Hydrodomus

Home Hydrogen Generation System
for Automotive Applications

Technical Specification
and Prototype Requirements

Research Document

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"Hydro" (water) + "Domus" (home) = Hydrogen at Home

Abstract

The transition to hydrogen-powered transportation faces a critical infrastructure challenge: while hydrogen Fuel Cell Electric Vehicle (FCEV) technology has matured to commercial viability, the refueling network remains severely limited compared to conventional fueling stations. This document presents the technical specification for **Hydrodomus**, a home-based hydrogen generation and storage system designed to address this infrastructure gap by enabling FCEV owners to produce and store hydrogen fuel at their residence.

The proposed system utilizes Proton Exchange Membrane (PEM) water electrolysis to generate high-purity hydrogen from water and electricity. The produced hydrogen is compressed to the automotive standard pressure of 700 bar and stored in a certified composite vessel, from which the user can refuel their vehicle using a standardized SAE J2601-compliant dispensing system.

This document provides comprehensive coverage of the underlying theoretical principles, including electrochemistry, thermodynamics of gas compression, and hydrogen storage physics. The system architecture is presented in detail, with component specifications derived from both commercial availability and technical requirements. Safety considerations and the regulatory certification pathway are thoroughly analyzed to ensure compliance with international standards including ISO 19880, EC 79/2009, and SAE J2601.

The technical analysis demonstrates that home hydrogen generation is feasible with current technology, with system efficiency in the range of 60–70% from electricity to stored hydrogen. The primary challenges identified include the high capital cost of 700 bar compression equipment and storage vessels, as well as the certification requirements for residential hydrogen systems. The document concludes with recommendations for prototype development and a roadmap toward commercial deployment.

Keywords: Hydrogen production, PEM electrolysis, home refueling, FCEV, 700 bar storage, SAE J2601

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List of Abbreviations

ATEX .... Explosive Atmospheres
BEV .... Battery Electric Vehicle
FCEV .... Fuel Cell Electric Vehicle
LEL .... Lower Explosive Limit
MEA .... Membrane Electrode Assembly
PEM .... Proton Exchange Membrane
TPRD .... Thermally-activated Pressure Relief Device

1. Introduction

This chapter introduces the context and motivation for home-based hydrogen generation systems. The current state of hydrogen mobility infrastructure is examined, and the fundamental concept of the Hydrodomus system is presented along with the objectives of this technical specification.

1.1 The Hydrogen Mobility Challenge

1.1.1 Current State of Hydrogen Vehicles

Hydrogen FCEVs represent one of the most promising pathways toward zero-emission transportation. Unlike Battery Electric Vehicles (BEVs), which store energy in batteries, FCEVs generate electricity on-board through an electrochemical reaction between hydrogen and oxygen, producing only water as a byproduct. This approach offers several advantages:

- **Rapid refueling**: A full tank can be achieved in 3–5 minutes, comparable to conventional vehicles
- **Long range**: Modern FCEVs achieve 500–700 km per tank
- **No degradation**: Unlike batteries, fuel cells do not suffer from cycle-dependent capacity loss
- **Weight advantage**: For larger vehicles and long-range applications, hydrogen storage is lighter than equivalent battery capacity

Several major automotive manufacturers have invested significantly in FCEV technology. The Toyota Mirai, now in its second generation, demonstrates the commercial maturity of the technology with a range exceeding 650 km. BMW has developed the iX5 Hydrogen, Hyundai offers the Nexo SUV, and various commercial vehicle manufacturers are developing hydrogen-powered trucks and buses.

The Fundamental Problem Despite technological maturity, FCEV adoption faces a critical barrier: the lack of refueling infrastructure. As of 2024, there are approximately 1,000 hydrogen refueling stations worldwide, compared to over 150,000 gasoline stations in the United States alone. This creates the well-known "chicken-and-egg" problem:

- Consumers hesitate to purchase FCEVs due to limited refueling options
- Infrastructure investors hesitate to build stations due to low vehicle population
- Vehicle manufacturers cannot achieve economies of scale without consumer demand

This situation contrasts sharply with BEVs, where home charging provides a baseline capability that mitigates range anxiety. An BEV owner can always charge at home overnight, even if public charging infrastructure is limited. FCEV owners have no equivalent option—until now.

1.1.2 The Home Refueling Concept

The Hydrodomus system proposes to break the infrastructure deadlock by bringing hydrogen production directly to the consumer's residence. Just as an BEV owner plugs in their vehicle overnight, a Hydrodomus owner would generate hydrogen at home using water and electricity.

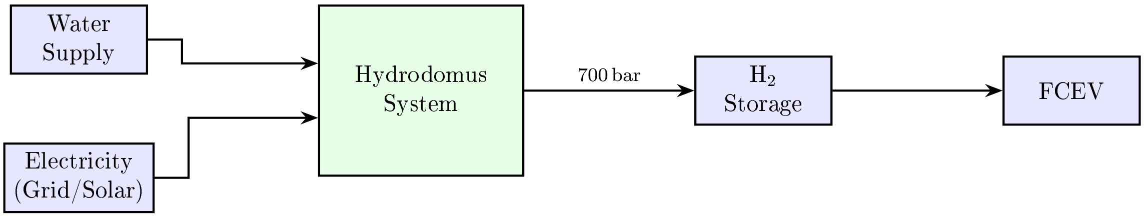

Figure 1.1: Conceptual overview of the Hydrodomus home hydrogen generation system. Water and electricity are converted to compressed hydrogen for vehicle refueling.

This approach transforms the infrastructure problem from a societal challenge into an individual solution. Each FCEV owner becomes independent of the public refueling network, at least for routine daily driving. The benefits include:

- **Energy independence**: Users are not dependent on the location or availability of public stations
- **Cost predictability**: Fuel costs depend on electricity prices rather than volatile hydrogen markets
- **Convenience**: Refueling occurs at home, similar to BEV charging
- **Grid integration**: The system can operate during off-peak hours or use surplus renewable energy

1.1.3 Overnight Charging Operation

A key operational mode for Hydrodomus mirrors the familiar experience of BEV charging: the vehicle is connected overnight, and by morning it is ready for the day's driving. This "plug and forget" paradigm offers compelling advantages:

User experience comparison:

- **BEV**: Plug in at night → 8 hours charging → 300 km range added
- **Hydrodomus**: Connect at night → 8 hours H_2 generation → 35 km range added
- **Weekly accumulation**: 7 nights × 35 km = 245 km/week capacity

While nightly range addition is less than BEV charging, it is sufficient for typical commuter patterns. The key insight is that most FCEV owners drive 200–300 km per week, well within the weekly production capacity of a 2 kW electrolyzer running overnight.

Smart grid integration:

- Automatic scheduling to off-peak electricity hours
- Integration with home energy management systems
- Potential demand response participation
- Solar PV surplus utilization during daytime
- Battery storage coordination for 24-hour optimization

No hydrogen bottles required:

Unlike alternative home hydrogen concepts that rely on delivered hydrogen cylinders, Hydrodomus generates hydrogen on-site from water and electricity. This eliminates:

- Bottle delivery logistics and scheduling
- Cylinder rental fees
- Storage space for multiple high-pressure bottles

- Regulatory complexity of storing delivered hydrogen

The continuous generation approach means the system produces small amounts of hydrogen constantly, accumulating over time in a compact buffer tank before final compression to 700 bar storage.

1.2 Market Context

1.2.1 Existing Solutions

The concept of home hydrogen generation is not entirely new, though no commercial system currently meets the requirements for automotive refueling at 700 bar. Existing approaches include:

Industrial electrolyzers: Large-scale PEM and alkaline electrolyzers are commercially available from manufacturers such as Nel, ITM Power, and Siemens. These systems are designed for industrial applications and typically produce hydrogen at low pressure (30 bar or less), requiring additional compression for automotive use.

Home hydrogen generators: Several companies have marketed small-scale hydrogen generators for laboratory or backup power applications. These typically operate at atmospheric pressure and produce insufficient quantities for vehicle refueling.

Toyota's home hydrogen concept: Toyota has announced development of a home hydrogen system in Japan, though details remain limited and the system appears targeted at the Japanese market with its specific regulatory environment.

1.2.2 Technology Readiness

The individual components required for a home hydrogen system are all commercially available:

- PEM electrolyzers at the 1–5 kW scale
- High-pressure hydrogen compressors capable of 700 bar
- Type IV composite hydrogen storage vessels
- SAE J2601-compliant dispensing nozzles

The challenge lies not in developing new technology but in integrating these components into a safe, certified, and cost-effective residential system.

1.3 Project Objectives

1.3.1 Technical Objectives

The Hydrodomus project aims to develop a complete home hydrogen generation system with the following technical specifications:

1. **Hydrogen production**: Minimum 0.5 kg/day production capacity using PEM electrolysis
2. **Storage pressure**: 700 bar (70 MPa) to match automotive standards
3. **Storage capacity**: Minimum 10 L at 700 bar, equivalent to approximately 0.4 kg H_2
4. **Dispensing**: SAE J2601-compliant refueling interface
5. **Efficiency**: System efficiency >60% (electricity to stored hydrogen)
6. **Safety**: Full compliance with applicable residential and hydrogen safety standards

1.3.2 Commercial Objectives

Beyond technical feasibility, the project must achieve commercial viability:

- Target system cost allowing payback within 5–7 years compared to station refueling
- Minimal maintenance requirements suitable for residential operation
- User-friendly interface requiring no specialized knowledge
- Certification pathway enabling legal installation in residential settings

1.4 Document Structure

This technical specification is organized as follows:

Chapter 2: Theoretical Background presents the scientific foundations required to understand the system, including electrochemistry of water electrolysis, thermodynamics of hydrogen compression, and gas storage physics.

Chapter 3: System Architecture describes the complete system design, including process flow, subsystem interactions, and control strategy.

Chapter 4: Component Specifications provides detailed requirements for each major component, with reference to commercially available solutions.

Chapter 5: Safety and Certifications analyzes the applicable safety standards and outlines the certification pathway for residential deployment.

Chapter 6: Conclusions and Future Work summarizes the technical findings and identifies next steps for prototype development.

2. Theoretical Background

This chapter presents the theoretical foundations necessary for understanding the design and operation of the Hydrodomus system. Starting from fundamental electrochemistry, we develop the principles governing water electrolysis, then proceed to the thermodynamics of gas compression and storage. These principles directly inform the engineering decisions presented in subsequent chapters.

2.1 Electrochemistry of Water Electrolysis

2.1.1 Fundamental Principles

Water electrolysis is the process of using electrical energy to decompose water into its constituent elements, hydrogen and oxygen. This electrochemical reaction is the reverse of the hydrogen-oxygen fuel cell reaction and represents a well-understood industrial process with over 200 years of history.

The overall reaction for water splitting is:

$$2\,H_2O_{(l)} \longrightarrow 2\,H_{2(g)} + O_{2(g)} \tag{2.1}$$

This deceptively simple equation conceals significant thermodynamic and kinetic complexity. The reaction is highly endothermic—it requires energy input—and does not occur spontaneously at ambient conditions. The energy required comes from the electrical power supplied to the electrochemical cell.

Why Water Splitting Requires Energy The thermodynamic requirement for water splitting can be understood from the perspective of chemical bond energies. In water, each oxygen atom forms two strong covalent bonds with hydrogen atoms. Breaking these O–H bonds requires energy input. While new H–H and O=O bonds form in the products, the total bond energy of the products is less than that required to break the reactant bonds. This energy difference must be supplied externally.

From a thermodynamic standpoint, the Gibbs free energy change for the reaction at standard conditions is:

$$\Delta G^0 = +237.1\,\text{kJ/mol} \tag{2.2}$$

The positive value indicates a non-spontaneous process—energy must be added to drive the reaction forward.

