International Hydrogen Ramp-up Programme – H2Uppp

Pre-Feasibility Study: Utility-Scale Green Hydrogen Production in Zakarpattia, Ukraine

Federal Ministry for Economic Affairs and Energy

N1 CAPITAL

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A

- **AC:** Alternating Current
- **ACER:** Agency for the Cooperation of Energy Regulators
- **AEL:** Alkaline (Electrolysis)
- **ALARP:** As Low As Reasonably Practicable
- **AN:** Explosion and fire hazardous outdoor installations (Ukrainian Fire Category)
- **ATEX:** Atmosphères Explosibles (European Directives for controlling explosive atmospheres)
- **AWE:** Alkaline Water Electrolysis

B

- **BAT:** Best Available Techniques
- **BESS:** Battery Energy Storage System
- **BFD:** Block Flow Diagram
- **BMWK:** German Federal Ministry for Economic Affairs and Climate Action
- **BMS:** Battery Management System
- **BOD:** Biological Oxygen Demand
- **BoP:** Balance of Plant

C

- **CAPEX:** Capital Expenditure
- **CC3:** Consequence Class 3 (Significant Consequences - Ukrainian building classification)
- **CEF:** Connecting Europe Facility
- **CEHC:** Central European Hydrogen Corridor
- **CESMP:** Construction Environmental and Social Management Plan
- **CIT:** Corporate Income Tax
- **CMU:** Cabinet of Ministers of Ukraine
- **COD:** Chemical Oxygen Demand (in wastewater context) or Commercial Operation Date (in project scheduling context)

D

- **DBN:** State Building Norms (*Derzhavni Budivelni Normy*)
- **DC:** Direct Current
- **DETC:** De-Energised Tap Changer (Off-Circuit Tap Changer)
- **DFC:** U.S. International Development Finance Corporation
- **DFI:** Development Finance Institution
- **DIAM:** State Inspection of Architecture and Urban Planning of Ukraine
- **DPT:** Detailed Plan of Territory
- **DSC:** Distribution System Code

- **DSO:** Distribution System Operator
- **DSTU:** State Standards of Ukraine (*Derzhavnyi Standart Ukrainy*)

E

- **EBRD:** European Bank for Reconstruction and Development
- **ECA:** Export Credit Agency
- **ECRB:** Energy Community Regulatory Board
- **EIA:** Environmental Impact Assessment
- **EIB:** European Investment Bank
- **EIC:** Energy Identification Code
- **ELL:** Emergency Localisation and Liquidation
- **EMS:** Energy Management System
- **ENTSO-E:** European Network of Transmission System Operators for Electricity
- **EPC:** Engineering, Procurement, and Construction
- **EPD:** Explosion Protection Document
- **ESD:** Emergency Shutdown
- **ESG:** Environmental, Social, and Governance
- **ESIA:** Environmental and Social Impact Assessment
- **ESMS:** Environmental and Social Management System
- **ESS:** Energy Storage System (or DC disconnect switch in PV context)
- **EU:** European Union

F

- **FCR:** Frequency Containment Reserves
- **FEED:** Front-End Engineering Design
- **FID:** Final Investment Decision
- **FOAK:** First-of-a-Kind
- **FRR:** Frequency Restoration Reserves

G

- **GC:** Gas Chromatograph
- **GDN:** Gas Distribution Network
- **GDS:** Gas Distribution System / Gas Metering Station
- **GHI:** Global Horizontal Irradiance
- **GHG:** Greenhouse Gas
- **GIZ:** Deutsche Gesellschaft für Internationale Zusammenarbeit GmbH
- **GKZ:** State Commission on Mineral Resources
- **GMS:** Gas Metering Station
- **GoO:** Guarantees of Origin
- **GTS:** Gas Transmission System
- **GTSOU:** Gas Transmission System Operator of Ukraine

H

- H_2**:** Hydrogen
- **HAC:** Hazardous Area Classification
- **HAZID:** Hazard Identification
- **HAZOP:** Hazard and Operability Study
- **HEE:** Hydrogen Equipment Enclosures
- **HER:** Hydrogen Evolution Reaction
- **HIC:** Hydrogen Induced Cracking
- **HP:** High Pressure

- **HPU:** Hydrogen Purification Unit
- **HRF:** High-Risk Facility
- **HV:** High Voltage
- **HYPRPlant:** Integrated PEM Electrolysis Plant (Specific Product Name)

I

- **IEA:** International Energy Agency
- **IEC:** International Electrotechnical Commission
- **IFI:** International Financial Institution
- **IFC:** International Finance Corporation
- **IMD:** Insulation Monitoring Device
- **IP:** Interconnection Point (or Ingress Protection)
- **IRR:** Internal Rate of Return
- **ISBL:** Inside Battery Limits
- **ISD:** Inherently Safer Design
- **ISO:** International Organisation for Standardisation

J

- **JT:** Joule-Thomson (Effect)

K

- **KOH:** Potassium Hydroxide
- **KTP:** Complete Transformer Substation (*Komplektna Transformatorna Pidstantsiya*)
- **kV:** Kilovolt
- **kW / kWh:** Kilowatt / Kilowatt*hour
- **kWp:** Kilowatt peak

L

- **LCOE:** Levelised Cost of Electricity
- **LCOH:** Levelised Cost of Hydrogen
- **LEL:** Lower Explosive Limit
- **LNG:** Liquefied Natural Gas
- **LoI:** Letter of Intent
- **LOPA:** Layers of Protection Analysis
- **LP:** Low Pressure
- **LV:** Low Voltage
- **LVS:** Low-Voltage Switchboard

M

- **MAD:** Maximum Allowable Discharge
- **MAPP:** Major Accident Prevention Policy
- **mFRR:** Manual Frequency Restoration Reserves
- **MIE:** Minimum Ignition Energy
- **MIGA:** Multilateral Investment Guarantee Agency
- **MPC:** Maximum Permissible Concentrations
- **MPPT:** Maximum Power Point Tracking
- **MUO:** Urban Planning Conditions and Restrictions
- **MV:** Medium Voltage
- **MW / MWh:** Megawatt / Megawatt-hour

N

- **N1C:** N1Capital
- **NAPB:** Regulatory Act on Fire Safety (*Normatyvnyi Akt z Pozhezhnoi Bezpeky*)
- **NDC:** Nationally Determined Contribution
- **NECP:** National Energy and Climate Plan
- **NEURC:** National Commission for State Regulation of Energy and Public Utilities
- **NPAOP:** Regulatory Act on Labor Protection (*Normatyvno-pravovyi akt z okhorony pratsi*)
- **NPV:** Net Present Value

O

- **O&M:** Operations and Maintenance
- **OER:** Oxygen Evolution Reaction
- **OHL:** Overhead Line
- **OLTC:** On-Load Tap Changer
- **OPEX:** Operational Expenditure
- **OSBL:** Outside Battery Limits
- **OWT:** Outlet Water Tanks

P

- **PCI:** Projects of Common Interest
- **PED:** Pressure Equipment Directive
- **PEM:** Proton Exchange Membrane
- **PEMFC:** Proton Exchange Membrane Fuel Cells
- **PFD:** Process Flow Diagram
- **PFS:** Pre-Feasibility Study
- **PLAS:** Plan for Localisation and Liquidation of Emergency Situations
- **PMI:** Projects of Mutual Interest
- **PMU:** Project Management Unit
- **PPA:** Power Purchase Agreement
- **PPE:** Personal Protective Equipment
- **PR:** Performance Requirement (EBRD)
- **PRREE:** Rules of the Retail Electricity Market
- **PRV:** Pressure Relief Valve
- **PS:** Performance Standard (IFC)
- **PSA:** Pressure Swing Adsorption
- **PSM:** Process Safety Management
- **PV:** Photovoltaic

Q

- **QCS:** Quality Control System
- **QRA:** Quantitative Risk Assessment

R

- **RED III:** Renewable Energy Directive III
- **REMIT:** Regulation on Wholesale Energy Market Integrity and Transparency
- **RES:** Renewable Energy Sources
- **RFB:** Redox Flow Battery
- **RFNBO:** Renewable Fuels of Non-Biological Origin
- **RO:** Reverse Osmosis
- **RODI:** Reverse Osmosis Deionisation

- **ROIV:** Remote-Operated Isolation Valve
- **RR:** Reserve Restoration

S

- **SACI:** State Architectural and Construction Inspectorate
- **SCADA:** Supervisory Control and Data Acquisition
- **SDS:** Small Distribution System
- **SEA:** Strategic Ecological Analysis
- **SEP:** Stakeholder Engagement Plan
- **SIL:** Safety Integrity Level
- **SIS:** Safety Instrumented System
- **SMR:** Steam Methane Reforming
- **SPP:** Solar Power Plant
- **SPS:** Sewage Pump Station
- **SPV:** Special Purpose Vehicle

T

- **TC:** Technical Conditions
- **TDLAS:** Tunable Diode Laser Absorption Spectroscopy
- **TEA:** Technical and Economic Analysis
- **TIC:** Total Installed Cost
- **ToR:** Terms of Reference
- **TSA:** Temperature Swing Adsorption
- **TSC:** Transmission System Code
- **TSO:** Transmission System Operator
- **TU:** Technical Conditions (*Tekhnichni Umovy*)

U

- **UGSF:** Underground Gas Storage Facilities
- **UF:** Ultrafiltration
- **UPS:** Uninterruptible Power Supply

V

- **VCE:** Vapour Cloud Explosion
- **VFD:** Variable Frequency Drive
- **VIP:** Virtual Interconnection Point

W

- **WACC:** Weighted Average Cost of Capital
- **WTP:** Water Treatment Plant

Z

- **ZRU:** Closed Switchgear (*Zakrytyj Rozpodilchij Prystrij*)

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Technical and Financial Estimates

- **Cost Estimates:** Capital Expenditure (CAPEX) and Operational Expenditure (OPEX) estimates presented in this study are classified as **Class 4 estimates** as defined by AACE International, with an expected accuracy range of **+/- 15% to 30%**.
- **Engineering Level:** The technical solutions described (layout, mass balance, grid connection) are at a **Pre-Design / Feasibility level** and are subject to refinement during the Front-End Engineering Design (FEED) phase.

Professional Advice The legal analysis provided regarding land use, permitting, and grid connection (including inputs from **Dentons**) is for informational purposes only and does not constitute formal legal advice. Recipients should seek their own independent legal, financial, and technical advice before taking any action based on the information contained in this document.

1 Executive Summary

1.1. Project Mandate and Strategic Rationale

This pre-feasibility study presents a comprehensive assessment of the technical, commercial, financial, and regulatory viability of developing an utility-scale green hydrogen production facility in the Zakarpattia Oblast of Western Ukraine. The project, spearheaded by N1Capital ("N1C"), envisions a phased development culminating in a 422 MW electrolysis plant in Uzhhorod, with its output primarily designated for the local offtakers and export to the European Union (EU). The study has been conducted under the auspices of the German Federal Ministry for Economic Affairs and Climate Action's (BMWK) International Hydrogen Ramp-up Program (H2Uppp), implemented by the Deutsche Gesellschaft für Internationale Zusammenarbeit (GIZ) GmbH.[1]

The project's strategic rationale is twofold. For Ukraine, it represents a cornerstone of a post-war green reconstruction strategy, leveraging the nation's vast renewable energy potential to enhance energy security, diversify its economy, and accelerate its integration into the European energy market. For the European Union, the project offers a proximate and scalable source of green hydrogen, directly contributing to the ambitious decarbonisation and energy independence goals articulated in the REPowerEU plan. [2]

The timing of this initiative carries particular strategic weight. Ukraine's post-war reconstruction is expected to mobilise several hundred billion euros in international financing, and the green hydrogen sector represents one of the most high-value vectors for productive capital deployment within that framework. Zakarpattia Oblast, as Ukraine's westernmost region sharing borders with four EU member states — Hungary, Slovakia, Romania, and Poland — is uniquely positioned as a natural gateway for future hydrogen trade flows into Central Europe. The project therefore transcends the development of a single industrial asset: it constitutes a proof-of-concept for Ukraine's broader hydrogen economy and a concrete demonstration of the country's readiness to participate in the European energy transition as a producing nation, not merely a transit corridor.

1.2. Scope of Assessment

The scope of this study is designed to provide a bankable analysis for potential investors, financiers, and public stakeholders. The assessment encompasses a detailed analysis of eight distinct technological and capacity scenarios, evaluating both Proton Exchange Membrane (PEM) and Alkaline (AEL) electrolyser technologies at four capacity scales: 2 MW, 20 MW, 100 MW, and 300 MW. The core analyses performed include: a macro-level assessment of EU and Ukrainian hydrogen markets; a granular review of the dual legal and regulatory frameworks governing production in Ukraine and export to the EU; a technical design and sizing for all eight scenarios; an evaluation of all required infrastructure interconnections (power, water, hydrogen); a comprehensive Environmental and Social Impact Assessment (ESIA) framework aligned with the stringent standards of International Financial Institutions (IFIs) such as the European Bank for Reconstruction and Development (EBRD) and the International Finance Corporation (IFC); and a detailed financial model to determine economic viability.

The study draws on primary data collection conducted on-site in Uzhhorod, including topographic surveys, hydrogeological assessments, grid interconnection consultations with Ukrenergo, and engagement with the Gas Transmission System Operator of Ukraine (GTSOU) regarding the existing hydrogen pipeline infrastructure. Market intelligence was gathered through direct engagement with potential EU offtakers and benchmarking against comparable European green hydrogen projects. The financial model was stress-tested across multiple scenarios for electrolyser CAPEX, and hydrogen selling price to ensure robustness under varying market and risk conditions.

1.3. Market Context and Strategic Rationale for Ukrainian Green Hydrogen

The global hydrogen market is undergoing a structural transformation, with demand for low-carbon hydrogen projected to expand significantly over the coming decades as governments and industries pursue decarbonisation commitments. The European Union has established ambitious targets for renewable hydrogen production and import, with import corridors from neighboring regions forming a critical component of supply diversification strategy.

Ukraine presents a compelling answer to this demand signal. The country possesses some of the highest renewable energy resource endowments in Europe. Zakarpattia Oblast specifically benefits from proximity to existing high-voltage grid infrastructure and a direct physical connection — via the existing hydrogen-capable pipeline network operated by GTSOU — to the developing Central European Hydrogen Corridor (CEHC). The project site is located just 500 metres from the Uzhhorod gas compressor station, making it one of the most strategically positioned green hydrogen development sites in

Eastern Europe. Producing green hydrogen in Uzhhorod is therefore not speculative infrastructure development: it is the logical industrial application of Ukraine's comparative advantage in renewable energy, at the precise geographic intersection of production potential and European demand.

1.4. Key Findings and Viability Verdict

The analysis confirms that the development of an utility-scale green hydrogen facility in Zakarpattia is technically feasible and can be commercially viable, provided that the identified regulatory, infrastructure, and financing risks are adequately mitigated through public support mechanisms, phased implementation, and continued regulatory alignment with the EU framework. The project benefits from a strategically advantageous location, combining proximity to existing high-voltage electricity and hydrogen infrastructure and a potential future connection to the Central European Hydrogen Corridor (CEHC). These factors position the site as a credible platform for both domestic hydrogen deployment and future cross-border exports.

Based on a comprehensive evaluation of technical flexibility, operational performance, site constraints, and long-term economic efficiency, this study recommends the 422 MW PEM-based configuration as the preferred reference scenario for utility-scale implementation. The PEM configuration offers a strong combination of technology maturity and system flexibility, including rapid response to intermittent renewable power, a compact physical footprint compatible with the site's land-use and protection zones, and a modular architecture that supports phased deployment in line with the gradual development of offtake markets and export infrastructure. At the same time, Alkaline electrolysis remains a viable alternative option, subject to the confirmation of sufficient and sustainable water availability. The final feasibility of large-scale Alkaline deployment will depend on the results of further hydrogeological investigations and the operational performance of on-site production wells as the project advances. Should water availability be confirmed at scale, Alkaline technology could be considered as part of later development phases. The selected 422 MW scale provides a balanced approach between risk management and scale efficiency. It mitigates initial capital exposure while still capturing economies of scale, including improved unit economics across balance-of-plant, infrastructure, and grid connection components. In addition, continued cost reductions in electrolyser technology (driven by the introduction of higher-capacity stacks, manufacturing scale-up, and increased competition among OEMs) are expected to further improve project economics over the coming years. Equipment suppliers' growing willingness to offer more competitive commercial terms for large-scale projects also will reinforce this trajectory.

The study evaluated both PEM and AEL technologies across four capacity scales, yielding eight distinct technical scenarios. PEM electrolysis was selected as the preferred technology for the 422 MW reference scenario on four key grounds: superior dynamic response enabling rapid ramp-up and ramp-down with variable renewable electricity input; a significantly more compact physical footprint per installed MW, material given the site's land-use constraints; a modular stack architecture enabling staged commissioning aligned with the phased commercial development pathway; and active OEM competition among major European suppliers which already generating cost reduction pressure on large-scale supply contracts. Alkaline electrolysis, with its lower system CAPEX per MW at equivalent scale, remains a viable alternative for later phases, contingent on confirmation of large-scale water availability through ongoing hydrogeological studies.

1.5. Phased Development Roadmap

A core structural conclusion of this study is that phased implementation is not merely a risk management tool — it is the fundamental value creation strategy for the project. The development roadmap proceeds in four clearly defined stages, each financially ring-fenced to enable staged capital mobilisation and protect early investors from downstream development risk.

Phase 1 — Pilot (2 MW, target commissioning 2027): The initial phase establishes operational proof-of-concept under Ukrainian conditions and creates a regulatory precedent within the Ukrainian permitting system. This phase will generate the first RFNBO-certified hydrogen output from Ukraine, establish the project's health, safety, and environmental management systems, and initiate structured stakeholder engagement with local communities and regulatory bodies. Hydrogen demand for this phase has already been pre-contracted with customers in Eastern Slovakia, with logistics based on pressurised gas containers and, in an initial phase, metal hydride storage solutions. Capital grant support is expected to be required to enable implementation at this stage.

Phase 2 — Commercial Demonstration (20 MW, target commissioning 2028): The second phase scales the facility to a level sufficient to support the first binding offtake contracts and generate bankable operational performance data for project financiers. At this scale, the project becomes eligible for project finance from IFIs and development banks, and the operational track record de-risks the subsequent scale-up for commercial lenders. This phase also coincides with the preparation of the Front-End Engineering Design (FEED) study required for the Final Investment Decision (FID) on Phase 3.

Phase 3 — Pre-Utility Scale (100 MW, target commissioning 2030): The third phase marks the transition to industrial-scale hydrogen production, with pipeline-based logistics becoming the primary delivery mechanism. At 100 MW, the project reaches the scale at which CAPEX unit economics become competitive — total CAPEX per kWel drops significantly compared to earlier phases — and the facility becomes a credible anchor for long-term, bankable offtake agreements with EU industrial customers. This phase is designed to coincide with the commissioning of the first operational segment of the Central European Hydrogen Corridor (CEHC) connecting Velke Kapusany to Košice.

Phase 4 — Utility Scale (300 MW additional capacity, target commissioning 2032, total H_2HUB: 422 MW): The final phase completes the full 422 MW H_2HUB configuration, bringing total annual RFNBO-grade hydrogen output to approximately **42,800 tonnes per year** — representing approximately 40% of the minimum throughput requirement of the full CEHC. This phase is contingent on the commissioning of the complete CEHC, the execution of sufficient long-term offtake agreements to support project finance, and the finalisation of the Ukrainian regulatory framework for hydrogen certification and grid injection.

1.6. Summary of Financial Projections

For the recommended 422 MW PEM scenario, the financial analysis projects a total installed capital cost (CAPEX) of approximately €1,109/kWel — competitive with European benchmarks and reflecting Ukraine's lower construction and labour cost base. At full capacity, annual output is estimated at approximately 42,800 tonnes of RFNBO-grade hydrogen per year, representing approximately 40% of the minimum throughput requirement of the Central European Hydrogen Corridor. The base case undiscounted LCOH (Year 5) for the 422 MW PEM configuration is 6.7 EUR/kg, with the full scenario range across all technology and scale configurations spanning 6.3 to 9.4 EUR/kg. These figures are presented on an undiscounted basis: given Ukraine's currently elevated war-related cost of capital, applying a conventional discount rate would materially increase the effective LCOH. It must be stated plainly: without access to public support instruments — including concessional debt, first-loss guarantees, or production subsidies — large-scale green hydrogen production in Ukraine is not commercially viable at current electricity prices and capital costs. The project's business case is built on the premise that blended public-private financing, combined with post-war reductions in electricity costs and continued electrolyser CAPEX decline, will progressively improve project economics through the development phases.

Sensitivity analysis confirms that LCOH is most sensitive to electricity price, number of full load hours (capacity factor), and total CAPEX — in that order. Under the base case electricity sourcing strategy — combining on-site PV, wind PPA, and day-ahead market procurement targeting a 60% capacity factor — the model confirms production economics consistent with anticipated EU hydrogen import price trajectories from 2030 onwards.

1.7. Critical Success Factors and Major Risks

The project's success hinges on several critical factors:

1. **Securing Bankable Offtake:** Converting the existing Letter of Intent (LoI) with Orlen and securing further long-term, bankable offtake agreements are paramount to guaranteeing revenue streams.
2. **Timely CEHC Development:** The project's utility-scale viability is directly tied to the commissioning of the Central European Hydrogen Corridor (CEHC) on its planned schedule (2032).
3. **Ukrainian Regulatory Reform:** The successful implementation of a clear, EU-aligned legal and normative framework for hydrogen production, grid injection, and certification in Ukraine is essential.
4. **Access to Concessional Finance:** A blended financing strategy involving IFIs and risk mitigation instruments is necessary to overcome the high Weighted Average Cost of Capital (WACC) in Ukraine. [6]

The most significant risks identified are ongoing military conflict and the destruction of the country's energy system, potential delays in the first development stages of the CEHC, regulatory uncertainty within Ukraine, and the high cost of capital deterring purely commercial investment. Additional material risks include: the slow development of EU hydrogen demand driven by delayed transposition of RED III into national law; sourcing sufficient water for Alkaline electrolysis configurations above 100 MW; the requirement for an upfront grid capacity reservation payment of approximately €10k/MW at an early development stage; and the dependence of full-scale grid connection on the construction of a new 400/110 kV substation by Ukrenergo, which carries implementation risk due to war-related infrastructure damage.

Community Engagement and Social License: Beyond technical and financial prerequisites, the project's long-term resilience depends on maintaining a robust social license to operate. Proactive and transparent community engagement, local employment commitments, and alignment with regional development priorities – including coordination with the Uzhhorod City Council and the Zakarpattia Oblast Military Administration – will be essential. The project also incorporates a Community Water Supply Initiative: surplus capacity from the on-site wells is planned to enable future connection of domestic potable and firewater supply for nearby villages, improving public health outcomes and strengthening stakeholder acceptance through equitable access to reliable water infrastructure.

1.8. H2Uppp Deliverables and Market Impact

In alignment with the objectives of the H2Uppp program, this study delivers more than a project-specific analysis. It provides a suite of replicable templates for key permitting documents, including the, Strategic Ecological Analysis (SEA), and an IFI-compliant Environmental Impact Assessment (EIA). Furthermore, it includes a detailed analysis of regulatory gaps and barriers, along with actionable recommendations for reform. These deliverables are designed to serve as a public good, de-risking the development process and reducing costs for all subsequent green hydrogen projects in Ukraine, thereby accelerating the growth of the entire sector. [37]

1.9. Strategic Recommendations and Next Steps

Based on the findings of this study, the following immediate actions are recommended:

1. For N1Capital: Prioritise the finalisation of a binding offtake agreement for the pilot phases (2 MW + 20 MW) and implement a pilot project (an electrolysis plant with an electrical capacity of 5MW) as well as Pre-FEED study that would support the FID for scaling up to 100MW. [73]
2. For Ukrainian Stakeholders: Utilise the regulatory analysis and templates from this study to inform the legislative process, focusing on creating a dedicated hydrogen law that aligns with EU standards and streamlines permitting.
3. For Project Development: Advance the project to the Front-End Engineering Design (Pre-FEED) stage for the recommended 100 MW PEM scenario, while simultaneously progressing the final stages of the grid and hydrogen interconnection studies with Ukrenergo and the Gas Transmission System Operator of Ukraine (GTSOU).

2. Strategic Context and Market Analysis

This section establishes the comprehensive market rationale for the Zakarpattia Green Hydrogen Project. It analyses the powerful demand-pull from the European Union's decarbonisation agenda and the unique supply-push potential of Ukraine, connected by the strategic Central European Hydrogen Corridor.

2.1. The Global and European Hydrogen Imperative

2.1.1. Decarbonisation Drivers and Policy Landscape

The European Union has established one of the world's most ambitious climate policy frameworks, creating a powerful regulatory driver for the rapid scale-up of a green hydrogen economy. The 'Fit for 55' package legally mandates a 55% net reduction in greenhouse gas emissions by 2030 compared to 1990 levels. This objective was further reinforced by the REPowerEU plan, which seeks to rapidly reduce dependence on Russian fossil fuels and accelerate the clean energy transition. [4]

Central to these strategies is the revised Renewable Energy Directive (RED III), which entered into force in 2023. RED III introduces legally binding targets for the use of Renewable Fuels of Non-Biological Origin (RFNBOs), of which green hydrogen is the primary example. The directive sets specific sub-targets for RFNBO consumption in the transport and industrial sectors, compelling hard-to-abate industries like refining, steel, and chemicals to procure green hydrogen. This policy architecture transforms the demand for green hydrogen from speculative to legally mandated, creating a secure and predictable market for producers who can meet the EU's stringent sustainability criteria. [10]

2.1.2. EU Hydrogen Demand and Import Targets

To meet its decarbonisation goals, the REPowerEU strategy quantifies the EU's hydrogen ambition with explicit targets for 2030: 10 million tonnes (Mt) of domestic renewable hydrogen production and 10 Mt of renewable hydrogen imports. The 10 Mt import target is a direct market signal to potential exporting regions, acknowledging that domestic EU production alone will be insufficient to meet the projected demand from industry and transport. This import dependency creates a significant commercial opportunity for countries with high renewable potential and strategic proximity to the EU, a category where Ukraine is uniquely positioned.[35]

2.1.3. Competitive Landscape for EU Hydrogen Supply

The race to supply the EU's hydrogen market is intensifying globally. Ukraine faces competition from several regions, each with distinct advantages. North African countries like Morocco and Egypt are developing large-scale projects, leveraging exceptional solar resources and established energy partnerships with EU member states. The Middle East, particularly Oman, is also positioning itself as a major exporter. [13]

However, Ukraine's competitive advantage lies in its geographical proximity and its direct connection to the EU's energy infrastructure via land-based pipelines. While competitors in North Africa and the Middle East will largely rely on seaborne transport of hydrogen derivatives like ammonia, which involves costly conversion and reconversion processes, Ukraine can potentially deliver pure gaseous hydrogen directly into the heart of Europe at a lower transport cost. This advantage is compounded by the technological and cost competition from China, whose manufacturers are driving down electrolyser prices, making it imperative for European projects to optimise every aspect of their value chain, including transport logistics. [7]

2.2. The Central European Hydrogen Corridor (CEHC): The Gateway to Market

2.2.1. CEHC Overview and Strategic Importance

The Central European Hydrogen Corridor (CEHC) is the critical infrastructure that underpins the entire business case for exporting Ukrainian hydrogen. It is a joint initiative launched in 2021 by four major gas Transmission System Operators (TSOs): Gas TSO of Ukraine (GTSOU), Eustream (Slovakia), NET4GAS (Czechia), and Open Grid Europe (OGE, Germany). The vision is to create a dedicated hydrogen "highway" to transport large volumes of hydrogen from the production centers in Ukraine to the industrial demand hubs in Central Europe. The project's location in Uzhhorod, merely 7 km from the Slovakian border and in close proximity to the key Chaslivtsi gas compressor station, is a decisive geographical advantage that minimises the cost and complexity of the "last mile" connection to this continental pipeline. [15] [17]

2.2.2. Technical Specifications and Timeline

Pre-feasibility studies for the CEHC have confirmed its technical viability. The corridor is designed to transport up to 144 GWh of hydrogen per day, equivalent to approximately 1.5 million tonnes per year, which would satisfy 15% of the EU's 2030 import target. A key element of the CEHC's cost-competitiveness is its plan to repurpose over 90% of the existing natural gas pipeline network. This approach drastically reduces the required investment compared to building new infrastructure, with the estimated cost for the 1,225 km section from the Ukrainian border to Germany being a relatively low 1.0-1.5 billion EUR. This results in a projected levelised cost of transmission in the range of 0.10 - 0.15 EUR/kg per 1,000 km, placing it at the lower end of European estimates and enhancing the competitiveness of Ukrainian hydrogen. The project is slated for commissioning by 2030, with initial sections becoming operational earlier. [18]

2.2.3. PCI/PMI Status and Implications

The strategic importance of the CEHC has been officially recognised by the European Commission through its inclusion in the first list of Projects of Common Interest (PCIs) and Projects of Mutual Interest (PMIs). This status is a significant de-risking factor for the entire value chain. It provides several advantages, including access to streamlined and accelerated permitting procedures across member states, improved regulatory conditions, and eligibility to apply for financial support from the EU's Connecting Europe Facility (CEF). For the Zakarpattia project, the PCI status of its export route provides greater certainty to investors and offtakers that the physical pathway to market will be realised in a timely manner. [19]

2.3. Ukrainian Hydrogen Potential and National Strategy

2.3.1. Resource Endowment

Analysis of Ukraine's and Zakarpattia's Energy Market: Role of Hydrogen and Expected Impact.

2.3.1.1. Overview of Ukraine's Energy System

Ukraine's energy system is undergoing a profound transformation shaped by long-term strategic shifts, wartime challenges, and integration into the European energy framework. Historically reliant on centralised and fossil-based generation, the system today is transitioning toward a more diversified, decentralised, and climate-resilient model.

2.3.1.2. National Generation Structure and Regional Distribution

Ukraine operates a multifaceted mix of power generation technologies, including nuclear, thermal (coal and gas), hydropower, and an expanding share of renewable sources such as solar and wind energy. Nuclear power remains the single largest contributor, accounting for approximately 50% of total electricity production. Key nuclear facilities are located in Zaporizhzhia(currently under temporary occupation and not contributing to the Ukrainian power system), Rivne, and Khmelnytskyi regions, which collectively form the backbone of baseload generation.

Thermal power plants, concentrated in the eastern and southern oblasts, continue to play a critical role in load balancing but face growing decarbonisation pressure. Hydropower – distributed along the Dnipro River basin – adds operational flexibility, especially during peak load periods and emergency grid balancing.

Wind energy, with installed capacity exceeding 1.7 GW, is mostly deployed in southern Ukraine, notably in Mykolaiv, Zaporizhzhia(currently under temporary occupation), and Odesa, where average wind speeds exceed 7 m/s at hub height. Solar photovoltaics (PV) have seen particularly rapid growth, reaching over 8.7 GW of capacity by early 2024.

2.3.1.3. National Transmission Infrastructure

All generation assets are linked through a high-voltage transmission system (220–750 kV), operated by the national TSO Ukrenergo. This network not only ensures internal stability and load distribution but also provides interconnection with neighbouring countries through synchronisation with ENTSO-E. The grid's topology reflects historic east-to-west energy flow patterns, though new decentralisation trends are reshaping this orientation.

Figure 2-1: Combined renewable energy generation: wind turbines and solar PV in Ukraine [160]

Figure 2-2: Electricity generation and transmission map of Ukraine, showing power plant types and high-voltage lines [161]

2.3.1.4. Role of Renewables and National Solar Capacity

Over the past decade, renewable energy – particularly solar photovoltaics (PV) – has evolved into a strategic pillar of Ukraine's energy transition. As of early 2024, total installed solar capacity exceeded 8.7 GW, positioning solar PV as the largest non-hydro renewable energy source in the country. This reflects not only strong domestic and foreign investment, but also policy support, such as green tariffs and more recently, the introduction of market-oriented feed-in premium schemes. [65]

Solar development in Ukraine has followed a dual-track pathway: large-scale, utility-connected PV parks on the one hand, and decentralised, behind-the-meter systems for businesses and households on the other. While southern oblasts such as Odesa, Mykolaiv, Dnipropetrovsk, and Zaporizhzhia remain dominant due to their high solar irradiance levels, significant capacity has also been deployed in central and even northern regions, demonstrating the technology's adaptability to diverse climatic conditions.

Figure 2-3: Top utility-scale solar power plants in Ukraine, including regional distribution and installed capacity (MW) [162]

Some of the largest and most technologically advanced solar PV plants in Ukraine include:

- Pokrovska SPP (240 MW, Dnipropetrovsk Oblast) – one of the largest in Eastern Europe, using bifacial modules and centralised inverter architecture.
- Primorska SPP (200 MW, Zaporizhzhia Oblast) – developed with international financing and integrating SCADA-based performance monitoring.
- Nikopol SPP (150 MW, Dnipropetrovsk Oblast) – built on a reclaimed industrial site, showcasing successful land-use conversion for clean energy.
- Ternovytsia SPP (~100 MW, Lviv Oblast) – among the largest in western Ukraine, demonstrating the westward expansion of utility-scale solar.

The geographic distribution of these utility-scale plants is closely linked to the solar irradiance potential across Ukrainian territory. According to the Global Solar Atlas, Global Horizontal Irradiance (GHI) levels in the southern and southeastern oblasts reach 1,300–1,400 kWh/m²/year, providing optimal conditions for high-yield PV generation. Even in western and northern oblasts, GHI levels in the range of 1,100–1,250 kWh/m²/year are sufficient for bankable projects using modern, high-efficiency modules.

