dramatically reduces production costs.

Who We Are

We are a team of innovators, engineers, and energy industry veterans committed to pushing the boundaries of what's possible in sustainable energy. Drawing on deep expertise across chemical engineering, power electronics, and materials science, we unite around a single goal: to make hydrogen a truly accessible, zero-emission energy source.

Our Mission

Our mission is to transform hydrogen from a specialized fuel into a practical, affordable, and clean cornerstone of the global energy system. We aim to enable businesses, communities, and entire industries to power their growth with reliable, zero-emission hydrogen—reducing carbon footprints while strengthening energy independence.

What We Do

At Tobe Energy, we create advanced electrolyzers that deliver industry-leading efficiency at a fraction of the cost of conventional systems. By integrating our electrolyzers as a core component of the electrical circuit—much like an LED replaces an incandescent bulb—we have reimagined hydrogen production to better serve rapidly evolving markets, from industrial manufacturing to AI data centers.

Our Vision

We envision a world where green hydrogen supports sustainable economic development, stabilizes grids, and fuels the most energy-intensive sectors without compromising affordability or the environment. By pioneering efficient, scalable hydrogen solutions, we seek to inspire a new era of clean energy innovation—propelling us toward a healthier planet and a more resilient future.