2.1.2 Electrode Reactions

The overall water splitting reaction occurs through two half-reactions at the electrodes of the electrolysis cell. The specific reactions depend on whether the system operates under acidic or alkaline conditions.

Acidic Conditions (PEM Electrolysis)

In PEM electrolysis, the membrane conducts protons (H^+) and the electrode reactions are:

Anode (Oxygen Evolution Reaction—OER):

$$2\,H_2O \longrightarrow O_2 + 4\,H^+ + 4\,e^- \qquad E^0 = +1.229\,\text{V} \tag{2.3}$$

Cathode (Hydrogen Evolution Reaction—HER):

$$4\,H^+ + 4\,e^- \longrightarrow 2\,H_2 \qquad E^0 = 0.000\,\mathrm{V} \tag{2.4}$$

At the anode, water molecules are oxidized, releasing oxygen gas, protons, and electrons. The protons migrate through the membrane to the cathode, while electrons flow through the external circuit. At the cathode, protons combine with electrons to form hydrogen gas.

Alkaline Conditions

In alkaline electrolysis, hydroxide ions (OH^-) are the mobile ionic species:

Cathode:

$$4\,H_2O + 4\,e^- \longrightarrow 2\,H_2 + 4\,OH^- \tag{2.5}$$

Anode:

$$4\,OH^- \longrightarrow O_2 + 2\,H_2O + 4\,e^- \tag{2.6}$$

Physical Interpretation The electrode reactions reveal why gas separation is inherent to the electrolysis process: hydrogen is produced exclusively at the cathode, while oxygen is produced exclusively at the anode. If the electrodes are physically separated (by a membrane or diaphragm), the gases remain separated and no additional purification is required. This is a fundamental advantage of electrolysis over thermal water splitting methods.

2.1.3 Thermodynamics of Electrolysis

Minimum Voltage Requirement

The minimum voltage required to drive electrolysis is determined by the thermodynamics of the reaction. The reversible cell voltage E_{rev} is related to the Gibbs free energy change by:

$$E_{rev} = \frac{\Delta G}{nF} \tag{2.7}$$

where n is the number of electrons transferred (4 for the overall reaction) and F is the Faraday constant (96 485 C/mol).

At standard conditions:

$$E^0_{rev} = \frac{237\,100\,\mathrm{J/mol}}{4 \times 96\,485\,\mathrm{C/mol}} = 1.229\,\mathrm{V} \tag{2.8}$$

This is the theoretical minimum voltage for water electrolysis at 25 °C and 1 bar.

Thermoneutral Voltage

In practice, the enthalpy change ΔH is more relevant than the Gibbs free energy because it accounts for the total energy required, including the entropy term. The thermoneutral voltage is:

$$E_{tn} = \frac{\Delta H}{nF} = \frac{285\,800\,\mathrm{J/mol}}{4 \times 96\,485\,\mathrm{C/mol}} = 1.481\,\mathrm{V} \tag{2.9}$$

At voltages below E_{tn}, the cell would absorb heat from the surroundings; above E_{tn}, the cell generates heat. Practical electrolyzers operate above the thermoneutral voltage due to various losses, meaning they always generate heat that must be managed.

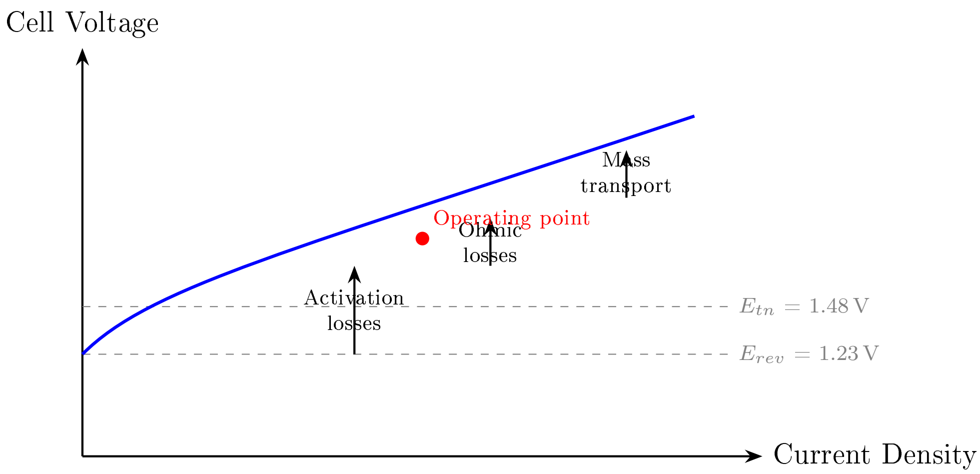

Figure 2.1: Polarization curve for a water electrolysis cell showing the relationship between cell voltage and current density. The gap between the reversible voltage E_{rev} and the operating voltage represents efficiency losses from activation overpotentials, ohmic resistance, and mass transport limitations.

Overpotentials and Efficiency Losses

Real electrolysis cells operate at voltages significantly higher than the reversible voltage due to various loss mechanisms:

Activation overpotential (η_{act}): Energy required to overcome the activation barrier for the electrode reactions. The oxygen evolution reaction has particularly high activation overpotential due to its complex four-electron mechanism.

Ohmic overpotential (η_Ω): Resistive losses in the membrane/electrolyte, electrodes, and current collectors. This term increases linearly with current density according to Ohm's law:

$$\eta_\Omega = i \cdot R_{cell} \tag{2.10}$$

Mass transport overpotential (η_{mt}): At high current densities, the supply of reactants or removal of products can become rate-limiting, causing additional voltage losses.

The total cell voltage is:

$$E_{cell} = E_{rev} + \eta_{act,a} + \eta_{act,c} + \eta_\Omega + \eta_{mt} \tag{2.11}$$

Energy Efficiency

The voltage efficiency of an electrolyzer is defined as:

$$\eta_V = \frac{E_{tn}}{E_{cell}} \tag{2.12}$$

Using the thermoneutral voltage accounts for the total energy content of the hydrogen produced. Modern PEM electrolyzers achieve voltage efficiencies of 70–80% at typical operating conditions.

The specific energy consumption is often expressed as:

$$E_s = \frac{E_{cell} \cdot n \cdot F}{M_{H_2}} = \frac{E_{cell} \times 2 \times 96485}{2.016 \times 3600} \approx 26.6 \times E_{cell} \quad [\mathrm{kWh/kg}] \tag{2.13}$$

For a cell operating at 1.8 V, the specific energy consumption is approximately 48 kWh/kg of hydrogen.

2.1.4 Nernst Equation and Temperature Effects

The reversible voltage for electrolysis depends on temperature and pressure according to the Nernst equation:

$$E_{rev} = E^0 - \frac{RT}{nF} \ln \left(\frac{a_{H_2} \cdot a_{O_2}^{0.5}}{a_{H_2O}} \right) \tag{2.14}$$

where a represents the activity of each species. For practical purposes, the temperature dependence of the reversible voltage can be approximated as:

$$E_{rev}(T) \approx 1.229 - 0.00085(T - 298) \quad [\mathrm{V}] \tag{2.15}$$

Practical Implications of Temperature Operating at elevated temperatures (50–80°C) provides several benefits:

- **Lower reversible voltage**: Reduces thermodynamic minimum energy requirement
- **Faster kinetics**: Exponentially reduces activation overpotential
- **Higher ionic conductivity**: Reduces ohmic losses in membrane
- **Trade-off**: Higher temperatures accelerate membrane degradation

The optimal operating temperature for PEM electrolyzers is typically 60–80°C, balancing efficiency gains against component longevity.

2.1.5 Catalyst Materials and Cost Considerations

The choice of catalyst materials significantly impacts both performance and system cost.

Cathode (HER) catalysts:

- Platinum (Pt) is the standard catalyst with loadings of 0.1–0.5 mg/cm^2
- Platinum cost: approximately €25–30/g (2024 prices)
- For a 100 cm^2 electrode: €250–1500 in catalyst alone
- Research focus: reducing Pt loading or substituting with Ni-based catalysts

Anode (OER) catalysts:

- Iridium oxide (IrO_2) required due to harsh oxidizing conditions
- Iridium cost: approximately €150–200/g (highly volatile, limited supply)
- Typical loading: 1–2 mg/cm^2
- Iridium is a critical bottleneck for PEM electrolyzer scale-up
- Research focus: mixed metal oxides (Ir-Ru), reduced loadings

2.1.6 Membrane Degradation Mechanisms

Understanding membrane degradation is critical for predicting system lifetime:

Chemical degradation:

- Hydrogen peroxide (H_2O_2) formation from gas crossover
- Radical attack on polymer backbone (Fenton mechanism)
- Fluoride release as degradation indicator

Mechanical degradation:

- Humidity cycling causes swelling/shrinking stress

- Creep under compression at elevated temperature
- Pinhole formation leading to gas crossover

Contamination:

- Cationic impurities (Ca^{2+}, Fe^{3+}) replace protons, reducing conductivity
- Chloride ions poison catalyst irreversibly
- Importance of high-purity water feed

2.1.7 Water Purity Requirements

The feed water quality is critical for PEM electrolyzer longevity:

Table 2.1: Water purity impact on electrolyzer performance

Contaminant	**Mechanism**	**Effect**
Chloride (Cl^-)	Catalyst poisoning	Irreversible performance loss
Calcium (Ca^{2+})	Ion exchange with membrane	Conductivity loss
Iron ($Fe^{2+/3+}$)	Fenton reaction catalyst	Accelerated degradation
Organics	Catalyst fouling	Increased overpotential
Silica (SiO_2)	Surface deposition	Blocked active sites

For home applications, tap water must be treated to achieve:

- Resistivity >1 MΩ·cm (conductivity <1 μS/cm)
- Total dissolved solids <1 ppm
- Chloride <0.1 ppm (critical)

A typical water treatment train consists of: sediment filter → activated carbon → reverse osmosis → mixed-bed deionizer.

2.1.8 Faraday's Laws of Electrolysis

Faraday's laws provide the quantitative relationship between electrical charge and the amount of substance produced:

First Law: The mass of substance produced is proportional to the charge passed:

$$m = \frac{Q \cdot M}{n \cdot F} = \frac{I \cdot t \cdot M}{n \cdot F} \tag{2.16}$$

For hydrogen production ($M = 2.016\,\text{g/mol}$, $n = 2$):

$$m_{H_2} = \frac{I \cdot t \cdot 2.016}{2 \times 96485} = 1.044 \times 10^{-5} \cdot I \cdot t \quad [\text{g}] \tag{2.17}$$

Practical Implications Faraday's law has important practical implications for system design:

- A 1 kW electrolyzer operating at 1.8 V draws approximately 556 A
- This produces hydrogen at a rate of 20.9 g/h or approximately 0.5 kg/day
- The oxygen production rate is exactly half the molar rate of hydrogen (from stoichiometry)

2.2 PEM Electrolysis Technology

2.2.1 Operating Principle

PEM electrolysis uses a solid polymer electrolyte—typically a perfluorosulfonic acid membrane such as Nafion—to conduct protons between the electrodes while providing gas separation. The technology was developed from PEM fuel cell research and offers several advantages for the Hydrodomus application.