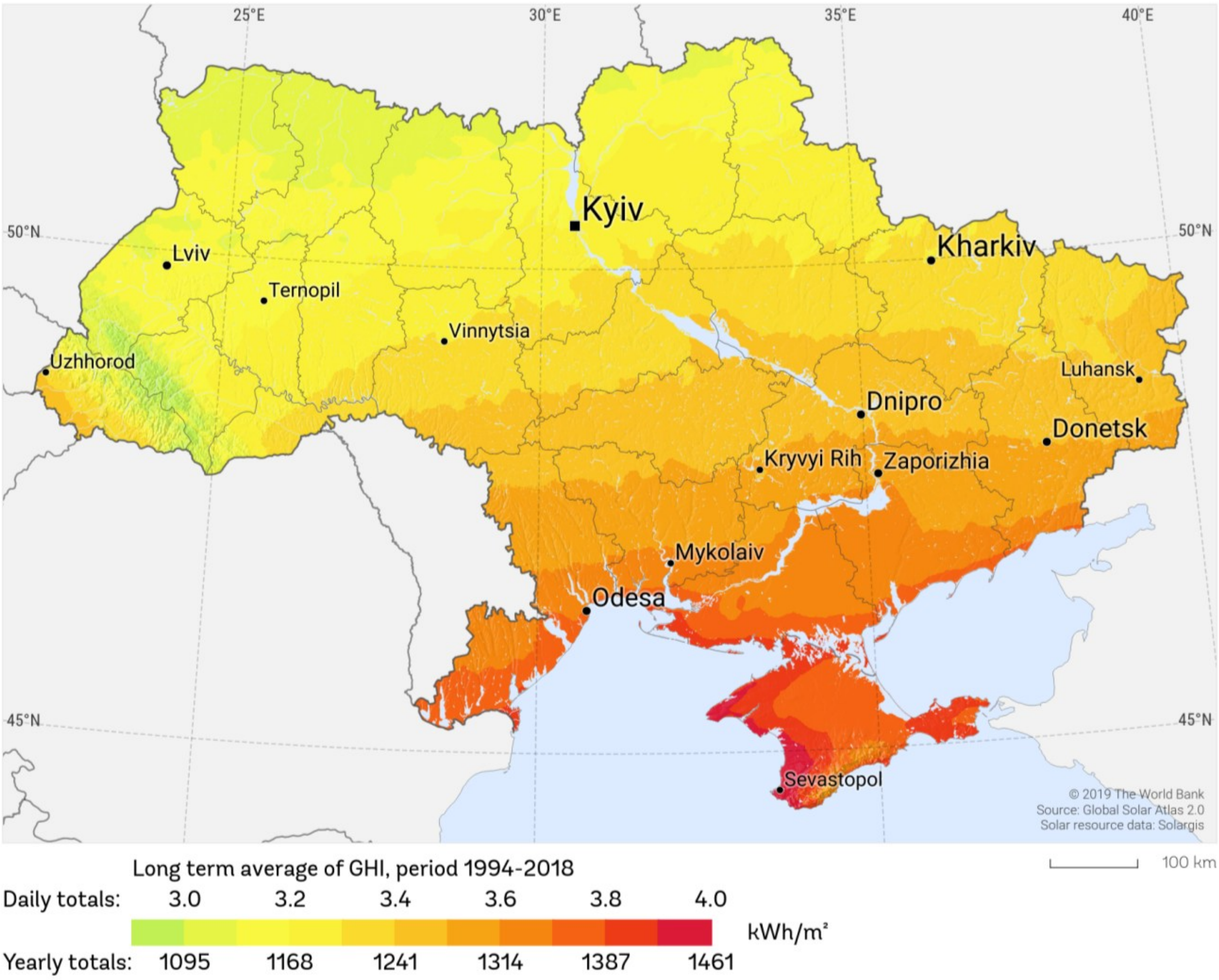


Figure 2-4: Global Horizontal Irradiation map of Ukraine, highlighting solar resource intensity by region [163]

From a technological standpoint, Ukraine's solar sector has rapidly adopted bifacial modules, single-axis tracking systems, and advanced digital monitoring platforms. These innovations have improved capacity factors and reduced the levelised cost of electricity (LCOE), even in regions with moderate irradiance.

Despite wartime disruptions and regulatory uncertainty, solar PV continued to expand in 2023-2024, particularly in the form of distributed generation for self-consumption. According to market data, over 800 MW of new capacity was added in 2024 alone, much of it installed on rooftops of commercial and industrial facilities or via modular ground-mounted systems.

This diversified solar portfolio not only contributes to Ukraine's decarbonisation objectives but also enhances energy resilience, especially in conflict-affected areas and grid-challenged regions. Moreover, solar infrastructure offers synergy with hydrogen production, battery storage, and local energy communities – key components of Ukraine's post-war recovery and long-term energy strategy.

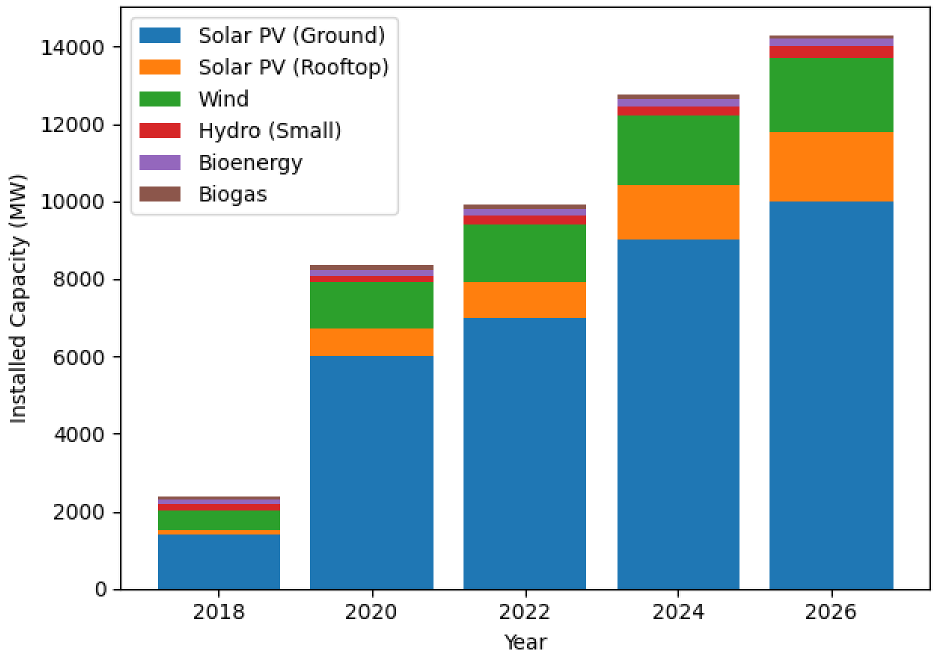


Figure 2-5: Installed Renewable Energy Capacity in Ukraine by Source (2018-2026, approx.)

2.3.1.5. Strategic Implications and European Integration

For Ukraine, this energy transition is both a strategic imperative and a recovery opportunity. Damage inflicted on legacy generation infrastructure due to war has accelerated modernisation efforts. At the same time, Ukraine's path to EU energy market integration – including adherence to the REPowerEU plan, the European Hydrogen Backbone, and the Paris Agreement – necessitates a fundamental realignment of the power system toward clean and flexible generation. [9]

Green hydrogen, produced via electrolysis from domestic renewables, is central to this strategy. It offers synergies with decarbonisation goals, enhances energy independence, and provides a scalable export product aligned with European demand trends. Regions such as Zakarpattia, with decentralised energy potential and direct access to EU markets, are uniquely positioned to pilot such innovation.

Additionally, renewable energy projects in western Ukraine benefit from simplified permitting regimes introduced during martial law, as well as financial and technical cooperation frameworks with European partners. These include access to investment instruments, guarantees, and capacity-building programs, further enabling infrastructure development in border regions.

2.3.1.6. Energy Situation in Zakarpattia

Zakarpattia Oblast occupies a strategically important position in the western part of Ukraine, bordering Hungary, Slovakia, and Romania. This region serves not only as a cross-border corridor for gas and electricity, but is also increasingly becoming a key node in the national energy system, particularly in light of Ukraine's shift toward decentralised and resilient energy models.

Traditionally, electricity supply in Zakarpattia has relied on imported power from the main Ukrainian grid via 400 kV, 220 kV, and 110 kV transmission lines. Major high-voltage connections run through Chop, Batyovo, and Dobron, serving both as transit corridors and regional distribution hubs. Several large nodal 110/35/10 kV substations operate in Uzhhorod, Mukachevo, Volovets, and Khust, with the Uzhhorod hub functioning as the central dispatch node for regional load balancing.

To reinforce this backbone, a large-scale upgrade program is underway. In 2023-2024, construction of a new 400/110 kV substation in Uzhhorod with 500 MVA capacity was initiated. This facility is part of Ukrenergo's broader effort to align Ukraine's transmission system with the ENTSO-E European network. Reconstruction of the 400 kV Mukachevo-Veľké Kapušany interconnection line is also planned, which will boost cross-border transmission capacity to 1 GW, contributing to the national target of 6 GW by 2030. [11]

Figure 2-6: High-voltage transmission network in Zakarpattia and interconnection points with Slovakia and Hungary

2.3.1.7. Rise of Distributed and Renewable Generation

In parallel with central grid modernisation, Zakarpattia has emerged as a leader in distributed renewable energy. As of early 2024, over 4,800 private households had installed rooftop PV systems, contributing ~138 MW of capacity. During peak sunshine in summer, this sector alone supplies up to 31% of the oblast's electricity demand (typical load: 250–300 MW). These installations are supported by local government rebate programs totaling up to 35 million UAH annually.

On the commercial side, more than 65 enterprises operate industrial-scale solar PV plants, with a combined capacity of around 244 MW, bringing the oblast's total solar capacity to over 380 MW. This helps balance daytime load and reduces reliance on imported electricity.

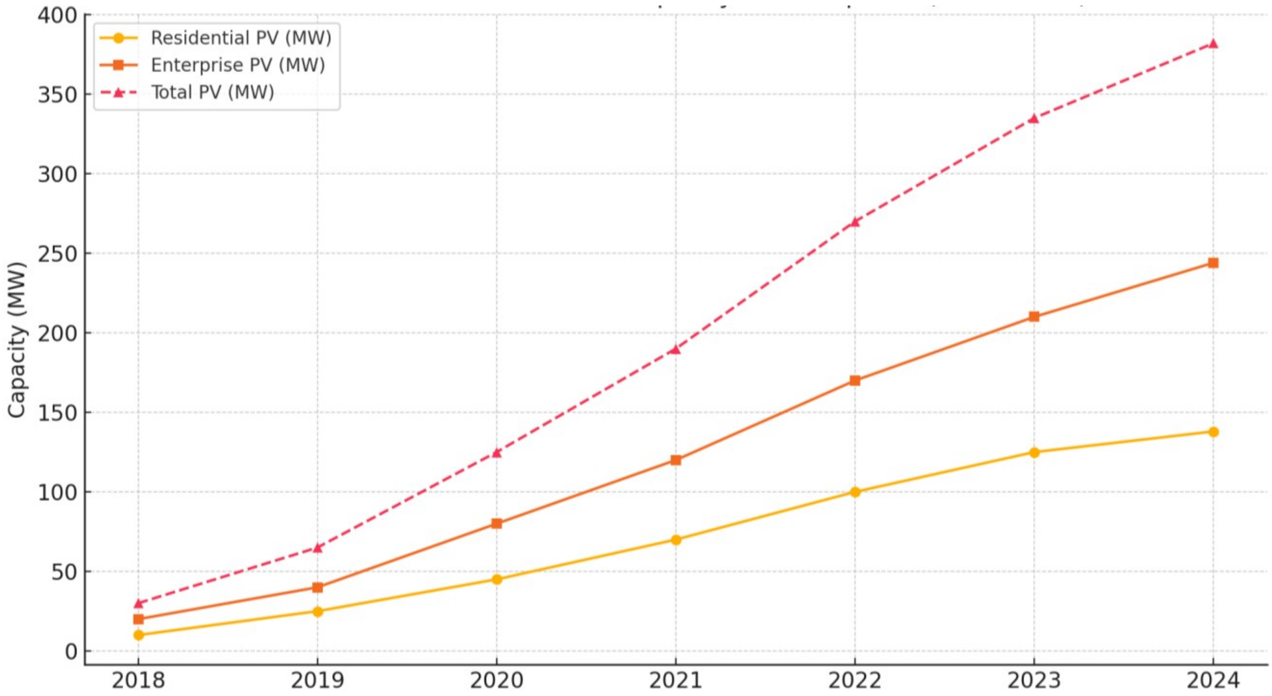


Figure 2-7: Growth of Installed Solar PV Capacity in Zakarpattia (2018–2024)

2.3.1.8. Emerging Wind and Hydro Capacity

In 2022, Zakarpattia launched its first high-altitude wind turbine near Nyzhni Vorota (4.8 MW), followed by a second unit in 2024 (5.2 MW). These facilities mark the beginning of wind energy development in the Carpathian foothills, where conditions are suitable for medium-scale wind systems.

In addition, over a dozen micro-hydro plants (100 kW to 5 MW) operate on local rivers, providing clean energy to remote settlements where grid expansion is economically unfeasible. These plants are vital for rural energy access and seasonal balancing during spring runoff.

2.3.1.9. Toward Regional Energy Self-Sufficiency

With its growing mix of decentralised generation, Zakarpattia is among the few oblasts in Ukraine capable of balancing internal electricity demand during favourable weather conditions (especially spring/summer). However, in winter months, the region still relies on imports from central and southern grids, which highlights the importance of firm backup capacity such as gas-fired generators or battery energy storage systems (BESS).

Zakarpattia is rapidly transforming from an import-dependent border region into a resilient, semi-autonomous energy territory balanced in terms of generation and consumption. This enhances energy security for its residents and creates the potential to export surplus clean electricity to neighbouring EU countries – a key step toward Ukraine's long-term integration into the European power system.

2.4. Decarbonisation Policy and the Potential of Renewable Energy Sources (RES)

2.4.1. National Climate and Energy Policy of Ukraine

Ukraine is steadily advancing toward a sustainable, low-carbon, and decentralised energy system. The foundation of its current climate and energy policy is the National Energy and Climate Plan (NECP) through 2030, and the updated Nationally Determined Contribution (NDC) submitted under the Paris Agreement.

According to these frameworks, Ukraine commits to:

- Reduce greenhouse gas (GHG) emissions by 65% compared to 1990;
- Achieve a minimum 27% share of renewable energy sources (RES) in final energy consumption by 2030;
- Improve energy efficiency across all sectors;
- Continue integration into the European ENTSO-E power system and reform domestic energy markets. [48]

Technology	2024 Installed (approx.)	2030 Target (MW)	Δ Capacity (MW)
Solar PV (Utility + Rooftop)	~7,300 MW	12,200 MW	+4,900 MW
On-shore Wind	~512 MW	6,214 MW	+5,702 MW
Off-shore Wind	–	100 MW	New
Bioenergy (Biomass + Biogas)	~319 MW	876 MW	+557 MW
Geothermal	–	40 MW	New

Table 2-1: National RES Capacity Targets by 2030

The NECP, officially approved by the Cabinet of Ministers in June 2024, is a binding national document under Ukraine's membership in the Energy Community. Its development involved the Ministry of Energy, Ministry of Economy, Ministry of Environment, and was supported by the EU, IEA, and expert groups including DiXi Group and Low Carbon Ukraine.
To operationalise these goals, Ukraine has established clear capacity targets across all major renewable energy technologies. These targets reflect both domestic decarbonisation priorities and compliance with EU directives under the Energy Community Treaty. [5]

2.4.2. RES Potential in Ukraine and the Zakarpattia Region

Ukraine possesses substantial technical and economic potential for expanding its renewable generation. According to the Institute of Renewable Energy of the National Academy of Sciences of Ukraine, the theoretical RES potential exceeds 70% of the country's total electricity demand.
Zakarpattia Oblast stands out for its geographic and natural diversity, offering a unique mix of solar radiation, wind flows, and water resources. These conditions create favorable prospects for all major forms of renewable generation:

- **Solar Energy:** With average annual irradiation of 1,200–1,400 kWh/m², the region supports both rooftop and ground-mounted photovoltaic (PV) systems. As of early 2024, total installed solar capacity exceeded 380 MW, including ≈138 MW from residential systems and ≈244 MW from commercial installations.
- **Wind Energy:** Mountain ridges in Volovets and Velykyi Bereznyi districts feature average wind speeds above 6.5 m/s at 100 m height. This enables large-scale wind projects, such as the Ostrovsky Wind Farm (planned up to 80 MW). The estimated technical wind potential of the region is 300–500 MW.
- **Small Hydropower:** With a river network exceeding 9,000 km, Zakarpattia has considerable potential for micro-hydro development. Existing and planned small hydro plants (100 kW to 5 MW) provide localised power to rural and mountainous communities with minimal environmental disruption.
- **Biomass and Biogas:** The forestry and agricultural sectors produce a significant volume of organic waste that can be used for biomass-fired heating and small-scale distributed cogeneration. Additionally, municipal biogas projects are being considered for organic waste processing and energy recovery.

2.5. Hydrogen Infrastructure Prospects

2.5.1. Strategic Role of Hydrogen in Ukraine's Energy Transformation

Hydrogen is increasingly recognised as a key enabler of energy system decarbonisation and resilience – both in Ukraine and across Europe. As the country works to rebuild and modernise its energy infrastructure, hydrogen offers a unique opportunity to serve as a dispatchable, controllable load that can absorb surplus renewable generation, provide demand-side flexibility, and stabilise the grid during peak demand or intermittency. [27]
In this context, the proposed hydrogen production facility in Uzhhorod – located in close proximity to upgraded high-voltage infrastructure and abundant solar potential – represents a strategic pilot hub. It can serve local energy balancing needs and support Ukraine's integration with the European hydrogen market, particularly through Slovakia. [30]

2.5.2. Hydrogen as an Export-Enabling Vector

Due to its border location and proximity to Slovakia, the Uzhhorod hydrogen facility is well-positioned to deliver green hydrogen to the EU. The Central European Hydrogen Corridor (CEHC) initiative foresees connection points at Veľké Kapušany-Kosice, with commercial commissioning expected by 2028-2029. [20]

Ukraine is currently working with Eustream, the GTSUA, and the EU Commission to prepare regulatory and physical infrastructure for this purpose. The Uzhhorod project could supply over 100 kt/year of RFNBO-compliant hydrogen, meeting minimum offtake volumes required by EU downstream partners. [116]

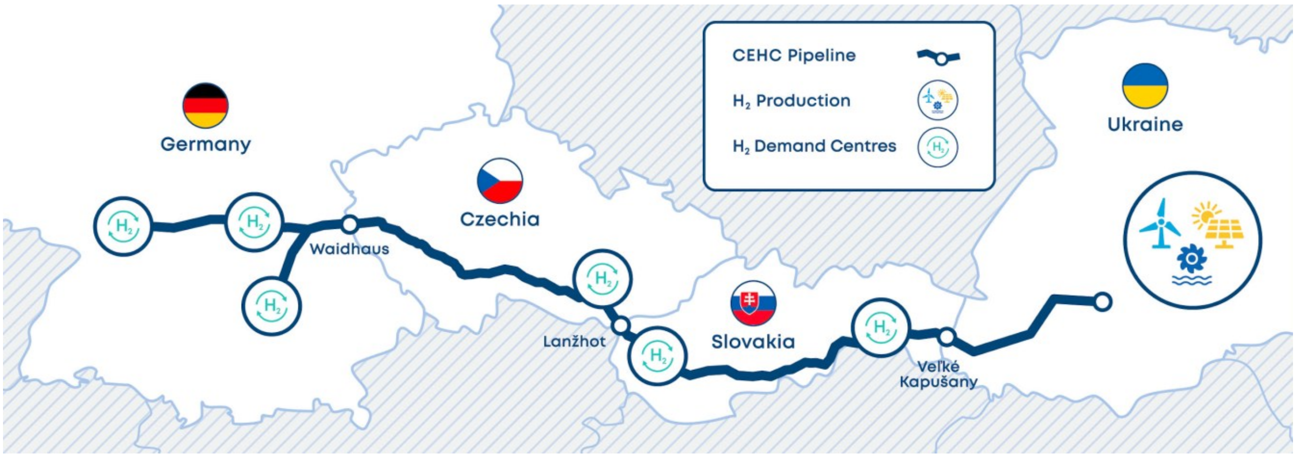


Figure 2-8: Central European Hydrogen Corridor (CEHC) and Uzhhorod Export Node [14]

2.5.3. PV+BESS Integration for Dispatchability

A core component of the infrastructure strategy involves PV+BESS systems optimised for hydrogen production. The energy architecture includes:

- Vertically mounted bifacial PV arrays (East/West orientation) to extend generation into morning/evening hours,
- Redox flow or Li-ion batteries provide load shifting, peak shaving, and buffering during cloudy conditions,
- SCADA + EMS control systems enabling real-time demand response and curtailment avoidance.

This setup enhances the plant's ability to operate during high-peak grid hours, reduce Levelised Cost of Hydrogen (LCOH), and qualify for RFNBO certification under EU regulations.

2.5.4. Project Effects: Regional and National Benefits

The implementation of a green hydrogen production facility in Uzhhorod is expected to generate substantial regional, national, and cross-border benefits – economic, environmental, technological, and geopolitical. This section outlines both the direct and indirect impacts of the project, grounded in modelling results, local data, and alignment with Ukraine's post-war recovery and European integration strategies. [32]

2.5.5. Regional Socio-Economic Development

Zakarpattia is a historically under-industrialised region with high emigration rates and limited access to modern infrastructure. The hydrogen project brings immediate and long-term socio-economic benefits, including:
Job creation: Up to 250 direct jobs during construction and 80-100 permanent operational positions across engineering, operations, and maintenance.
Supply chain stimulation: Opportunities for local civil engineering, logistics, construction, water/wastewater systems, and metalwork industries.
Education and workforce development: Cooperation with vocational and technical institutions in Uzhhorod and Mukachevo to train local specialists in renewable energy, electrolysis, and automation systems.
Municipal co-benefits: Investment in electricity, water, and wastewater infrastructure, some of which will directly benefit nearby communities currently lacking centralised services.

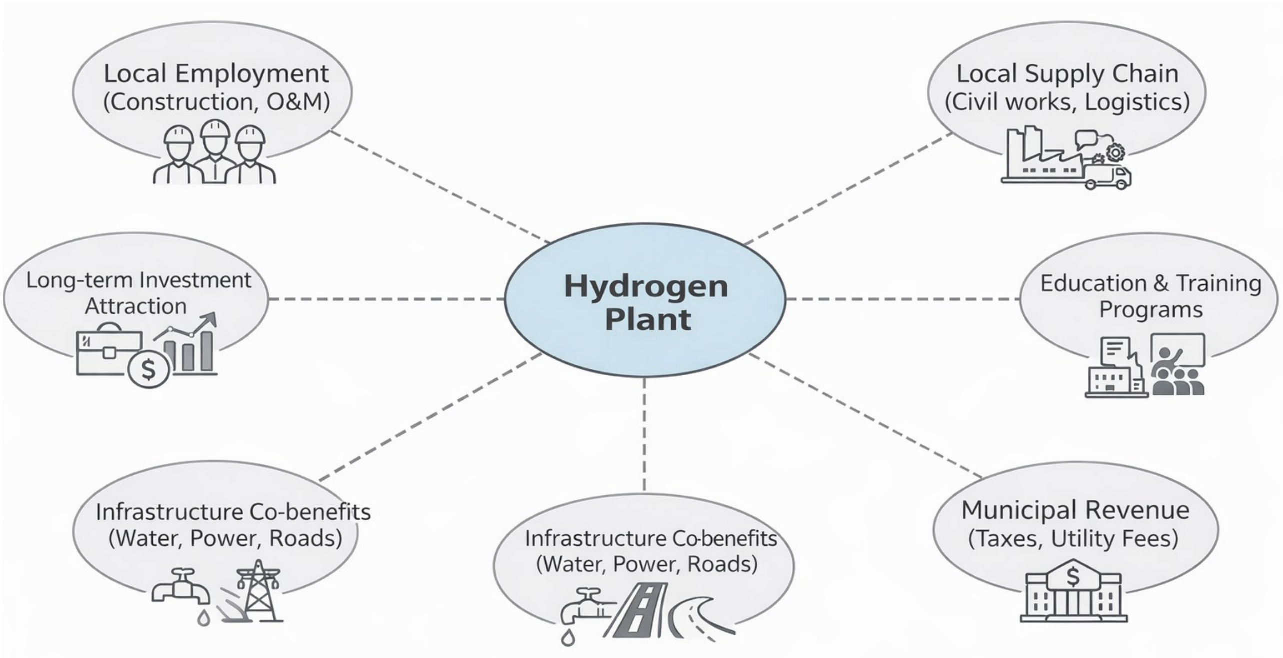


Figure 2-9: Regional economic multiplier effect from hydrogen project investments

2.5.6. Energy Resilience and Decentralisation

The project enhances energy stability in western Ukraine by:

- Reducing dependency on electricity imports during peak demand periods,
- Allowing island mode operations with PV+BESS in emergency scenarios,
- Enabling load balancing and curtailment reduction for Zakarpattia's growing renewable fleet,
- Strengthening the Uzhhorod and Mukachevo energy hubs, which are already key in cross-border power exchange.

This aligns with Ukraine's national goal of improving resilience through decentralised, renewable-driven infrastructure – especially relevant under martial law and wartime grid disruptions.

2.5.7. Contribution to National Climate Targets

The facility directly supports Ukraine's National Energy and Climate Plan (NECP) and Updated Nationally Determined Contribution (NDC) by:

- Enabling the production of low-emission hydrogen for domestic decarbonisation in transport, industry, and heat;
- Unlocking renewable electricity utilisation through flexible electrolyser loads;
- Substituting imported fossil fuels in high-value sectors;
- Providing a compliant product for EU RFNBO certification under RED II and III.

Hydrogen Type	CO_2 Emissions (kg CO_2/kg H_2)
Grey H_2 (SMR without CCS)	~9–10
Blue H_2 (SMR with Carbon Capture)	~3.7–6.2
Green H_2 (Electrolysis with 100% RES)	~0–1
Electrolysis with Grid Electricity (EU avg, 2022)	~20–25

Table 2-2: CO_2 Emissions per ton of hydrogen

2.5.8. Strategic Role in EU Integration and Export

The hydrogen project is a gateway initiative for Ukraine's future participation in the European hydrogen economy:

- It is aligned with the CEHC (Central European Hydrogen Corridor) and slated to connect via Veľké Kapušany-Košice by 2028-2029. [25]
- It meets export thresholds of 100 kt/year required by European offtakers such as Wien Energie, Slovnaft, Orlen, Veolia;
- It accelerates regulatory harmonisation and technical interoperability with EU hydrogen and energy systems.

This elevates Ukraine's position from energy consumer to renewable energy and hydrogen exporter – with significant geopolitical and economic upside.

2.5.9. Environmental and Public Health Co-Benefits

Beyond GHG reduction, the hydrogen plant will improve local conditions by:

- Minimizing air pollution (no particulate matter or NOx emissions),
- Encouraging sustainable land use (e.g., dual-use PV over agricultural land),
- Reducing reliance on diesel generators in isolated areas.

Together, these factors contribute to clean air, climate resilience, and rural revitalisation.

2.5.10. National Hydrogen Strategy

While the full-scale Russian invasion has delayed its finalisation, Ukraine's draft Hydrogen Strategy, published by the Ministry of Energy in early 2024, outlines a clear, phased roadmap for market development. The strategy aligns with EU objectives and prioritises green hydrogen for both domestic decarbonisation and export. [16]

- **Short-term (2022-2025):** Focuses on establishing the foundational legal and regulatory framework, strengthening partnerships with potential EU offtakers, and preparing the gas transport system for hydrogen blending and transport.
- **Medium-term (2026-2030):** Envisages the scaling up of electrolysis capacity to serve both export and growing domestic demand.
- **Long-term (2030-2050):** Aims for Ukraine to become a major hydrogen hub for Europe, transitioning its gas grid to pure hydrogen transport. [23]

This study and its deliverables directly support the goals of the short-term phase by identifying legal barriers and providing templates to accelerate development.

2.5.11. Current Project Pipeline

The N1C projects in Uzhhorod (400 MW) and Mukachevo (200 MW) are at the forefront of Ukraine's emerging hydrogen sector. They are part of a growing pipeline of projects in Western Ukraine, including a 100 MW project by Ecooptima and Austria's RAG AG in Lviv Oblast and a 100 MW plant by Hydrogen Ukraine, also in Zakarpattia. By being one of the first utility-scale projects to undergo a rigorous, IFI-compliant feasibility study, the Uzhhorod project is positioned to serve as a pathfinder. The H2Uppp-funded templates and regulatory analysis generated by this study will directly benefit these other projects, creating a multiplier effect and contributing to the rapid maturation of the entire Ukrainian hydrogen market.

2.6. Potential Offtake Markets and Demand Analysis

A critical element of the project's de-risking strategy is its phased development, which is carefully synchronised with the phased rollout of its export infrastructure and the development of proximate offtake markets. This approach avoids the common "chicken-and-egg" dilemma where large-scale production awaits guaranteed transport and offtake, while infrastructure and offtakers await guaranteed supply. The project instead builds its market presence incrementally.

2.6.1. Primary Offtake Hubs

- **Slovakia (Košice) - Initial Market:** The project's initial production phases (2 MW in 2027, 20 MW in 2028) are timed to align perfectly with the completion of the first stretch of the CEHC, an 80 km pipeline from Veľké Kapušany at the Ukrainian border to Košice, Slovakia, which is planned for 2028-2029. Košice is concurrently developing the "EastGate H_2V," the first hydrogen valley in Slovakia, with 9 million EUR in EU funding. This initiative will deploy hydrogen buses and foster industrial hydrogen use, creating a ready-made, geographically proximate market for the project's early, smaller-scale output. Potential large industrial users in the area, such as the U.S. Steel Košice plant, represent a significant anchor demand opportunity. [26] [56]

- **Germany (Bavaria) and Austria - Long-Term Market:** As the full CEHC becomes operational post-2028, the project will scale up to its full capacity (100-300 MW) to supply the major industrial demand centers in Southern Germany and Austria. The Bavarian Hydrogen Roadmap, for instance, projects regional demand to grow from ~5 TWh today to 10 TWh by 2030 and up to 75 TWh by 2040, with a heavy reliance on imports. The CEHC provides a direct, cost-effective route to these lucrative long-term markets. [28] [29]

2.6.2. Offtake Agreement Status

Market validation for the project's initial phase is already being established. N1C is in active negotiations with Ukranian, Slovakian and Polish multinational companies with operations across Central Europe. With several customers we have a Letters of Intent (LoI) covering the offtake of hydrogen from the first two pilot stages (2 MW + 20 MW) that provides tangible evidence of market demand and significantly enhances the project's bankability for the initial investment phase. And for the third and fourth stages we had LoIs with the GTS Ukraine and EUSTREAM as availability of the Hydrogen pipeline is a crucial milestone of delivering big amounts of hydrogen directly to the key customers in the EU and obviously playing a critical role in minimizing logistics costs. [138]

2.7. Implementation roadmap, regulatory strategy, and legal framework

2.7.1. Introduction: strategic project architecture

Investor Summary: This section defines the comprehensive Execution Strategy for the investment and construction project aimed at establishing a 422 MW green hydrogen production facility in the Zakarpattia region. This document has been developed based on a deep audit of Ukrainian legislation, technical reports (WPG, Solargamma), a legal memorandum (Dentons), and the stringent requirements of international financial institutions for "Bankable" projects. [47]

The project is classified as an object with Significant Consequences (Class CC3) according to DSTU 8855:2019 "Determination of Consequence (Liability) Class." This classification mandates the highest standards for reliability, safety, and the approval procedure for design documentation, ensuring maximum asset protection for investors.

2.7.2. Project lifecycle within the Ukrainian legal framework

The implementation of the project follows a strict algorithm regulated by Ukrainian urban planning legislation and FIDIC standards. The detailed stage-gate process is outlined below to demonstrate process transparency and control.

Table 2-3: Lifecycle Matrix for a CC3 Project (Execution Roadmap)

Phase	Scope of Work	Key Regulatory Standard	Deliverable (Milestone)
I. Initiation & Concept (Pre-Development)	PFS development, technology selection, land plot audit, preliminary LCOH calculation.	+	Investment Memorandum, Feasibility Study (FS).
II. Permitting	Land allocation (DTP), securing Grid Connection Agreements (Technical Conditions for electricity/gas), EIA, Subsoil License.	Land Code, Law "On Regulation of Urban Planning Activities", Law "On EIA".	Urban Planning Conditions (MUO), EIA Conclusion, Subsoil License.
III. Design & Engineering	Development of **Stage "P" (Project)**, passing Comprehensive State Expert Review, development of **Stage "R" (Working Docs)**.	DBN A.2.2-3:2014, DSTU 8855:2019.	Positive Expert Report, **Construction Permit (DIAM)**.

Phase	Scope of Work	Key Regulatory Standard	Deliverable (Milestone)
IV. Construction & EPC	Procurement (Long Lead Items), Construction & Assembly Works, Commissioning.	DBN A.3.1-5:2016 "Organisation of Construction Production".	Acts of Completed Works, Equipment Certificates.
V. Commissioning & Operation	Obtaining the Readiness Certificate, grid connection, generation licensing.	Procedure for Acceptance into Operation (CMU Resolution No. 461).	Facility Readiness Certificate, NEURC License.

Investor Note: The project is currently transitioning from Phase I to Phase II. The rigorous adherence to the CC3 lifecycle ensures that all "Red Flags" are identified and mitigated before the Final Investment Decision (FID). [12]

2.7.3. Land relations and urban planning documentation

The foundation of the project's realisation is a juridically clean land asset. To date, the consolidation of three plots totaling 28.98 ha has been successfully completed.

Current Status and Change of Designated Purpose

In accordance with the Land Code of Ukraine and Law No. 1475-IX, the procedure for changing the designated purpose of the land from agricultural to industrial use has been executed.

- **Secured Categories:**
  - **Code 11.02:** "For the placement and operation of main, auxiliary, and support buildings and structures of processing, machine-building, and other industries."
  - **Code 14.01:** "For the placement, construction, operation, and maintenance of buildings and structures of energy-generating enterprises."
- **Status: completed**. Information has been entered into the State Land Cadastre (DZK).

Detailed Territory Plan (DPT)

The next critical step is the development and approval of the Detailed Territory Plan. According to Art. 19 of the Law of Ukraine "On Regulation of Urban Planning Activities," the DTP details the provisions of the general plan and defines the planning organisation and development of the territory.

- **Necessity:** Without an approved DTP, it is impossible to obtain Urban Planning Conditions and Restrictions (MUO), which serve as the baseline data for design.
- **Procedure:**
  1. Decision by the Syurte Village Council session to authorise DTP development.
  2. Development of the DTP draft by a certified design organisation (accounting for sanitary protection zones, fire access roads).
  3. Conducting public hearings regarding urban planning documentation (duration: minimum 30 days).
  4. Approval of the DTP by the Village Council session.

Industrial Park Creation (Incentive Mechanism)

To optimise the project's financial metrics (lowering CAPEX and OPEX), registering the site as an Industrial Park (or joining an existing one) is strategically vital.