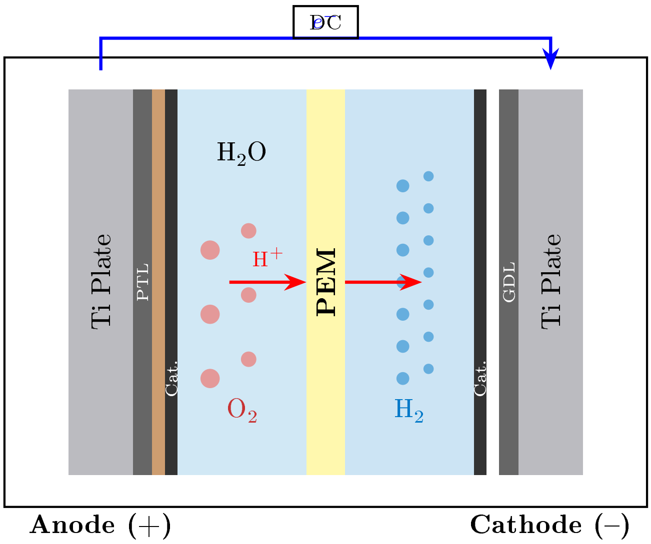

Figure 2.2: Cross-sectional schematic of a PEM electrolysis cell. Water is fed to the anode where it is oxidized to oxygen and protons. Protons migrate through the membrane to the cathode where they combine with electrons to form hydrogen. The membrane provides inherent gas separation.

2.2.2 Membrane Electrode Assembly

The Membrane Electrode Assembly (MEA) is the core component of a PEM electrolyzer, consisting of:

Proton exchange membrane: Typically Nafion (perfluorosulfonic acid), 50–200 µm thick. The membrane conducts protons with conductivity of 0.1–0.2 S/cm when hydrated, while being impermeable to gases and electrons.

Catalyst layers: Platinum-based catalysts for the cathode (HER) and iridium oxide for the anode (OER). Catalyst loadings are typically 0.5–2 mg/cm^2. The high cost of iridium is a significant contributor to PEM electrolyzer cost.

Porous transport layers: Gas diffusion layers (GDL) on the cathode side and porous transport layers (PTL) on the anode side facilitate reactant distribution and product removal.

2.2.3 Advantages for Home Application

PEM technology offers several advantages that make it well-suited for the Hydrodomus application:

1. **Compact design**: High current densities (1–3 A/cm^2) enable small footprint
2. **Solid electrolyte**: No liquid caustic chemicals requiring special handling

3. **Dynamic response**: Can follow variable power input (suitable for solar integration)
4. **High purity output**: Produces >99.99% pure hydrogen directly
5. **Pressurized operation**: Some systems operate at elevated pressure, reducing compression requirements
6. **Low maintenance**: No electrolyte management required

2.2.4 Performance Characteristics

Typical performance parameters for commercial PEM electrolyzers:

Table 2.2: Typical performance parameters for PEM electrolyzers

Parameter	**Typical Value**
Cell voltage	1.7–2.0 V
Current density	1–3 A/cm^2
Operating temperature	50–80 °C
Operating pressure	1–30 bar
Specific energy consumption	50–55 kWh/kg H_2
System efficiency (LHV)	60–70%
Hydrogen purity	>99.99%
Lifetime	>60,000 hours

2.3 Thermodynamics of Gas Compression

2.3.1 Compression Work

Compressing hydrogen from electrolyzer output pressure to storage pressure requires mechanical work. The minimum work for isothermal compression of an ideal gas is:

$$W_{iso} = nRT \ln\left(\frac{p_2}{p_1}\right) \tag{2.18}$$

For compressing 1 kg of hydrogen from 1 bar to 700 bar at 298 K:

$$W_{iso} = \frac{1000}{2.016} \times 8.314 \times 298 \times \ln(700) = 8.07\,\mathrm{MJ} = 2.24\,\mathrm{kWh} \tag{2.19}$$

2.3.2 Real Gas Effects

At high pressures, hydrogen deviates significantly from ideal gas behavior. The compressibility factor Z accounts for these deviations:

$$pV = ZnRT \tag{2.20}$$

For hydrogen at 700 bar and 25 °C, $Z \approx 1.5$, meaning the gas occupies 50% more volume than predicted by the ideal gas law. This has important implications:

- More compression work is required than the ideal gas calculation suggests
- Storage capacity is less than ideal gas predictions
- Density at 700 bar is approximately 40 kg/m^3 rather than the ideal 57 kg/m^3

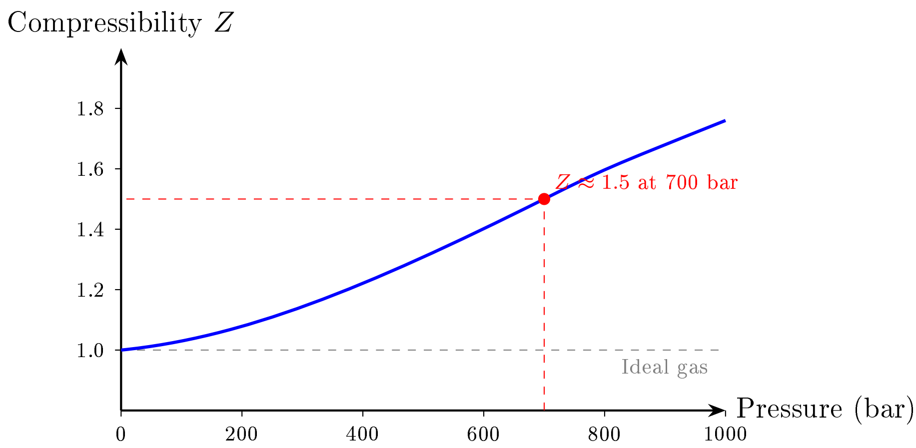

Figure 2.3: Compressibility factor Z for hydrogen as a function of pressure at 25 °C. At 700 bar, hydrogen deviates significantly from ideal gas behavior with $Z \approx 1.5$.

2.3.3 Compression Efficiency

Real compressors operate closer to adiabatic than isothermal conditions, especially at high compression ratios. For multi-stage adiabatic compression with intercooling:

$$W_{adi} = \frac{\gamma}{\gamma - 1} \cdot nRT_1 \cdot N \left[\left(\frac{p_2}{p_1} \right)^{\frac{\gamma-1}{N\gamma}} - 1 \right] \tag{2.21}$$

where N is the number of compression stages and $\gamma = 1.41$ for hydrogen.

Including mechanical inefficiencies, practical compression energy is typically 3–5 kWh/kg for compression from 30 bar to 700 bar.

2.3.4 Multi-Stage Compression Design

For high compression ratios, multi-stage compression with intercooling is essential. The optimal number of stages minimizes total work while keeping discharge temperatures manageable.

Optimal pressure ratio per stage: For N stages with equal pressure ratios:

$$r_{stage} = \left(\frac{p_{final}}{p_{initial}} \right)^{1/N} \tag{2.22}$$

For compression from 30 bar to 700 bar:

- 2 stages: $r = 4.83$ per stage
- 3 stages: $r = 2.87$ per stage
- 4 stages: $r = 2.19$ per stage (typical choice)

Discharge temperature calculation:

$$T_{discharge} = T_{inlet} \times r^{\frac{\gamma-1}{\gamma}} \tag{2.23}$$

With 4 stages starting at 25 °C and $\gamma = 1.41$:

$$T_{discharge} = 298 \times 2.19^{0.29} = 298 \times 1.25 = 373\,\text{K} = 100\,°\text{C} \tag{2.24}$$

This is manageable with standard materials. Intercoolers return the gas to near-ambient temperature between stages.

2.3.5 Joule-Thomson Effect

When compressed hydrogen expands (e.g., during dispensing), the Joule-Thomson effect determines whether the gas heats or cools:

$$\mu_{JT} = \left(\frac{\partial T}{\partial p}\right)_H \tag{2.25}$$

For hydrogen at room temperature, μ_{JT} is negative (inversion temperature $\approx$ 200 K), meaning hydrogen *heats up* upon expansion at typical operating temperatures. This has important implications:

- **During fast refueling**: Expanding hydrogen heats the vehicle tank
- **Pre-cooling requirement**: Station dispensers cool hydrogen to −40 °C for fast fills
- **Home application advantage**: Slow fill allows heat dissipation, no pre-cooling needed

2.3.6 Heat Management in Compression

The compression process generates significant heat that must be removed:

Heat generated per stage:

$$Q = \dot{m} \cdot c_p \cdot (T_{discharge} - T_{inlet}) = \dot{m} \cdot c_p \cdot T_{inlet} \cdot (r^{\frac{\gamma-1}{\gamma}} - 1) \tag{2.26}$$

For a system producing 0.5 kg/day (20.8 g/h):

- Heat per stage: approximately 100 W at full operation
- Total compression heat: 300–400 W for 3–4 stages
- Cooling method: Air-cooled intercoolers adequate for residential scale

2.4 Hydrogen Storage

2.4.1 Storage Methods Overview

Hydrogen can be stored in several forms:

- **Compressed gas**: Most mature technology, used in vehicles
- **Liquid hydrogen**: Higher density but requires cryogenic temperatures (20 K)
- **Metal hydrides**: Solid-state storage with high volumetric density but heavy
- **Chemical carriers**: Ammonia, methanol, or liquid organic hydrogen carriers

For the Hydrodomus application, compressed gas storage at 700 bar is the appropriate choice as it matches the automotive standard.

2.4.2 Compressed Gas Storage

Pressure-Volume Relationship

The amount of hydrogen stored in a vessel depends on pressure, temperature, and vessel volume. Using the real gas equation:

$$m = \frac{pVM}{ZRT} \tag{2.27}$$

For a 10 L vessel at 700 bar and 25 °C:

$$m = \frac{700 \times 10^5 \times 0.01 \times 2.016 \times 10^{-3}}{1.5 \times 8.314 \times 298} = 0.38\,\text{kg} \tag{2.28}$$

This represents approximately 7% of a Toyota Mirai's full tank capacity (5.6 kg).

Storage Vessel Types

High-pressure hydrogen vessels are classified into four types:

Table 2.3: Hydrogen storage vessel classification

Type	Construction	Max Pressure	Application
I	All-metal (steel)	200–300 bar	Industrial
II	Metal liner + composite hoop wrap	300–450 bar	Industrial
III	Metal liner + full composite wrap	350–700 bar	Vehicles, stationary
IV	Polymer liner + full composite wrap	700 bar	Vehicles

Type IV vessels, using a high-density polyethylene (HDPE) liner with carbon fiber reinforced polymer (CFRP) overwrap, are standard for 700 bar automotive applications. These vessels are designed to fail safely through controlled leakage rather than catastrophic rupture.

2.4.3 Safety Considerations

Physical Properties of Hydrogen

Understanding hydrogen's physical properties is essential for safe system design:

Table 2.4: Physical and safety properties of hydrogen compared to other fuels

Property	Hydrogen	Methane	Gasoline
Density at STP (kg/m^3)	0.0899	0.717	720–780
Lower Explosive Limit (LEL) (vol%)	4.0	5.0	1.0
Upper Explosive Limit (UEL) (vol%)	75	15	7.6
Auto-ignition temp. (°C)	585	540	230–480
Min. ignition energy (mJ)	0.02	0.29	0.24
Flame velocity (m/s)	2.65	0.37	0.37
Diffusion coeff. in air (cm^2/s)	0.61	0.16	0.05

Implications for Safety Design Several properties have important safety implications:

- **Wide flammability range**: Hydrogen can ignite over a broad range of concentrations, but this also means it disperses to below flammable concentrations more readily than other fuels
- **Low ignition energy**: Eliminates static discharge as a potential ignition source requirement
- **High diffusivity**: Hydrogen disperses rapidly in open environments, reducing accumulation risk
- **Buoyancy**: Being 14 times lighter than air, hydrogen rises rapidly, making outdoor releases relatively safe
- **No toxicity**: Unlike carbon monoxide, hydrogen is non-toxic; the primary hazard is asphyxiation in confined spaces

Deflagration vs. Detonation

A critical safety distinction exists between deflagration (subsonic flame propagation) and detonation (supersonic). Hydrogen-air mixtures can detonate under specific conditions, but detonation requires:

- Concentration near stoichiometric (29%)
- Confinement
- Strong ignition source or long flame path

In open or well-ventilated environments, hydrogen fires typically deflagrate rather than detonate, producing less destructive overpressure.

2.5 Energy Balance

2.5.1 System Efficiency

The overall efficiency of the Hydrodomus system can be expressed as:

$$\eta_{system} = \eta_{electrolyzer} \times \eta_{compression} \times \eta_{storage} \tag{2.29}$$

With typical values:

- $\eta_{electrolyzer} = 70\%$ (based on LHV)
- $\eta_{compression} = 90\%$ (mechanical efficiency)
- $\eta_{storage} = 98\%$ (accounting for minor leakage)

The overall system efficiency is approximately 62%.

2.5.2 Energy Requirements

For producing 1 kg of hydrogen at 700 bar:

Table 2.5: Energy breakdown for producing 1 kg of stored hydrogen

Process	**Energy (kWh/kg)**
Electrolysis (at 70% efficiency)	47.6
Compression (30 bar → 700 bar)	3–5
Balance of plant	1–2
Total	**52–55**

The Lower Heating Value (LHV) of hydrogen is 33.3 kWh/kg, so the electricity-to-hydrogen efficiency is:

$$\eta = \frac{33.3}{54} \approx 62\% \tag{2.30}$$

2.6 Continuous On-Site Generation vs. Bottled Hydrogen

A fundamental advantage of home hydrogen generation is the elimination of bottled hydrogen logistics. This section analyzes the theoretical basis for continuous on-site production.

2.6.1 The Overnight Generation Paradigm

Unlike bottled hydrogen delivery, which requires periodic bulk refills, on-site electrolysis enables continuous, low-rate production that matches consumption patterns. The key insight is that vehicle refueling is episodic (minutes per week) while electricity consumption can be distributed over extended periods.

Energy storage comparison:

Consider a homeowner needing 1 kg of hydrogen per week (approximately 100 km of driving):

Table 2.6: Comparison of hydrogen supply methods

Parameter	Station Fill	Bottle Delivery	On-Site Generation
Fill frequency	Weekly trip	Monthly delivery	Continuous
Storage needed	Vehicle tank only	50–200 bar bottles	10–20 L buffer
Electricity demand	N/A	N/A	2 kW × 27 h/week
Peak power	N/A	N/A	2 kW
Logistics	User drives	Truck delivery	None
Independence	Low	Medium	High

2.6.2 Overnight Production Calculations

Utilizing off-peak electricity rates, a system can produce hydrogen primarily during night hours:

Scenario: 8-hour overnight window (22:00–06:00)

- Electrolyzer power: 2 kW
- Energy consumed per night: 16 kWh
- Hydrogen produced per night: $\frac{16}{54} \approx 0.30\,\mathrm{kg}$
- Weekly production (7 nights): 2.1 kg
- Driving range equivalent: 200–250 km/week

This matches typical commuter patterns without requiring daytime operation.

Extended operation scenario:

If the system operates 12 hours overnight (20:00–08:00):

- Energy consumed: 24 kWh
- Hydrogen produced: 0.44 kg/night
- Weekly production: 3.1 kg
- Range equivalent: 300–400 km/week

2.6.3 Grid Tariff Optimization

Time-of-use electricity pricing provides an economic advantage for overnight production:

Cost calculation example (France):

- Hydrogen cost at peak rate: $54 \times 0.27 =$ €14.58/kg
- Hydrogen cost at off-peak: $54 \times 0.13 =$ €7.02/kg
- Station price comparison: €10–15/kg
- Off-peak advantage: 30–50% cost reduction vs. station

Table 2.7: Example electricity tariff structures (2024 typical rates)

Region	Peak	Off-Peak	Ratio	Off-Peak Hours
France (EDF Tempo)	€0.27/kWh	€0.13/kWh	2.1×	22:00–06:00
Germany	€0.35/kWh	€0.25/kWh	1.4×	22:00–06:00
California (TOU)	$0.45/kWh	$0.20/kWh	2.3×	21:00–08:00
UK (Economy 7)	£0.30/kWh	£0.10/kWh	3.0×	00:00–07:00

2.6.4 Elimination of Bottle Logistics

On-site generation eliminates the entire bottled hydrogen supply chain:

Bottled hydrogen challenges:

- Bottle rental fees: €5–15/month per cylinder
- Delivery charges: €30–50 per delivery
- Minimum order quantities
- Storage space for multiple cylinders
- Safety certification for bottle storage
- Dependency on delivery schedules

On-site generation advantages:

- No recurring delivery costs
- No bottle rental
- Continuous availability
- Smaller footprint (single buffer tank vs. multiple bottles)
- Full control over production schedule
- Integration with home solar PV possible

2.6.5 Buffer Sizing for Overnight Operation

The buffer tank size determines the operational flexibility:

$$V_{buffer} = \frac{m_{daily} \times M_{H_2}}{p_{buffer} \times Z \times R \times T} \times 10^6 \quad [\text{L}] \tag{2.31}$$

For 0.5 kg/day production at 30 bar buffer pressure:

- Required volume: approximately 200 L at atmospheric equivalent
- At 30 bar: approximately 7 L physical volume
- Practical buffer: 10–20 L provides margin for compressor cycling

The buffer decouples electrolyzer operation from compressor operation, enabling continuous low-rate electrolysis while the compressor operates in batch mode.

3. System Architecture

This chapter presents the complete system architecture for the Hydrodomus home hydrogen generation system. The design philosophy emphasizes safety, modularity, and ease of installation while meeting the technical requirements established in Chapter 1.

3.1 System Overview

3.1.1 Functional Description

The Hydrodomus system performs four primary functions:

1. **Hydrogen generation**: Electrolyze water to produce hydrogen gas
2. **Gas separation and purification**: Separate hydrogen from oxygen and water vapor
3. **Compression**: Increase hydrogen pressure to 700 bar
4. **Storage and dispensing**: Store compressed hydrogen and transfer to vehicle

These functions are implemented through five interconnected subsystems, as shown in Figure 3.1.

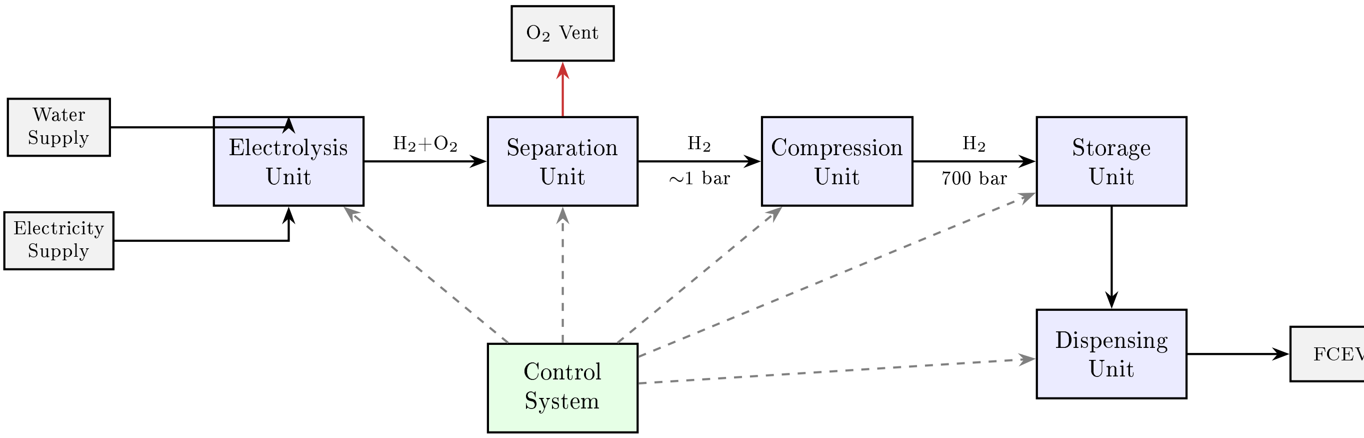

Figure 3.1: Hydrodomus system block diagram showing the five main subsystems and their interconnections. Solid arrows indicate gas flow; dashed arrows indicate control signals.

3.1.2 Design Philosophy

The system design follows several key principles:

Safety first: All design decisions prioritize safety. The system includes multiple layers of protection against hydrogen release and operates fail-safe in all identified failure modes.

Modularity: Each subsystem is designed as a replaceable module, enabling maintenance and future upgrades without complete system replacement.

Residential compatibility: The system is designed for installation in a residential garage or utility space, with consideration for noise, footprint, and electrical requirements.

Autonomous operation: Once started, the system operates automatically with minimal user intervention, similar to a home appliance.

3.2 Process Flow

3.2.1 Normal Operation Sequence

The standard operating sequence proceeds as follows:

Phase 1: Startup

1. System performs self-check (sensor verification, leak detection)
2. Water level verified in reservoir
3. Electrical supply verified
4. Control system initializes all subsystems

Phase 2: Production

1. Electrolyzer powered up, reaching operating temperature
2. Water fed to electrolyzer at controlled rate
3. Hydrogen and oxygen produced at electrodes
4. Gases separated; oxygen vented safely
5. Hydrogen flows to low-pressure buffer

Phase 3: Compression

1. When buffer pressure reaches setpoint, compressor activates
2. Multi-stage compression to 700 bar
3. Intercooling between stages
4. Compressed hydrogen flows to storage vessel

Phase 4: Standby

1. When storage reaches target pressure, production pauses
2. System enters low-power standby mode
3. Monitoring continues for safety parameters

Phase 5: Dispensing

1. User connects nozzle to vehicle
2. System verifies connection integrity
3. Controlled pressure release to vehicle tank
4. Flow terminated when vehicle tank full or user stops

3.2.2 Process and Instrumentation

Figure 3.2 presents the detailed process flow with instrumentation points.

3.3 Subsystem Descriptions

3.3.1 Electrolysis Unit

The electrolysis unit generates hydrogen and oxygen from water using PEM technology.

Key specifications:

- Stack power: 1–2 kW nominal

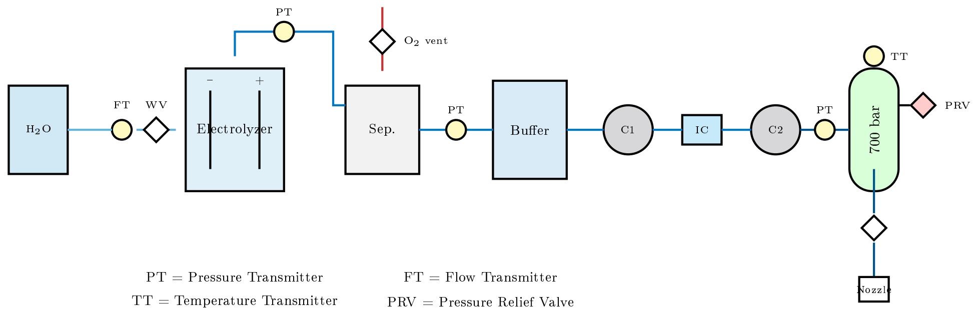

Figure 3.2: Process and instrumentation diagram (P&ID) showing major equipment and instrumentation. Blue lines indicate hydrogen flow; equipment labeled with standard ISA symbols.

- Operating pressure: 1–5 bar (atmospheric to slightly elevated)
- Operating temperature: 50–80°C
- Water consumption: ∼1 L/h at full power
- Hydrogen output: ∼20 g/h at full power

The electrolyzer includes:

- PEM stack with integrated cooling
- Water circulation system with deionization
- Power electronics (DC power supply)
- Gas-liquid separators for each electrode

3.3.2 Separation Unit

The separation unit ensures high-purity hydrogen by removing:

- Residual oxygen (if any crossover through membrane)
- Water vapor
- Trace contaminants

For PEM electrolysis, the membrane provides inherent separation, so this unit primarily performs:

- Water knockout (condensation)
- Drying (desiccant or refrigerated)
- Oxygen venting (with flame arrestor)

3.3.3 Compression Unit

The compression unit increases hydrogen pressure from electrolyzer output (∼1–5 bar) to storage pressure (700 bar).