- **Legal Basis:** Law of Ukraine No. 5018-VI "On Industrial Parks," Tax and Customs Codes (2022 amendments).
- **Fiscal Incentives for the Investor (Tax Shield):**
  - **Exemption from Import Duty** on new equipment (electrolysers, compressors, BESS).
  - **Exemption from Import VAT (20%)** on equipment.
  - **Exemption from Corporate Income Tax (CIT)** for 10 years (subject to reinvestment conditions).
- **Action Plan:** Submission of the Park Concept to the Ministry of Economy of Ukraine for inclusion in the Register of Industrial Parks..

2.7.4. Water supply and subsoil use critical resource security

Based on the comparative analysis of options provided in the Technical and Economic Analysis (TEA 01/02-WPG/56), the project engineering team has officially approved Option 1: Autonomous Water Supply via Dedicated Artesian Wells.

Resource Base and Intake Parameters:

- Source: Groundwater from Quaternary deposits.
- Location: Land Plot No. 1 (Syurtivska Territorial Community).
- Design Well Depth: Up to 105 meters (pursuant to geological section No. 2Pr-Ch).
- Configuration (Stage 4): A cluster of 5–6 operational wells with an individual flow rate of 40–60 m³/hour each.
- Sanitary Protection Zone (SPZ): A Tier I SPZ radius of 30 meters has been established for each well (integrated into the general plot plan within construction constraints).

During the Pre-Feasibility Study (PFS) phase, the following milestones have been achieved:

- Development of WPG TEA (01/02-WPG/56): A full calculation of the water consumption and wastewater balance has been performed for all 4 project stages (from 2 MW to 422 MW).
- Chemical Audit: Archived water quality data in the vicinity of the Chaslivtsi GMS and Baranintsi Substation were analysed to serve as the design basis for the WTP.

To legalise the water intake during 2025-2026, the following administrative cycle must be completed:

Step 1: Geological and Economic Assessment (GEO) – Timeline: 6–8 months

- Drilling of the first exploration-and-production well.
- Pumping tests to determine actual yield and the radius of influence on neighboring water intakes.
- Preparation of the GEO report and its defense before the State Commission on Mineral Resources (GKZ).

Step 2: Licensing (Special Subsoil Use Permit) – Timeline: 3–4 months

- Submission of the application package to the State Service of Geology and Mineral Resources (Derzhgeonadra) of Ukraine for a special permit to extract groundwater (required as volume >300 m³/day).
- Legal Basis: Subsoil Code of Ukraine.

Step 3: Special Water Use Permit – Timeline: 30 days

- Obtaining water withdrawal limits and approving wastewater discharge conditions from the State Agency of Water Resources (Derzhvodahentstvo).
- Data entry into the EIA register (within the framework of the comprehensive environmental conclusion).

2.7.5. Power supply and grid integration

Technical Conditions (TC) and Connection

Connection Point: newly constructed 400/110 kV Substation "Baranintsi" (NPC Ukrenergo).

- **Regulation:** Governed by the Transmission System Code.
- **Status: Preliminary Technical Conditions have been obtained**.
- **Next Steps:**
  - Development of the Feasibility Study for the Power Evacuation Scheme (FS PES).
  - Signing the Connection Agreement with the Transmission System Operator (TSO) – NPC Ukrenergo.
  - Design and construction of the power transmission line (Cable/Overhead Line 110 kV).

"Active Consumer" Model (Prosumer)

Law of Ukraine No. 3220-IX introduced the "Active Consumer" mechanism, which is ideal for this business model.

- **Core Concept:** The project can consume electricity from the grid to power electrolysers (when solar is unavailable) and sell surplus energy from the PV/BESS to the grid (when electrolysers are idle or generation is excessive) using the **Net Billing** mechanism.
- **Investor Advantage:** Ability to offset consumption and generation volumes, significantly reducing operational energy costs (OPEX).
- **Constraint:** Sales volume is capped at 50% of installed capacity, requiring precise balancing.

Guarantees of Origin (GOs)

To export hydrogen to the EU as "Renewable Fuel of Non-Biological Origin" (RFNBO), the "green" status of the electricity used must be verified.

- **Regulation:** CMU Resolution No. 227, Law of Ukraine "On the Electricity Market."
- **Action:** Registration of generating units (Solar PV) in the **NEURC** (Regulator) registry. Issuance of electronic certificates for every MWh produced. [67]

2.7.6. Hydrogen infrastructure and export logistics

The project is oriented towards export via the Central European Hydrogen Corridor (CEHC). The nearest entry point is the Gas Metering Station (GMS) "Chaslovtsy" (Distance: ~500-1000 m). [21]

GTS Connection and Technical Conditions

- Regulator: LLC "Gas TSO of Ukraine" (GTSOU).
- Regulatory Base: Gas Transmission System Code.
- Procedure:

- Submission of an application for Technical Conditions (TC) to connect to the main gas pipeline.
- Design of the connection node and commercial metering unit. Metering must be conducted in Energy Units (kWh), not cubic meters, as mandated by Law of Ukraine No. 1850-IX "On Amendments... Regarding the Implementation of Gas Metering and Settlements in Energy Units".
- Construction of a high-pressure spur pipeline (50-70 bar).

Cross-Border Interconnection

Given the proximity to the border, harmonisation of technical hydrogen parameters (quality, pressure, odorisation) with the Slovak TSO – Eustream – is required.

- Document: Interconnection Agreement between GTSOU and Eustream.
- Quality Standard: Hydrogen must meet Grade A (ISO 14687) or CEHC specifications (Impurities: O2 < 10 ppm, H_2O < 5 ppm).

2.7.7. Environmental safety and impact assessment (EIA)

The project falls under the First Category of activities posing increased environmental danger (Art. 3 of the Law of Ukraine "On Environmental Impact Assessment" – chemical production).

EIA Procedure (Environmental Impact Assessment)

The process is strictly regulated and takes 4 to 6 months.

Notification: Publication of the "Notification of Planned Activity" in the Unified EIA Register.

- EIA Report: Development of a detailed report (executed by a licensed entity). The report must include dispersion modeling, noise assessment, and impact on groundwater and biodiversity.
- Public Hearings: A mandatory stage. Under the martial law regime (CMU Resolution No. 1321), hearings are conducted via video conference, which simplifies logistics while requiring meticulous preparation of presentation materials.
- Transboundary Consultations (Espoo Convention): Given the distance to Slovakia (7 km), the Ministry of Environmental Protection of Ukraine is obligated to notify the Slovak side. This confirms the project's legitimacy for EU investors.
- EIA Conclusion: Obtaining the final document from the Ministry of Environmental Protection and Natural Resources. This conclusion is a mandatory prerequisite for starting design and construction.

2.7.8. Industrial safety and civil protection (wartime specifics)

In the current context, safety issues are paramount.

Facility Classification

- Consequence Class: CC3 (Significant Consequences).
- High-Risk Facility: According to the Law "On High-Risk Facilities," the project is subject to identification and registration with the State Service of Ukraine on Labor Issues (Derzhpratsi).
- Requirements: Development of a PLAS (Plan for Localisation and Liquidation of Emergency Situations), Safety Declaration, and an automated early warning system.

Engineering and Technical Measures for Civil Protection (ITM GZ)
The design documentation must contain a special section on Civil Protection (approved by the State Emergency Service - SES).

- Shelters: Design of dual-use protective structures (bomb shelters) for shift personnel.
- Physical Protection: Use of gabions and reinforced concrete structures to protect critical nodes (H_2 storage tanks, compressors) from fragmentation damage.
- Warning Systems: Integration into the local civil defense warning system.

2.7.9. Design stages and expert review

For CC3 objects, three-stage design is legislatively mandated (DBN A.2.2-3:2014).

Table 2-4: Design Staging

Stage	Description	Approval / Validation
Feasibility Study (TEO)	Detailed economic calculation, selection of core technological solutions, general plan scheme.	Approved by the Client (Investor).
Project (Stage "P")	The main "Approvable" stage. All sections are developed (GenPlan, Tech, Arch, Civil Works, HVAC, Water, Electrical, EIA, Civil Defense).	Subject to mandatory **Comprehensive State Expert Review** (SE "Ukrderzhbudekspertyza" or equivalent). Checks structural integrity, durability, fire safety, and environmental compliance.
Working Documentation (Stage "R")	Detailed drawings for construction execution, equipment and material specifications.	Issued for construction ("Issued for Construction") after obtaining the Construction Permit.

Construction Permit
After obtaining a positive Expert Report for Stage "P", the Client submits an application through the electronic system to the State Inspection of Architecture and Urban Planning (DIAM) to obtain the Permit for Construction Works.

2.7.10. Risk management and insurance

To protect investments under war risk conditions, the following mechanisms are envisaged:

War Risk Insurance:

- **MIGA (World Bank Group):** Political Risk Insurance program covering expropriation and war damage.
- **DFC (US International Development Finance Corporation):** Financing and insurance for US/Joint projects in Ukraine.
- **National ECAs:** Export Credit Agencies of equipment supplier countries (e.g., Euler Hermes for Germany) can insure deliveries.

Legal Protection: Structuring the project via English Law (using an SPV in a foreign jurisdiction) and utilizing international arbitration clauses in contracts.

2.7.11. Conclusion

The developed roadmap demonstrates that the Green H_2 Uzhhorod project has a clear, legislatively substantiated path to implementation. The presence of **secured land**, proximity to **critical infrastructure** (400 kV Substation and hydrogen Transmission System), and the utilisation of **state support mechanisms** (Industrial Park, Active Consumer) render this project one of the most prepared hydrogen assets in Eastern Europe.
Adherence to the procedures and standards described above (CC3, EIA, GEO) guarantees the **juridical purity (Permitting Complete status)** of the project and its compliance with the rigorous requirements of international institutional investors. [71]

3. Hydrogen Infrastructure and Grid Injection Strategy

3.1. Executive Summary and Technical Mandate

This comprehensive technical report serves as the definitive engineering and regulatory roadmap for the H_2 **project in Zakarpattia**. Unlike traditional feasibility studies that focus on a static end-state, this document analyses the dynamic evolution of the facility from a standalone 2 MW Pilot Plant to a **422 MW Pan-European Energy Hub.**

The core mandate of this report is to design and validate a multi-modal logistics strategy capable of supporting the project's phased growth:

- **Early Phase (Stages 1–2):** Establishment of a "Virtual Pipeline" via high-pressure tube trailers to supply local industrial off-takers and regional customers in the cross-border zone.
- **Mature Phase (Stages 3–4):** Physical integration with the high-pressure hydrogen grid for bulk export to the European Union.

The project is strategically sited approximately 500-700 meters from the Chaslivtsi Compressor Station, a critical node on the "Brotherhood" (Urengoy–Pomary–Uzhhorod) pipeline system. This location offers a dual competitive advantage: immediate access to regional road networks for trailer distribution and direct proximity to the EU hydrogen transit corridor for future utility-scale injection. [127]

3.1.1. Project Engineering Context: From Local Supply to Continental Export

The **green H_2 project in Zakarpattia** is structured as a phased industrial development, designed to mitigate technical and commercial risks through a flexible logistics approach. The engineering strategy covers **four distinct stages** and **8 technical solutions** (utilizing both Alkaline and PEM technologies), ensuring the facility remains operational and profitable at every scale.

Evolution of Logistics and Off-take Strategy:

- **Decentralised Distribution (Stages 1-2):** For the initial capacities (2–20 MW), the report defines the engineering requirements for a **Trailer Loading Terminal**. This infrastructure allows for the direct shipment of compressed hydrogen (350–500 bar) to potential customers in the Zakarpattia region and neighboring EU border districts, fostering a local hydrogen economy before the pipeline connection is activated. [61]
- **Centralised Transmission (Stages 3-4):** As production scales to 100–400 MW, the primary logistics vector shifts to the **Hydrogen Transmission System (HTS)**. The facility must condition, meter, and inject hydrogen in a state that is hydraulically and chemically compatible with the high-pressure transit flows directed toward Slovakia and Hungary.

Table 3-1: Project Phasing and Technical Solutions Matrix

Stage	Name	Capacity H_2	Logistics & Off-take Strategy	Solutions (PEM / Alkaline)
Stage 1	Pilot	2 MW	**Virtual Pipeline (Trailers).** Construction of a Tube Trailer filling station. Supply to local pilot projects, industrial consumers, and mobility partners in the Uzhhorod region. Island-mode capability.	**Sol. 1:** Alkaline (2.0 MW) **Sol. 2:** PEM (2.0 MW)
Stage 2	Scale-up	20 MW	**Regional Expansion.** Expansion of the trailer fleet and loading bays. Targeting commercial off-takers in Western Ukraine and cross-border truck deliveries. Preparation for grid balancing services.	**Sol. 3:** Alkaline (20 MW) **Sol. 4:** PEM (20 MW)
Stage 3	Large-Scale	100 MW	**Hybrid Logistics.** Commissioning of the direct pipe connection to Chaslivtsi GMS. Transition to bulk export via HTS. Trailer terminal remains as a backup and for local merchant supply.	**Sol. 5:** Alkaline (100 MW) **Sol. 6:** PEM (100 MW)
Stage 4	Hub	300 MW	**Pan-European Export.** Full operation as a CEHC node. 100% integration with the European Hydrogen Backbone. Trailer operations become auxiliary.	**Sol. 7:** Alkaline (300+ MW) **Sol. 8:** PEM (300+ MW)

3.1.2. Strategic Regional Importance and Investment Potential

The project's location in the Uzhhorod district of Zakarpattia Oblast transforms it into a strategic bridge between Ukraine and the EU.

Development of Border Business Zones: By initiating supply via trailers in Stages 1-2, the project catalyses the development of a local "Hydrogen Valley." This creates opportunities for local businesses (transport, logistics, green manufacturing) to decarbonise early, leveraging the project's proximity.

Proximity to Western Border: Located less than 2 km from the EU border, the site minimises transport costs for both road (trailers) and pipe logistics. This unique geography allows for flexible export optionality – delivering by truck to nearby hubs in Slovakia/Hungary or by pipe to distant markets in Germany/Austria.

Investment Attractiveness: The phased "Pilot-to-Hub" approach significantly de-risks the investment. Investors can validate revenue streams through local/regional sales (Stage 1-2) with lower CAPEX before committing to the major infrastructure required for the export phases (Stage 3-4). This alignment with both regional development needs and EU energy security goals maximises access to green financing.

3.1.3. The "Rule-Taker" Strategic Paradigm

A foundational premise of this analysis is the recognition of the project's strategic position as a "Rule-Taker." While physically located in Ukraine, the commercial viability of the facility is entirely dependent on its integration into the Central European Hydrogen Corridor (CEHC) and the acceptance of its product by downstream Transmission System Operators (TSOs) in the EU, specifically Eustream in Slovakia.

Consequently, the technical design criteria – ranging from discharge pressures to trace impurity limits – are defined not by current Ukrainian domestic norms, which are largely nascent regarding hydrogen, but by the evolving, stringent standards of the European Union's Gas Decarbonisation Package 2024 and the technical codes of the CEHC consortium. Engineering assessment confirms that the successful export of up to 400 MW of green hydrogen requires a connection node capable of delivering hydrogen at pressures between 40 and 50+ bar, with a purity in the range of 98% to 99.5%, aligning with ENOH standards for repurposed hydrogen pipelines. [119]

3.1.4. Technology Selection Implications

The integration into the hydrogen grid requires a thorough alignment of electrolyser operational characteristics with the injection pressure requirements (40–50 bar). The techno-economic analysis for utility-scale phases necessitates an evaluation of both Alkaline (AEL) and Proton Exchange Membrane (PEM) technologies based on Total Cost of Ownership (TCO).

- Compression Analysis for Alkaline Systems (AEL): Standard AEL electrolysers produce hydrogen at pressures ranging from near-atmospheric (1–5 bar) to mid-pressure (15-20 bar). Raising H2 pressure to the 40–50 bar target requires multi-stage compression, incurring an energy penalty of approximately 2.5 – 3.0 kWh/kg H2. While this introduces a parasitic load and necessitates the use of reciprocating compressors (requiring specialised foundations and maintenance), these costs represent a relatively small fraction of the total production volume and do not constitute a decisive barrier to AEL adoption, provided that CAPEX advantages are significant.
- PEM Systems Performance Analysis: PEM technology offers the advantage of delivering hydrogen at 30–40 bar natively via electrochemical processes. This simplifies the balance-of-plant (BoP) architecture, requiring only a small single-stage booster compressor to meet the 40–50+ bar injection target and reducing the compression energy penalty to < 0.5 kWh/kg H2. However, the final technology selection must be based on a holistic comparison of CAPEX, OPEX, stack degradation rates, and operational flexibility under intermittent RES supply. Compression and pipeline transport costs, while relevant, are not the primary determinants of the Levelised Cost of Hydrogen (LCOH).

3.1.5. Regulatory Gap and Mitigation

The report addresses the "Rule-Maker" aspect of the project within the Ukrainian jurisdiction. Current analysis of the Gas Transmission System (GTS) Code indicates that while frameworks for natural gas and biomethane exist, a dedicated legal structure for pure hydrogen injection is mandatory for utility-scale deployment. Relying solely on the issuance of site-specific "Technical Conditions" (TU) — a mechanism extrapolated from the biomethane market — is considered unrealistic for the 100 MW+ phases.

To establish a viable legal basis for the design, construction, and commissioning of the hydrogen connection infrastructure, the following regulatory roadmap is required:

1. Enactment of a comprehensive "Hydrogen Law" aligned with the EU Hydrogen and Gas Decarbonisation Package (Directive (EU) 2024/1788 and Regulation (EU) 2024/1789).

2. Formal designation of GTSOU as a hydrogen transmission system operator, authorised by the National Regulatory Commission (NEURC) to invest in, operate, and charge tariffs for hydrogen infrastructure.
3. Implementation of Hydrogen Network Codes covering: connection rules, capacity booking, commercial balancing, tariff structures, cross-border trade, and hydrogen quality/certification (H2 purity standards).
4. Approval of specific technical safety and maintenance standards for high-pressure hydrogen infrastructure.

In parallel, technical preparations for the 100 MW phase must proceed in close coordination with GTSOU to identify optimal segments for pipeline repurposing and grid connectivity.

3.2. Strategic Infrastructure Context: The Central European Hydrogen Corridor (CEHC)

3.2.1. The "Brotherhood" Pipeline Legacy and Repurposing

The **green H_2 project in Zakarpattia** is designed as the upstream anchor of the Central European Hydrogen Corridor (CEHC). This initiative, driven by a consortium of four major TSOs – GTSOU (Ukraine), Eustream (Slovakia), NET4GAS (Czech Republic), and OGE (Germany) – aims to establish a dedicated hydrogen "highway" capable of transporting up to **144 GWh per day** (approx. 1.5 million tonnes per year) from Eastern Europe to demand centers in Germany by 2032. [24]

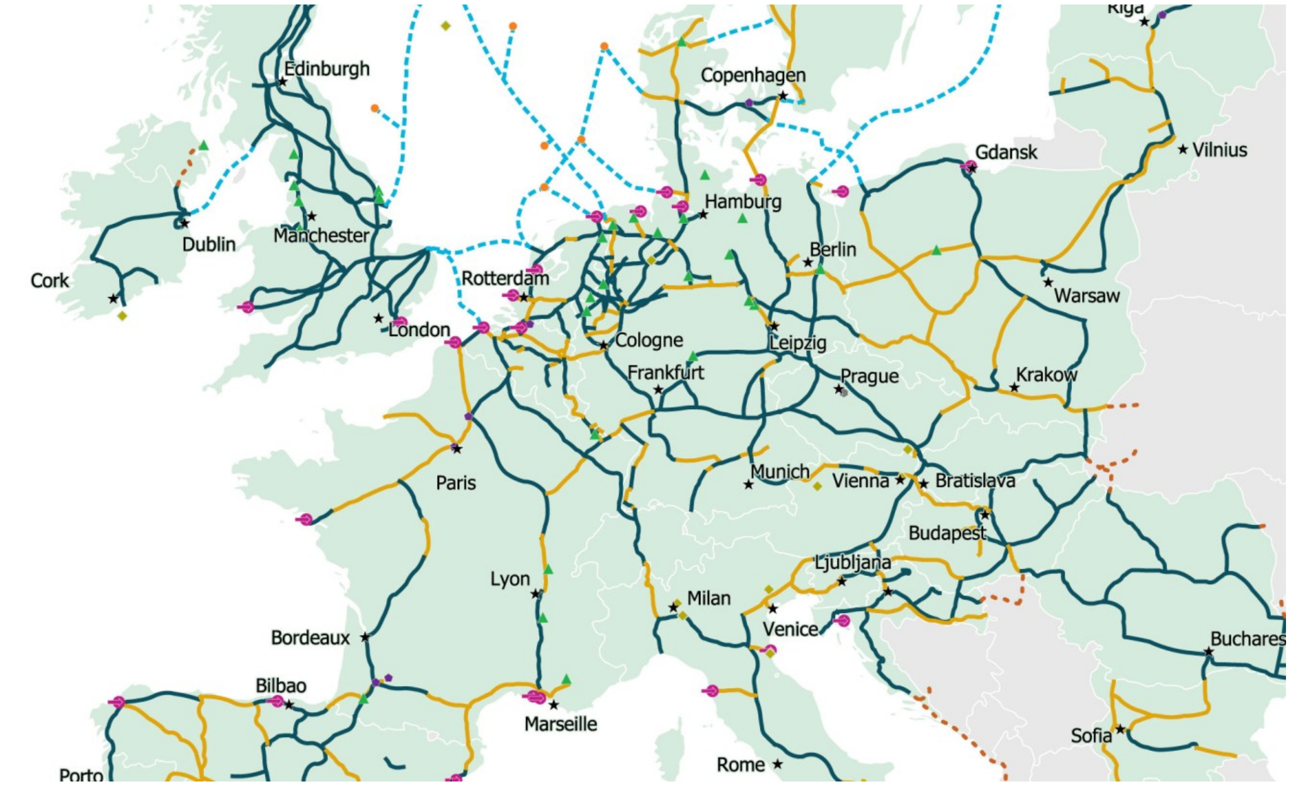


Figure 3-1: The European Hydrogen Backbone (EHB) initiative [164]

The CEHC leverages the immense existing capacity of the **Urengoy–Pomary–Uzhhorod** trunk pipeline corridor (also known as "Brotherhood / Bratstvo"). This major export natural gas pipeline system historically runs to Uzhhorod and then onwards toward Central/Western Europe. [66]

Pipeline Technical Characteristics:

- **Reported diameter:** 56 inches (1,420 mm).
- **Length:** ~4,500 km (with ~1,160 km in Ukraine).
- **Commissioned:** 1984 (as commonly cited).
- **Route Description:** In Ukraine, it delivers gas to an Uzhhorod pumping/compressor area near the Slovak border and also to "smaller pumping stations" toward the Hungarian and Romanian borders.

Figure 3-2: GTS of Ukraine [165]

The strategic decline in natural gas transit volumes has created a unique opportunity to repurpose one or more of these parallel lines exclusively for hydrogen transport without compromising regional energy security. For the Uzhhorod project, this repurposing strategy implies connecting to vintage steel infrastructure retrofitted for hydrogen service. The legacy pipeline steels (typically grades equivalent to API 5L X52 to X70) must be assessed for susceptibility to hydrogen embrittlement. CEHC feasibility studies indicate that these pipelines can safely transport hydrogen provided operating pressures are managed to control hoop stress and gas quality minimises impurities.

3.2.2. Cross-Border Interconnection Points and Hydraulic Gateway

While the physical connection occurs at the Chaslivtsi compressor station in Ukraine, the hydraulic boundary condition is defined by the intake parameters of the Eustream system.

Documented Cross-Border Interconnection Points Relevant to Uzhhorod:

(A) Ukraine–Slovakia: Uzhhorod / Velke Kapusany

- **Type:** Interconnection Point (IP)
- **EIC Code:** 21Z000000000085L
- **Status**: GTSOU lists this as an interconnection point used for nominations (Entry/Exit). Slovakia's TSO Eustream publicly refers to Veľké Kapušany as an entry point on the Ukrainian–Slovak border.

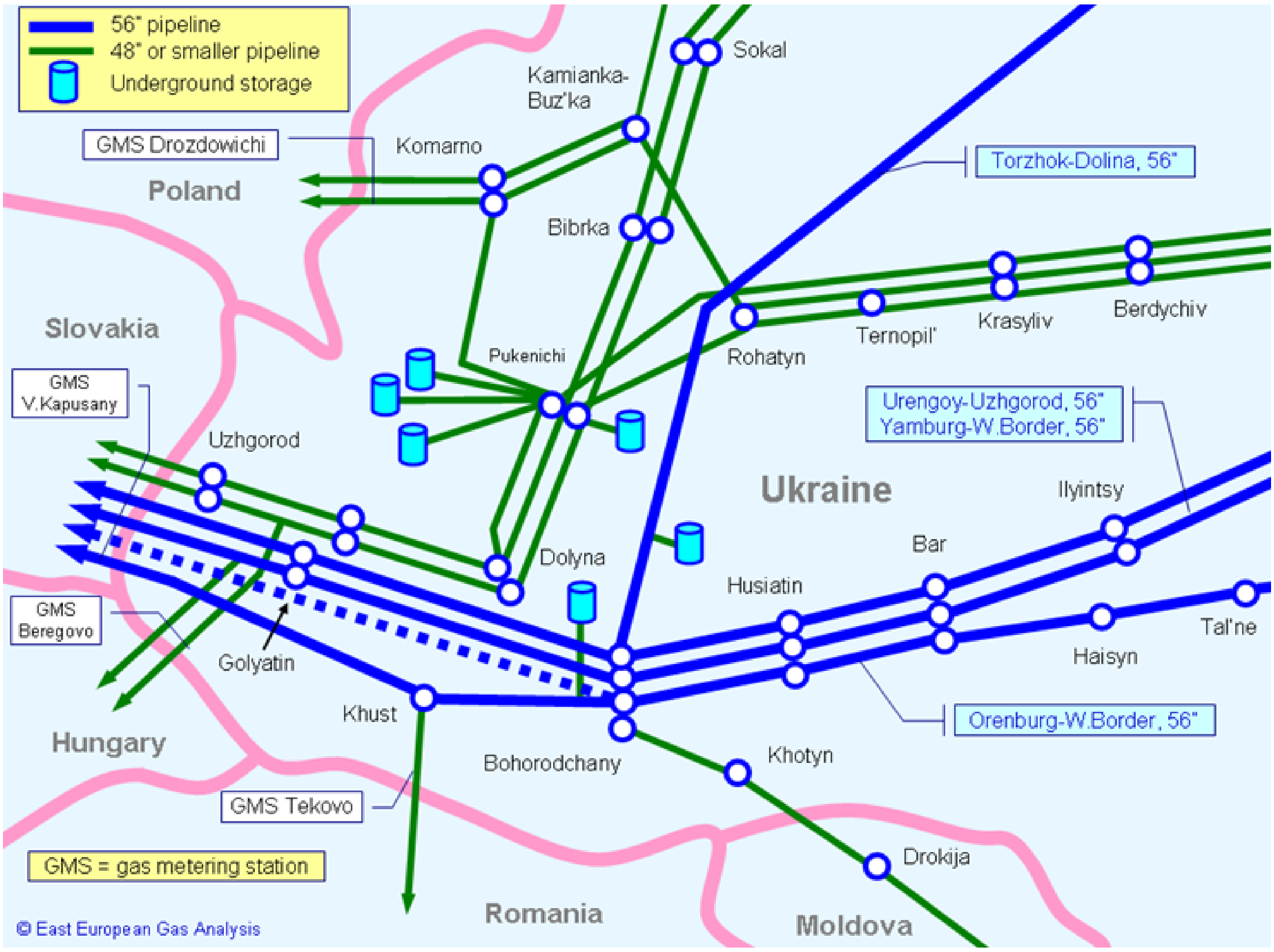


Figure 3-3: Gas Pipelines and Export Terminals of Uzhhorod Area, Ukraine [166]

(B) Ukraine–Slovakia: Budince

- **Type:** Interconnection Point (IP)
- **EIC Code:** 21Z000000000357E
- **Status:** GTSOU lists Budince as an interconnection point. In public announcements regarding maintenance near the UA–SK border, GTSOU stated it believed it was possible to offer intermittent capacity up to 110 million m³/day for transportation from Ukraine to Slovakia.

(C) Ukraine–Hungary: VIP "Bereg"

- **Type:** Virtual Interconnection Point (VIP)
- **EIC Code:** 21Z000000000507L
- **Status:** Hungary's TSO FGSZ documents that (from 1 Jan 2020) the same business rules applied at the physical points Beregovo (UA) and Beregdaróc (HU) and that nominations/capacity booking were handled via the VIP "Bereg" concept. GTSOU announced firm capacity increases for VIP "Bereg" (Hungary → Ukraine direction) to 9,763 tcm/day. [155]

Hydraulic Requirement at Velke Kapusany:

Analysis indicates that the CEHC pipelines will operate in a pressure envelope of 50 to 70 bar. Consequently, the Uzhhorod injection node must guarantee a firm delivery capacity at these pressures, regardless of fluctuations in the electrolyser's production rate. [120]

3.2.3. Strategic Interoperability, Security, and CEHC Routing

The project's integration into the CEHC carries significant geopolitical weight, recognised as a Project of Common Interest (PCI) and Project of Mutual Interest (PMI) by the European Commission (Status 10.4). [22]

CEHC Routing and Scope:

The CEHC aims to create a hydrogen "highway" connecting:

1. Ukraine (Production Region)
2. Slovakia
3. Czech Republic
4. Germany (Demand Center)

The initiative foresees connection points at **Velké Kapušany–Košice**, with commercial commissioning expected by 2028–2029. The Uzhhorod project is positioned to supply over **40 kt/year** of RFNBO-compliant hydrogen, meeting minimum offtake volumes required by EU downstream partners.

To ensure interoperability, the Uzhhorod facility must demonstrate that its operations will not disrupt the stability of the transnational grid. This requires the implementation of advanced SCADA systems capable of real-time data exchange with the dispatch center of GTSOU in Kyiv.

3.2.4. National Strategy and Context (Ukraine)

Ukraine's draft Hydrogen Strategy positions green hydrogen as a cornerstone of the country's future energy system and a key instrument for decarbonisation. The strategy defines phased objectives across the short term (2022–2025), medium term (2026–2030), and long term (2031–2050). [3]

Strategic Priorities:

- Development of green hydrogen production, transportation, and storage infrastructure.
- Establishment of a robust regulatory framework and favourable investment conditions.
- Promotion of hydrogen exports, particularly to the European Union.

Capacity Targets:

- **Short-term (2022–2025):** Establishing foundations and early export capabilities.
- **Medium-term (2026–2030):** Capacity target of **10-12 GW** (aligned with EU initiatives), supporting both growing domestic demand and export markets.
- **Long-term (2031–2050):** Full transition to green hydrogen, utilising up to 50% of existing energy capacity. [3]

Impact Targets:

- **Economic:** GDP increase driven by green energy integration (4–6% by 2030 and 12–15% by 2050).
- **Energy Security:** Reduced dependence on fossil fuels and enhanced energy system flexibility.

National Renewable Energy Action Plan (2030):

In August 2024, the Ukrainian government approved an Action Plan outlining substantial increases in renewable energy capacity:

- **Solar:** Expansion from 7,327 MW to 12,200 MW.
- **Onshore Wind:** Increase from 512 MW to 6,214 MW.
- Green Hydrogen Production: Up to 44,957 thousand tonnes per year.
- **Biomethane:** Up to 21.8 billion cubic metres per year.

Policy and Project Spotlight: H_2U Hydrogen Valley (Odessa Region)

While the Zakarpattia project focuses on the "Brotherhood" corridor, parallel developments validate the national commitment. The H_2U Hydrogen Valley initiative (Reni, Odesa region) involves:

- 120 MW solar power plant and 80 MW wind power plant.
- 100 MW electrolysis facility.
- Initial production target: 7,000–8,000 tonnes of hydrogen annually.
- Logistics via the Danube to Central Europe.

3.3. EU Market Entry Requirements (The 'Rule-Taker' Position)

The commercial viability of the project relies on selling hydrogen to premium EU offtakers via the CEHC. The product hydrogen must meet strict technical acceptance criteria defined by pipeline infrastructure limitations and end-user quality requirements.

3.3.1. Hydraulic Parameters: Pressure Regimes

The pressure at the point of injection is the critical hydraulic design parameter, determining the sise and power of the compression system.

- **Operating Pressure Envelope:** Based on the technical specifications of the "Brotherhood" pipelines and Velke Kapusany station, the target injection pressure is **50 to 70 bar** (5.0–7.0 MPa). The system must be capable of injecting at the upper limit to overcome line packing events.
- **Design Consequence:** This requirement validates the choice of PEM electrolysis. With PEM delivering at 30+ bar, a single-stage booster is sufficient to bridge the gap to 70 bar, reducing the compression energy penalty to below **0.5 kWh/kg**.

3.3.2. Hydrogen Quality and Purity Standards

The definition of "hydrogen quality" is subject to intense standardisation within the EU. The project aligns with the emerging consensus to ensure fungibility.

3.3.2.1. Purity Levels: The Strategic Choice

The industry faces a bifurcation in purity standards:

1. **Infrastructure Baseline (98%-99,5%):** Some infrastructure operators advocate for a 98 mol% minimum for repurposed grids due to residuals in vintage pipelines. [118]
2. **End-User Requirement (99.97%):** Target markets in mobility and sensitive industry require **ISO 14687 Grade D**, mandating **≥ 99.97%** purity to protect Proton Exchange Membrane Fuel Cells (PEMFC) from impurities. [34]

Project Strategy: To maximise commercial value and avoid forcing offtakers to invest in expensive on-site purification, the Uzhhorod facility is designed to meet the **ISO 14687 Grade D (99.97%)** standard at the plant gate. This "future-proofs" the asset and aligns with the trajectory of EU regulation. [140]

3.3.2.2. Critical Contaminants and Limits

Meeting the 99.97% target requires rigorous control of specific contaminants:

- **Oxygen (O_2):** Critical safety hazard. While natural gas codes allow up to 1% oxygen, hydrogen standards mandate **<10 ppm (0.001%)** to prevent combustible mixtures and protect catalysts. The facility must employ de-oxo catalytic recombination units if raw hydrogen exceeds this limit.
- **Water (H_2O) and Dew Point:** Essential to prevent corrosion and hydrates. The standard for high-pressure transmission is <-8°C at 70 bar. However, pure hydrogen best practices demand a dew point of **-70°C** (approx. 5 ppmv). This necessitates Temperature Swing Adsorption (TSA) dryers.
- **Sulfur Compounds:** Trace sulfur poisons fuel cell catalysts. The limit is **< 0.004 mg/m³**. Crucially, this implies the hydrogen transported via the CEHC will likely be **non-odorised**, representing a shift in safety protocols compared to natural gas.
- **Carbon Oxides (CO, CO_2):** Limits for CO are extremely low (e.g., < 0.2 ppm) due to poisoning effects on platinum catalysts.

3.3.3. Regulatory Alignment: The 2024 Gas Package

The technical design is framed by the **EU Hydrogen and Gas Decarbonisation Package 2024** (Directive EU 2024/1788 and Regulation EU 2024/1789). Key implications include:

- **Cross-Border Interoperability:** Mandates TSO cooperation to avoid restrictions based on gas quality.
- **Certification:** Introduces Union-wide certification for renewable hydrogen (RFNBO), requiring granular data collection (e.g., hourly temporal correlation) which the project's instrumentation must support. [154]
- **Standardisation:** Relies on CEN/CENELEC standards. The project tracks the revision of **EN 16726** and development of **CEN/TS 17977** (Hydrogen in rededicated systems). [148] [147]

3.4. Ukrainian Regulatory Framework (The 'Rule-Maker' / Gap Analysis)

The project faces a "regulatory gap" between the existing natural gas-centric codes in Ukraine and the needs of a modern hydrogen facility. [121]

3.4.1. Technical Standards and Quality Specifications for the Hydrogen Grid

The design of the export interface in Uzhhorod is based exclusively on dedicated hydrogen infrastructure standards. Applying existing GTS Code regulations for natural gas (methane grid) is deemed irrelevant, as the dedicated hydrogen grid requires autonomous regulation of physico-chemical parameters and material specifications.

Key Design Principles:

- Purity Standards: For bulk hydrogen transmission via repurposed pipelines, the target purity level is set between 98% and 99.5%. This threshold aligns with European Hydrogen Network (ENOH) recommendations and accounts for the technical condition of the existing pipeline assets.
- Materials Science: Material selection and H2-readiness assessments are conducted based on specialised standards (e.g., ASME B31.12 or ISO/TR 15916) rather than general natural gas regulations.
- Commercial Metering: In alignment with EU regulations, hydrogen transmission and supply settlements are performed strictly in energy units (kWh). Technical volume metering (m3) at connection nodes serves as the basis for conversion into energy, leveraging the consistent heating value of hydrogen. Transition to mass-based accounting (kg) for pipeline transport is not envisioned. [128]

Table 3-2: Technical Requirements for Hydrogen Grid Injection

Parameter	Target Hydrogen Grid Standard (CEHC/ENOH)	Engineering Justification & Requirements
Operating Pressure	40 – 50 bar	Aligns with the synchronised operational regimes of GTSOU (Ukraine) and Eustream (Slovakia) for dedicated hydrogen transmission.
Hydrogen Purity	98% – 99.5%	Standard for repurposed pipeline assets; 99.97% (Grade D) is not required for bulk transit and would incur prohibitive purification costs.
Commercial Metering	Energy (kWh)	Mandatory fiscal accounting in energy units. Volume (m3) or mass (kg) data serves as the technical basis for real-time energy conversion.
Water Dew Point (H2O)	≤ 5 ppm (−70°C)	Requires Temperature Swing Adsorption (TSA) drying to prevent internal corrosion and ensure integrity of high-pressure hydrogen assets.
Oxygen Content (O2)	≤ 10 ppm (0.001%)	Critical safety limit to prevent material degradation and maintain the design life of repurposed steel pipelines.
Sulphur Content (S)	≤ 0.004 mg/m³	Standard methane odorisation is incompatible; requires sulphur-free seals (PTFE/EPDM) and specialised leak detection systems.
Material Integrity	H2-Compatible Steel	Mandatory validation of hydrogen embrittlement resistance in accordance with ASME B31.12 or API 5L (H2-ready specifications).
Delivery Temperature	+2°C to +30°C	Optimal thermal range to prevent soil heaving/settlement and maintain coating integrity of the buried pipeline segments.

3.4.2. Regulatory Roadmap and Connection Framework

For the implementation of 100 MW+ phases targeted at cross-border export to the EU, relying on the existing "Technical Conditions" (TU) mechanism for non-standard gas grid connections is deemed insufficient. The project necessitates the establishment of a dedicated legal and regulatory framework for the hydrogen sector.

The procedural pathway is divided into two parallel tracks:

Preliminary Assessment Stage (Current): Coordination with the Gas Transmission System Operator of Ukraine (GTSOU) through joint technical studies and the preparation of materials for preliminary connection assessments. The outputs of this stage are advisory opinions and conceptual integration schemes into the hydrogen grid, which serve as the technical basis for the Feasibility Study but do not constitute final, legally binding TUs.

Formal Licensing Stage (Post-Legislation): The issuance of mandatory Technical Conditions for the design and construction of the connection interface (HMS) will only be feasible following the official enactment of the "Hydrogen Law" and respective Hydrogen Network Codes. Final requirements for pressure (40–50 bar), purity (98% – 99.5% H2), and commercial metering in energy units (kWh) will be established based on the new legal acts, harmonised with the EU Hydrogen and Gas Decarbonisation Package.

In the absence of a "Hydrogen Network Code," the project will utilise the "Technical Conditions" (TU) mechanism used for non-standard connections. This process is currently documented by GTSOU as handling requests to assess the possibility of connection and issuing technical specifications.

3.5. Technical Connection Solution (Chaslivtsi Node)

This section details the physical infrastructure for the 100-400 MW expansion at the Chaslivtsi node. The design prioritises safety, accuracy, and flexibility. *Note: Equipment is described by technical specification; specific brands are omitted or genericised. [136]*

3.5.1. Hydrogen Metering Station (HMS) Design

The HMS serves as the fiscal "cash register" and quality "gatekeeper," located in a secure, explosion-proof compound.

- **Metering Technology:** Accurate metering of low-density hydrogen is critical. The design specifies **High-Pressure Coriolis Mass Flow Meters** for primary runs. These measure mass directly, independent of pressure/temperature, eliminating errors associated with volumetric calculations and Equations of State (EOS). They offer high accuracy (<0.1%) and immunity to density fluctuations. [135]
  - *Alternative:* For full 400 MW (7500-7600 kg/h H2) flow rates, large-bore **H_2-Ready Ultrasonic Flow Meters** calibrated for hydrogen's speed of sound may be used in parallel streams for high rangeability.
- **Metrological Certification:** Equipment will comply with the **Measuring Instruments Directive (MID) 2014/32/EU** and OIML recommendations. Meters will be calibrated at accredited EU laboratories (e.g., in the Netherlands) with certificates recognised by GTSOU. [34]

3.5.2. Quality Control System (QCS)

To ensure 98.0%-99.5% purity and protect the pipeline, the GMS features a redundant QCS.

- **Hydrogen Chromatographs (HC):** Fast-response **Process Hydrogen Chromatographs** will continuously monitor bulk H_2 and impurities (N2, Ar, CO, CO2). Cycle times will be optimised to < 3 minutes for rapid isolation.
- **Moisture Analysers:** To meet the -70°C dew point, **Tunable Diode Laser Absorption Spectroscopy (TDLAS)** analysers will be used. These offer non-contact, highly sensitive measurement at sub-ppm levels without the drift of capacitive sensors.
- **Oxygen Analysers:** Dedicated paramagnetic or electrochemical oxygen analysers will monitor O2 levels (limit 10 ppm), hardwired into the Emergency Shutdown (ESD) system.

3.5.3. Compression Architecture

- **The PEM Benefit:** Using PEM electrolysers delivering at 30 bar requires only a **Single-Stage Booster Compressor Station** to reach pipeline pressure (40-50+ bar).
- **Compressor Type:** The design specifies **Hydraulically Driven Diaphragm Compressors** or **Slow-Speed Reciprocating Compressors**. These positive displacement technologies use triple-diaphragm designs to ensure absolute separation between process hydrogen and hydraulic oil, guaranteeing oil-free hydrogen delivery to protect downstream fuel cells.
- **Control:** Equipped with Variable Frequency Drives (VFD) to match the variable solar-driven production rate.

3.5.4. Piping and Material Selection

- **Station Piping:** All high-pressure piping within the GMS and compressor station will be fabricated from **Austenitic Stainless Steel** (grades equivalent to 316L or 304L). The lattice structure of these steels is highly resistant to hydrogen diffusion and embrittlement.
- **Connector Pipeline:** High-grade carbon steel pipe (e.g., API 5L X42 or X52) may be used for the connection line if strictly controlled for hardness and heat treatment to resist Hydrogen Induced Cracking (HIC). Higher strength grades (X70+) are avoided unless rigorously qualified. [156]
- **Joints:** Welded connections are maximised. Flanges use high-integrity sealing systems tested for hydrogen permeation.

Table 3-3: Proposed Equipment List for H_2 Injection Node

Sub-System	Equipment	Preferred Technology	Specification Highlights
Compression	Booster Compressor	Hydraulic Piston / Diaphragm	Oil-free, High pressure (30->70 bar), VFD control.

Sub-System	Equipment	Preferred Technology	Specification Highlights
Metering	Mass Flow Meter	High-Pressure Coriolis	Direct mass measurement, <0.1% accuracy, Stainless wetted parts.
	Check Meter	Ultrasonic (H_2 Ready)	High turndown ratio, calibrated for H_2 speed of sound.
Analysis	Hydrogen Chromatograph	Process GC (Fast Cycle)	Monitor Impurities (N2, CO, CO2); <3 min cycle.
	Moisture Analyser	Tunable Diode Laser (TDL)	Non-contact, sub-ppm detection (-70°C dew point).
	Oxygen Analyser	Paramagnetic / Electrochemical	Safety critical, hardwired to ESD.
Control	Flow Computer	Custody Transfer Computer [139]	Programmed for Hydrogen Mass flow calculations.
Safety	ESD Valves	Ball Valve, SIL 3 Actuator	Hydrogen service trim, fugitive emission packing (Class AH).
Detection	Fire/Hydrogen Detectors	UV/IR Flame, Ultrasonic Leak	Detects invisible H_2 flames and high-frequency leak signatures.

3.6. Operations & Risks

3.6.1. Risk Assessment (Section 8.0 Input)

- **Technical Risk - Leakage:** Small H_2 molecules can leak through standard seals. **Mitigation:** Welded joints, helium leak testing, and Ultrasonic Leak Detectors in the GMS.
- **Technical Risk - Embrittlement:** Pipeline failure due to hydrogen diffusion. **Mitigation:** 316L stainless steel for station piping, X52 restriction for pipelines, and Pipeline Integrity Management System (PIMS). [131]
- **Technical Risk - Reverse Flow:** Grid hydrogen backflowing into the plant. **Mitigation:** SIL 3 rated Non-Return Valves and automated ESD triggered by differential pressure.
- **Regulatory Risk - Metrology:** Lack of certified H_2 calibration in Ukraine. **Mitigation:** Calibration of master meters in EU facilities with mutual recognition by GTSOU via Technical Conditions.
- **Regulatory Risk - Injection Refusal:** TSO refusal due to purity spikes. **Mitigation:** Redundant analysers with 2oo3 (two-out-of-three) voting logic and buffer storage blending.

3.6.2. Key Regulatory Barriers & Required Permits

Unlike biomethane, which functions as an extension of the existing natural gas network, hydrogen infrastructure requires a completely autonomous regulatory and institutional framework. The primary barrier is the systemic absence of a hydrogen market structure. [124]

Key Regulatory Barriers:

- Institutional Status of the Operator: Lack of formal designation of GTSOU as the Hydrogen Transmission System Operator (HTSO). Without this, investments in hydrogen-specific assets cannot be integrated into the Regulated Asset Base (RAB).
- Absence of Approved Tariff Methodology: Injection and transmission tariffs for H2 must be established and approved by NEURC. Direct tariff negotiations between the TSO and the producer are legally prohibited; the project must adhere to a standardised, regulated tariff framework.
- Lack of Hydrogen Transmission System Code (HTS Code): Absence of codified rules for balancing, capacity booking, and market interaction protocols specific to hydrogen.
- Certification and Guarantees of Origin: Requirement for a national green hydrogen certification system that is recognised within the EU for cross-border trade purposes.

Required Permits (Post-Legal Framework Implementation):

- Hydrogen Operator License: Mandatory for GTSOU to operate the dedicated network.

- NEURC Investment Program Approval: To legitimise CAPEX for the connection node and pipeline repurposing.
- High-Risk Work Permit (H2-specific): Specialised authorisation for operating hydrogen equipment at 40–50 bar.
- HMS Certificate of Conformity: For the energy-based (kWh) commercial metering station, meeting metrological standards for pure hydrogen.

3.7. Conclusion

The technical feasibility of integrating the green H_2 project in Zakarpattia project into the Central European Hydrogen Corridor (CEHC) is robust, provided that all design solutions align with the EU Hydrogen and Gas Decarbonisation Package. The selection of electrolysis technology must be based on a comprehensive Total Cost of Ownership (TCO) analysis. While PEM systems offer an advantage in achieving the 40–50 bar injection pressure by reducing compression requirements, this factor is not the sole determinant of the LCOH and must be evaluated alongside CAPEX and operational flexibility under intermittent RES supply.

The project's realisation and risk mitigation are contingent upon the establishment of a complete regulatory framework, including the enactment of a "Hydrogen Law," approval of hydrogen network codes, and technical safety standards. A critical prerequisite for cross-border export is the signing of an Interconnection Agreement between the hydrogen transmission operators of Ukraine and Slovakia (Eustream). A "Design for Compliance" strategy, incorporating energy-based accounting in kWh and the use of hydrogen-ready materials, will ensure the seamless conversion of renewable energy into a high-value commercial product at the Velke Kapusany border point.

4. Legal and Regulatory Framework

The project's success is contingent on navigating a complex, dual-layered regulatory landscape: the established, stringent framework of the European Union, which the project must comply with for export, and the nascent, evolving framework in Ukraine, which the project must help shape. This section provides a deep-dive analysis of both, fulfilling the H2Uppp program's objective to identify barriers and create pathways for the broader Ukrainian hydrogen market.

4.1. EU Regulatory Compliance for Market Access (The 'Rule-Taker' Position)

To be sold as "renewable hydrogen" in the EU and count towards the mandatory targets under RED III, the project's output must strictly adhere to the criteria defined in the RED II Delegated Acts (Commission Delegated Regulation (EU) 2023/1184 and Commission Delegated Regulation (EU) 2023/1185) for RFNBOs. Ukraine, as an exporter, is a 'rule-taker' and must demonstrate full compliance. [8] [75]

4.1.1. RED II/III Delegated Acts on RFNBOs

The Commission Delegated Regulation (EU) 2023/1184 established the core sustainability criteria for green hydrogen production.

- **Additionality:** This principle requires that the renewable electricity used for electrolysis comes from newly installed generation capacity, preventing the diversion of existing renewable power from the electricity grid. The project is designed for compliance through two primary mechanisms: a) the use of a co-located, directly-wired 400 MWp new-build solar PV plant, and b) the potential use of Power Purchase Agreements (PPAs) with other newly constructed N1C-developed wind and solar assets located within the same electricity bidding zone (e.g., in Odessa Oblast). The time lag between the commissioning of the renewable plants and the hydrogen facility will not exceed the 3-year limit stipulated in the regulation.
- **Temporal Correlation:** This requires a close match in time between renewable electricity production and its consumption by the electrolyser. The project will demonstrate compliance with the mandated hourly matching requirement through the installation of dedicated Smart Control and Data Acquisition (SCADA) systems and certified metering equipment, providing auditable proof of simultaneous generation and consumption.
- **Geographical Correlation:** This principle requires that production and consumption occur within the same bidding zone or in interconnected zones with no congestion. The project fully complies, as the production facility and its associated renewable assets are located within Ukraine's single electricity bidding zone, which has been synchronised with the European Network of Transmission System Operators for Electricity (ENTSO-E) since March 2022.

4.1.2. Greenhouse gas (GHG) Savings Threshold

The Commission Delegated Regulation (EU) 2023/1185 mandate that RFNBOs must achieve a life-cycle GHG emissions saving of at least 70% compared to a fossil fuel comparator of 94 g CO_2eq/MJ. As the project will utilise 100% renewable electricity from new assets and water, its lifecycle emissions will be minimal, comfortably exceeding this threshold. The study will include a preliminary lifecycle assessment calculation to formally document this. [60]

4.1.3. Certification of Origin

Demonstrating compliance with the above criteria requires third-party certification through an EU-recognised voluntary scheme.

- **Analysis of Schemes:** An evaluation of available schemes indicates that CertifHy and ISCC EU are the most suitable options. CertifHy is a well-established European scheme specifically for hydrogen Guarantees of Origin (GoO), while ISCC EU is a broader sustainability certification system recognised under RED II. This study recommends initiating the pre-certification process with CertifHy, which has been officially recognised by the European Commission to issue RFNBO certification, to ensure market access from the first day of operation.[33]
- **Process and Cost:** The certification process involves a detailed audit of the project's design, operational plans, and data logging systems. The associated costs, including initial audit fees and annual renewal fees, will be incorporated into the project's operational expenditure (OPEX) model. [74]

4.2. Ukrainian Regulatory Framework: Barriers and Pathways to Reform (The 'Rule-Maker' Position)

A core finding, as stated in the H2Uppp grant application, is that Ukraine's current legal and regulatory framework is "not fit for purpose" for green hydrogen development. This creates significant uncertainty and risk, which this study aims to address directly by producing actionable templates and recommendations. The project's role is not just to comply with rules, but to help establish them.

4.2.1. Current Status Assessment

As of 2025, Ukraine lacks a dedicated, comprehensive law governing the production, transport, and certification of renewable hydrogen. While a framework draft law was presented in mid-2025, it has not yet been enacted. Existing energy legislation does not define "green hydrogen" or establish rules for its integration into energy networks, creating a legal vacuum for investors. This study's analysis of specific barriers in permitting, environmental assessment, and grid connection will provide concrete input for policymakers to finalise this crucial legislation.

4.2.2. Permitting and Land Use (Deliverable: DPT Template)

- **Detailed Plan of Territory (DPT):** The development of a DPT is a critical step in Ukrainian spatial planning, required to change the functional zoning of a land plot. The project's 37-hectare site must be re-designated from its current classification to one permitting industrial and energy facilities. This process, which involves local municipal approvals, is identified as a medium-risk activity with the potential for delays. Recent legislation has extended the validity of the DPT mechanism until 2028, providing a window of legal certainty for the project.
- **Deliverable:** To address this challenge for the broader market, a key deliverable of this study is a standardised DPT template. This template, provided in Appendix C, is designed for adaptation by other hydrogen projects in Ukraine. It includes a compilation of relevant city-planning norms and a "red flag" checklist to help developers identify and mitigate potential site selection risks early in the development process.

4.2.3. Environmental Permitting (Deliverables: SEA & EIA Templates)

- **SEA/EIA Process:** Under Ukrainian law, projects of this scale require a Strategic Ecological Analysis (SEA) and a full Environmental Impact Assessment (EIA), which includes public consultations. While Ukraine has a structured process, a critical challenge for bankability arises from the potential gap between national requirements and the more rigorous standards of international financiers. [38]
- **IFI Standard Alignment:** The project's ability to secure financing from institutions like the EBRD and IFC is directly dependent on its EIA process adhering to their respective Performance Standards (IFC PS 1-8, EBRD PR 1-10). These standards demand a more comprehensive assessment scope, including detailed biodiversity baseline studies (EBRD PR6), analysis of cumulative impacts, development of a formal Stakeholder Engagement Plan (EBRD PR10), and establishment of a community grievance mechanism (IFC PS1). Ukraine's recent focus on fast-tracking permits to enhance energy resilience during wartime creates a potential conflict with the time-intensive due diligence required by IFIs. A project that rushes through a national EIA process may find itself un-bankable. [39]
- **Deliverables:** To bridge this gap, this study provides standardised templates for both the SEA (Appendix D) and a comprehensive, IFI-compliant EIA (Appendix E). The EIA template is explicitly designed to meet the requirements of both Ukrainian law and the EBRD/IFC Performance Standards, providing a robust framework for future developers seeking international finance. It highlights key site selection criteria and proposes mitigation strategies relevant to hydrogen facilities. [40] [104]

4.2.4. Grid and Hydrogen Interconnection Regulations (Deliverable: Hydrogen Interconnection ToR)

- **Electricity Grid:** The project requires a connection to the high-voltage transmission grid operated by NEC Ukrenergo. Recent legislative changes have introduced new rules for connection, including an advance payment for capacity reservation (e.g., 10 EUR per kW) and defined validity periods for Technical Conditions (TCs), which are now valid for up to three years, extendable to six. The ongoing interconnection feasibility study for the 400kV Baranyntsi substation will provide the specific technical requirements and costs for the project's connection.
- **Hydrogen Grid:** A significant regulatory barrier is the absence of a defined technical and legal framework for injecting pure hydrogen into Ukraine's gas transmission system. While the GTSOU is conducting research on hydrogen blending, clear standards for quality, pressure, metering, and tariffs for pure hydrogen injection do not yet exist.

- **Deliverables:** The hydrogen interconnection study conducted as part of this project will produce two critical deliverables to address this vacuum. The first is a template "Terms of Reference" (ToR) for regulating the interconnection to a dedicated hydrogen pipeline like the CEHC. The second is a concise checklist of key technical and legal factors to assist other developers in assessing potential pipeline connection points. These documents will provide a foundational framework for the GTSOU and the national regulator to develop formal standards.
- **Technical Standards:** Ukraine has adopted several key international standards relevant to hydrogen, such as DSTU ISO 14687 for fuel quality and DSTU ISO 22734 for electrolysers. However, a full review is necessary to identify any gaps where further adoption of EU standards is required to ensure seamless cross-border interoperability and export compatibility [103]

4.2.5. Regulatory Framework and Procedure for Grid Connection in Ukraine

The connection of industrial-scale consumers and renewable energy facilities to the power system of Ukraine is governed by a comprehensive regulatory framework that defines technical, procedural, and organisational requirements for grid access. This framework is of particular importance for hydrogen production projects, which combine high installed electrical capacity, continuous operating regimes, and increased requirements for reliability of power supply.

Under Ukrainian legislation, electrical networks are classified by voltage levels ranging from low-voltage distribution systems to high-voltage transmission networks. Depending on the installed capacity and voltage class of the electrical installation, connection may be implemented either to the distribution networks operated by regional distribution system operators or to the transmission network operated by the national transmission system operator. As a general rule, projects with installed capacities exceeding several megawatts are connected at voltage levels of 35 kV, 110 kV, or higher and fall outside the scope of standard connection procedures.

Grid connections are formally divided into **standard** and **non-standard** categories. Standard connections are limited in terms of both capacity and distance to the connection point and are not applicable to large industrial or energy projects. Consequently, hydrogen production facilities are typically subject to **non-standard connection procedures**, which involve individual technical solutions and project-specific assessments.

A key element of the non-standard connection process is the preparation and approval of a **feasibility study** agreed with the grid operator. This document plays a central role in determining the technical viability of the connection and serves as the basis for issuing technical specifications. The feasibility study assesses the impact of the new electrical installation on the existing power system, including load flows, available transmission capacity, reliability margins, and potential bottlenecks in adjacent networks. It also defines the scope of necessary measures related to grid reinforcement, relay protection, automation, and emergency control systems.

In practice, feasibility studies for non-standard connections are typically developed by qualified engineering consultants with access to initial data from the grid operator. Several alternative connection options are usually considered and compared on a technical and economic basis. While cost estimates at this stage are indicative and based on aggregated benchmarks, the study provides a critical foundation for subsequent design, permitting, and investment decisions.

Following approval of the feasibility study, the grid operator issues **technical specifications** and a draft connection agreement. These documents define the connection point, voltage level, reliability category, scope of works on both the operator's and the consumer's side, and the responsibilities of each party. The connection process then proceeds through detailed design, land allocation for linear infrastructure, construction and installation works, testing, and commissioning.

Connection timelines for non-standard projects vary depending on capacity, voltage level, and the extent of required network upgrades. Under standard regulatory conditions, implementation periods may range from several months to more than one year. Additional risks may arise if significant reconstruction of existing substations, overhead lines, or protection systems is required, potentially affecting both schedule and capital expenditure.

Special regulatory provisions apply during periods of martial law, introducing a **temporary connection procedure** for industrial consumers. This mechanism allows projects of strategic importance to obtain temporary grid access under simplified and accelerated conditions. Temporary connections are subject to clearly defined technical requirements and are intended to ensure continuity of economic activity during extraordinary circumstances. After the termination of martial law, all temporary connections must be brought into compliance with the standard regulatory framework within a specified period, including the conclusion of permanent connection agreements and full technical alignment with the grid codes.

From a project development perspective, early and comprehensive consideration of the regulatory framework for grid connection is essential. Insufficient preparation at the pre-project stage may lead to delays, additional technical requirements imposed by the operator, or substantial increases in connection costs. Conversely, a well-structured feasibility study that realistically reflects network constraints, operational requirements, and regulatory procedures significantly reduces implementation risks and provides a robust basis for selecting the optimal grid connection solution.

5. Technical Feasibility and System Design

This section provides a detailed technical assessment of the project, translating the concept into a feasible engineering design. It evaluates the site resources, compares core technologies, and models the eight specified scenarios to determine the optimal configuration for development.

5.1. Site and Resource Assessment

5.1.1. Comparison of Mukachevo and Uzhhorod Nodes for Grid Connection

At the early stage of project development, the option of connecting the facility to the transmission grid via the Mukachevo 400 kV substation was considered. This node is one of the largest in Zakarpattia and plays a crucial role in cross-border power flows. However, a detailed review of the connection conditions and implementation aspects revealed several substantial limitations that made Mukachevo less feasible compared to the alternative solution:

5.1.1.1. Technical limitations

- According to the issued technical requirements, connection to Mukachevo would require extensive additional works related to the retrofitting of power facilities with relay protection devices, automation, emergency control systems, as well as the reconstruction and expansion of the existing 400/110 kV distribution and transmission substation.
- Ukrenergo's documentation also emphasised the need to assess and eliminate "bottlenecks" in adjacent 110-750 kV networks without clearly specifying the names of the transmission lines and substations to be reconstructed, which created additional uncertainty regarding costs and timelines.

5.1.1.2. Financial risks and uncertainties

- Implementing the connection through Mukachevo would require significant capital expenditures associated with the modernisation of substation infrastructure and the procurement of expensive equipment (power transformers, 110-400 kV circuit breakers, telemechanics servers, etc.), as well as reactive power compensation and voltage regulation devices.
- In addition, the lack of precise information regarding the condition of certain equipment and the scope of reconstruction of the morally and physically outdated Mukachevo substation and the electrical networks of the adjacent energy hub complicated budget planning and increased investment risks.

5.1.1.3. Priority load of Mukachevo node

- The Mukachevo substation is primarily focused on supporting cross-border flows towards Slovakia and Hungary, serving as a key element of interconnection capacity.
- Integration of a new 400 MW generation/load project into this node could compromise reliability and would require complex regime coordination with Ukrenergo and neighboring transmission system operators.

5.1.1.4. Alternative solution – Uzhhorod

- The newly constructed Uzhhorod substation is located closer to the planned project site and provides technical capability to accommodate new capacity without large-scale reconstruction.
- Unlike Mukachevo, Uzhhorod is not burdened with such critical cross-border transit functions, which reduces the risk of refusal or imposition of excessively costly technical requirements.
- The agreement and technical conditions already issued by Ukrenergo for connection at Uzhhorod (Contract No. 01/145-25 and Technical Requirements No. 09/363/2025 of 07.08.2025) confirm that the connection can be implemented within predictable costs and timelines.

5.1.1.5. Logistics and project development perspective

- From the perspective of future project expansion and integration with other renewable energy facilities, Uzhhorod offers more flexible conditions for scaling capacity.
- Proximity to industrial consumers and other prospective energy projects in the region additionally strengthens the case for Uzhhorod as the optimal connection point.

5.1.2. Additional updates (August 2025)

In August 2025, LLC Solargamma received from NPC Ukrenergo a package of documents including the draft Connection Agreement for the electrical installations of a green hydrogen production plant near Mukachevo with a capacity of 400 MW,

and its integral annex – Technical Requirements No. 09/363/2025 dated 07.08.2025 for the connection of electrical installations to the transmission system of the IPS of Ukraine.
According to the presented package, NPC Ukrenergo together with LLC Solargamma undertakes to gradually provide in 2028 the technical capability to connect the 400 MW plant. For this purpose, the following measures are envisaged:

- Expansion of the 400 kV bay at the existing Mukachevo substation;
- Construction of two 400 kV overhead lines from Mukachevo to a new 400 kV substation, including an outdoor switchyard (ORU-400 kV) with installation of at least three 400/110/35 kV power transformers, an ORU-110 kV and a 35 kV switchgear;
- Construction of 110 kV overhead lines for external power supply and a 110 kV substation of LLC Solargamma with MV switchgear for supplying the plant;
- Conducting system studies (load flow and short-circuit analysis) to identify bottlenecks in the adjacent network and define the scope of reconstruction of relay protection and automation in connection with the new capacity.

In the near future, a similar package of documents is expected to be received for the project site in the Uzhhorod area. According to the developed Feasibility Study, the power supply of consumers at this site is envisaged through similar technical solutions with connections from the existing 400 kV overhead line Mukachevo-Velke Kapusany.
Upon receipt of the package, a detailed techno-economic analysis will be performed to compare implementation options for both sites, taking into account the cost of connection to the existing energy infrastructure (both electrical and hydrogen). According to preliminary assessment, the Uzhhorod site at this stage may be recognised as the priority option, given its close proximity to hydrogen infrastructure and the absence of necessity for expanding the 400 kV bay at Mukachevo substation.
Based on the analysis of technical, financial, and strategic factors, selecting the Uzhhorod substation instead of the initially considered Mukachevo option is the most rational decision. It minimises risks, reduces investment uncertainties, and ensures that the project can be realised within the planned timeframe.

5.1.3. Site Characteristics

The selected project site is a 37-hectare plot located near Uzhhorod in the Zakarpattia Oblast, with geographical coordinates 48.531264N, 22.304015E. Its location is highly strategic, offering critical advantages for a large-scale hydrogen export project. It is situated approximately 1 km from the planned new 400kV Baranyntsi substation, minimizing the length and cost of the grid connection. Furthermore, it is only about 500 meters from the Chaslivtsi gas compressor station, a key node in the Ukrainian gas transmission system and the designated injection point for the Central European Hydrogen Corridor. This proximity to essential power and transport infrastructure significantly reduces project complexity and capital expenditure.
In addition, the site area can be expanded up to 45-50 hectares in later project stages, if required to support further capacity growth and additional infrastructure.

5.1.4. Solar Resource Analysis

The Zakarpattia region, while not the sunniest in Ukraine, offers adequate solar resources for utility-scale PV generation. Based on publicly available solar irradiation data, the co-located 400 MWp solar plant is expected to operate with an annual capacity factor sufficient to form the baseload of the project's power supply. Detailed analysis using PV modeling software (e.g., PVsyst or NREL's PVWatts) will be conducted to generate an hourly production profile for the plant. This profile is essential for sizing the electrolyser system and modeling the operational dynamics of the hybrid power supply strategy, ensuring compliance with the EU's temporal correlation requirements. [31]

5.1.4.1. Rationale for Vertical East/West Bifacial PV in Hydrogen Systems

Traditional south-facing photovoltaic (PV) arrays are designed to maximise total annual energy yield, typically producing peak power around midday (11:00–15:00). However, in the context of green hydrogen production, timing matters more than volume:

- Electrolysers are economically optimised when running during peak-tariff hours (morning & evening);
- Midday power prices in Ukraine often collapse due to PV oversupply;
- Hydrogen systems require load stability, not just energy quantity.

To address this mismatch, the Uzhhorod project considers vertically mounted bifacial PV panels with East/West orientation. These arrays generate more power during the morning (8:00–11:00) and late afternoon (16:00–20:00) – aligning better with:

- Peak electricity tariffs;
- Optimal electrolyser utilisation profiles;
- Grid injection limits. [49]

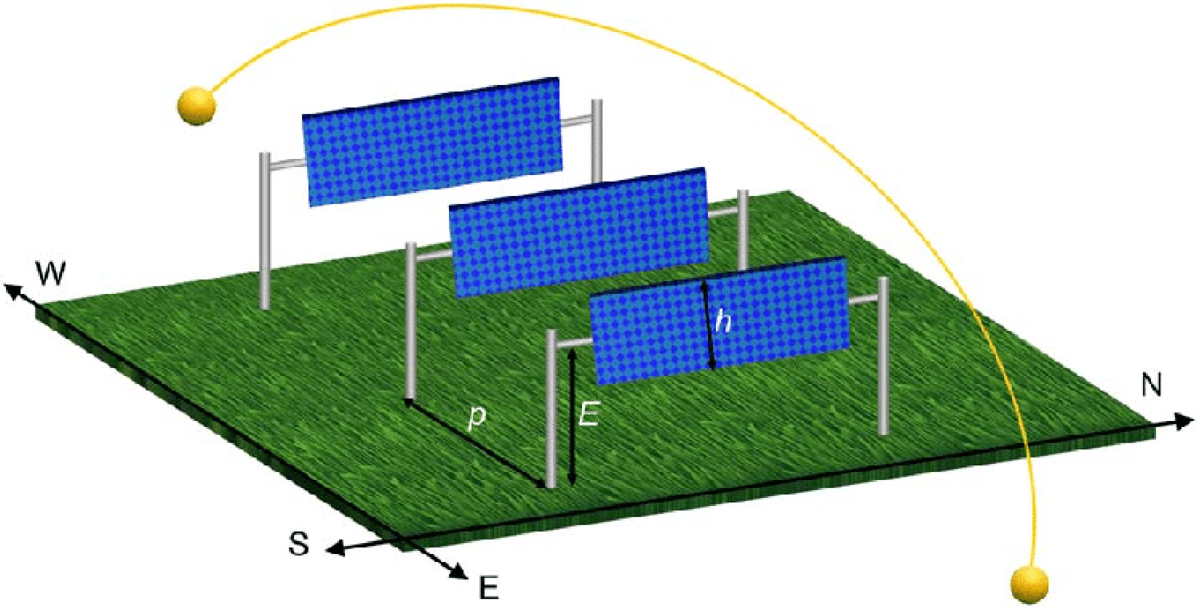


Figure 5-1: Schematic Layout of Vertically Mounted East–West Bifacial PV Array [169]

5.1.4.2. Performance and Economic Comparison: Vertical vs. South-Facing PV

The feasibility study compares two photovoltaic system configurations for a 4 MW solar power plant in Zakarpattia Oblast, Ukraine:

- A traditional south-facing fixed-tilt array at 27°, optimised for annual yield.
- A vertical bifacial installation (east-west facing), simulated as a combined result of east-facing and west-facing vertical arrays.

Although the traditional system yields ~2.2% higher annual generation, the integration of a Battery Energy Storage System (BESS) introduces new dynamics that can shift the value proposition in favor of the bifacial vertical approach.