Compression approach:

Multi-stage reciprocating (piston) compression is the only practical technology for achieving 700 bar at the required flow rates. A typical configuration uses:

- Stage 1: 1–5 bar → 30–50 bar
- Stage 2: 30–50 bar → 200–250 bar

- Stage 3: 200–250 bar → 700 bar

Intercoolers between stages prevent excessive temperature rise during compression. The hydrogen temperature must be controlled to prevent damage to downstream components and storage vessels.

Alternative technologies considered:

- **Ionic compressors**: Use ionic liquid as piston; lower maintenance but limited availability
- **Metal hydride compressors**: Thermal cycling of hydrides; no moving parts but slow
- **Electrochemical compression**: Integrated with electrolyzer; emerging technology

3.3.4 Storage Unit

The storage unit holds compressed hydrogen until dispensing. Key requirements:

- Vessel type: Type III or Type IV composite
- Working pressure: 700 bar
- Volume: 10–50 L (depending on usage pattern)
- Safety features: Thermally-activated Pressure Relief Device (TPRD), pressure relief valve, burst disc

The storage vessel includes a valve assembly with:

- Manual isolation valve
- Solenoid-operated fill valve
- Check valve (prevent backflow)
- TPRD for fire protection
- Pressure transducer

3.3.5 Dispensing Unit

The dispensing unit transfers hydrogen from storage to the vehicle. It must comply with SAE J2601 fueling protocols.

SAE J2601 requirements:

- Pre-cooling: Vehicle tanks require cooled hydrogen to prevent overheating during fast fill
- Pressure ramp rate: Controlled to prevent thermal stress
- Communication: Protocol for determining vehicle tank state
- Nozzle standard: ISO 17268 Type B (700 bar)

For home application, the “slow fill” protocol is appropriate:

- Fill time: 10–30 minutes (vs. 3–5 minutes at stations)
- No pre-cooling required
- Simpler pressure management
- Lower equipment cost

3.4 Control System

3.4.1 Control Architecture

The control system manages all subsystem operations through a hierarchical architecture:

Level 1 - Safety systems: Hardwired safety interlocks that operate independently of software

- Emergency stop circuits
- Hydrogen detector alarms
- Overpressure relief
- Fire detection

Level 2 - Process control: PLC-based automation

- Electrolyzer power management
- Compressor sequencing
- Pressure and temperature control
- Fill protocol execution

Level 3 - User interface: Touch screen or app-based interface

- System status display
- Start/stop commands
- Schedule programming
- Maintenance alerts

3.4.2 Operating Modes

Production mode: System actively generating and compressing hydrogen

- Electrolyzer at set power level
- Compressor cycling to maintain buffer pressure
- Storage pressure increasing

Standby mode: Storage full, system idle

- Electrolyzer off
- Compressor off
- Safety monitoring active
- Ready for dispensing

Dispensing mode: Transferring hydrogen to vehicle

- Production may continue simultaneously
- Controlled pressure release
- Fill protocol management

Maintenance mode: System isolated for service

- All processes stopped
- Valves in safe positions
- Technician access enabled

3.5 Original Concept Sketch

Figure 3.3 shows the original concept sketch developed during the initial design phase, illustrating the basic system layout and component arrangement.

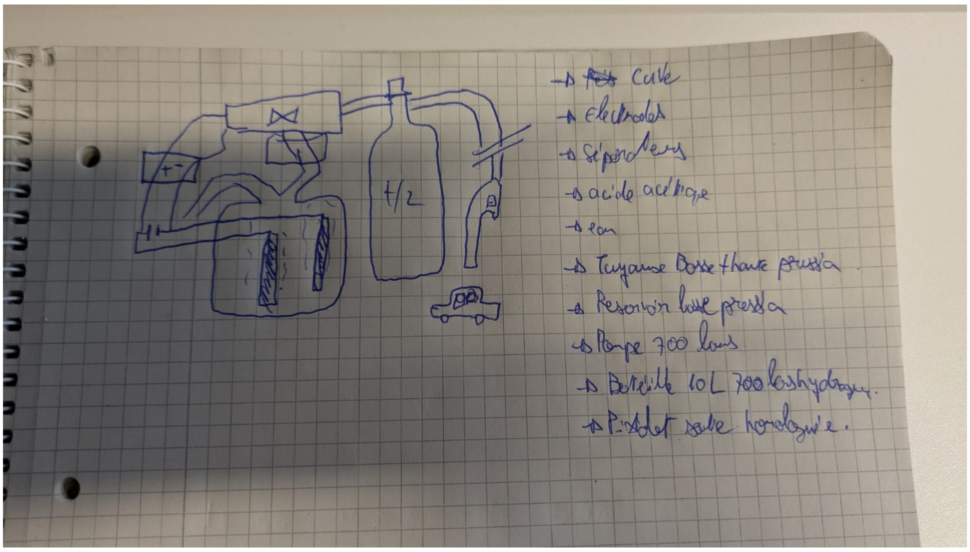

Figure 3.3: Original hand-drawn concept sketch showing the proposed system layout. The sketch illustrates the electrolysis tank with electrodes and separator, low-pressure buffer, compressor, high-pressure storage vessel, and connection to vehicle. Component list visible on right side.

3.6 Installation Considerations

3.6.1 Space Requirements

The complete system is designed to fit within a residential garage or utility space:

Table 3.1: Estimated system dimensions and space requirements

Component	Dimensions (cm)	Floor Space (m^2)
Electrolyzer unit	60 × 40 × 80	0.24
Compressor unit	80 × 60 × 100	0.48
Storage vessel (10 L)	20 dia × 80	0.04
Control cabinet	40 × 30 × 60	0.12
Total footprint		**∼1.5**
Service clearance		**∼1.0**

3.6.2 Utilities

Electrical:

- Supply: 240 V single-phase or 400 V three-phase
- Power: 3–5 kW peak, 2 kW average during production
- Metering: Separate sub-meter recommended for energy tracking

Water:

- Connection: Standard household supply
- Quality: Tap water acceptable; internal treatment provides deionization
- Consumption: ~10 L/day at full production

Ventilation:

- Requirement: Minimum 0.5 ACH (air changes per hour) when operating
- Natural ventilation may be sufficient for well-ventilated garages
- Forced ventilation recommended for enclosed spaces

3.6.3 Environmental Conditions

- Operating temperature: 5–40°C
- Storage temperature: –20–50°C
- Humidity: 20–80% RH (non-condensing)
- Protection class: IP54 minimum for outdoor-rated components

4. Component Specifications

This chapter provides detailed specifications for the major components of the Hydrodomus system. For each component, design requirements are established based on the system architecture, and commercially available solutions are identified where possible.

4.1 Component Overview

Table 4.1 summarizes the major components derived from the original concept sketch and engineering analysis.

Table 4.1: Summary of major system components

No.	Component	Function
1	Electrolysis tank (Cuve)	Water container and electrochemical cell
2	Electrodes	Anode and cathode for water splitting
3	Separator membrane	Gas separation between H_2 and O_2
4	Electrolyte/Water	Reactant and ionic conductor
5	Low-pressure tubing	Gas transport at low pressure
6	Low-pressure reservoir	Buffer storage before compression
7	High-pressure compressor	Compression to 700 bar
8	Storage vessel	High-pressure hydrogen storage
9	Dispensing nozzle	Vehicle connection interface
10	Control system	System automation and safety

4.2 Electrolysis Stack

4.2.1 Requirements

The electrolyzer must meet the following requirements:

Table 4.2: Electrolyzer requirements

Parameter	Minimum	Target
Production rate	0.3 kg/day	0.5 kg/day
Electrical power	1.5 kW	2.0 kW
Efficiency (LHV basis)	60%	70%
Output pressure	1 bar	5–30 bar
Hydrogen purity	99.9%	99.99%
Lifetime	40,000 h	60,000 h

4.2.2 Technology Selection

PEM electrolysis is selected over alkaline electrolysis for the following reasons:

1. **No liquid electrolyte**: Eliminates handling of caustic KOH solution
2. **Compact footprint**: Higher current density enables smaller stack

3. **Dynamic response**: Suitable for variable renewable input
4. **High purity output**: No electrolyte contamination
5. **Elevated pressure operation**: Some stacks operate at 30+ bar, reducing compression

4.2.3 Commercial Options

Several manufacturers offer PEM electrolyzer stacks in the target power range:

Table 4.3: Representative commercial PEM electrolyzer options

Manufacturer	Model	Power	Output	Pressure
Nel	M Series	1–2 kW	0.4 Nm^3/h	30 bar
ITM Power	HGAS	0.5–2 kW	0.5 Nm^3/h	15 bar
Enapter	EL 2.1	2.4 kW	0.5 Nm^3/h	35 bar
H-TEC Systems	ME100	1 kW	0.22 Nm^3/h	30 bar

4.2.4 Stack Configuration

A typical PEM stack for the Hydrodomus application consists of:

- **Active area**: 50–100 cm^2 per cell
- **Number of cells**: 10–20 cells in series
- **Cell voltage**: 1.7–2.0 V
- **Stack voltage**: 17–40 V DC
- **Current**: 50–100 A

4.3 Power Electronics

4.3.1 DC Power Supply

The electrolyzer requires a regulated DC power supply with the following characteristics:

- Input: 230 V AC single-phase or 400 V AC three-phase
- Output: 0–50 V DC, 0–100 A
- Regulation: ±1% voltage, ±2% current
- Efficiency: >92%
- Control interface: 0–10 V or 4–20 mA analog, or digital (Modbus/CAN)

4.3.2 Grid Integration

For solar integration, the power supply should accommodate:

- Variable input power tracking
- Maximum power point tracking (MPPT) integration
- Grid/solar switching logic
- Battery backup option for overnight operation

4.4 Water System

4.4.1 Water Quality Requirements

PEM electrolyzers require high-purity water to prevent membrane degradation:

Table 4.4: Water quality requirements for PEM electrolysis

Parameter	Requirement
Conductivity	$<1\ \mu$S/cm
Total dissolved solids	<1 ppm
Chloride	<0.1 ppm
pH	5–7

4.4.2 Water Treatment System

The water treatment system includes:

1. **Particulate filter**: 5 μm cartridge filter
2. **Carbon filter**: Removes chlorine and organics
3. **Reverse osmosis**: Removes dissolved solids
4. **Deionization**: Mixed-bed ion exchange resin
5. **Storage tank**: 10–20 L treated water buffer

Water consumption is approximately 1 L per 111 g of hydrogen produced (stoichiometric), or about 9 L/kg H_2 accounting for losses.