Table 5-1: Technical Comparison of Vertical Bifacial vs. South-Facing PV Systems (4 MW, Zakarpattia Region)

Parameter	Vertical Bifacial (East + West)	South-facing Traditional (27°)
Installation Type	Vertical, East + West	Fixed Tilt, South-facing
Tilt Angle	90°	27°
Azimuth Angle	±90°	0° (South)
System Capacity (kWp)	4000	4000
System Losses (%)	14%	14%
Yearly PV Energy Production (kWh)	4,578,448	4,680,737
Yearly In-Plane Irradiation (kWh/m²)	753.76 (avg. of east/west)	1491.05
Year-to-Year Variability (kWh)	115,677 (avg. of east/west)	160,522
Angle of Incidence Loss (%)	-4.22%	-2.94%
Spectral Effects Gain (%)	1.25%	1.31%
Temp. & Low Irradiance Loss (%)	-8.95%	-7.20%
Total Losses (%)	-24.07%	-21.52%

5.1.5. Generation Profile Alignment with Load and Grid Conditions

Table 5-2: Comparative Daily Output and BESS Operation Profile for PV Configurations

Time of Day	South-facing (27°) Output	Vertical Bifacial Output	Typical Demand	BESS Role
Morning (6–10)	Low	Moderate	Medium/High	Discharge
Midday (10–16)	Peak	Medium	Low	Charge
Evening (17–21)	Medium/Low	Moderate	High	Discharge
Night (21–6)	None	None	Low/Medium	Idle

Vertical bifacial systems provide more balanced generation during morning and evening hours, where demand and tariffs may be higher. This reduces the required depth of storage and aligns better with real-world usage patterns.

5.1.6. BESS Utilisation and Operational Efficiency

The vertical bifacial system's generation profile enables more consistent charging and discharging cycles throughout the day. This operational stability not only enhances overall battery efficiency but also contributes to longer battery life by reducing thermal and cycle-related stress. Additionally, the midday generation peak is less pronounced compared to a traditional south-facing system, lowering the risk of overgeneration and curtailment.

Vertical bifacial arrays also demonstrate superior winter performance due to their vertical alignment, which minimises snow accumulation and maximises rear-side gain from ground reflectivity – especially when surface albedo is high (e.g., snow, concrete).

5.1.7. Economic Advantage under Dynamic Tariff Conditions

In markets with time-of-use pricing or dynamic tariffs, the ability to shift energy availability using storage is a critical asset. By storing excess generation during midday and dispatching it during high-demand, high-price periods in the morning and evening, the system can maximise its revenue per kilowatt-hour produced.

A vertical bifacial PV system integrated with BESS supports higher self-consumption ratios and allows for more strategic participation in the energy market. The flatter, more stable generation profile reduces reliance on large battery capacity while increasing opportunities for price arbitrage and load shifting. This makes the system especially well-suited to flexible grid environments and decentralised energy models.

Table 5-3: Strategic Comparison of PV Configurations with Integrated Battery Storage

Factor	Traditional (27°)	Vertical Bifacial + BESS
Annual Yield	Slightly higher (2.2%)	Slightly lower
Energy Use Efficiency	Moderate	High with BESS
Peak Demand Coverage	Limited	Strong
Storage Sise Requirements	Larger (more midday excess)	Smaller (flatter curve)
Snow/Irradiance Performance	Moderate	Better in winter
Suitability for Agro-PV	Low	High

European Commission

Performance of grid-connected PV

PVGIS-5 estimates of solar electricity generation:

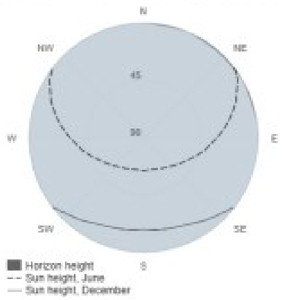
Provided inputs:

Latitude/Longitude:	48.515,22.297
Horizon:	Calculated
Database used:	PVGIS-SARAH3
PV technology:	Crystalline silicon
PV installed:	4000 kWp
System loss:	14 %

Simulation outputs

Slope angle:	27 °
Azimuth angle:	0 °
Yearly PV energy production:	4680737.26 kWh
Yearly in-plane irradiation:	1491.05 kWh/m²
Year-to-year variability:	160522.59 kWh
Changes in output due to:	
Angle of incidence:	-2.94 %
Spectral effects:	1.31 %
Temperature and low irradiance:	-7.2 %
Total loss:	-21.52 %

Outline of horizon at chosen location:



Monthly energy output from fix-angle PV system:

Monthly in-plane irradiation for fixed-angle:

Monthly PV energy and solar irradiation

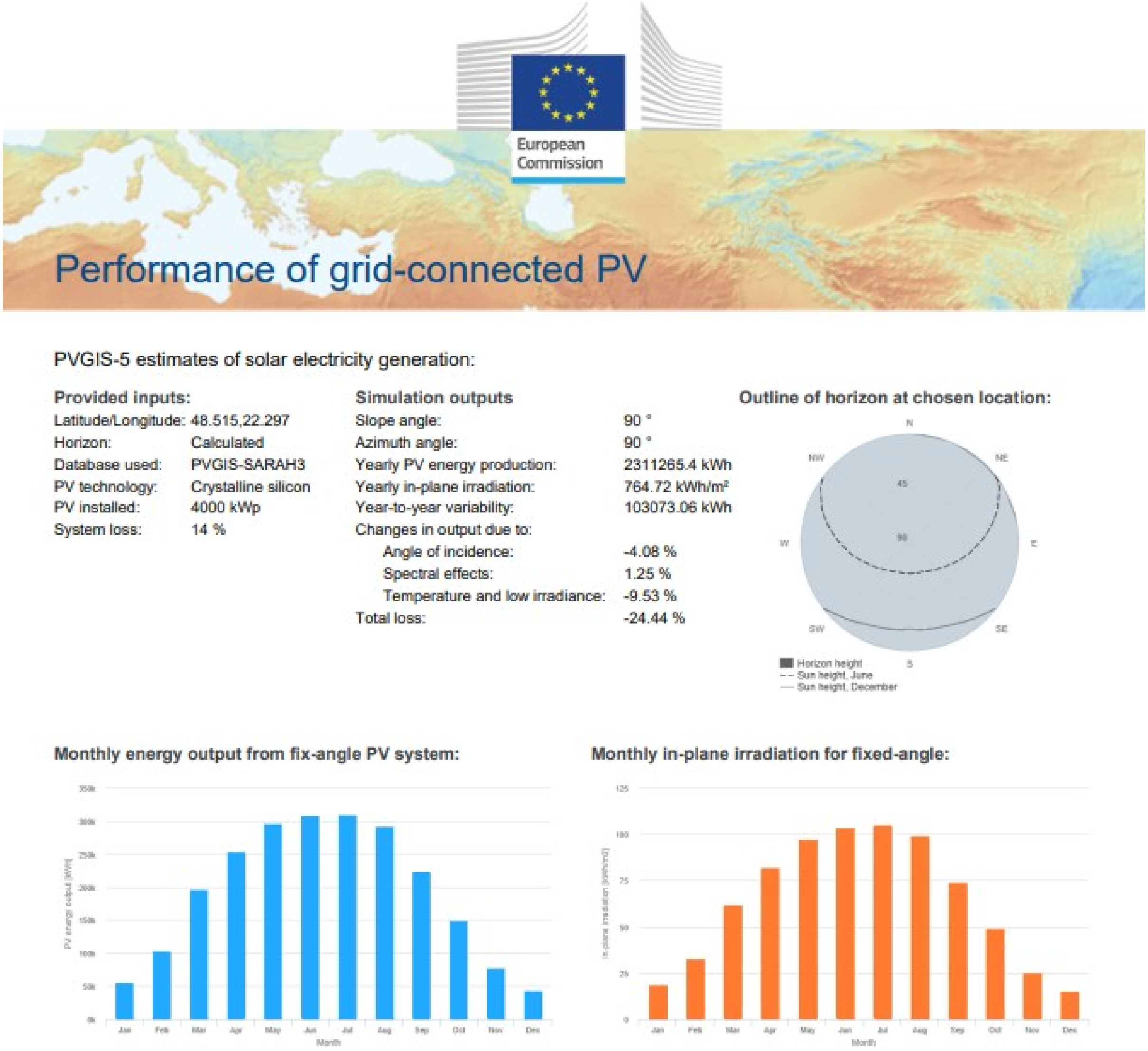
Month	E_m	H(i)_m	SD_m
January	134847.3	39.9	26241.1
February	227533.6	67.2	47321.4
March	409861.9	123.5	75285.8
April	508393.3	160.0	62665.7
May	563584.7	181.9	66718.2
June	576527.4	190.0	50656.3
July	588843.0	196.0	44554.3
August	573733.2	190.4	51779.6
September	454123.9	145.9	60600.9
October	335107.8	103.5	60620.6
November	193512.5	58.1	42728.4
December	114669.3	34.7	27052.1

E_m: Average monthly electricity production from the defined system [kWh].

H(i)_m: Average monthly sum of global irradiation per square meter received by the modules of the given system [kWh/m²].

SD_m: Standard deviation of the monthly electricity production due to year-to-year variation [kWh].

Figure 5-2: Annual PV Energy Output and Solar Irradiation Profile – Fixed-Angle South-Facing System (27° Tilt, 4,000 kWp, Uzhhorod)



Monthly PV energy and solar irradiation

Month	E_m H(i)_m	SD_m
January	55766.418.5	8850.4
February	103634.82.8	21280.4
March	196358.81.8	34563.9
April	254013.82.3	31442.3
May	296135.97.5	32603.6
June	309064.503.8	34738.9
July	309725.405.1	28579.4
August	292356.99.2	22609.4
September	223310.64.1	30755.2
October	149918.48.9	25767.4
November	76906.425.4	17831.9
December	44075.415.3	9936.0

E_m: Average monthly electricity production from the defined system [kWh].
H(i)_m: Average monthly sum of global irradiation per square meter received by the modules of the given system [kWh/m²].
SD_m: Standard deviation of the monthly electricity production due to year-to-year variation [kWh].

Figure 5-3: Annual PV Energy Output and Solar Irradiation Profile – Vertical South-Facing Bifacial System (90° Tilt, Azimuth 90°, 4,000 kWp, Uzhhorod)

European Commission

Performance of grid-connected PV

PVGIS-5 estimates of solar electricity generation:

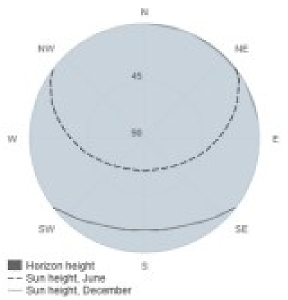
Provided inputs:

Latitude/Longitude:	48.515,22.297
Horizon:	Calculated
Database used:	PVGIS-SARAH3
PV technology:	Crystalline silicon
PV installed:	4000 kWp
System loss:	14 %

Simulation outputs

Slope angle:	90 °
Azimuth angle:	-90 °
Yearly PV energy production:	2267183.04 kWh
Yearly in-plane irradiation:	742.8 kWh/m²
Year-to-year variability:	128281.03 kWh
Changes in output due to:	
Angle of incidence:	-4.36 %
Spectral effects:	1.25 %
Temperature and low irradiance:	-8.37 %
Total loss:	-23.69 %

Outline of horizon at chosen location:



Monthly energy output from fix-angle PV system:

Monthly in-plane irradiation for fixed-angle:

Monthly PV energy and solar irradiation

Month	E_m H(i)_m	SD_m
January	57107.118.8	13106.7
February	101146.31.7	19598.7
March	191746.59.6	37922.0
April	251755.80.6	36237.9
May	290481.94.9	42055.3
June	296158.98.8	30268.4
July	304612.102.6	25379.4
August	287945.96.7	34755.0
September	216811.71.1	28790.2
October	146926.47.3	25853.3
November	77899.425.4	15962.6
December	44592.215.3	9509.4

E_m: Average monthly electricity production from the defined system [kWh].
H(i)_m: Average monthly sum of global irradiation per square meter received by the modules of the given system [kWh/m²].
SD_m: Standard deviation of the monthly electricity production due to year-to-year variation [kWh].

Figure 5-4: Annual PV Energy Output and Solar Irradiation Profile – Vertical East/West-Oriented Bifacial PV System (90° Tilt, Azimuth –90°, 4,000 kWp, Uzhhorod)

The use of vertical East/West-oriented bifacial PV is a strategic optimisation for hydrogen production sites like Uzhhorod. Although slightly less productive in annual energy terms, these systems deliver significantly higher revenue per kWh, improve grid compatibility, and reduce the need for midday storage. Combined with BESS and load-flexible electrolysers, vertical PV arrays can form the backbone of a resilient, cost-effective renewable hydrogen architecture.

5.2. Battery Energy Storage Systems (BESS) Technology Evaluation

5.2.1. Definition and Purpose of Battery Energy Storage Systems

A Battery Energy Storage System (BESS) is an integrated electrochemical energy storage solution designed to store electrical energy in chemical form and release it when required. A typical BESS consists of battery modules or cells, power conversion systems (inverters and converters), control and protection systems, thermal management, and auxiliary infrastructure.

BESS is widely used in modern power systems to provide flexibility, controllability, and reliability. Unlike conventional generation assets, battery systems are capable of near-instantaneous response, bidirectional power flow, and precise control of both active and reactive power. These characteristics make BESS a key enabling technology for systems with a high share of variable renewable energy and for electrically intensive industrial processes.

In large-scale energy projects, BESS is not considered a standalone asset but rather a system-level component that enhances the performance, stability, and economic efficiency of the overall energy infrastructure.

Across electricity systems, BESS is deployed to perform a wide range of functions, including:

- short-term power balancing and frequency stabilisation,
- peak shaving and load leveling,
- congestion management and network support,
- backup power and black-start capability,
- energy shifting and arbitrage in electricity markets.

These applications are increasingly combined within a single installation, allowing BESS to deliver multiple value streams depending on operational priorities and market conditions.

5.2.2. Role of BESS in Green Hydrogen Production Systems

In green hydrogen projects, BESS plays a strategic role as an interface between the electrical power system and the electrolyser plant. Electrolysers are electrically driven chemical processes that operate most efficiently under stable and predictable power conditions. Frequent load fluctuations, ramping, and interruptions negatively affect efficiency, lifetime, and operational safety.

Within a hydrogen production facility, BESS supports the following core functions:

- **Power Stabilisation and Load Conditioning**
  BESS absorbs short-term power deviations originating from the grid or upstream generation and delivers a smoothed power profile to the electrolysers. This reduces electrical and thermal stress on stacks, power electronics, and balance-of-plant systems.
- **Energy Buffering and Operational Flexibility**
  By temporarily storing electrical energy, BESS decouples electricity supply from hydrogen production. This allows the plant to maintain stable operation despite variability in upstream power availability or grid conditions.
- **System Resilience and Safety Support**
  In the event of grid disturbances or outages, BESS supplies power to critical auxiliary systems such as cooling circuits, control systems, instrumentation, and safety equipment. This capability enables controlled shutdown procedures or limited island-mode operation, significantly enhancing plant safety.

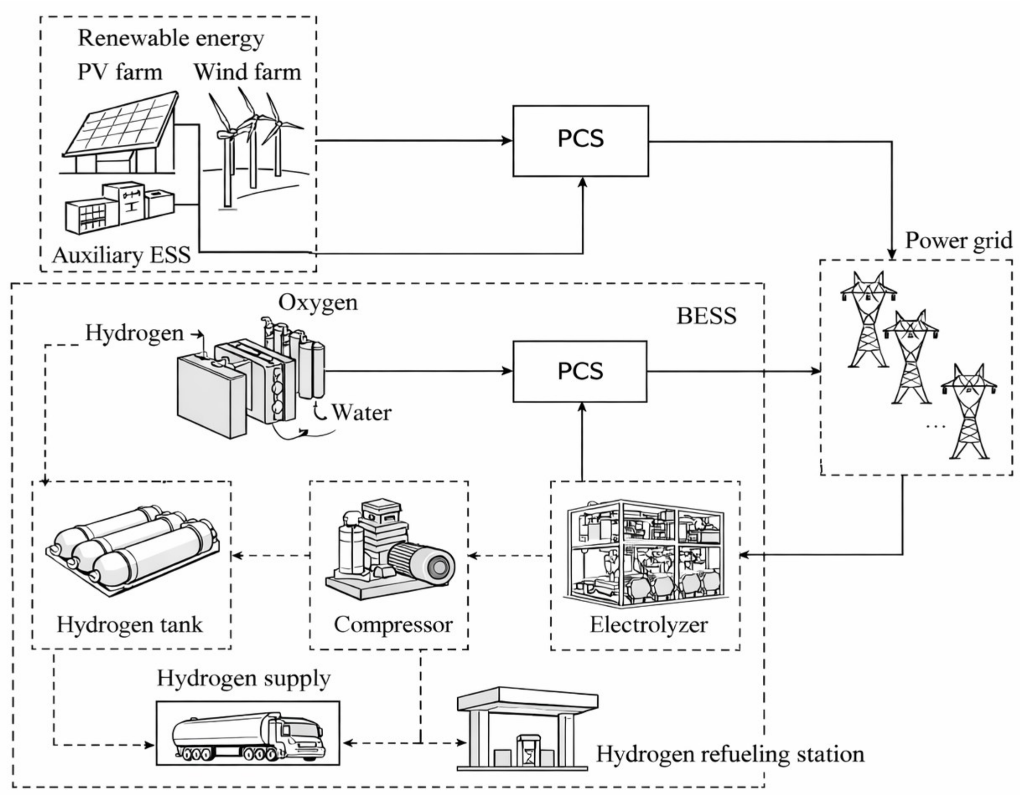


Figure 5-5: Conceptual Integration of BESS within a Green Hydrogen Production Facility

5.2.3. Overview of BESS Technology Families

Several battery technologies are available or under development for utility-scale energy storage. For hydrogen-related applications, the most relevant technology families include:

- Lithium-Ion (Li-ion) batteries,
- Redox Flow Batteries (RFBs),
- Sodium-based and other emerging electrochemical systems.

Each technology differs in energy density, cycle life, response speed, safety characteristics, scalability, and maturity. Technology selection therefore depends on the intended operational profile and risk tolerance of the project.

5.2.4. Lithium-Ion Battery Technology

Lithium-Ion batteries are the most widely deployed energy storage technology globally. They are based on lithium intercalation chemistry and are typically supplied in modular containerised systems. The most common chemistries for stationary applications are Lithium Iron Phosphate (LFP) and Nickel Manganese Cobalt (NMC).

Key characteristics of Lithium-Ion BESS include high round-trip efficiency, fast response times, compact footprint, and a highly mature manufacturing and supply ecosystem. These systems are well suited for short- to medium-duration storage applications and for projects requiring rapid deployment and standardised solutions.

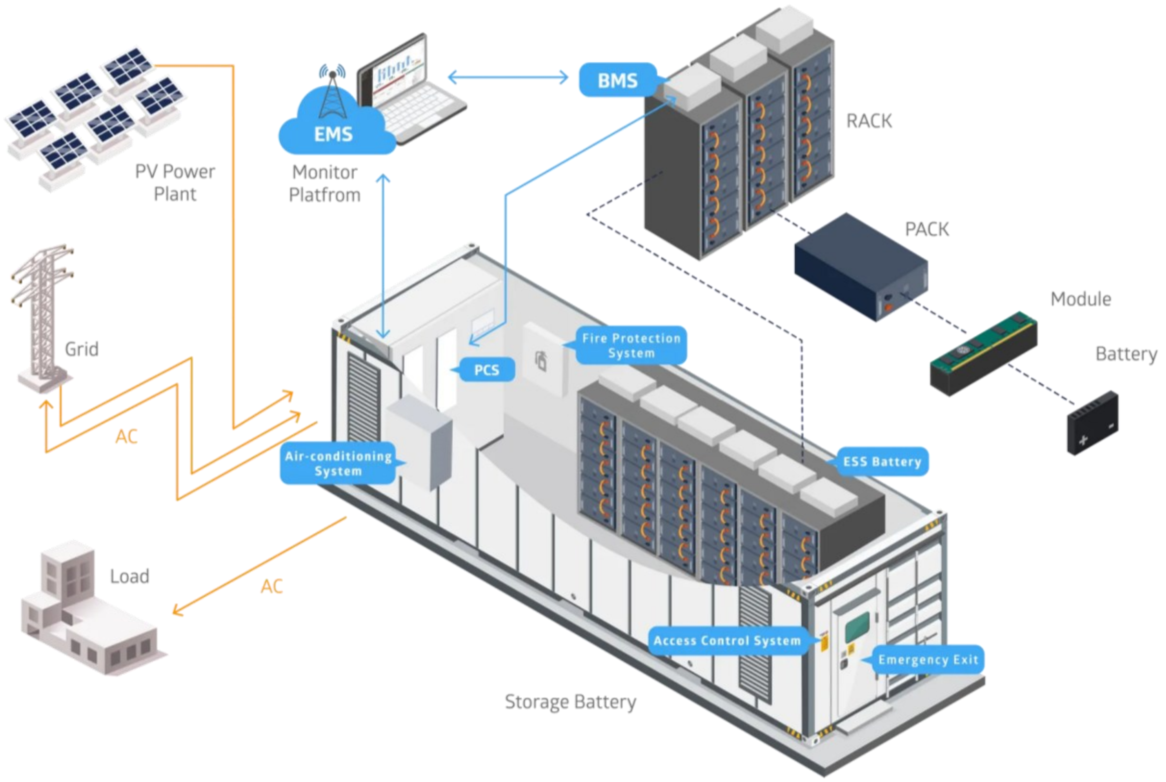


Figure 5-6: Typical Containerised Lithium-Ion BESS Configuration [170]

5.2.5. Redox Flow Battery Technologies

Redox Flow Batteries store energy in liquid electrolytes circulating through electrochemical cells. Power and energy capacity are decoupled: power is determined by the sise of the cell stack, while energy is determined by the volume of electrolyte tanks.

Vanadium Redox Flow Batteries (VRFB)

VRFBs are the most mature flow battery technology and are characterised by long cycle life and inherent fire safety. They are well suited for long-duration energy storage with frequent cycling.

Hydrogen-Based Flow Batteries

Certain flow battery concepts use hydrogen as an active electrochemical component. These systems offer theoretical synergies with hydrogen infrastructure but remain at an early stage of commercial deployment and typically require site-specific engineering solutions.

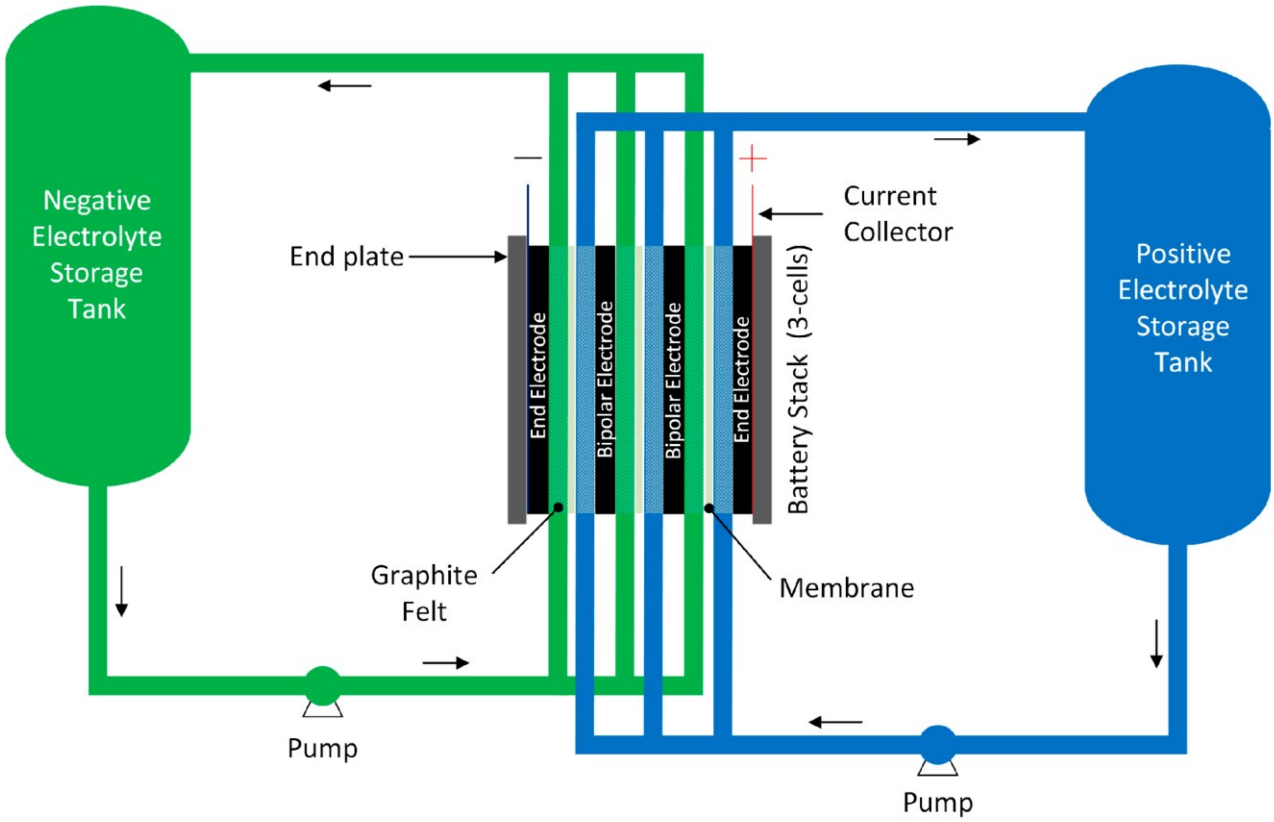


Figure 5-7: Conceptual Flow Battery Architecture (Tank-Based Energy Storage) [171]

5.2.6. Comparative Assessment of BESS Technologies

Table 5-4: Comparative Characteristics of Utility-Scale BESS Technologies

Parameter	Lithium-Ion Batteries	Redox Flow Batteries
Technology maturity	High	Medium
Commercial deployment	Widespread	Limited but growing
Typical storage duration	Short–medium	Medium–long
Response time	Very fast	Fast
Cycle life	Medium	Very high
Degradation behavior	Capacity fade over time	Minimal degradation
Safety considerations	Requires active protection	Inherently non-flammable
Footprint	Compact	Larger
Modularity	High	Moderate
Engineering complexity	Standardised	Site-specific

5.2.7. Technology Selection and Preferred Option

For the initial stages of the project, Lithium-Ion BESS is selected as the preferred technology. This choice is driven by its high commercial maturity, standardised design, proven operational performance, and availability of experienced EPC and O&M providers.

Lithium-Ion systems provide sufficient performance for the intended operational roles in the hydrogen plant while minimizing implementation risk and upfront capital complexity. Alternative battery technologies remain under consideration for future expansion phases, where longer-duration storage requirements and lifecycle economics may justify their deployment.

5.2.8. Electricity Market Participation and Energy Arbitrage Using BESS

Beyond internal plant optimisation, BESS enables participation in electricity markets through energy arbitrage. Energy arbitrage refers to charging the battery during periods of low electricity prices and discharging during periods of higher prices, thereby capturing price differentials. [64]
In hydrogen projects, arbitrage can be applied in several ways:

- reducing the effective cost of electricity supplied to electrolysers,
- optimizing the allocation of electricity between hydrogen production, storage, and grid export,
- supporting congestion management and redispatch requests from the system operator.

While arbitrage revenues are subject to regulatory access and market conditions, BESS provides the technical capability to respond dynamically to price signals. In this feasibility study, arbitrage is treated as an upside potential rather than a base-case revenue stream, improving overall project robustness without increasing dependency on volatile market income.

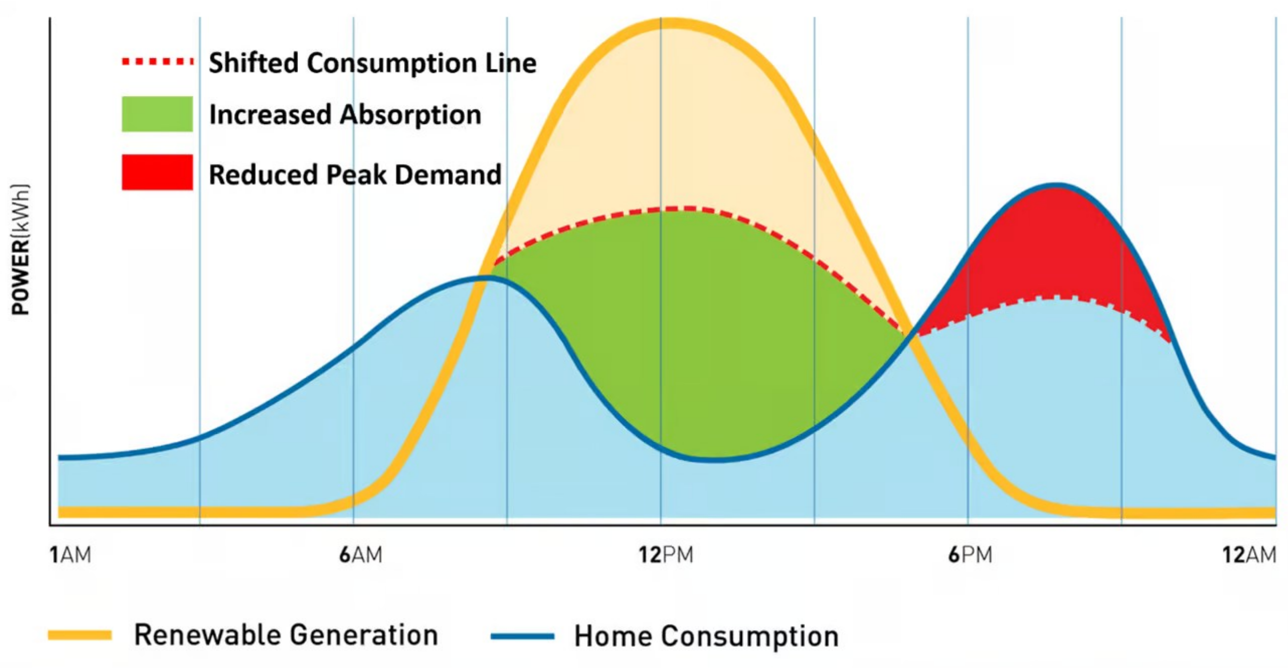


Figure 5-8: Conceptual Illustration of Electricity Arbitrage Using BESS [172]

5.2.9. Conclusion

Battery Energy Storage Systems are a foundational component of modern green hydrogen projects. By stabilizing power supply, enhancing operational flexibility, improving system resilience, and enabling market participation, BESS significantly strengthens both the technical and economic feasibility of the project.
For the proposed development stages, Lithium-Ion technology offers the optimal balance between performance, maturity, cost, and implementation risk. As the project scales, alternative storage technologies may be reassessed to further optimise long-duration energy management and lifecycle economics.

5.3. Electrolyser Technology Evaluation

The choice of electrolyser technology is a fundamental decision that impacts the project's cost, efficiency, and operational flexibility. The two leading commercially available technologies for large-scale applications, Alkaline (AEL) and Proton Exchange Membrane (PEM), are evaluated below. [58]

Table 5-5: Technology Trade-Off Matrix: PEM vs. Alkaline Electrolysis

Parameter	Proton Exchange Membrane (PEM)	Alkaline (AEL)	Rationale & Implications for Zakarpattia Project
Capital Cost (CAPEX)	Higher initial cost (990-3,950EUR/kW), but rapidly decreasing with scale and manufacturing improvements.	Lower initial cost (660-3,100 EUR/kW), mature technology with an established supply chain.	AEL offers a lower upfront investment, but PEM's falling cost curve may make it competitive on a total cost of ownership basis, especially for later project phases.
Operational Flexibility	Excellent. Rapid start-up/shutdown times and a wide operating range (10-100%). Ideal for pairing with intermittent renewables.	Limited. Slower response times and a narrower operating range (~20-100%). Better suited for continuous, baseload operation.	PEM's flexibility is a major advantage for a project primarily powered by solar PV, allowing it to efficiently capture fluctuating energy supply and maximise hydrogen output.
System Footprint	More compact. Operates at higher current densities (>1 A/cm^2), requiring less physical space for the same output capacity.	Larger. Operates at lower current densities, resulting in a larger physical footprint for the electrolyser stacks.	The compact nature of PEM is advantageous for the 37-hectare site, allowing more efficient land use and potentially leaving room for future expansion.
Hydrogen Purity	Very high (99.999%+) directly from the stack due to the solid polymer membrane preventing hydrogen crossover.	High (99.5-99.9%), but the liquid electrolyte can introduce impurities, often requiring additional downstream purification.	PEM's inherent high purity may reduce the CAPEX and OPEX of the downstream hydrogen purification system needed to meet stringent pipeline quality specifications.
Technology Maturity	Commercially mature and in a rapid scale-up phase for industrial use. Backed by significant global R&D investment.	Very mature. A well-established, proven technology used in industrial applications for decades.	AEL represents a lower technology risk, while PEM offers greater potential for future performance and cost improvements.
Operating Pressure	Can deliver hydrogen at high pressure (30 bar or higher) directly, reducing compression needs.	Typically operates at lower pressures (near-atmospheric to 10 bar), requiring more energy for downstream compression.	PEM's ability to deliver pressurised hydrogen directly reduces the energy consumption and cost of the multi-stage compression needed to reach the 30-50 bar pipeline injection pressure.

5.3.1. Modular Architecture

Regardless of the chosen technology, the plant will be designed with a modular architecture. This approach involves using standardised, pre-fabricated, skid-mounted electrolyser units (e.g., 4 MW or 10 MW blocks) that can be combined to achieve the desired total capacity. This "building block" design offers significant advantages for the Zakarpattia project:

- **Scalability:** It allows for the planned phased ramp-up from the 2 MW pilot to the full 400 MW capacity by simply adding more modules.
- **Faster Construction:** Factory assembly and testing of modules reduces on-site construction time and risk.
- **Improved Maintainability:** Individual modules can be taken offline for maintenance without shutting down the entire plant, increasing overall availability. [62]

5.3.2. Scenario Analysis and Sizing (Core Technical Analysis)

This subsection presents the core technical data for the eight scenarios under consideration, forming the basis for the subsequent economic and financial evaluation.

Table 5-6: 8-Scenario Technical Specification Matrix

Scenario ID	Electrolyser Tech	Capacity (MW)	H_2 Output (t/yr)	Electricity Input (GWh/yr)	Water Input (m³/yr)
PILOT-AEL-2	Alkaline (AEL)	2	107.4	6.0	2,100
PILOT-PEM-2	PEM	2	105	6.0	2,100
PHASE1-AEL-20	Alkaline (AEL)	20	1,074	60	20,400
PHASE1-PEM-20	PEM	20	1,074	60	21,000
SCALE-AEL-100	Alkaline (AEL)	100	5370	300	102,000
SCALE-PEM-100	PEM	100	5700	300	110,100
FULL-AEL-300	Alkaline (AEL)	300	16,110	900	303,900
FULL-PEM-300	PEM	300	17,100	900	330,000

Assumptions: example for 3000 full load hours (~34% capacity factor); AEL efficiency 56 kWh/kg; PEM efficiency 52.6-57 kWh/kg;.

5.3.3. Balance of Plant (BOP) Design

The Balance of Plant encompasses all the auxiliary systems required to support the core electrolyser function. The conceptual design includes:

- **Water Treatment System (WTS):** A multi-stage system comprising Ultrafiltration (UF), Reverse Osmosis (RO), and Electrodeionisation (EDI) to produce the ultrapure demineralised water required by the electrolysers.
- **Hydrogen Processing:** A gas processing train including purification (to remove residual oxygen and water vapor), drying, and a multi-stage compressor system to raise the hydrogen pressure to the 30-50 bar required for pipeline injection.
- **Power Electronics:** A dedicated substation with transformers and high-power rectifiers to convert the AC power from the grid and PV plant to the DC power required by the electrolysers.
- **Cooling Systems:** A closed-loop cooling circuit with heat exchangers to manage the significant waste heat generated by the electrolysis process.

5.4. Detailed technical comparison of PEM and Alkaline (AEL) technologies

The selection of an appropriate electrolysis technology is a foundational strategic decision for any utility-scale green hydrogen project. This choice dictates not only the initial capital investment but also defines the plant's operational flexibility, resource efficiency, and long-term economic viability, particularly when coupled with variable renewable energy sources. This section provides a foundational, academic-level understanding of the two principal low-temperature electrolysis technologies under consideration for the Zakarpattia project: Proton Exchange Membrane (PEM) and Alkaline (AEL) electrolysis. A thorough grasp of their fundamental operating principles is essential for the comparative technical and financial analysis that follows.

5.4.1. Proton Exchange Membrane (PEM) Electrolysis

General Description

Proton Exchange Membrane (PEM) electrolysis is a highly responsive technology that splits demineralised water into hydrogen and oxygen using a solid polymer electrolyte. The core of a PEM cell is a specialised membrane, typically made of Nafion, which is impermeable to gases but selectively conductive to protons (H^+). This solid membrane is coated on both sides with noble metal catalysts from the Platinum Group Metals (PGM). At the anode, an iridium-based catalyst facilitates the Oxygen Evolution Reaction (OER), splitting water into oxygen, protons, and electrons. The protons migrate through the solid polymer membrane to the cathode, where a platinum-based catalyst facilitates the Hydrogen Evolution Reaction (HER), combining the protons with electrons from the external circuit to form high-purity hydrogen gas. PEM electrolysers typically operate within a temperature range of 50°C to 80°C and are known for their ability to produce hydrogen at significant pressure directly from the stack.

Cell Stack Cross-Section
A conceptual cross-section of a single PEM electrolysis cell, which is layered repeatedly to form a stack, consists of the following components in sequence:

- **Bipolar Plate (Anode Side):** A corrosion-resistant plate that distributes demineralised water across the anode, provides electrical contact, and channels the produced oxygen gas away.
- **Gas Diffusion Layer (GDL) - Anode:** A porous titanium-based material that facilitates the uniform distribution of water to the catalyst and allows oxygen to exit the cell.
- **Iridium Catalyst (Anode):** A thin layer of catalyst applied to the membrane where the water-splitting reaction (OER) occurs.
- **Solid Polymer Membrane:** The central electrolyte that transports protons from the anode to the cathode while physically separating the hydrogen and oxygen gas streams.
- **Platinum Catalyst (Cathode):** A thin layer of catalyst applied to the membrane where the hydrogen formation reaction (HER) occurs.
- **Gas Diffusion Layer (GDL) - Cathode:** A porous carbon-based material that allows the produced hydrogen gas to exit the cell while providing electrical contact.
- **Bipolar Plate (Cathode Side):** An engineered plate that channels the hydrogen gas away from the cathode and provides the electrical connection to the next cell in the stack.

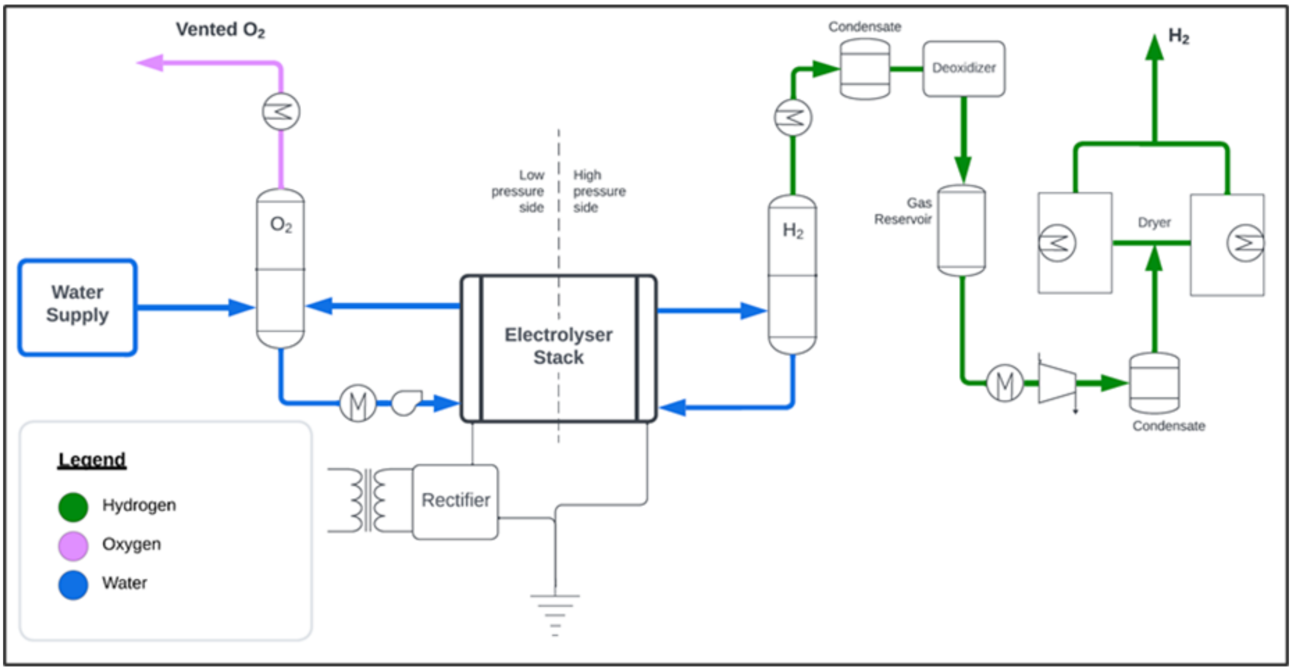


Figure 5-9: Conceptual Cross-Section of a PEM Electrolysis Cell and BoP

The Balance of Plant (BoP) for a PEM electrolyser system is characterised by its relative simplicity. The process begins with a robust water treatment system feeding high-purity demineralised water to the anode side of the electrolyser stack. On the anode side, a mixture of oxygen and unreacted water is separated, with the water often being recirculated. On the cathode side, a mixture of hydrogen gas and water vapor exits the stack. This wet hydrogen stream is then directed to downstream purification units, which typically include a DeOxo (deoxygenation) unit to remove trace oxygen by catalytically reacting it with hydrogen to form water, followed by a dryer system (e.g., pressure swing adsorption - PSA) to remove the remaining water vapor. The absence of a corrosive liquid electrolyte loop simplifies material selection and reduces the complexity of the BoP compared to AEL systems. [51]

5.4.2. Alkaline (AEL) Electrolysis

General Description

Alkaline (AEL) electrolysis is the most commercially mature and widely deployed electrolysis technology. The process involves splitting water in a liquid alkaline electrolyte, typically a 20-30% solution of potassium hydroxide (KOH) in water. The electrolyser stack consists of multiple cells, where each cell contains a cathode and an anode separated by a porous diaphragm. This diaphragm is permeable to the liquid electrolyte, allowing for the transport of hydroxide ions (OH^-), but it serves as a physical barrier to prevent the mixing of the produced hydrogen and oxygen gases. The electrodes are typically made from nickel-based materials, avoiding the need for expensive PGM catalysts. AEL systems operate at elevated temperatures, generally in the range of 70°C to 90°C, to enhance reaction kinetics and ionic conductivity. [53]

Cell Stack Cross-Section

A conceptual cross-section of a single AEL cell consists of the following core components:

- **Anode:** The positive electrode where the oxygen evolution reaction occurs. Hydroxide ions are consumed to produce oxygen gas, water, and electrons.
- **Diaphragm:** A porous separator (e.g., Zirfon®) soaked in the KOH electrolyte. Its primary function is to physically separate the hydrogen and oxygen gas streams while allowing the transport of hydroxide ions.
- **Cathode:** The negative electrode where the hydrogen evolution reaction occurs. Water molecules are split to produce hydrogen gas and hydroxide ions.
- **Electrolyte Flow:** The liquid KOH solution circulates through the cell, supplying reactant water, transporting hydroxide ions from the cathode to the anode, and removing waste heat.

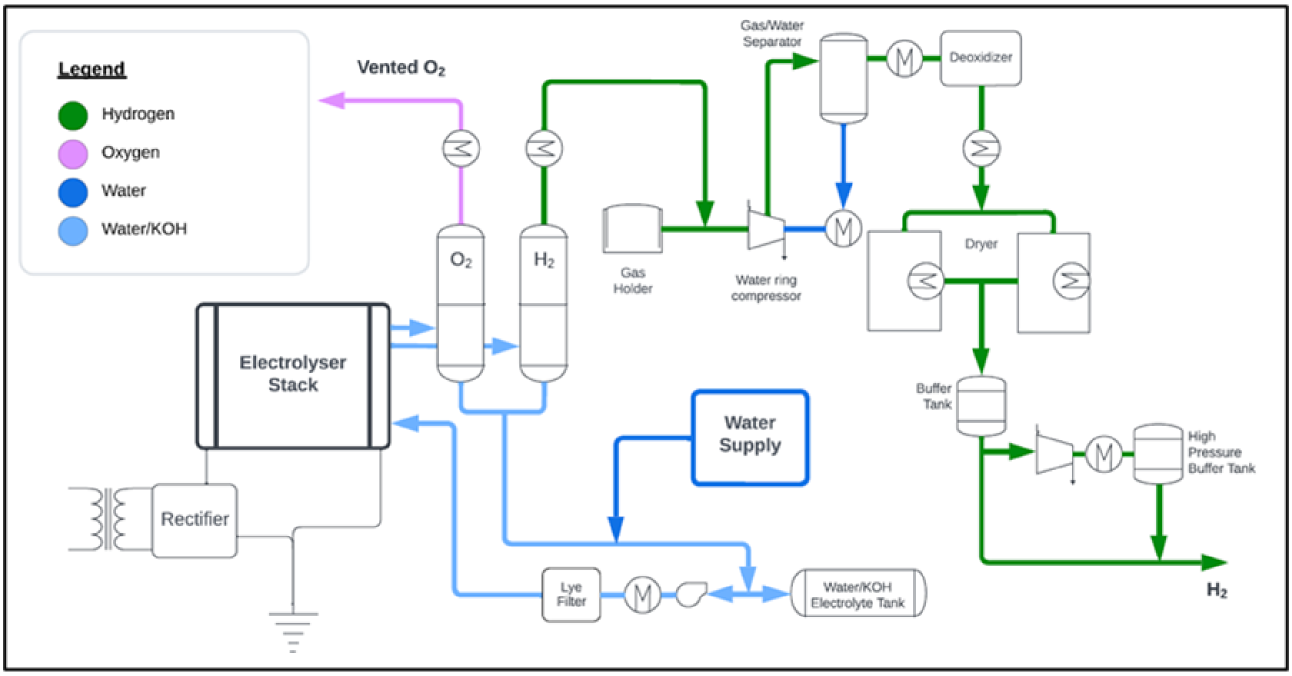


Figure 5-10: Conceptual Cross-Section of an Alkaline Electrolysis Cell and BoP

The Balance of Plant for an AEL system is defined by its mandatory electrolyte circulation loop. The central component is a large Water/KOH Electrolyte Tank, from which the electrolyte is pumped through the electrolyser stack. As hydrogen and oxygen are produced, a two-phase mixture of gas and electrolyte exits each side of the stack and flows into separate gas/water separators. In these separators, the hydrogen and oxygen gases are separated from the liquid electrolyte. The electrolyte is then passed through a lye filter to remove impurities, cooled, and recirculated back to the main electrolyte tank. The separated hydrogen and oxygen streams, saturated with water and containing traces of KOH, are then routed to downstream purification units. Similar to PEM, these typically include a DeOxo unit and a dryer to achieve the final required hydrogen purity. The complexity and maintenance requirements of the electrolyte loop are a key distinguishing feature of the AEL BoP.

This foundational overview of the core technologies now provides the basis for a direct comparison of their practical performance metrics and operational characteristics.

5.4.3. Technical Benchmarking (2025-2030 Outlook)

5.4.3.1. Introduction to Performance Benchmarking

A strategic technical benchmark is critical for de-risking technology selection and ensuring long-term project success. This section critically evaluates Alkaline (AEL) and Proton Exchange Membrane (PEM) technologies against a set of key performance indicators (KPIs) that are paramount for a utility-scale plant directly coupled with intermittent renewable energy. The analysis is based on a forecast horizon of 2025-2030, synthesizing data from leading industry reports, manufacturer specifications, and European research agendas to provide a forward-looking perspective relevant to the project's investment timeline.

5.4.3.2. Comparative Performance Analysis

Table 5-7: Comparison of Electrolyser Technologies and Strategic Implications

Metric	Proton Exchange Membrane (PEM)	Alkaline (AEL)	Strategic Implication for Zakarpattia Project
Efficiency (System Level, EOL)	**58.4 kWh/kg H_2**	**48 kWh/kg H_2** (2030 Stack Target)	The PEM figure represents a verified End-of-Life system consumption. The AEL figure is a 2030 *stack-level* target; system-level consumption will be 5-8% higher. While AEL appears more efficient under ideal conditions, PEM's superior performance under dynamic loads is projected to result in a lower *real-world* average energy consumption when powered by solar PV, a critical factor for the project's financial model and OPEX.
Degradation Rate	**~0.12 % / 1,000h**	**~0.08 % / 1,000h**	AEL's lower degradation rate under steady-state conditions is invalidated by the project's operational profile. The frequent cycling and dynamic loading inherent to solar power are known to accelerate AEL degradation. This is a critical risk factor that significantly increases the plant's lifetime power draw and negates AEL's perceived durability advantage in this specific application.
Flexibility (Ramp Rate)	Up to **100% / second**	**0.2 - 20% / second**	**PEM's superior ramp rate is a decisive advantage.** It allows the electrolyser to precisely follow the rapid fluctuations of solar PV generation, maximizing the capture of available renewable energy and minimizing curtailment. This capability is also a prerequisite for providing high-value grid ancillary services like Frequency Containment Reserves (FCR).
Flexibility (Start-Up Time)	Cold: < 10 min Warm: < 1 min [^1]	Cold: < 60 min Warm: 1 - 10 min	Faster start-up times directly translate to increased hydrogen production. In a solar-driven scenario with daily or frequent shutdowns, PEM's ability to quickly restart minimises production losses during periods of intermittent

Metric	Proton Exchange Membrane (PEM)	Alkaline (AEL)	Strategic Implication for Zakarpattia Project
			solar availability (e.g., morning ramp-up or passing cloud cover).
Flexibility (Load Range)	**0 - 160%**	**10 - 110%**	**This is a critical operational and safety differentiator.** PEM's ability to operate down to 0% load is ideal for solar integration. In contrast, AEL systems face a significant safety risk at low partial loads. Academic studies have found "alarming HTO [hydrogen in oxygen] contents at current densities below 20% of the nominal load" (Kraakman), creating explosive gas mixtures. This forces AEL systems to shut down completely during periods of low solar irradiance, leading to production losses and increased mechanical stress.
Hydrogen Purity (Upstream of Purification)	High, with O_2 content **≤ 4000 ppm**.	Lower, with higher cross-contamination of O_2 into H_2 stream, especially at partial loads.	While both technologies require a downstream purification BoP (DeOxo and dryer units) to meet ISO 14687-2 standards, PEM's higher initial purity reduces the load and operational stress on these downstream components.

This comparative analysis demonstrates that while technical specifications are converging in some areas, critical differences in flexibility and operational safety have a profound impact on resource consumption and system design.

5.4.4. Resource Consumption Analysis

5.4.4.1. Introduction to Resource Efficiency

Beyond core performance metrics, the consumption of critical resources – primarily water and energy – is a fundamental determinant of a project's operational viability, cost structure, and environmental sustainability. A thorough analysis of these inputs is essential for accurate operational expenditure (OPEX) forecasting and responsible site planning. This section quantifies and compares the specific water and lifecycle energy requirements for both PEM and AEL technologies across all planned stages of the Zakarpattia project.

5.4.4.2. Water Consumption Balance Methodology

The total water balance for an electrolysis plant includes the stoichiometric water required for the chemical reaction (~9 L/kg H_2), water for plant cooling systems, and other Balance of Plant uses such as in purification steps. Based on a comprehensive review of operational data, which indicates a typical range of 20-60 L/kg H_2, this analysis adopts a central value of 22 L/kg H_2 for total plant water consumption. Annual H_2 production is calculated based on a representative PEM system Begin-of-Life (BOL) efficiency of 52.1 kWh/kg H_2 and an 80% annual capacity factor. It is critical to note that electrolyser systems, particularly PEM technology, are highly sensitive to water purity. Any impurities can damage the catalyst and membrane, shortening the stack's lifespan. Therefore, a robust demineralised water treatment system is a mandatory prerequisite for both technologies. [50]

The following table outlines the estimated annual water consumption for each planned stage of the project, assuming an 80% capacity factor to reflect a realistic operational scenario with a renewable power source.

Table 5-8: Consumption Table

Project Stage	Capacity (MW)	Annual H_2 Production (Tonnes)	Estimated Annual Water Consumption (m^3)
Pilot	2	269	5,918
Commercial Demonstration	20	2,689	59,158
Utility-Scale Phase 1	100	13,445	295,790
Utility-Scale Phase 2	300	40,335	1,183,182

5.4.4.3. Lifecycle Energy Consumption Stack vs. System Efficiency

A crucial distinction in energy analysis is between stack-level and system-level efficiency. The electrolyser stack is only one component of the overall plant. The Balance of Plant (BoP) – which includes rectifiers, pumps, cooling systems, gas purification, and control systems – introduces a parasitic energy load. Analysis of manufacturer data indicates this parasitic load increases the overall energy consumption figure by approximately 5-12% compared to the stack efficiency alone. For example, a PEM system with a stack consumption of 51.2 kWh/kg H_2 has a total system consumption of 5.62 kWh/kg H_2, representing a 9.5% increase due to BoP loads.

Comparative Analysis

While 2030 performance targets suggest a convergence of stack efficiencies for both PEM and AEL towards approximately 48 kWh/kg, this figure represents performance under ideal, steady-state conditions. In a real-world application powered by intermittent solar energy, PEM's superior flexibility and widЦer operational load range allow it to operate more efficiently across a variable power profile. AEL systems, constrained by their minimum load limits and slower ramp rates, are forced into inefficient standby modes or complete shutdowns more frequently, leading to a higher average lifecycle energy consumption per kilogram of hydrogen produced. Therefore, PEM technology is projected to offer a lower effective energy consumption and superior overall energy efficiency in the context of the Zakarpattia project.

The consumption of these key resources directly influences the required physical infrastructure needed to manage the plant's inputs and outputs.

5.4.5. Infrastructure & Connection Strategy

5.4.5.1. Introduction to System Integration

The strategic alignment of the chosen electrolyser technology with existing and planned infrastructure is a critical factor for project success. A technology choice is not made in isolation; it has direct and significant consequences for downstream gas handling processes and the plant's relationship with the electrical grid. This section evaluates how the choice between PEM and AEL fundamentally impacts downstream compression requirements for grid injection and unlocks the potential for the plant to offer valuable ancillary services, enhancing grid stability and creating additional revenue streams.

5.4.5.2. Gas Distribution and Compression

Output Pressure Analysis

A key differentiator between the two technologies is their native hydrogen output pressure. Atmospheric Alkaline (AEL) systems, the most common configuration, typically operate at pressures of less than 10 bar. In contrast, Proton Exchange Membrane (PEM) systems from leading manufacturers are designed to operate at significantly higher pressures, typically in the range of **30-40 bar**, with advanced systems capable of reaching even higher levels directly from the stack.

Compression Strategy for Grid Injection

For the 100 MW and 400 MW stages, the project requires hydrogen to be delivered at a plant gate pressure of **40-50 bar** for injection into the gas transmission network. The implications of this requirement vary drastically between the two technologies:

- **PEM:** With a native output pressure of 30-40 bar, a PEM system requires only a small, single-stage "booster" compressor – or potentially no additional compression at all, depending on the final system design. This dramatically reduces the energy-intensive mechanical compression stage, resulting in significant savings in both capital expenditure (CAPEX) for compression equipment and long-term operational expenditure (OPEX) from lower electricity consumption.

- **AEL:** To raise hydrogen pressure from near-atmospheric levels to the required 40-50 bar, an AEL system necessitates a complex and costly multi-stage mechanical compression train. This compression system represents a substantial capital investment and imposes a significant and continuous energy penalty on the plant's operational budget, reducing overall system efficiency.

5.4.5.3. Electrical Grid Services Potential

Ancillary Services Overview

Grid ancillary services are essential for maintaining the stability and reliability of the power grid. Key services include Frequency Containment Reserves (FCR), which provide automatic, near-instantaneous responses to stabilise grid frequency, and manual Frequency Restoration Reserves (mFRR), which are activated over minutes to restore the system balance. The ability to provide these services is increasingly valuable to grid operators managing systems with high penetration of variable renewables.

Technology Suitability

The technical capabilities of the electrolyser technology determine its suitability for providing these high-value services.

- **PEM:** With ramp rates measured in seconds or sub-seconds, PEM electrolysers are exceptionally well-suited for providing the fastest and most valuable grid services, such as FCR. Their dynamic response allows them to act as a large, controllable load that can be adjusted almost instantly to support grid stability.
- **AEL:** The slower response times of AEL systems, measured in minutes, largely preclude their participation in fast-response markets like FCR. Their flexibility is limited to providing slower services, which typically command lower market prices.

Strategic Value

By selecting PEM technology, the Zakarpattia project positions itself not just as a hydrogen producer, but also as a strategic asset for the Ukrainian power grid. The ability to participate in ancillary service markets creates a potential secondary revenue stream, enhancing the project's overall financial performance. This dual function provides greater strategic value to the national grid operator by helping to integrate more renewable energy and improve system-wide flexibility.

The significant differences in infrastructure requirements and grid service potential have a direct and measurable impact on the project's financial outlook.

Definition of system services

System services are all services necessary for the operation of a transmission and distribution system, and can be organised in different categories in this report we explore:

- Ancillary services (frequency and non-frequency); and
- Congestion management products.

There are system services which are not included in the report (e.g. inertia for local grid stability, black start capability or fast frequency response – particularly useful for small island operation capability) as these would rely on additional equipment being included in the plant specifications.10 Technical requirements for system services may differ across TSOs, especially for services such as voltage control and congestion management. In the following table, we present some typical examples of key features of the different system services we have included in our analysis.

Table 5-9: System services (+ congestion management)

Category	Service Type	Sub-Service	Specifications
Ancillary services	Frequency ancillary services (mainly for balancing)	Frequency Containment Reserves (FCR)	FAT: 30 sec.Min. sise: 1 MWSymmetry: YesBid duration: 4 h
		Automatic Frequency Restoration Reserves (aFRR)	FAT: 5 min.Min. sise: 1 MWSymmetry: NoBid duration: 15 min.
		Manual Frequency Restoration Reserves (mFRR)	FAT: 12.5 min.Min. sise: 1 MWSymmetry: NoBid duration: 15 min.
		Reserve Restoration (RR)	FAT: 30 min.Min. sise: 1 MWSymmetry: NoBid duration: 15 min.–1 h.
	Non-frequency ancillary services	Voltage Control	FAT: few sec. to 15 min.Min. sise: n.a.Symmetry: NoBid duration: n.a.
Congestion Management	Services for congestion management	Congestion management through redispatch and curtailment	FAT: 15 min.Min. sise: 1 to 10 MW.Symmetry: NoBid duration: n.a.

Frequency ancillary services or balancing services
"Balancing" means all actions and processes, on all timelines, through which Transmission System Operators (TSOs) ensure, in a continuous way, the maintenance of system frequency within a predefined stability range, and compliance with the amount of reserves needed with respect to the required quality. [46]
Balancing is organised in different steps. For the purpose of this report, we explore the following:

Frequency Containment Reserves (FCR)
Sometimes known as primary reserve, FCR refers to the active power reserves available to contain system frequency after the occurrence of an imbalance. FCR is a standardised frequency response product dispatched for frequency deviations in less than 30 seconds. This product is generally traded in a capacity price (and possibly also including price) and is dispatched automatically by contracted flexibility providers on command of the grid operator. The frequency containment process stabilises the frequency after the disturbance at a steady-state value within the permissible maximum steady-state frequency deviation by a joint action of FCR within the whole synchronous area.

Frequency Restoration Reserves (FRR)
FRR are the active power reserves available to restore system frequency to the nominal frequency and – for asynchronous areas – consisting of more than one load-frequency control (LFC) area – to restore power balance to the scheduled value. FRR include operating reserves with an activation time between 30 seconds and 15 minutes. In most countries there is a capacity payment for keeping capacity available and an energy payment if the service is activated. FRR includes automatic (aFRR) and manual (mFRR) activation:

- **Automatic Frequency Restoration Reserves (aFRR):** Also known as secondary reserve power, aFRR must be completely activated in 5 minutes and its name indicates that it is dispatched automatically by a contract flexibility provider on command of the grid operator. It has historically been provided (in some countries) mostly by gas-fired power plants.
- **Manual Frequency Restoration Reserves (mFRR):** Also known as tertiary reserve power, mFRR helps to restore the grid frequency by full activation time of 12.5 minutes. mFRR is activated during periods of long deviations in the power grid that cannot be resolved by the other upstream balancing services (FCR or aFRR).

Reserve Restoration (RR)
RRs are the active power reserves available to restore or support the required level of FRR to be prepared for additional system imbalances, including generation reserves. RR is a standardised frequency response product that supports the required level of FRR for additional imbalances with a full activation time of 30 minutes.

Non-frequency ancillary services

Non-frequency ancillary service refers to a service used by a transmission system operator or distribution system operator for steady-state voltage control, fast reactive current injections, inertia for local grid stability, short-circuit current, black start capability and island operation capability. For the purpose of this report, our analysis is limited to voltage control.

- **Voltage control or reactive power control:** A product that dispatches reactive power reserves in real-time to maintain the voltage level within the specified range of the synchronous area. Thus, it is not an energy balancing service.

Congestion Management Products

Congestion refers to a situation in which all requests from market participants to trade between network areas cannot be accommodated because they would significantly affect the physical flows on network elements that cannot accommodate those flows. It refers to overload of grid components, over- and under-voltage and/or forced usage of the local fail-over capacity in the distribution system. Congestion management aims to limit or avoid exceeding network congestion driven by the need to mitigate the risks posed by overload.

Electrolyser potential for providing different system services

This subsection maps the electrolyser technical capabilities with the system services requirements presented in the previous sections, with the aim of identifying the technical potential for the different electrolyser technologies to provide system services.

It is important to note that the results from this evaluation are based only on a technical assessment at this point. In particular, our assessment below does not consider whether economic constraints exist that might limit the real-world applicability of such technologies for TSOs purposes. In other words, an electrolyser's operability mode to provide certain system services may be feasible from a technical point of view, but it may also be economically unfeasible.

We also note that the mapping of electrolyser technologies to system services may evolve in the future. For instance, the lack of data on SOEC flexibility creates a high degree of uncertainty around their suitability to provide system services, and the definition of system services itself may also change going forward. [59]

The following table shows whether each electrolyser technology can provide each type of system service (today and in the medium term).

Table 5-10: Mapping of electrolysers and system services

	Alkaline		PEM		SOEC	
	Today	2030	Today	2030	Today	2030
FCR	Yes with limits	Yes with limits	Yes with limits	Yes with limits	No	Uncertainty about flexibility
aFRR	Yes with limits	Yes with limits	Yes	Yes	No	Uncertainty about flexibility
mFRR	Yes	Yes	Yes	Yes	No	Uncertainty about flexibility
RR	Yes	Yes	Yes	Yes	No	Uncertainty about flexibility
Voltage control			Electrolysers can provide reactive power, if they are equipped with self-commutated rectifiers.			
Congestion management	Yes	Yes	Yes	Yes	No	Uncertainty about flexibility

5.4.6. Financial Impact Analysis

5.4.6.1. Introduction to Economic Viability

The ultimate selection criterion for the project's electrolysis technology is its long-term economic viability. This is determined not by a single metric, but by a holistic analysis of capital expenditures (CAPEX), operational expenditures (OPEX), and physical footprint, which together influence the Levelised Cost of Hydrogen (LCOH). This section provides an anonymised financial comparison based on current and projected data for equipment from Tier-1 European and global suppliers, offering a clear perspective on the financial trade-offs between PEM and Alkaline technologies.

5.4.6.2. Capital Expenditure (CAPEX) Cost Comparison (€/kW)

Historically, AEL technology has held a CAPEX advantage due to its maturity and use of non-precious metal catalysts. However, with rapid innovation and scaling in PEM manufacturing, this gap is narrowing significantly.

- Alkaline (AEL): System costs were approximately €500-750/kW in 2025, with projections to fall to around €300-500/kW by 2030.
- PEM: System costs were approximately €1000-1500/kW in 2025, with projections to decrease to around €700-900/kW by 2030.

While AEL maintains a lower upfront cost today, the projected convergence by 2030 indicates that initial CAPEX will become a less significant differentiator over the project's investment horizon.

Stack vs. BoP Breakdown

The total system CAPEX is composed of two main elements: the electrolyser stack (where the electrochemical reaction occurs) and the Balance of Plant (BoP), which includes power electronics, water treatment, gas purification, and cooling systems. The stack typically accounts for a significant portion of the total cost, ranging **from 40% to 60%**. As production scales, the costs for standardised BoP components are expected to see significant reductions, contributing heavily to the overall decline in system CAPEX for both technologies.

5.4.6.3. Operational Expenditure (OPEX)

Maintenance Costs

Maintenance OPEX, typically expressed as a percentage of initial CAPEX, covers routine servicing, spare parts, and labor. The figures for the two technologies are comparable, with PEM showing a slight advantage.

- **Alkaline (AEL):** 2 - 3% of CAPEX annually.
- **PEM:** 1 - 2.5% of CAPEX annually.

Stack Replacement Strategy

The stack is a consumable component with a finite lifespan, and its replacement is a major lifecycle cost.

- **AEL:** Stacks have a longer rated lifetime under continuous, steady-state operation, with 2030 targets reaching **60,000-90,000 hours**.
- **PEM:** Stacks have a shorter rated lifetime, with 2030 targets of **40,000-60,000 hours**.

These rated lifetimes, established under steady-state conditions, are not representative for a solar-driven operational profile. The frequent start-stop cycles and dynamic loads inherent in a solar-powered scenario are known to accelerate the degradation of AEL components, potentially shortening their effective lifespan significantly. PEM technology is inherently more robust to such cycling. Therefore, PEM's more frequent but predictable and manageable stack replacement cycle may prove more favorable from a total cost of ownership (TCO) perspective, avoiding unscheduled downtime and performance loss associated with AEL degradation under dynamic conditions.

5.4.6.4. Physical Footprint and Power Density

Comparative Analysis

Power density refers to the amount of hydrogen that can be produced per unit of land area. Due to its ability to operate at higher current densities, PEM technology offers a significantly more compact design. For a 100 MW plant, the estimated land requirements are:

- **PEM Plant:** 1.3 - 2,2 hectares
- **Alkaline Plant:** 1.4 - 2.5 hectares

Site Suitability
PEM's higher power density and smaller footprint provide a distinct advantage for site planning. This compactness simplifies the overall plant layout, reduces civil works costs, and provides greater flexibility for optimizing the use of available land and accommodating future expansions.
While the financial metrics provide a quantitative comparison, the final recommendation must synthesise these economic factors with the critical operational and strategic realities of integrating with a solar PV power source.

5.4.7. Synthesis & Recommendation for Solar PV Integration

5.4.7.1. Introduction to the Final Recommendation

The preceding analysis has provided a comprehensive evaluation of Proton Exchange Membrane (PEM) and Alkaline (AEL) electrolysis, comparing their fundamental technologies, operational performance, resource consumption, infrastructure impacts, and financial profiles. This final section synthesises these multifaceted findings to provide a definitive and evidence-based recommendation for the electrolysis technology best suited for the "Solar PV + Electrolyser" operational scenario envisioned for the green H_2 project in Zakarpattia.

5.4.7.2. The Case for PEM in a Solar-Driven Project

Based on a holistic assessment of all technical and commercial factors, **Proton Exchange Membrane (PEM) electrolysis is the unequivocally recommended technology for this project.** This conclusion is supported by several critical advantages that directly align with the challenges and opportunities of a plant coupled with intermittent solar power.

Superior Flexibility for Renewable Integration PEM's core design enables performance characteristics that are fundamentally better suited to the variable output of a solar PV plant. Its rapid ramp rates (up to 100%/second), fast start-up times (<10 minutes from cold), and exceptionally wide operational load range (0-160%) allow it to maximise hydrogen production by closely tracking solar availability. This minimises energy curtailment and lost revenue, which are major economic drawbacks for less flexible systems.

Enhanced Grid Stability and Revenue The dynamic response capabilities of PEM technology position the plant as a valuable asset to the Ukrainian national grid. Its ability to participate in high-value ancillary service markets, particularly fast-response services like Frequency Containment Reserves (FCR), creates a significant secondary revenue stream. This not only improves project bankability but also contributes to grid stability, facilitating greater integration of renewable energy nationwide.