4.5 Compression System

4.5.1 Right-Sizing for Residential Application

A critical design principle for Hydrodomus is avoiding overspecification. Commercial hydrogen station compressors are designed for high throughput (fast fills in 3–5 minutes), requiring massive flow rates and power consumption. For overnight home generation, a much smaller compressor suffices:

Why station-scale equipment is inappropriate:

- Station compressors: 50–100 kg/h capacity, 50–100 kW power
- Home requirement: 0.5 kg/day = 21 g/h, <1 kW power
- Overspecification factor: 100× or more
- Result: Unnecessary cost, noise, maintenance, and complexity

4.5.2 Requirements

The compressor must match the electrolyzer output rate, not the vehicle fill rate. Since the vehicle is connected overnight, the buffer slowly accumulates compressed hydrogen:

Flow rate clarification:

- **Production rate**: 0.3–0.6 Nm^3/h matches electrolyzer output
- **Dispensing rate**: 5–10 L/min at 700 bar sufficient for slow vehicle fill
- Buffer tank decouples production from dispensing

Table 4.5: Compressor requirements for residential overnight operation

Parameter	Specification
Inlet pressure	1–30 bar
Outlet pressure	700 bar
Flow rate (production matching)	0.3–0.6 Nm^3/h
Dispensing flow rate	5–10 L/min at 700 bar
Compression ratio (overall)	23–700:1
Number of stages	3–4
Power consumption	0.3–0.8 kW
Cooling	Air-cooled (sufficient for residential scale)
Noise level	<60 dB (residential compatibility)

4.5.3 Compressor Technology

Reciprocating piston compressors are the standard technology for high-pressure hydrogen compression. Key design considerations include:

Materials compatibility: Hydrogen causes embrittlement in many steels. Suitable materials include:

- 316L stainless steel for wetted parts
- Aluminum alloys for certain applications
- Specialized alloys (Inconel, Hastelloy) for high-stress areas
- PTFE or PEEK seals and gaskets

Lubrication: Oil-free (dry) compression is preferred to avoid hydrogen contamination. Alternatives include:

- PTFE piston rings
- Ionic liquid lubrication
- Diaphragm compressors (completely oil-free)

4.5.4 Intercooling

Each compression stage generates significant heat. For adiabatic compression, the temperature rise is:

$$T_2 = T_1 \left(\frac{p_2}{p_1}\right)^{\frac{\gamma-1}{\gamma}} \tag{4.1}$$

Without intercooling, a single-stage compression from 1 bar to 700 bar would raise hydrogen temperature to over 1000 °C—clearly unacceptable.

Multi-stage compression with intercooling to near-ambient temperature between stages limits the peak temperature to manageable levels (typically $<150\,°\mathrm{C}$).

4.5.5 Commercial Options

4.6 Storage System

4.6.1 Vessel Specifications

4.6.2 Vessel Construction

Type IV vessels consist of:

Table 4.6: Representative high-pressure hydrogen compressors

Manufacturer	Type	Pressure	Flow	Power
PDC Machines	Diaphragm	900 bar	1 Nm^3/h	3 kW
Maximator	Piston	700 bar	5 Nm^3/h	5 kW
Haskel	Piston	1000 bar	2 Nm^3/h	2 kW
HyET Hydrogen	Electrochemical	200 bar	1 kg/day	1 kW

Table 4.7: Storage vessel specifications

Parameter	Specification
Type	III or IV composite
Working pressure	700 bar
Test pressure	1050 bar (1.5×)
Minimum burst	1575 bar (2.25×)
Volume	10–50 L
H_2 capacity	0.4–2 kg
Design life	15 years / 5500 cycles
Operating temperature	–40 to +85°C

1. **Liner**: High-density polyethylene (HDPE), 3–5 mm thick
2. **Overwrap**: Carbon fiber reinforced polymer (CFRP)
3. **Outer protection**: Impact-resistant cover
4. **Boss**: Aluminum or steel end fitting for valve attachment

4.6.3 Cost Considerations

High-pressure composite vessels represent a significant portion of system cost:

- Type IV 700 bar vessels: €2000–€5000 for 10–50 L
- Primary cost driver: Carbon fiber material
- Cost reduction expected as production scales with FCEV market

4.7 Dispensing System

4.7.1 Nozzle and Receptacle

The dispensing interface must comply with ISO 17268 and SAE J2600:

- Nozzle type: H70 (700 bar, hydrogen)
- Connection: Proprietary latching mechanism
- Infrared communication: Vehicle tank status exchange
- Breakaway: Safety disconnect under tension
- Grounding: Equipotential bonding

4.7.2 Fill Protocol

SAE J2601 defines fueling protocols. For home application, the "non-communication" fueling protocol with reduced flow rate is appropriate:

- Precooling: Not required (slow fill)
- Target pressure: Based on ambient temperature lookup table
- Fill rate: Limited to prevent thermal stress
- Termination: Pressure equalization or timer

4.7.3 Dispensing Hardware

- High-pressure hose: 700 bar rated, 1–2 m length
- Flow meter: Optional, for usage tracking
- Pressure regulator: Downstream pressure control
- Check valve: Prevent backflow
- Emergency shutoff: Pneumatic or solenoid operated

4.8 Safety Systems

4.8.1 Hydrogen Detection

Hydrogen sensors are distributed throughout the system:

- Near electrolyzer
- Near compressor
- Near storage vessel
- In enclosure/room

Sensor specifications:

- Technology: Catalytic bead or electrochemical
- Range: 0–4% (0–100% LEL)
- Alarm setpoints: 10% LEL (warning), 25% LEL (shutdown)
- Response time: $<$30 seconds to 50% of final value

4.8.2 Pressure Relief

Multiple pressure relief mechanisms protect against overpressure:

1. **Pressure relief valve**: Set at 110% of working pressure
2. **Burst disc**: Backup protection at 125% of working pressure
3. **TPRD**: Thermally-activated relief for fire exposure

4.8.3 Emergency Shutdown

Emergency shutdown (ESD) capability includes:

- Manual ESD button: Accessible at system and room exit
- Automatic ESD triggers: H_2 detection, fire detection, overpressure
- ESD actions: Stop production, close isolation valves, de-energize ignition sources

4.9 Control and Instrumentation

4.9.1 Sensors

Table 4.8: Control system sensor list

Tag	Service	Range	Type
PT-001	Electrolyzer H_2 outlet	0–50 bar	Piezoelectric
PT-002	Buffer tank	0–50 bar	Piezoelectric
PT-003	Compressor interstage	0–100 bar	Strain gauge
PT-004	Storage vessel	0–1000 bar	Strain gauge
TT-001	Electrolyzer stack	0–100°C	RTD
TT-002	Compressor discharge	0–200°C	Thermocouple
TT-003	Storage vessel	–40–100°C	RTD
FT-001	Water inlet	0–5 L/h	Turbine
LT-001	Water tank level	0–100%	Capacitive
AT-001–004	H_2 detection	0–4%	Catalytic

4.9.2 Controller

A programmable logic controller (PLC) or industrial PC manages system operation:

- Digital I/O: Valve control, pump control, status indicators
- Analog I/O: Sensor inputs, power control outputs
- Communication: Ethernet, Modbus, or CAN bus
- Data logging: Local storage + cloud upload option
- HMI: Touch screen display or web interface

5. Safety and Certifications

This chapter addresses the safety considerations and regulatory requirements for deploying a hydrogen generation system in a residential environment. The certification pathway for commercial deployment is outlined, with reference to applicable international standards.

5.1 Hazard Analysis

5.1.1 Hazard Identification

A systematic hazard identification for the Hydrodomus system reveals the following primary hazards:

Table 5.1: Primary hazards and consequences

Hazard	Cause	Potential Consequence
Hydrogen release	Leak, rupture, seal failure	Fire, explosion, asphyxiation
High pressure	Vessel failure, hose rupture	Projectile hazard, jet release
Electrical	Short circuit, insulation failure	Shock, fire, ignition source
Oxygen enrichment	O_2 accumulation	Enhanced combustion
Chemical	Water treatment chemicals	Skin/eye irritation
Mechanical	Moving parts (compressor)	Injury during maintenance

5.1.2 Risk Assessment

Using a standard risk matrix approach, each hazard is evaluated for likelihood and consequence severity:

Table 5.2: Risk assessment summary

Hazard	Likelihood	Severity	Risk Level	Mitigation
H_2 leak (minor)	Possible	Moderate	Medium	Detection, ventilation
H_2 release (major)	Unlikely	Severe	Medium	Vessel certification
Vessel rupture	Rare	Critical	Medium	Design standards
Fire	Unlikely	Severe	Medium	Detection, suppression
Electrical shock	Unlikely	Moderate	Low	Grounding, insulation

5.2 Safety Design Features

5.2.1 Inherent Safety

The system design incorporates inherent safety principles:

Minimize: Keep hydrogen inventory as low as practical

- Small storage vessel (10 L) vs. station-scale (1000 L+)
- Minimal piping and dead volumes
- Production rate matched to consumption

Substitute: Use less hazardous alternatives where possible

- PEM electrolysis (no caustic electrolyte) vs. alkaline
- Low-pressure electrolyzer operation

Moderate: Reduce severity of potential incidents

- Outdoor or well-ventilated installation
- Small orifices limit release rate
- Flame arrestors prevent flashback

Simplify: Reduce complexity and failure modes

- Minimal number of fittings
- Welded connections preferred over threaded
- Fail-safe valve positions

5.2.2 Layers of Protection

The system implements multiple independent protection layers:

Layer 1: Process design

- Design pressure margins (1.5× working pressure test)
- Material selection for hydrogen compatibility
- Leak-tight construction

Layer 2: Basic process control

- Automatic shutdown on process limits
- Pressure control loops
- Temperature monitoring

Layer 3: Safety instrumented systems

- Independent safety PLC
- Redundant sensors for critical measurements
- Automatic emergency shutdown

Layer 4: Physical protection

- Pressure relief valves
- Burst discs
- TPRD

Layer 5: Emergency response

- Manual emergency stop
- Hydrogen detection and alarm
- Fire detection and notification

5.2.3 Hydrogen Detection System

Hydrogen detection is critical because hydrogen is odorless, colorless, and has a wide flammability range.

Sensor placement:

- At ceiling level (hydrogen rises)

- Near each potential leak source
- At ventilation exhaust points
- Near storage vessel valve assembly

Alarm logic:

- Warning alarm at 10% LEL (0.4% H_2)
- Automatic shutdown at 25% LEL (1% H_2)
- Sensor fault alarm on signal loss

5.2.4 Ventilation Requirements

Adequate ventilation prevents hydrogen accumulation in case of a release:

$$Q_{vent} \geq \frac{\dot{V}_{H_2,max}}{0.01} \times SF \tag{5.1}$$

where $\dot{V}_{H_2,max}$ is the maximum potential release rate and SF is a safety factor (typically 2–4).

For the Hydrodomus system with maximum production of $0.5\,\mathrm{Nm^3/h}$:

$$Q_{vent} \geq \frac{0.5}{0.01} \times 2 = 100\,\mathrm{m^3/h} \tag{5.2}$$

This is easily achieved with natural ventilation in a standard garage or with a small exhaust fan.