Reduced Downstream Infrastructure Costs PEM's ability to generate hydrogen at high pressure (30-40 bar) directly addresses the project's 40-50 bar grid injection requirement with minimal or no downstream mechanical compression. This circumvents the need for a multi-stage compression train, an ancillary system that would add significant parasitic load (~3-5% of total plant energy consumption) and represent a substantial portion of the Balance of Plant CAPEX for an AEL system. The resulting reduction in both CAPEX and OPEX is a major long-term financial advantage for the PEM pathway.

Mitigated Operational and Safety Risks The operational profile of a solar-powered plant involves frequent periods of low power output. For AEL technology, operation at low partial loads (<20%) significantly increases the risk of gas crossover, where hydrogen permeates the diaphragm into the oxygen stream, creating a potentially explosive gas mixture. This inherent safety concern forces AEL systems into frequent, stressful shutdowns. PEM technology, with its solid polymer membrane, is far more robust under such cycling and does not face the same degree of crossover risk at low loads, ensuring safer and more reliable operation.

5.4.8. Strategic Technological Assessment and Financial Outlook

Preferred Technological Pathway: PEM Electrolysis

Based on the specific operational profile of the **green H_2 project in Zakarpattia** – characterised by deep integration with intermittent Solar PV generation and the requirement for high-pressure injection into the Central European Hydrogen Corridor (CEHC) – **PEM (Proton Exchange Membrane) technology is identified as the preferred baseline.** The long-term financial case for PEM is driven by its superior dynamic responsiveness, which allows for maximum capture of volatile renewable energy, and its native 30-bar output pressure, which significantly reduces Capital Expenditure (CAPEX) and energy penalties associated with downstream compression infrastructure. These factors result in a competitive long-term Levelised Cost of Hydrogen (LCOH) and enhanced eligibility for grid ancillary service markets.

Alkaline Electrolysis (AEL) as a Proven Alternative

While PEM is the recommended pathway for the solar-centric model, **Alkaline technology remains a robust and highly viable alternative**, particularly as a secondary option for future expansion phases or baseload scenarios. The strengths of AEL that provide a strong alternative case include:

- **Lower Initial CAPEX:** AEL stack modules currently offer a lower upfront investment cost per kW, which can be advantageous in capital-constrained environments or projects with a higher proportion of stable grid power.
- **Established Maturity and Scale:** As a proven industrial workhorse with decades of operational track record, AEL benefits from a highly stable global supply chain and standardised maintenance protocols.
- **Supply Chain Resilience:** Unlike PEM, Alkaline systems do not rely on scarce platinum-group metals (iridium and platinum), making the technology less susceptible to commodity price volatility and supply bottlenecks for noble metals.
- **Extended Mechanical Lifetime:** AEL systems are known for exceptional stack durability, often demonstrating mechanical lifetimes exceeding 80,000 hours when operated in steady-state environments.

Conclusion

For the dynamic, renewable-focused business case of the Uzhhorod Hub, **PEM offers the most favorable financial outlook** and operational flexibility. However, **Alkaline technology represents a credible and de-risked alternative**, providing an "infrastructure-ready" backup solution should the project's energy mix shift toward baseload power or if global PGM supply constraints impact PEM availability. Maintaining technology-neutrality during the early procurement stages ensures maximum bargaining power and a resilient long-term development strategy.

5.5. Plant Layout and Technological Solutions

5.5.1. General Concept: Plot Plans and Process Flow Schemes for the Green Hydrogen Hub (Stages 1–4, Solutions No. 1–8)

Section 5.5 establishes a unified technical approach to describing plant layout (plot plan) and technological chains of the Green Hydrogen Hub (Ukraine) across Stage 1–Stage 4 and alternative configurations Solutions Nº1–Nº8.

Objectives of Section 5.5:

- fix plot plan feasibility at Pre-Design stage (without FEED-level detail);
- establish a unified logic of zoning, infrastructure corridors, utilities, and hydrogen logistics;
- fix industrial safety principles: fire separation distances, emergency access, hazardous areas (ATEX linkage), qualitative HAZID. [102]

Description boundaries of Section 5.5:

- included:
  - functional zoning and staged hub development logic;
  - buildings and structures strictly per drawing explications (plot plans);
  - process chain “water + power → electrolysis → H_2 conditioning → compression/buffering → delivery (trailers/network)”;
  - BoP systems (water treatment, thermal management/cooling, instrument air, nitrogen, control/safety, drains);
  - hydrogen logistics and interfaces (to trailers or to gas distribution network);
  - tables “Explication → Fire Category (UA) → ATEX Zone → Key safeguards”;
  - ATEX & Hazardous Area Summary (conceptual, IEC 60079-10-1);
  - fire separation distances (fire gaps) tabulated from actual drawing dimensions;
  - qualitative HAZID Summary mapped to explication positions;
  - Water / Sewer / Fire philosophy (with water calculations only where explicitly required by the solution scope).
- excluded:
  - FEED level: CFD dispersion, QRA, LOPA/SIL, full HAZOP, P&IDs, detailed instrumentation/valve specification, detailed building structural design, detailed utility design deliverables.

Units: m, bar, MW. Operating time is treated in hours/year (8760 h = 100%) where used for capacity-load calculations.

5.5.1.1. Regulatory Framework and Standards for Layout and Design Solutions (Ukraine & International)

Layout decisions, fire hazard categorisation, fire separation principles, sanitary zones, utilities, and hazardous area classification within Section 5.5 are based on:

- Ukrainian legal/regulatory documents and building codes (primary);
- international standards/guidance (for hydrogen and ATEX logic) where no direct national analogue exists or where hydrogen-specific detail is required at Pre-Design.

A) Ukraine – construction, planning, fire safety

- DBN V.1.1-7:2016 – fire safety of construction objects.
- DBN B.2.2-12:2019 – planning and development of territories.
- NAPB A.01.001-2014 – fire safety rules in Ukraine.
- NAPB B.03.002-2007 – determination of explosion and fire hazard categories of premises/buildings/outdoor installations.

B) Ukraine – water supply, sewerage, sanitary and water use

- DBN V.2.5-74:2013 – water supply. External networks and facilities.
- DBN V.2.5-75:2013 – sewerage. External networks and facilities.
- DSanPiN 2.2.4-171-10 – water hygiene; sanitary protection of sources. A conservative well sanitary zone R = 30 m is adopted across all hub solutions (fixed on drawings).
- Water Code of Ukraine – requirements for special water use permits and discharges.

C) Ukraine – occupational/industrial safety (framework)

- Applicable NPAOP requirements – framework for organisational and technical measures; detailed mapping is refined at FEED.

D) International standards – ATEX/Hazardous Areas

- IEC 60079-10-1 – hazardous area classification (gas atmospheres) as HAC basis.
- IEC 60079-14 – electrical installations in hazardous areas (FEED/Design level requirements).

E) International standards – hydrogen systems and logistics

- ISO 22734 – hydrogen generators using water electrolysis (safety and functional requirements).
- ISO 19880-1 – requirements for hydrogen delivery/refuelling interfaces (applied where relevant).
- ISO 14687 – hydrogen product quality framework (as applicable to target specifications).
- EIGA / CGA guidance (incl. CGA G-5.5 venting practice) – reference practice for venting philosophy and safe layout.

5.5.1.2. Unified Hub Concept: The “Core + Infrastructure Backbone” Principle

The Green Hydrogen Hub is treated as an industrial complex developed in stages, where early stages establish an infrastructure backbone and subsequent stages connect new process capacity to the already built systems.

Unified development logic:

- Stage 1 (Solutions №1–№2): pilot capacities (AWE 2.0 MW / PEM 2 MW) and establishment of the baseline infrastructure backbone (water intake and pumping, fire water reserve, initial power infrastructure, access roads, access control).
- Stage 2 (Solutions №3–№4): scale-up to 20 MW using Stage 1 infrastructure; expansion of the power block (substation/grids, BESS, PV park).
- Stage 3 (Solutions №5–№6): industrial 100 MW and implementation of hydrogen-to-network transmission nodes (compression, GDS, vent stack), reinforcement of utilities and logistics.
- Stage 4 (Solutions №7–№8): final 300 MW configuration and fixation of the final site structure as a single production hub.

The “core + infrastructure backbone” principle:

- “Core” – hydrogen production and conditioning blocks (electrolysis, purification/drying/quality, compression, buffering, delivery).
- “Backbone” – scalable systems avoiding redesign: water/fire water, sewerage/wastewater, power/substations, roads/fire access, access control, sanitary zones, utility corridors.

5.5.1.3. Unified Sitting Philosophy: Outdoor Process Units and Permanent Buildings

The equipment placement philosophy combines outdoor installations and permanent buildings depending on scale and technology:

1. Containerised/outdoor concepts prioritising natural ventilation
   Applicable to modular solutions aiming to minimise permanent buildings (e.g., Solutions №1, №2, №4, №6, №8 and certain logistics nodes in other solutions). The concept includes:
   - outdoor placement priority,
   - organised upward venting (vent stacks / controlled discharge),
   - capability for H_2 detection and ESD,
   - functional segregation of zones and traffic flows.
2. Permanent industrial buildings (integrated plant / H_2 plant building) with forced ventilation
   Applicable to industrial-scale solutions where the process "core" is implemented as an integrated plant building (notably Solutions №3, №5, №7). Safety is achieved through:
   - forced ventilation and controlled internal air exchange,
   - H_2 detection, ESD, and organised venting routes,
   - localisation of leak sources and ignition source control,
   - maintaining separation distances and safe corridors at the building boundary and adjacent nodes.

5.5.2. tage 1 (Pilot) – Solution №1 – 2.0 MW Hydrogen Plant – Alkaline Electrolysis (AWE)

5.5.2.1. Stage 1 / Solution No. 1: General Concept and Strategic Role in Hub Development

Stage 1 "Pilot", Solution N°1 provides for construction of a 2.0 MW pilot hydrogen production unit based on Alkaline Electrolysis (AWE) with containerised/modular arrangement of process nodes and establishment of the baseline hub infrastructure backbone.

The role of Solution N°1 in the hub development:

- commissioning a pilot production and validating the full chain "water → electrolysis → conditioning → compression → tube-trailer dispatch";
- creating and commissioning infrastructure that is then used in later stages (water intake / pumping / fire water reserve as the infrastructure backbone);
- establishing the initial power zone (PV + BESS + substation) to enable flexible power supply to the pilot plant;
- fixing the baseline safety philosophy: well sanitary zones, fire separation distances, hazardous area classification, operational and emergency access roads. [105]

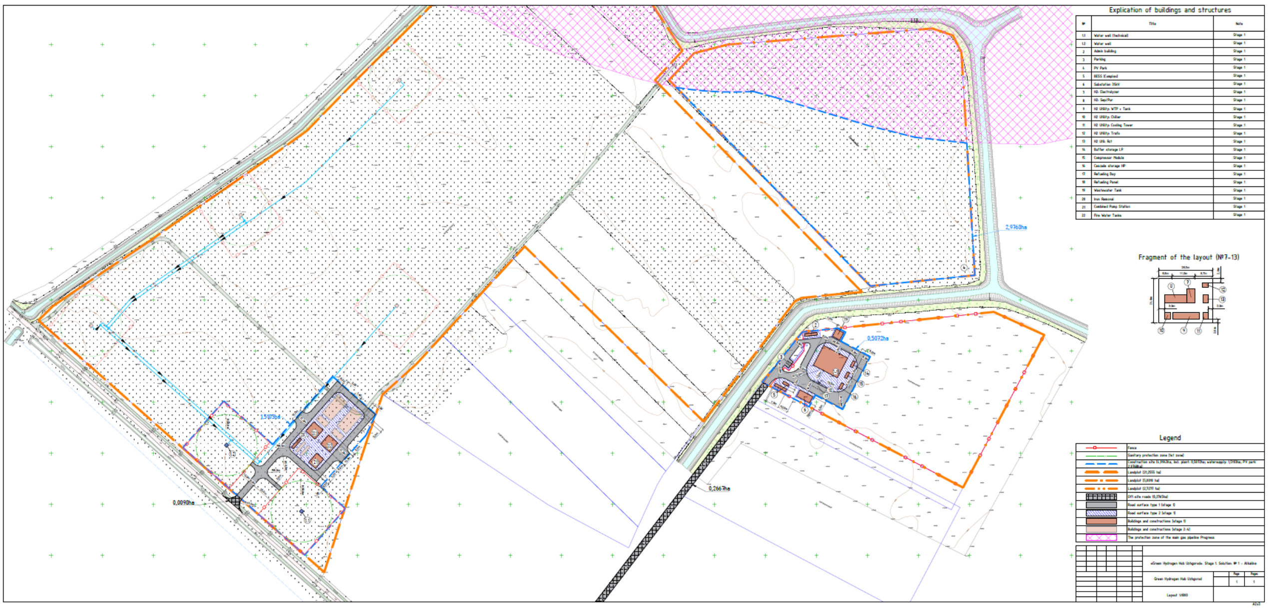


Figure 5-11: General Plan for Green Hydrogen Hub Uzhhorod, Stage 1 (Pilot) - 2MW, Solution N°1 - Alkaline

5.5.2.2. Spatial Layout, Land Requirements, and Functional Zoning

The layout is developed against the General Plan “Green Hydrogen Hub Uzhhorod”. Stage 1 “Pilot”. Solution N°1.

The drawing legend/area table fixes the following area references:

- Construction site: 4.9943 ha (includes the components below).
- Plant (hydrogen production / process zone): 0.5072 ha.
- Water supply (intake/treatment/fire water, infrastructure zone): 1.5103 ha.
- PV park: 2.9768 ha.

  Additionally, two area figures (0.2667 ha and 0.0098 ha) are shown as plots for access roads and infrastructure elements. These values are integrated into the TEA as per the drawing, with final boundaries and routing to be confirmed during the FEED stage.

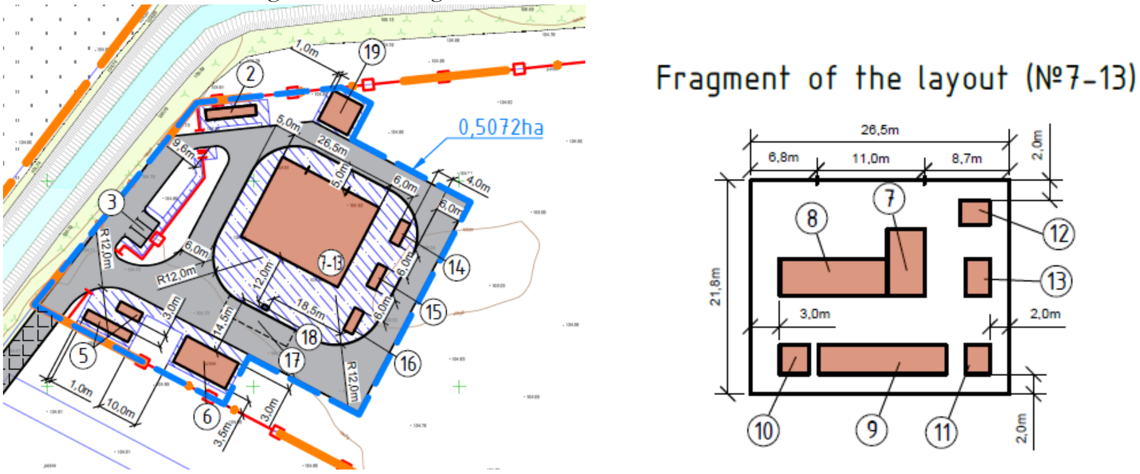


Figure 5-12: Fragments of the General Plan for Green Hydrogen Hub Uzhhorod, Stage 1 (Pilot)-2MW, Solution N°1-Alkaline. Plant Area.

Functional zoning of Solution N°1 follows a strict segregation principle:

- Administrative & auxiliary zone: containerised admin building and staff/visitor parking.
- Power zone: PV park, BESS, and 35 kV substation.
- Hydrogen process zone: electrolysis, separation/purification, water treatment, cooling, compression, buffering, HP cascade, and trailer filling interface.
- Water/fire-water infrastructure zone: wells, iron removal, combined pump station, fire water tanks.
- Wastewater zone: wastewater tank(s).

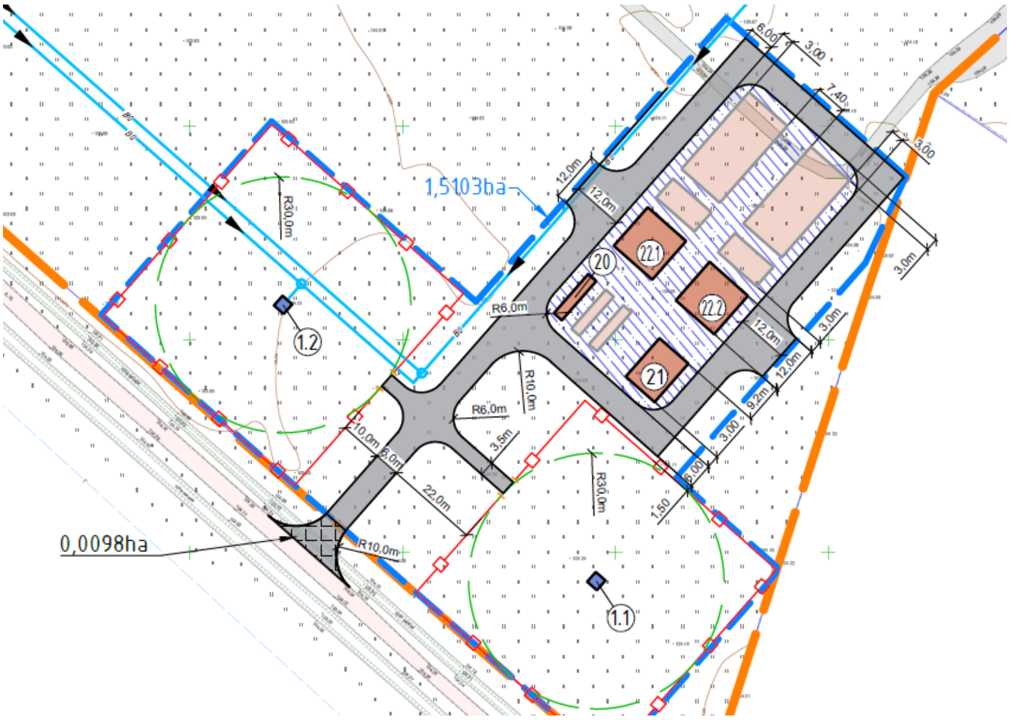


Figure 5-13: Fragment of the General Plan for Green Hydrogen Hub Uzhhorod, Stage 1 (Pilot), Solution N°1. Water/fire-water infrastructure zone.

Unified sanitary principle for the intake: a sanitary zone R = 30 m around each well (1.1 and 1.2), with no permanent buildings inside the zone.

5.5.2.3. Table of Buildings/Structures

The Stage 1 / Solution N°1 explication on the drawing includes positions 1.1–22. Fire hazard categorisation (UA) is shown in the Section 4.3 format (AN/V/D), with NAPB B.03.002-2007 as the categorisation basis (detailed premises/outdoor installation categorisation is refined at FEED). Hazardous area linkage is developed conceptually per IEC 60079-10-1.

Consolidated table "Explication → Fire Category (UA) → ATEX Zone → Key safeguards" (Solution N°1):

Adopted UA fire hazard categories for feasibility level:

- AN – explosion and fire hazardous outdoor hydrogen installations (gas).
- V – fire hazardous (electrical installations, cable systems, power containers).
- D – non-combustible substances in cold state / auxiliary facilities without handling flammable gases.

Table 5-11: Explication, Fire Category, and ATEX Zone for Solution N°1

Pos. N° – Title	Fire Category (UA)	ATEX Zone (concept)	Key safeguards (layout & systems)
1.1 Water well (technical)	N/A	Non-hazardous	Sanitary zone R=30 m; fenced/marked; controlled access
1.2 Water well	N/A	Non-hazardous	Sanitary zone R=30 m; no permanent buildings within zone
2 Admin building	D	Non-hazardous	Located outside hydrogen hazardous areas; controlled access
3 Parking	N/A	Non-hazardous	Outside hazardous zones; defined pedestrian routes

Pos. Nº – Title	Fire Category (UA)	ATEX Zone (concept)	Key safeguards (layout & systems)
4 PV Park	N/A	Non-hazardous	Electrical safety; fenced; segregated from H_2 process zone
5 BESS (Complex)	V	Non-hazardous	Dedicated fenced zone; fire detection/suppression per vendor; separation by layout
6 Substation 35kV	V	Non-hazardous	Electrical segregation; earthing; access control
7 H_2: Electrolyser	AN	Zone 2 (around equipment)	Outdoor installation; ventilation; H_2 detection; ESD; controlled venting upward
8 H_2: Sep/Pur	AN	Zone 2 (around equipment)	Deoxo/drying; temperature monitoring; ESD; vent routing to safe points
9 H_2 Utility: WTP + Tank	D	Non-hazardous	Demin water production; bunding/drain control; chemical handling procedures
10 H_2 Utility: Chiller	D	Non-hazardous	Cooling reliability; alarms; safe shutdown on fault
11 H_2 Utility: Cooling Tower	D	Non-hazardous	Drift control; safe access; winterisation measures
12 H_2 Utility: Trafo	V	Non-hazardous	Electrical segregation; earthing; fire protection measures
13 H_2 Util: Rct	V	Non-hazardous	Rectifier protection; arc/short protection; smoke detection (where applicable)
14 Buffer storage LP	AN	Zone 2 (around vessel)	PRV/venting; ESD isolation; gas detection; separation distances
15 Compressor Module	AN	Zone 2 (around module)	Gas detection near seals; ESD; hot surface control; Ex-rated equipment
16 Cascade storage HP	AN	Zone 2 (around storage)	Impact protection; ESD segmentation; controlled access
17 Refueling Bay	AN	Zone 2 (area)	Drive-through geometry; emergency stop; exclusion zones; bonding/earthing
18 Refueling Panel	AN	Zone 1 (local) + Zone 2 (vicinity)	Breakaway coupling concept; interlocks; gas detection; E-stop
19 Wastewater Tank	N/A	Non-hazardous	Controlled collection; tanker removal interface; spill control
20 Iron Removal	D	Non-hazardous	Water treatment; drainage control; chemical handling procedures
21 Combined Pump Station	V	Non-hazardous	Water supply + fire pumps; redundancy; test/maintenance access
22 Fire Water Tanks	N/A	Non-hazardous	2×250 m³ reserve (hub backbone); ring main interface; level monitoring

5.5.2.4. Hydrogen Production Process Chain (AWE 2.0 MW) and BoP Systems

The Solution Nº1 process chain implements a complete cycle of hydrogen production, conditioning, compression, and tube-trailer dispatch, supported by Stage 1 utilities as the baseline hub infrastructure backbone.

1) Water – intake, pre-treatment, demineralisation (Pos. 1.1, 1.2, 20, 21, 9)

- Raw water is supplied from wells: 1.1 Water well (technical) and 1.2 Water well.
- Water is routed to Pos. 20 Iron Removal as a pre-treatment step.

- Further distribution is performed via Pos. 21 Combined Pump Station, providing supply to process users and an interface with fire pumps / fire ring main.
- Demineralised water preparation for electrolysis is implemented within Pos. 9 H_2 Utility: WTP + Tank (water treatment + buffer/storage), ensuring the required feed quality and stable supply under dynamic operation.

2) Power supply for electrolysis and BoP (Pos. 4, 5, 6, 12, 13)

- Power supply is provided from Pos. 4 PV Park, with flexibility/buffering via Pos. 5 BESS (Complex) and distribution via Pos. 6 Substation 35kV.
- Electrolysis process users are supplied through Pos. 12 H_2 Utility: Trafo (transformer) and Pos. 13 H_2 Util: Rct (rectifier), delivering DC power to the AWE stack and supplying auxiliary systems.

3) AWE electrolysis and primary gas-liquid separation (Pos. 7, 8)

- Pos. 7 H_2: Electrolyser is the alkaline electrolyser where water is split into hydrogen and oxygen using DC power.
- The post-electrolysis gas stream is routed to Pos. 8 H_2: Sep/Pur (separation/purification node) providing primary separation of hydrogen from moisture and residual impurities and preparing the gas for deep purification/drying.

4) Hydrogen purification and drying to Grade 5.0 (Pos. 8, 10)

The conditioning logic includes a multi-step chain:

- a deoxo reactor to remove trace oxygen by catalytic recombination of O_2 with H_2 to form water;
- cooling/condensation of moisture using Pos. 10 H_2 Utility: Chiller;
- final drying to the target dew point and residual oxygen content.

  As a result, hydrogen is delivered to Grade 5.0 (99.999%), with target parameters (dew point below -65°C and O_2 < 5 ppm as a design-specification reference).

5) Thermal management and cooling (Pos. 11, 10)

- Process heat rejection and cooling of circulation loops are provided via Pos. 11 H_2 Utility: Cooling Tower (stake cooling) and associated heat exchange circuits.
- Pos. 10 Chiller ensures the temperature regime for gas conditioning units (moisture condensation and drying stability).

6) Buffering, compression, HP cascade, and trailer dispatch (Pos. 14–18)

- Purified hydrogen is routed to Pos. 14 Buffer storage LP, which decouples electrolysis dynamics from compression dynamics.
- Hydrogen is then compressed in Pos. 15 Compressor Module to high pressure (design target 350–500 bar as the dispatch range).
- Compressed hydrogen is accumulated in Pos. 16 Cascade storage HP enabling cascade trailer filling.
- Dispatch is performed at Pos. 17 Refueling Bay via Pos. 18 Refueling Panel. Logistics is arranged so that the filling area is functionally separated from administrative zones and includes emergency stops and organisational safety controls.

7) Wastewater and drains (Pos. 19)

- Process and sanitary effluent is collected in Pos. 19 Wastewater Tank, enabling accumulation/removal and preventing uncontrolled discharge to soil.

5.5.2.5. Conceptual Block Flow Diagram (BFD): Solution No. 1

The conceptual block flow diagram below reflects the Solution №1 process chain by explication positions:

Block Flow Diagram (Solution №1, Stage 1, AWE 2.0 MW):

- Water wells (1.1, 1.2) → Iron Removal (20) → Combined Pump Station (21) → WTP + Tank (9) → Electrolyser (7)
- PV Park (4) + BESS (5) + Substation (6) → Trafo (12) → Rectifier (13) → Electrolyser (7)
- Electrolyser (7)↔ Cooling Tower (11) → Sep/Pur (8) ↔ Chiller (10) → Buffer LP (14) → Compressor (15) → Cascade HP (16) → Refueling Bay (17) → Refueling Panel (18) → Tube Trailers
- Wastewater → Wastewater Tank (19)

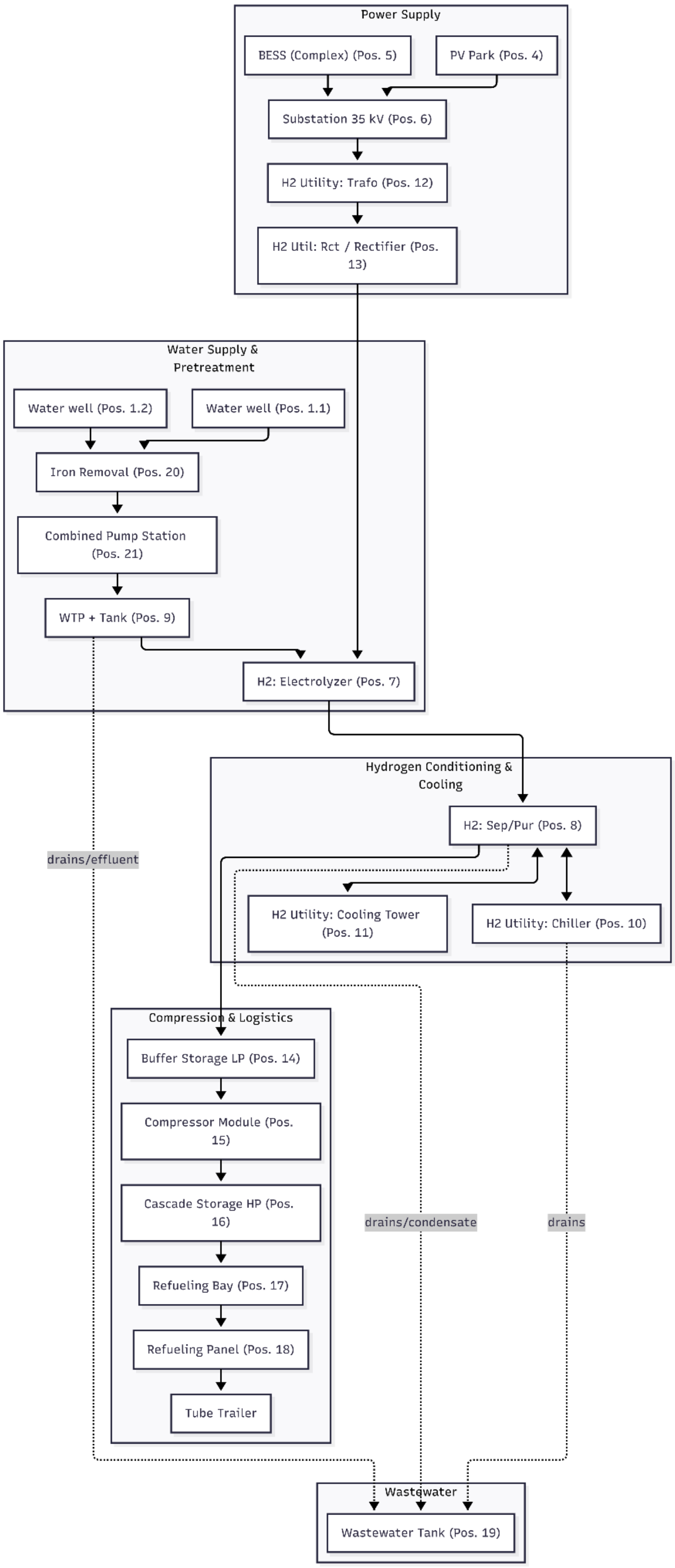


Figure 5-14: Conceptual Block Flow Diagram for Solution Nº1 (Alkaline 2.0 MW)

5.5.2.6. ATEX & Hazardous Area Summary (Solution №1)

Hazardous area classification is developed conceptually per IEC 60079-10-1 for gas atmospheres, assuming that key hydrogen nodes are installed outdoors with natural ventilation and controlled upward venting capability. Internal classifications inside containers/modules are refined at FEED.

HAC summary table (Solution №1):

- Pos. 7 Electrolyser – Zone 2 around external leak sources (concept).
- Pos. 8 Sep/Pur – Zone 2 around gas conditioning nodes; deoxo thermal risks are addressed in safeguards.
- Pos. 14 Buffer LP – Zone 2 around vessel and valves; PRV/vent routed to safe point.
- Pos. 15 Compressor – Zone 2 around compressor and sealing points; Ex equipment, detection, and ESD.
- Pos. 16 Cascade HP – Zone 2 around HP storage and piping; vehicle impact protection and ESD segmentation.
- Pos. 17 Refueling Bay – Zone 2 across the filling bay during dispensing.
- Pos. 18 Refueling Panel – Zone 1 locally at couplings + Zone 2 in the vicinity (concept).

5.5.2.7. Fire Separation Distances (Fire gaps)

The Solution №1 drawing applies conservative fire/safety separations, including R12.0 m indications for the hydrogen process area and R30.0 m for the well sanitary zone.

Fire separation philosophy of Solution №1:

- segregation of the administrative zone (Pos. 2–3) from hydrogen installations (Pos. 7–18) with a baseline separation not less than 12 m as a conservative Pre-Design level;
- ensuring fire brigade access (loop/access roads) to key nodes of the hydrogen zone;
- preventing any permanent buildings/structures within the R = 30 m sanitary zone around wells.

Table 5-12: Fire Separation Distances for Solution №1

From (Pos. No – Title)	To (Pos. No – Title)	Adopted separation on drawing	Design intent / comment
1.1 Water well	Any permanent building/structure	R30.0 m	Sanitary protection zone, no permanent buildings
1.2 Water well	Any permanent building/structure	R30.0 m	Sanitary protection zone, no permanent buildings
7 H_2: Electrolyser	Non-hydrogen zones (e.g., 2 Admin building)	R12.0 m (baseline)	Conservative separation indicated on drawing for H_2 process cluster
14 Buffer storage LP	2 – Admin building	R12.0 m (baseline)	H_2 equipment segregated from admin areas
15 Compressor Module	3 – Parking	R12.0 m (baseline)	Segregation of public/staff area from compression node
16 Cascade storage HP	17 – Refueling Bay	R12.0 m (baseline)	Separation within hydrogen logistics sub-zone
18 Refueling Panel	3 – Parking	R12.0 m (baseline)	Local Zone 1 at couplings; separation to non-hazard areas

5.5.2.8. HAZID Summary (Solution №1)

The HAZID is prepared at Pre-Design level (qualitative) to fix key hazards and the safeguards to be detailed at FEED. Nodes are mapped to Solution №1 explication.

HAZID Summary Table (Solution №1):

Table 5-13: Fire Separation Distances for Solution №1

Node (Pos. № – Title)	Deviation / Hazard	Credible causes	Consequences	Safeguards (assumed at Pre-Design)	Recommendations (FEED)	Priority
7 H_2: Electrolyser	H_2 leak to atmosphere	Fittings/flanges leak, seal failure, maintenance error	Explosive atmosphere; ignition → flash fire	Outdoor placement; ventilation; H_2 detection; ESD; separation R12	Detector coverage and voting; vent routing verification	H
7 H_2: Electrolyser	O_2 release / enrichment	Vent termination in low area; mixing with H_2 vents	Increased fire severity / ignition sensitivity	Separate vent routing; outdoor dispersion	Confirm O_2 discharge point and separation	M
8 H_2: Sep/Pur	Deoxo overheating	Elevated O_2, control failure, cooling loss	Hot spots; damage; ignition potential if leak	Temperature monitoring; ESD; chiller support	Independent high-temp trip; define O_2 limits	H
10 Chiller	Loss of cooling	Power loss, pump fault	Off-spec H_2 drying; trips	Alarms; safe shutdown logic	Confirm redundancy and shutdown sequence	M
14 Buffer storage LP	Overpressure / PRV release	Isolation of PRV, control valve failure	H_2 release; escalation	PRV; venting to safe point; ESD	PRV sizing; lock-open critical valves	H
15 Compressor Module	Seal leak / hot surfaces	Seal wear; vibration; poor maintenance	Jet fire/flash fire	Gas detection; ESD; Ex-rated drives	Add local detectors; vibration monitoring; hot surface control	H
16 Cascade storage HP	Line rupture / impact	Vehicle impact; fatigue; valve failure	Jet fire; rapid release	Access control; separation; ESD segmentation	Add crash barriers; validate supports and isolation points	H
17 Refueling Bay	Release during coupling	Human error; worn O-rings; hose fault	Local Zone 1 ignition; injury	Procedures; E-stop; bonding/earthing	Interlocks; breakaway couplings; exclusion zones	H
5 BESS (Complex)	Thermal runaway	Cell defect; overcharge	Fire, toxic smoke	Dedicated zone; separation by layout	Vendor-specific suppression/detection; smoke management	M
Whole site	Lightning/static	Inadequate bonding; storm	Ignition source	Earthing concept; bonding	Lightning protection and testing program	H

5.5.2.9. *Water / Sewer / Fire philosophy (Stage 1 backbone for the hub)*

Solution №1 establishes the hub water and fire-water infrastructure backbone:

- Pos. 21 Combined Pump Station – water distribution node and location of pumping groups (including fire pumps as part of the backbone).
- Pos. 22 Fire Water Tanks – fire water reserve 2×250 m³ as baseline infrastructure reused in Stages 2–4.
- Pos. 19 Wastewater Tank – collection of industrial/sanitary effluent at early stage with organised removal/transfer to treatment per project solution.