5.2.5 Fire Protection

Fire prevention:

- Elimination of ignition sources in classified areas
- Grounding and bonding of all metallic components
- Non-sparking materials and tools
- ATEX-rated equipment where required

Fire detection:

- UV/IR flame detectors for hydrogen fires (hydrogen flames are nearly invisible)
- Heat detectors as backup
- Integration with building fire alarm if applicable

Fire response:

- Automatic shutdown of hydrogen production
- Closure of isolation valves
- Notification to user/monitoring service
- TPRD prevents vessel rupture in fire

Table 5.3: Key standards for hydrogen systems

Standard	Scope
ISO 19880-1	Gaseous hydrogen fueling stations—General requirements
ISO 19880-3	Valves
ISO 19880-5	Hoses and hose assemblies
ISO 19880-8	Fuel quality control
ISO 17268	Refueling connection devices
ISO 22734	Hydrogen generators using water electrolysis
ISO 16111	Transportable gas storage devices

5.3 Applicable Standards

5.3.1 International Standards

5.3.2 European Regulations

Table 5.4: European regulatory requirements

Regulation	Scope
EC 79/2009	Type-approval of hydrogen-powered motor vehicles
EC 406/2010	Hydrogen components and systems
ATEX 2014/34/EU	Equipment for potentially explosive atmospheres
PED 2014/68/EU	Pressure Equipment Directive
LVD 2014/35/EU	Low Voltage Directive (electrical safety)
EMC 2014/30/EU	Electromagnetic Compatibility

5.3.3 SAE Standards

Table 5.5: SAE standards for hydrogen fueling

Standard	Scope
SAE J2601	Fueling protocols for light duty gaseous hydrogen vehicles
SAE J2799	Hydrogen surface vehicle to station communications
SAE J2600	Compressed hydrogen surface vehicle fueling connection
SAE J2579	Standard for fuel systems in fuel cell and other hydrogen vehicles

5.4 Certification Pathway

5.4.1 Component Certification

Individual components must be certified before system integration:

Pressure vessels:

- Certification to ISO 11119-3 (composite cylinders) or EC 79/406
- Type approval testing including burst, cycling, environmental exposure
- Periodic inspection requirements (typically 3–5 years)

Electrolyzer:

- CE marking for European market
- ISO 22734 compliance
- Electrical safety (LVD) and EMC compliance

Compressor:

- PED compliance for pressure equipment
- ATEX certification if located in hazardous area
- Machinery Directive compliance

5.4.2 System Certification

The integrated system requires additional certification:

Hazardous area classification:

- Define Zone 1/Zone 2 areas around hydrogen equipment
- Ensure all equipment in classified areas has appropriate rating
- Document in installation drawing

Functional safety:

- Safety Integrity Level (SIL) assessment
- Safety instrumented function design
- Proof testing requirements

Installation approval:

- Building permit requirements vary by jurisdiction
- Fire department notification/approval
- Insurance requirements

5.4.3 Certification Bodies

Relevant notified bodies and certification organizations include:

- TÜV (Germany)—Pressure equipment, ATEX, functional safety
- DNV GL—Hydrogen systems, risk assessment
- Bureau Veritas—Product certification
- UL (United States)—Electrical safety, hydrogen equipment

5.5 Installation Requirements

5.5.1 Location Selection

Preferred installation locations:

- **Outdoor**: Ideal for natural ventilation; weather protection required

- **Garage**: Common residential option; requires ventilation assessment
- **Utility room**: Acceptable if well-ventilated
- **Basement**: Generally not recommended due to ventilation challenges

5.5.2 Separation Distances

Minimum separation distances from ignition sources and building features:

Table 5.6: Recommended separation distances

Feature	Distance (m)
Building openings (windows, doors)	3
Air intakes (HVAC)	5
Lot line / public way	3
Other flammable storage	3
Electrical panels (non-rated)	1.5

5.5.3 Electrical Classification

The area around hydrogen equipment is classified per IEC 60079-10-1:

- **Zone 1**: Within 0.5 m of potential leak sources (valves, fittings)
- **Zone 2**: 0.5–2 m from Zone 1 boundary, or entire enclosed space
- **Non-hazardous**: Outdoors with adequate ventilation, beyond Zone 2

All electrical equipment within classified zones must have appropriate Explosive Atmospheres (ATEX) rating.

5.6 Operational Safety

5.6.1 User Training

System users should receive training covering:

- Normal operation procedures
- Emergency shutdown procedures
- Hydrogen safety awareness
- Basic maintenance tasks
- When to call for professional service

5.6.2 Maintenance Requirements

5.6.3 Emergency Procedures

Hydrogen leak detected:

1. Do not create sparks or flames
2. Press emergency stop if safe to do so
3. Evacuate area
4. Call emergency services if leak continues
5. Do not re-enter until cleared

Table 5.7: Maintenance schedule

Task	**Interval**	**Performed By**
Visual inspection	Monthly	User
Water system check	Monthly	User
Sensor calibration	6 months	Technician
Leak check	Annually	Technician
Vessel inspection	3–5 years	Certified inspector
Stack replacement	10+ years	Manufacturer

Fire:

1. Evacuate immediately
2. Call emergency services
3. Do not attempt to extinguish hydrogen fire (let it burn out)
4. Inform responders of hydrogen presence

6. Conclusions and Future Work

This chapter summarizes the key findings of the technical specification and outlines the path forward for prototype development and commercial deployment.

6.1 Summary of Findings

6.1.1 Technical Feasibility

The analysis presented in this document demonstrates that home-based hydrogen generation for FCEV refueling is technically feasible using currently available technology. The key technical conclusions are:

Hydrogen production:

- PEM electrolysis is the preferred technology for residential applications
- A 2 kW electrolyzer can produce approximately 0.5 kg H_2 per day
- System efficiency of 60–70% (electricity to stored hydrogen) is achievable
- Water consumption is modest ($\sim$10 L/day)

Compression and storage:

- Multi-stage piston compression is required to reach 700 bar
- Type IV composite vessels provide safe, certified storage
- A 10 L vessel stores $\sim$0.4 kg H_2, sufficient for $\sim$50 km range

Dispensing:

- SAE J2601 slow-fill protocol is appropriate for home application
- Standard ISO 17268 nozzles ensure vehicle compatibility
- Fill times of 10–30 minutes are acceptable for overnight use

6.1.2 Safety Assessment

The safety analysis indicates that a residential hydrogen system can be operated safely with appropriate design measures:

- Multiple independent protection layers mitigate risks
- Hydrogen detection and automatic shutdown prevent hazardous accumulation
- Certified pressure vessels and relief systems protect against overpressure
- Ventilation requirements are achievable in typical garage installations

6.1.3 Regulatory Pathway

A clear certification pathway exists through:

- ISO standards for hydrogen generation (ISO 22734) and fueling (ISO 19880)
- European regulations for pressure equipment and ATEX compliance
- SAE standards for vehicle fueling interface

The regulatory framework is developing but is sufficiently mature to support product development.

6.2 Economic Considerations

6.2.1 Capital Cost Estimate

Based on component costs identified in Chapter 4:

Table 6.1: Estimated system capital cost

Component	Cost (EUR)
PEM electrolyzer (2 kW)	8,000–15,000
Water treatment system	500–1,000
Compressor (700 bar)	5,000–10,000
Storage vessel (10 L, Type IV)	2,000–4,000
Dispensing system	2,000–4,000
Control system	1,500–3,000
Safety systems	1,000–2,000
Installation and commissioning	2,000–5,000
Total	**22,000–44,000**

6.2.2 Operating Costs

Table 6.2: Estimated operating costs

Item	Consumption	Annual Cost (EUR)
Electricity (€0.20/kWh)	55 kWh/kg × 100 kg/yr	1,100
Water	10 L/kg × 100 kg/yr	20
Maintenance	–	300–500
Total		**1,400–1,600**

6.2.3 Comparison with Station Refueling

At current hydrogen station prices of €10–15/kg:

- Annual fuel cost at station: €1,000–1,500 for 100 kg/year
- Annual fuel cost with Hydrodomus: €1,100 (electricity only)
- Simple payback on operating cost savings: Not favorable

The economic case improves significantly with:

- Lower electricity prices (e.g., self-generated solar)
- Higher hydrogen station prices (price volatility)
- Value of convenience and independence
- Future reductions in equipment cost

6.2.4 On-Site Generation vs. Bottled Hydrogen Delivery

An alternative to station refueling is home delivery of hydrogen cylinders. This section compares the economics of bottle delivery against on-site electrolysis.

Bottled Hydrogen Cost Structure

Industrial hydrogen delivered in cylinders has the following typical cost components:

Table 6.3: Bottled hydrogen delivery cost breakdown (European market, 2024)

Cost Component	Unit Cost	Annual Cost (100 kg/yr)
Hydrogen gas (industrial grade)	€15–25/kg	€1,500–2,500
Cylinder rental (200 bar, 50 L)	€8–15/month per cylinder	€200–360
Delivery charge	€40–80 per delivery	€240–480
Cylinder deposit (refundable)	€150–300 per cylinder	(one-time)
Regulator and fittings	€200–500	(one-time)
Annual recurring cost		**€1,940–3,340**

Practical limitations of bottled hydrogen for automotive use:

- Industrial cylinders deliver at 200 bar maximum—cannot directly fill 700 bar vehicle tanks
- Would require on-site compression anyway (defeating the purpose)
- 50 L cylinder at 200 bar contains only ~0.8 kg H_2 (one cylinder per week minimum)
- Storage of multiple high-pressure cylinders requires safety certification
- Delivery scheduling creates dependency and potential fuel gaps

On-Site Electrolysis Cost Structure

Table 6.4: On-site hydrogen generation cost breakdown

Cost Component	Unit Cost	Annual Cost (100 kg/yr)
Capital costs (amortized over 15 years):		
Electrolyzer system	€8,000–15,000	€533–1,000
Compressor (700 bar)	€5,000–10,000	€333–667
Storage and dispensing	€5,000–10,000	€333–667
Operating costs:		
Electricity (off-peak €0.13/kWh)	55 kWh/kg	€715
Water	10 L/kg	€20
Maintenance	lump sum	€300–500
Total annual cost		**€2,234–3,569**
With solar self-consumption		**€1,519–2,854**

Economic Comparison: Bottles vs. On-Site Generation

Key Finding: Bottles Are Not Viable for Automotive Use

The analysis reveals that **bottled hydrogen is not a practical solution** for home FCEV refueling:

1. **Pressure mismatch**: Industrial bottles (200 bar) cannot fill automotive tanks (700 bar) directly
2. **Compression still required**: Adding a compressor negates the simplicity advantage of bottles
3. **Higher long-term cost**: Recurring delivery and rental fees exceed electricity costs

Table 6.5: 10-year total cost of ownership comparison

Scenario	Year 1	Year 10	10-Year TCO
Bottled hydrogen (if 700 bar compression added):			
Equipment + bottles	€8,000	–	€8,000
Annual operating	€2,500	€2,500	€25,000
Total			**€33,000**
Hydrodomus on-site generation (grid electricity):			
Equipment	€25,000	–	€25,000
Annual operating	€1,400	€1,400	€14,000
Total			**€39,000**
Hydrodomus with solar PV (50% self-consumption):			
Equipment	€25,000	–	€25,000
Annual operating	€900	€900	€9,000
Total			**€34,000**

4. **Logistics burden**: Weekly deliveries, scheduling, and storage management
5. **Safety complexity**: Storing multiple high-pressure cylinders requires certification

On-site electrolysis advantages:

1. **Direct 700 bar production**: No intermediate pressure limitations
2. **Zero logistics**: Water and electricity are already available at home
3. **Predictable costs**: Electricity prices more stable than hydrogen commodity prices
4. **Energy independence**: Solar integration eliminates grid dependency
5. **Scalable**: Production rate adjustable to match consumption

Break-Even Analysis

The higher capital cost of on-site generation is offset by lower operating costs:

$$t_{breakeven} = \frac{C_{electrolyzer} - C_{bottles,equipment}}{C_{bottles,annual} - C_{electrolyzer,annual}} \tag{6.1}$$

With typical values:

$$t_{breakeven} = \frac{25000 - 8000}{2500 - 1400} = \frac{17000}{1100} \approx 15.5 \text{ years} \tag{6.2}$$

With solar self-consumption (50%):

$$t_{breakeven} = \frac{17000}{2500 - 900} = \frac{17000}{1600} \approx 10.6 \text{ years} \tag{6.3}$$

Conclusion: On-site generation reaches cost parity with bottles in 10–15 years, with the additional benefits of convenience, independence, and no logistics burden. For users with existing solar PV installations, the economics are clearly favorable.

6.3 Startup Investment Requirements

6.3.1 Minimum Viable Development Costs

Developing Hydrodomus from concept to market-ready product requires phased investment:

Table 6.6: Development phase investment requirements

Phase	Investment (EUR)	Duration
Phase 1: Lab prototype	15,000–25,000	6 months
Phase 2: High-pressure integration	40,000–60,000	12 months
Phase 3: Certification testing	50,000–100,000	12 months
Phase 4: Field trials (5 units)	100,000–150,000	18 months
Phase 5: Production tooling	200,000–500,000	12 months
Total to market	**405,000–835,000**	3–4 years

6.3.2 Regional Cost Variations

Installation and permitting costs vary significantly by market:

Table 6.7: Estimated installation costs by region

Region	Equipment	Installation	Permitting
EU (average)	€25k–40k	€3k–8k	€1k–5k
USA	$30k–50k	$5k–15k	$2k–10k
Japan	¥3.5M–5.5M	¥0.5M–1M	¥0.3M–0.8M
China	CNY 180k–280k	CNY 20k–50k	CNY 10k–30k

6.3.3 Available Subsidies and Incentives

Government support can significantly improve project economics:

European Union:

- EU Hydrogen Strategy funding programs
- National hydrogen subsidies (Germany: up to 80% for innovative projects)
- Clean Hydrogen Joint Undertaking grants
- VAT exemptions in some countries

United States:

- Federal tax credits (45V Clean Hydrogen Production Credit)
- California Clean Fuel Reward program
- State-level incentives (varies by state)
- DOE loan guarantees for demonstration projects

Japan:

- METI hydrogen equipment subsidies (up to 50%)
- Municipal incentives in Tokyo, Osaka
- ENE-FARM residential fuel cell program extension potential

6.4 Target Customer Segments

6.4.1 B2C (Business-to-Consumer) Markets

1. Early Adopters and Environmental Pioneers

- Profile: High-income, technology-enthusiastic homeowners

- Motivation: Environmental leadership, energy independence
- Willingness to pay: Premium pricing acceptable
- Market size: 1–3% of potential FCEV owners
- Geographic focus: California, Germany, Netherlands, Japan

2. Rural and Remote FCEV Owners

- Profile: Homeowners >50 km from nearest hydrogen station
- Motivation: Practicality, no alternative fueling option
- Price sensitivity: Moderate (compared to station travel cost)
- Market size: 40–60% of potential FCEV owners in early markets
- Geographic focus: Rural Europe, US Midwest, Australian outback

3. Solar PV Owners Seeking Energy Independence

- Profile: Existing rooftop solar installation (>5 kW)
- Motivation: Maximize self-consumption, grid independence
- Value proposition: Use excess solar for fuel production
- Market size: 5–10% of solar homeowners with suitable capacity
- Geographic focus: Australia, Southern Europe, Sunbelt USA

4. Small Fleet Owners (1–5 Vehicles)

- Profile: Small businesses, family operations with multiple FCEVs
- Motivation: Fuel cost control, operational simplicity
- Use case: Delivery services, professional services, farm operations
- Market size: 10–15% of B2C addressable market

6.4.2 B2B (Business-to-Business) Markets

1. Automotive Dealerships

- Value proposition: Differentiation, customer convenience offering
- Use case: Demo unit for customer experience, service center fueling
- Sales model: Direct partnership with Toyota, Hyundai, BMW dealers
- Revenue: Unit sales plus ongoing service contracts

2. Property Developers (Hydrogen-Ready Homes)

- Value proposition: Future-proof premium developments
- Use case: Pre-installed or prepared infrastructure in new builds
- Geographic focus: California, Japan, Netherlands, Germany
- Revenue: Bulk unit sales, maintenance contracts

3. Corporate Fleet Managers

- Value proposition: Reduce fueling logistics, predictable costs
- Use case: Company car pools, executive vehicles, service fleets
- Market entry: Pilot programs with sustainability-focused corporations
- Revenue: Multi-unit installations, long-term service agreements

4. Renewable Energy Companies

- Value proposition: Power-to-gas demonstration, grid balancing
- Use case: Wind/solar integration showcase, customer engagement
- Partnership model: Co-development, co-branding opportunities
- Revenue: Technology licensing, joint ventures

5. Research Institutions

- Value proposition: Compact hydrogen generation for laboratories
- Use case: Fuel cell research, materials testing, education
- Sales approach: Academic pricing, research partnerships
- Revenue: Unit sales, collaborative R&D funding

6.4.3 Global Market Analysis

Table 6.8: Regional market attractiveness assessment

Factor	**EU**	**USA**	**Japan**	**Korea**	**China**
FCEV population	Med	Low	High	High	Med
H_2 stations	Low	V. Low	Med	Med	Low
Regulations	High	Med	High	High	Med
Elec. cost	High	Med	High	Med	Low
Off-peak	Good	Good	Limited	Good	Good
Incentives	Strong	Strong	V. Strong	Strong	Strong
Solar potential	Good	Excellent	Mod	Mod	Excellent
Overall	**High**	**Med+**	**V. High**	**High**	**Med**

Priority Market Recommendations:

1. **Japan (Tier 1)**: Highest FCEV density, strong government support, established hydrogen culture, regulatory framework exists. Entry strategy: Partnership with Toyota or local energy company.
2. **Germany/Netherlands (Tier 1)**: Strong regulatory push, high environmental awareness, developed solar infrastructure. Entry strategy: TÜV certification, partnership with energy utilities.
3. **California (Tier 1)**: FCEV market leader in USA, strong incentives, solar-rich. Entry strategy: CARB certification, partnership with fuel cell vehicle dealers.
4. **South Korea (Tier 2)**: High FCEV adoption (Hyundai Nexo), government hydrogen roadmap. Entry strategy: KC certification, partnership with Hyundai network.
5. **Australia (Tier 2)**: Emerging hydrogen economy, excellent solar resources, vast distances to stations. Entry strategy: Focus on rural/remote markets.

6.5 Prototype Development Plan

6.5.1 Phase 1: Laboratory Prototype

Objectives:

- Validate component integration
- Characterize system performance
- Identify design improvements

Scope:

- Commercial electrolyzer integration
- Low-pressure testing (<30 bar)
- Manual operation
- Laboratory environment only

6.5.2 Phase 2: High-Pressure Prototype

Objectives:

- Demonstrate full pressure capability
- Validate safety systems
- Conduct vehicle refueling tests

Scope:

- Integration of 700 bar compressor
- Certified storage vessel
- Automated control system
- SAE J2601 compliant dispensing

6.5.3 Phase 3: Field Trials

Objectives:

- Validate real-world performance
- Gather user feedback
- Support certification process

Scope:

- Installation at 3–5 pilot sites
- 12-month operational period
- Performance monitoring and data collection
- Regulatory engagement

6.6 Recommendations

6.6.1 Technical Recommendations

1. **Prioritize elevated-pressure electrolysis**: Select an electrolyzer with >30 bar output to reduce compression requirements and cost
2. **Consider electrochemical compression**: Emerging technology that could replace mechanical compressors with lower cost and maintenance
3. **Design for solar integration**: Include capability for direct DC coupling to photovoltaic systems
4. **Implement remote monitoring**: Enable proactive maintenance and safety monitoring through cloud connectivity

6.6.2 Business Recommendations

1. **Partner with vehicle manufacturers**: Collaboration with Toyota, Hyundai, or BMW could provide market access and technical validation
2. **Target early adopter markets**: Focus on regions with limited hydrogen infrastructure and high environmental awareness
3. **Explore lease/subscription models**: Reduce upfront cost barrier through alternative ownership models
4. **Seek regulatory engagement**: Proactive engagement with authorities to clarify permitting requirements

6.7 Conclusion

The Hydrodomus home hydrogen generation system represents a viable approach to addressing the infrastructure barrier facing hydrogen mobility. While capital costs remain high, the technology is mature and the regulatory pathway is defined. As FCEV adoption grows and component costs decrease with volume production, home hydrogen generation could become an attractive option for environmentally conscious consumers seeking energy independence.

The immediate next step is to proceed with laboratory prototype development to validate the integrated system concept and refine the technical specifications. Success at this stage will provide the foundation for subsequent high-pressure development and eventual commercialization.

A. Appendix: Reference Data

A.1 Reference Vehicle Specifications

Table A.1: Hydrogen fuel cell vehicle specifications (2024 models)

Vehicle	**Tank Capacity**	**Pressure**	**Range**	**Fuel Economy**
Toyota Mirai (2nd gen)	5.6 kg	700 bar	650 km	0.86 kg/100km
Hyundai Nexo	6.3 kg	700 bar	666 km	0.95 kg/100km
BMW iX5 Hydrogen	6.0 kg	700 bar	504 km	1.19 kg/100km
Honda CR-V e:FCEV	4.3 kg	700 bar	435 km	0.99 kg/100km

A.2 Physical Constants

Table A.2: Physical constants used in calculations

Constant	**Symbol**	**Value**
Faraday constant	F	$96\,485\,\mathrm{C/mol}$
Universal gas constant	R	$8.314\,\mathrm{J/(mol \cdot K)}$
Molar mass of H_2	M_{H_2}	$2.016\,\mathrm{g/mol}$
Molar mass of H_2O	M_{H_2O}	$18.015\,\mathrm{g/mol}$
Molar mass of O_2	M_{O_2}	$32.00\,\mathrm{g/mol}$
Standard temperature	T_0	$298.15\,\mathrm{K}$
Standard pressure	p_0	$101\,325\,\mathrm{Pa}$

A.3 Hydrogen Properties

Table A.3: Selected properties of hydrogen

Property	**Value**
Molecular formula	H_2
Molecular weight	$2.016\,\mathrm{g/mol}$
Density at STP	$0.0899\,\mathrm{kg/m^3}$
Density at 700 bar, 25°C	$\sim 40\,\mathrm{kg/m^3}$
Boiling point	$20.3\,\mathrm{K}$ ($-252.9\,°\mathrm{C}$)
Critical temperature	$33.2\,\mathrm{K}$
Critical pressure	$13.0\,\mathrm{bar}$
Lower heating value (LHV)	$120\,\mathrm{MJ/kg} = 33.3\,\mathrm{kWh/kg}$
Higher heating value (HHV)	$142\,\mathrm{MJ/kg} = 39.4\,\mathrm{kWh/kg}$
Specific heat ratio γ	1.41
Thermal conductivity	$0.187\,\mathrm{W/(m \cdot K)}$ at 300 K
Viscosity	$8.9 \times 10^{-6}\,\mathrm{Pa \cdot s}$ at 300 K

Table A.4: Energy conversion factors for hydrogen

Conversion	**Value**
1 kg H_2 (LHV)	33.3 kWh
1 kg H_2 (HHV)	39.4 kWh
1 Nm^3 H_2	0.0899 kg
1 kg H_2	11.1 Nm^3
1 kg H_2 at 700 bar	∼25 L
1 L H_2 at 700 bar	∼40 g

A.4 Energy Conversion Factors

A.5 Compressibility Factor Data

Table A.5: Compressibility factor Z for hydrogen at 25 °C

Pressure (bar)	**Compressibility Z**
1	1.000
50	1.032
100	1.065
200	1.132
350	1.240
500	1.355
700	1.520
900	1.695

A.6 Electrolyzer Energy Consumption

Table A.6: Electrolyzer energy consumption at various cell voltages

Cell Voltage (V)	**Energy (kWh/kg)**	**Efficiency (%)**
1.48 (thermoneutral)	39.4	100
1.60	42.6	92
1.70	45.2	87
1.80	47.9	82
1.90	50.5	78
2.00	53.2	74
2.10	55.9	70

A.7 SAE J2601 Fueling Parameters

Table A.7: SAE J2601 H70 (700 bar) fueling parameters

Parameter	**Value**
Nominal working pressure	700 bar
Maximum fueling pressure	875 bar
Target state of charge	95–100%
Maximum fuel temperature	85 °C
Minimum dispenser temperature (fast fill)	−40 °C
Non-communication fill time (typical)	10–30 min
Communication fill time (typical)	3–5 min