Hydrogen fire philosophy:
hydrogen is not extinguished by water; water is used for exposure cooling and protection of evacuation paths;
key measures: ESD, detection, ventilation, isolation of leak source, controlled venting.

5.5.3. Stage 1 (Pilot) – Solution №2 – 2 MW Hydrogen Plant – PEM Electrolysis

5.5.3.1. Stage 1 / Solution No. 2: General Concept and Strategic Role in Hub Development

Stage 1 “Pilot”, Solution No. 2 involves the construction of a pilot hydrogen production plant based on PEM electrolysis. The solution features a containerised/modular arrangement of key nodes and leverages the Stage 1 hub backbone infrastructure (water supply, fire-water reserve, civil pads, and access roads). Solution No. 2 validates the full chain “water → PEM electrolysis → drying/purification → buffering → compression → HP cascade → tube-trailer dispatch”, with emphasis on dynamic operation and RES integration.

Strategic role of Solution No. 2 in hub development:

- validate PEM process behaviour (ramping, H_2 quality, operational robustness);
- validate safety-first layout principles and HAC/ESD/detection for a containerised PEM solution;
- reuse common Stage 1 backbone (wells / iron removal / pumping / fire-water tanks / access) for later stages.

5.5.3.2. Spatial Layout, Land Requirements, and Functional Zoning

Figure 5-12: General Plan for Green Hydrogen Hub Uzhhorod, Stage 1 (Pilot)-2 MW, Solution N°2-PEM

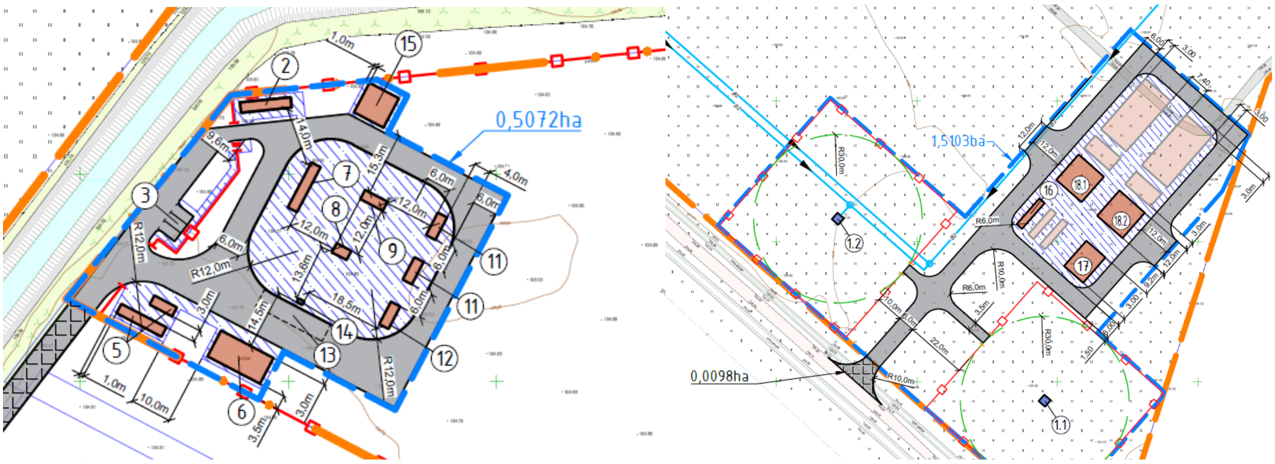


Figure 5-15: Fragments of the General Plan for Green Hydrogen Hub Uzhhorod, Stage 1 (Pilot) 2 MW, Solution N°2 PEM. Plant Area, Water/fire-water infrastructure zone.

The layout is developed against the Stage 1 (Pilot) general plan for Solution No. 2. Functional zoning follows strict segregation:

- Administrative & auxiliary zone: containerised admi building (Pos.2) and parking (Pos.3) located outside hydrogen hazardous areas.
- Power zone: PV park (Pos.4), BESS (Pos.5) and 35 kV substation (Pos.6) segregated from hydrogen installations.
- Hydrogen process zone: integrated PEM process container (Pos.7), cooler (Pos.8), power supply container (Pos.9), LP buffer (Pos.10), compressor (Pos.11), HP cascade (Pos.12), trailer loading and filling interface (Pos.13–14).
- Water / fire-water infrastructure zone: wells (Pos.1.1, 1.2), iron removal (Pos.16), combined pumping/fire pump station (Pos.17), fire-water tanks (Pos.18).
- Wastewater zone: wastewater tank (Pos.15).

Unified sanitary principle: R = 30 m sanitary zone around each well (Pos.1.1 and Pos.1.2), with no permanent buildings inside.

5.5.3.3. Table of Buildings/Structures

Solution No. 2 explication includes positions 1.1–18. Ukrainian fire hazard categorisation is shown in AN/V/D format (to be refined at FEED per UA regulations), and hazardous area linkage is developed conceptually per IEC 60079-10-1 for gas atmospheres (final HAC to be confirmed at FEED). The equipment/buildings list is taken from the Solution No. 2 Major Equipment Specification.

Adopted UA fire hazard categories for feasibility level:

- AN – explosion and fire hazardous outdoor hydrogen installations (gas).
- V – fire hazardous (electrical installations, cable systems, power containers).
- D – non-combustible substances in cold state / auxiliary facilities without handling flammable gases.

Consolidated table “Explication → Fire Category (UA) → ATEX Zone → Key safeguards” (Solution N°2)

Table 5-14: Consolidated Explication and Safety Matrix for Solution N°2

Pos. N° – Title	Fire Category (UA)	ATEX Zone (concept)	Key safeguards (layout & systems)
1.1 Water well (technical)	N/A	Non-hazardous	Sanitary zone R=30 m; fenced/marked; controlled access
1.2 Water well	N/A	Non-hazardous	Sanitary zone R=30 m; no permanent buildings within zone
2 Admin building	D / D	Non-hazardous	Located outside hydrogen hazardous areas; controlled access; emergency muster point outside H_2 zones
3 Parking	N/A	Non-hazardous	Outside hazardous zones; defined pedestrian routes; no parking in H_2 logistics corridors
4 PV Park	N/A	Non-hazardous	Electrical safety; fenced; segregated from H_2 process zone
5 BESS (Complex)	V / V	Non-hazardous	Dedicated fenced zone; detection/suppression per vendor; separation by layout
6 Substation 35 kV	V / V	Non-hazardous	Electrical segregation; earthing; access control
7 PEM Electrolyser + Purification + WTP (Integrated Process Container)	An / A	Zone 2 (around container leak sources)	Outdoor placement; forced/natural ventilation as per vendor; H_2 detection; ESD; controlled venting upward; no ignition sources; Ex-rated where required
8 H_2 Utility: Cooler	D / D	Non-hazardous	Cooling reliability; alarms; safe shutdown on fault; winterisation measures
9 H_2 Util: Power Supply (Rectifier + Transformer container)	D / D	Non-hazardous	DC electrical safety; arc/short protection; earthing & bonding; restricted access
10 Buffer storage LP (30 bar)	An / A	Zone 2 (around vessel/valves)	PRV/vent to safe point; ESD isolation; gas detection; separation distances; impact protection

Pos. Nº – Title	Fire Category (UA)	ATEX Zone (concept)	Key safeguards (layout & systems)
11 Compressor Module (500 bar)	An / A	Zone 2 (around module & seals)	Gas detection near seals; ESD; hot surface control; Ex-rated equipment; segregation from public/staff zones
12 Cascade storage HP (300–500 bar)	An / A	Zone 2 (around storage & piping)	Crash barriers; ESD segmentation; controlled access; venting to safe point
13 Refueling Bay (trailer concrete pad)	N/A	Zone 2 (area during dispensing)	Drive-through geometry; emergency stop; exclusion zones; bonding/earthing; traffic management
14 Refueling Panel	An / A	Zone 1 (local at couplings) + Zone 2 (vicinity)	Breakaway coupling concept; interlocks; gas detection; E-stop; bonding/earthing
15 Wastewater Tank	N/A	Non-hazardous	Controlled collection; tanker removal interface; spill control
16 Iron Removal (container)	D / D	Non-hazardous	Drainage control; chemical handling procedures; bunding where applicable
17 Combined Pump Station	D / D	Non-hazardous	Water supply + fire pumps; redundancy; test/maintenance access
18 Fire Water Tanks (2×250 m³)	N/A	Non-hazardous	Fire water reserve; ring main interface; level monitoring; protected access

5.5.3.4. Hydrogen Production Process Chain (PEM 2 MW) and BoP Systems – Expanded Description

The Solution No. 2 process chain implements the complete cycle: water intake and conditioning → PEM electrolysis (Pos.7) → integrated purification/drying → LP buffering → high-pressure compression → HP cascade storage → tube-trailer dispatch via a refuelling panel. Layout and safety philosophy align with ISO 22734, EIGA Doc 15, CGA G5.5, IEC 60079-10-1 and UA fire/industrial safety requirements (final confirmation at FEED).

1) Water – intake, pre-treatment, demineralisation (Pos. 1.1, 1.2, 16, 17, 7)

Water is sourced from wells Pos.1.1 (technical/backup) and Pos.1.2 (main). Pre-treatment (iron removal) is provided by Pos.16, with distribution via Pos.17. Demineralised water preparation is integrated in the PEM process container Pos.7; required water quality is per vendor specification (final values to be confirmed at FEED).

2) Power supply for PEM and BoP (Pos. 4, 5, 6, 9)

Power is provided by PV (Pos.4) supported by BESS (Pos.5) and routed through the 35 kV substation (Pos.6). Pos.9 provides transformer/rectifier functions feeding DC power to the PEM stack and auxiliaries. Safety measures include selective protection, ESD logic, earthing/bonding, and ignition source control near hydrogen nodes.

3) PEM electrolysis and primary phase separation (Pos. 7)

Pos.7 hosts PEM electrolysis producing H_2 and O_2. The container includes primary moisture separation, water management loops, pressure/temperature control, and safe oxygen vent routing (separated from hydrogen vents, to a safe upward discharge point – to be confirmed at FEED/vendor design). Key risks: H_2 leaks, oxygen enrichment, DC hazards, overheating, cooling loss; barriers: H_2 detection, ESD, ventilation, controlled venting, ignition control.

4) Hydrogen purification and drying to Grade 5.0 (Pos. 7, 8)

PEM typically delivers high initial purity, yet stable dew point and impurity control are required for compression/dispatch. Purification/drying is integrated in Pos.7 (concept: coalescing/filtration, adsorption drying, dew point control; optional O_2 polishing if required). Pos.8 (dry cooler & chiller) supports stable thermal conditions for the PEM container and drying package. [142]

5) Thermal management and cooling (Pos. 8)

Pos.8 provides the cooling loop (water/glycol depending on climate) for heat rejection from Pos.7 and auxiliaries, including winterisation measures per local climate norms (to be finalised at FEED).

6) Buffering, compression, HP cascade, and tube-trailer dispatch (Pos. 10–14)
Hydrogen flows to LP buffer Pos.10 (30 bar), then to compressor Pos.11 (diaphragm, 500 bar), then to HP cascade Pos.12 (300–500 bar). Dispatch is via Pos.13 (refuelling bay/pad) and Pos.14 (refuelling panel) with E-Stop, interlocks, bonding/earthing, and defined exclusion zones.
7) Wastewater and drains (Pos. 15)
Process and sanitary effluent is collected in Pos.15 for organised removal/transfer to treatment under the project wastewater solution; detailed composition to be confirmed at FEED.

5.5.3.5. Conceptual Block Flow Diagram (BFD): Solution No. 2

The conceptual block flow diagram below reflects the Solution No. 2 process chain by explication positions.
Block Flow Diagram (Solution №2, Stage 1, PEM 2 MW):
Water wells (1.1, 1.2) → Iron Removal (16) → Combined Pump Station (17) → PEM Process Container with WTP (7)

- PV Park (4) + BESS (5) + Substation (6) → Power Supply (9) → PEM Process Container (7)
- PEM Process Container (7) ↔ Cooler (8) → Buffer LP (10) → Compressor (11) → Cascade HP (12) → Refueling Bay (13) → Refueling Panel (14) → Tube Trailers
- Wastewater → Wastewater Tank (15)

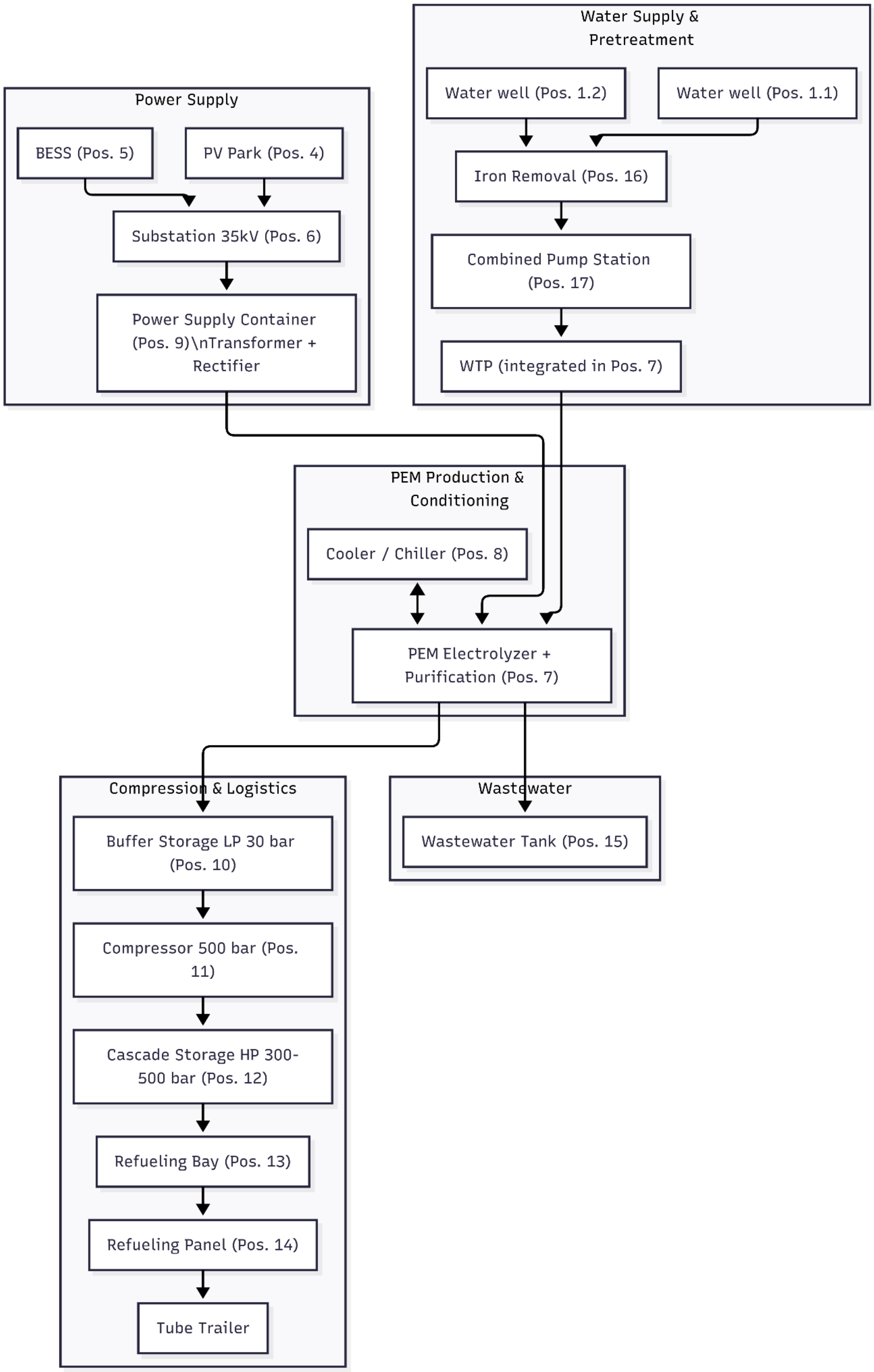


Figure 5-16: Conceptual Block Flow Diagram for Solution N°2 (PEM 2 MW)

5.5.3.6. ATEX & Hazardous Area Summary (Solution №2)

Hazardous area classification is developed conceptually per IEC 60079-10-1, assuming outdoor installation of key hydrogen nodes with natural ventilation and controlled upward venting. Internal container zoning is refined at FEED based on vendor data, ventilation rates, and release sources.

HAC summary (concept):

- Pos.7 PEM process container – Zone 2 around external leak sources.
- Pos.10 LP buffer – Zone 2 around vessel/valves; PRV/vent routed to a safe point.
- Pos.11 Compressor – Zone 2 around compressor and sealing points; Ex equipment, detection, ESD.
- Pos.12 HP cascade – Zone 2 around storage/piping; crash protection and ESD segmentation.
- Pos.13 Refuelling bay – Zone 2 during dispensing.
- Pos.14 Refuelling panel – Zone 1 locally at couplings + Zone 2 in vicinity.

5.5.3.7. Fire Separation Distances (Fire gaps)

At pre-design level, conservative separations are applied:

- baseline segregation of the admin zone (Pos.2–3) from hydrogen installations (Pos.7–14) – not less than 12 m (conservative);
- fire brigade access to key hydrogen nodes;
- no permanent buildings within the well sanitary zone R=30 m.

Table 5-15: Fire Separation Distances for Solution N°2

From (Pos. N° – Title)	To (Pos. N° – Title)	Adopted separation	Design intent / comment
1.1 Water well	Any permanent building/structure	R30.0 m	Sanitary protection zone, no permanent buildings
1.2 Water well	Any permanent building/structure	R30.0 m	Sanitary protection zone, no permanent buildings
7 PEM Process Container	Non-hydrogen zones (e.g., 2 Admin building)	R12.0 m (baseline)	Conservative separation for H_2 process cluster
10 Buffer storage LP	2 Admin building	R12.0 m (baseline)	Segregation of H_2 pressure vessels from admin area
11 Compressor module	3 Parking	R12.0 m (baseline)	Segregation of compression node from public/staff area
12 Cascade storage HP	13 Refuelling bay	R12.0 m (baseline)	Separation within hydrogen logistics sub-zone
14 Refuelling panel	3 Parking	R12.0 m (baseline)	Local Zone 1 at couplings; separation to non-hazard areas

5.5.3.8. HAZID Summary (Solution №2)

HAZID is prepared at pre-design level (qualitative) to fix key hazards and safeguards to be detailed at FEED (HAZOP/LOPA as required). Nodes are mapped to the Solution No. 2 explication.

Table 5-16: HAZID Summary Table for Solution №2

Node (Pos. № – Title)	Deviation / Hazard	Credible causes	Consequences	Safeguards (assumed at Pre-Design)	Recommendations (FEED)	Priority
7 – PEM Process Container	H_2 leak to atmosphere	Fittings leak, maintenance error,	Explosive atmosphere;	Outdoor placement; ventilation; H_2	Confirm detector mapping/voting; validate vent routing	H

Node (Pos. № – Title)	Deviation / Hazard	Credible causes	Consequences	Safeguards (assumed at Pre-Design)	Recommendations (FEED)	Priority
		component failure	ignition → flash fire	detection; ESD; separation R12		
7 – PEM Process Container	O_2 release / enrichment	Poor vent termination, mixing with H_2 vents	Increased fire severity / ignition sensitivity	Separate O_2 vent routing; outdoor dispersion	Confirm O_2 discharge point and separation	M
8 – Cooler	Loss of cooling	Power loss, pump fault, fan failure	Overheating → trips; potential equipment damage	Alarms; safe shutdown logic	Define shutdown sequence; winterisation requirements	M
10 – LP Buffer	Overpressure / PRV release	Control failure, blocked outlet, isolation error	H_2 release; escalation potential	PRV; vent to safe point; ESD	PRV sizing; lock-open critical valves; vent dispersion check	H
11 – Compressor	Seal leak / hot surfaces	Seal wear, vibration, poor maintenance	Jet fire/flash fire	Gas detection; ESD; Ex-rated drives; hot surface control	Add local detectors; vibration monitoring; maintenance concept	H
12 – HP Cascade	Line rupture / impact	Vehicle impact, fatigue, valve failure	Rapid release; jet fire	Access control; crash barriers; ESD segmentation	Validate barriers/traffic scheme; supports and isolation points	H
13–14 – Refuelling	Release during coupling	Human error, worn seals, hose fault	Local Zone 1 ignition; injury	Procedures; E-stop; bonding/earthing	Interlocks; breakaway couplings; exclusion zones	H
5 – BESS	Thermal runaway	Cell defect; overcharge	Fire, toxic smoke	Dedicated zone; separation by layout	Vendor suppression/detection; smoke management	M
Whole site	Lightning/static	Inadequate bonding; storm	Ignition source	Earthing & bonding	Lightning protection design and testing program	H

5.5.3.9. Water / Sewer / Fire philosophy (Stage 1 backbone for the hub)

Solution № 2 establishes the hub water and fire-water infrastructure backbone:

- Pos. 17 Combined Pump Station – water distribution node and location of pumping groups (including fire pumps as part of the backbone).
- Pos. 18 Fire Water Tanks – fire water reserve 2×250 m³ as baseline infrastructure reused in Stages 2–4.
- Pos. 15 Wastewater Tank – collection of industrial/sanitary effluent at early stage with organised removal/transfer to treatment per project solution (Stage 1-2).

Hydrogen fire philosophy: hydrogen is not extinguished by water; water is used for exposure cooling and protection of evacuation paths. Key measures: fast detection, ESD, ventilation, isolation of leak source, controlled venting.

5.5.4. Stage 2 – Solution №3 – 20 MW Hydrogen Plant – Alkaline Water Electrolysis (AWE)

5.5.4.1. Stage 2 / Solution No. 3: General Concept and Strategic Role in Hub Development

Stage 2, Solution No. 3 scales the hub to an industrial level by deploying a **20 MW AWE plant** (two 10 MW trains) within a dedicated H_2 Plant Building with integrated BoP systems and industrial utilities. The solution transitions from Stage 1 pilot validation to continuous industrial operation, with increased requirements for electrical infrastructure (110 kV connection /

~tens of MVA load), water treatment (RO/EDI inside the plant building), heat rejection (two large cooling towers), and tube-trailer dispatch logistics (two filling posts).

Strategic role of Solution No. 3 in hub development:

- scale AWE production to 20 MW and validate an industrial layout (process hall + external cooling/compression/storage nodes);
- reuse and confirm the Stage 1 backbone (wells/iron removal/pumping/fire-water tanks) with potential well-field expansion to meet demand;
- establish the Stage 2 power zone (PV park ~16.88 ha with 110 kV substation + BESS ~2,5 ha) as the base for further hub expansion.

5.5.4.2. Spatial Layout, Land Requirements, and Functional Zoning

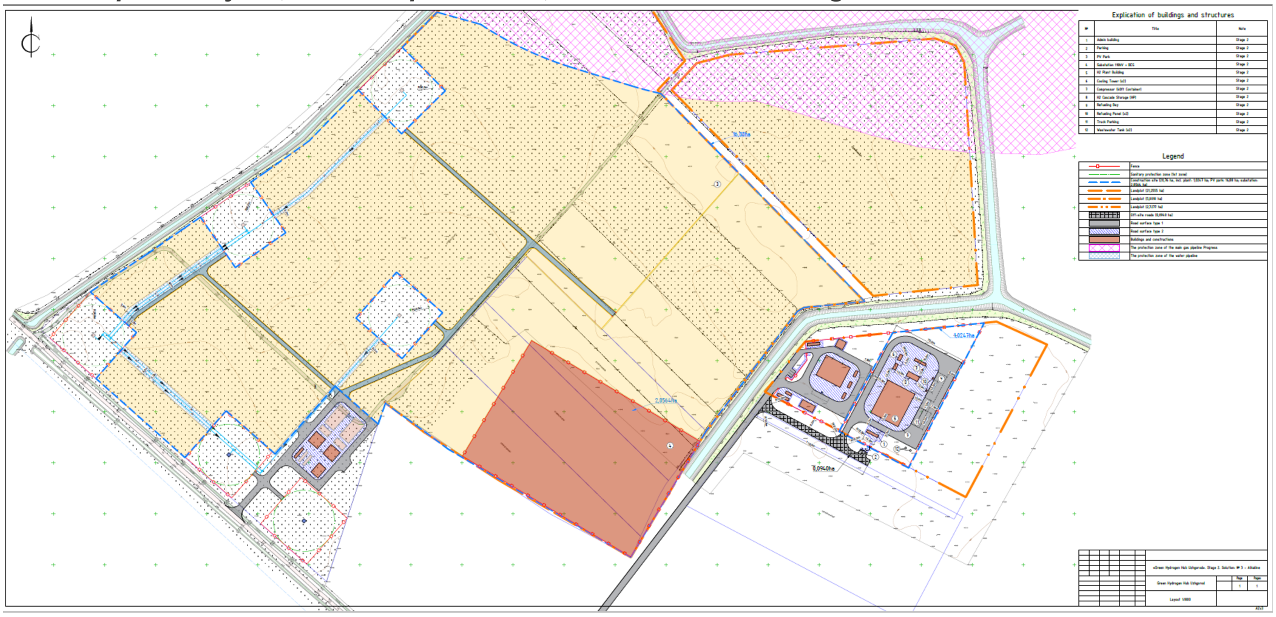


Figure 5-17: General Plan for Green Hydrogen Hub Uzhhorod, Stage 2 –20 MW, Solution N°3-Alkaline

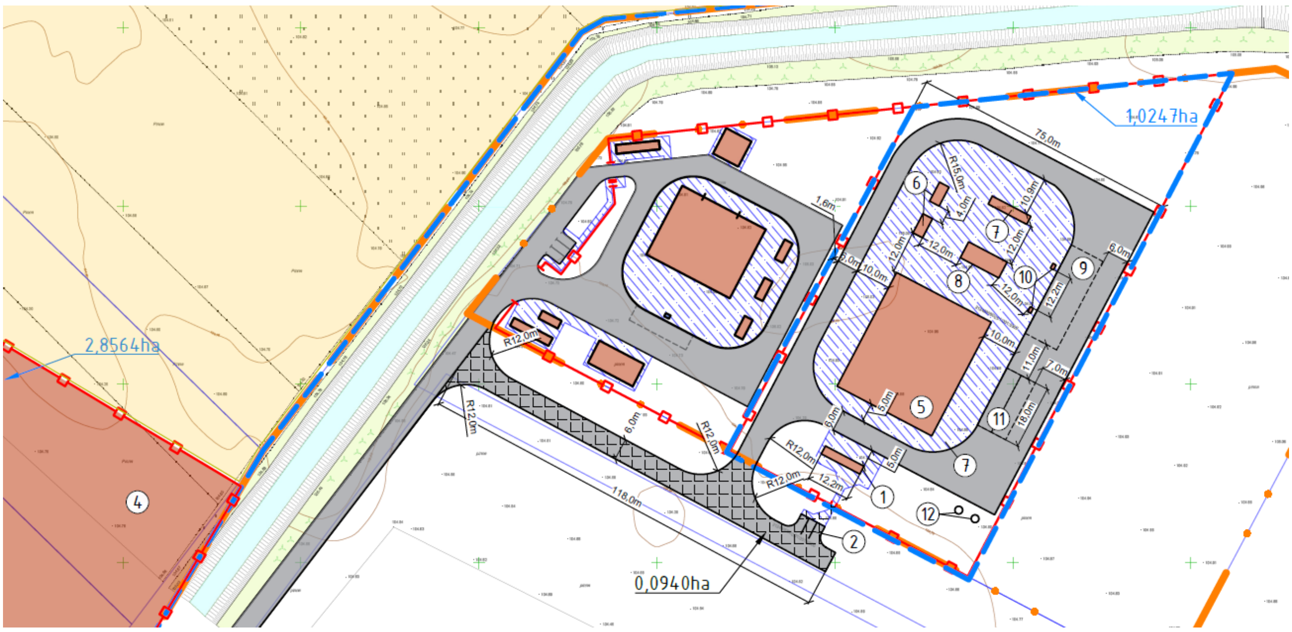


Figure 5-18: Fragments of the General Plan for Green Hydrogen Hub Uzhhorod, Stage 2–20 MW, Solution N°3–Alkaline. Plant Area.

Solution No. 3 (Stage 2) layout follows strict functional segregation (as Stage 1), shifting from containerised pilot nodes to an industrial process building:

- Administrative & auxiliary zone: Admin building (Pos.1) + Parking (Pos.2).
- Stage 2 power zone: PV Park (Pos.3) + 110 kV Substation + BESS (Pos.4), with substation/BESS located inside the PV zone.
- Hydrogen process zone: H_2 Plant Building (Pos.5) hosting the main process hall (2×10 MW AWE stacks + BoP), external cooling towers (Pos.6), compressor container (Pos.7), HP cascade (Pos.8), dispatch area (Pos.9–11).
- Water / fire-water backbone from Stage 1: Iron Removal Station (Pos.13), Combined Pump Station (Pos.14), Fire Water Tanks (Pos.15) reused as existing Stage 1 assets.
- Wastewater: Wastewater tanks (x2) (Pos.12).

Safety / restriction zones embedded into the layout:

- 20.0 m safety distance around the H_2 Plant Building and HP storage areas;
- R = 30.0 m sanitary exclusion around wells remains applicable for any well-field expansion;
- truck flow is separated from personnel traffic/parking.

Land area figures for Stage 2 are not stated in the available Solution №3 text (to be taken from the general plan legend/drawing set).

5.5.4.3. Table of Buildings/Structures

Solution No. 3 explication includes new Stage 2 assets (Pos.1–12) and reuse of Stage 1 backbone utilities (Pos.13–15: iron removal / pump station / fire-water tanks).

UA fire hazard categorisation is applied per NAPB B.03.002-2007 (final refinement at FEED).

Adopted UA fire hazard categories for feasibility level:

- AN – explosion and fire hazardous outdoor hydrogen installations (gas).
- V – fire hazardous (electrical installations, cable systems, power containers).
- D – non-combustible substances in cold state / auxiliary facilities without handling flammable gases.

Table 5-17: Consolidated Explication and Safety Matrix for Solution №3

Pos. Nº – Title	Fire Category (UA)	ATEX Zone (concept)	Key safeguards (layout & systems)
1 – Admin building (40ft)	D	Non-hazardous	Outside H_2 safety distances; controlled access; emergency muster outside H_2 zones
2 – Parking	N/A	Non-hazardous	Outside hazardous/safety zones; separation from truck logistics
3 – PV Park (~20 ha)	N/A	Non-hazardous	Fenced power zone; segregation from H_2 process zone
4 – Substation 110 kV + BESS	V / D	Non-hazardous	Dedicated fenced zone; earthing/bonding; BESS fire safety per vendor; access control
5 – H_2 Plant Building (2×10 MW AWE + BoP)	An / A	Zone 2 (building perimeter concept), indoor zoning to be confirmed	20 m safety distance; gas detection; explosion-proof ventilation; ESD; ignition control; segregated electrical rooms
6 – Cooling Tower (x2)	D	Non-hazardous	Cooling redundancy; safe access; drift control; winterisation
7 – Compressor (40ft)	An / A	Zone 2 (around module & seals)	Gas detection near seals; ESD; hot surface control; Ex-rated where required; separation 20 m concept
8 – H_2 Cascade Storage (HP, 500 bar)	An / A	Zone 2 (around storage & piping)	Impact/crash protection; ESD segmentation; controlled access; separation 20 m concept
9 – Refueling Bay (2 trailers)	An / A	Zone 2 (area during dispensing)	Drive-through logistics; E-stop; exclusion zones; bonding/earthing

Pos. Nº – Title	Fire Category (UA)	ATEX Zone (concept)	Key safeguards (layout & systems)
10 – Refueling Panel (x2)	An / A	Zone 1 (local at couplings) + Zone 2 (vicinity)	Interlocks; E-stop; gas detection; bonding/earthing; breakaway concept to be confirmed
11 – Truck Parking	N/A	Non-hazardous	Dedicated waiting area; separated from personnel parking
12 – Wastewater Tank (x2)	N/A	Non-hazardous	Controlled collection; spill control; organised removal
Iron Removal Station (existing Stage 1)	D	Non-hazardous	Pre-treatment; drainage control; chemical handling procedures
Combined Pump Station (existing Stage 1)	V	Non-hazardous	Water distribution + fire pumps; redundancy; testing/maintenance access
Fire Water Tanks (x2, existing Stage 1)	N/A	Non-hazardous	Baseline hub backbone; ring main interface; level monitoring

5.5.4.4. *Hydrogen Production Process Chain (AWE 20 MW) and BoP Systems – Expanded Description*

Solution No. 3 implements the full industrial chain "water → AWE → separation/purification/drying → compression → HP storage → tube-trailer dispatch", designed for continuous operation.

1) Water – intake, pre-treatment, demineralisation (Stage 1 backbone + Pos.5)

Source: Stage 1 well field with potential expansion to meet **~4.0–8.0 m³/h** demand.

Pre-treatment: **Iron Removal Station**.

Final polishing: **RO/EDI inside H_2 Plant Building (Pos.5)** producing demin water **conductivity < 5 µS/cm**, buffered internally before feeding electrolyser loops.

2) Electrolysis (20 MW Alkaline) – core reaction and operating envelope (Pos.5)

Two **10 MW** alkaline trains.

Electrolyte **30% KOH**, nominal operation at **15–16 bar(g)** and **85–90°C**.

Power rectification via indoor transformer-rectifier units (concept).

3) Gas separation and purification (Pos.5)

Hydrogen + electrolyte stream goes to gas-lye separation skids; hydrogen then passes through **Deoxo** and **TSA drying**.

Product: **Grade 5.0 (99.999%)**, dew point **< -70°C**.

4) Thermal management and cooling (Pos.6)

Heat load is approx. **~7–8 MW thermal**; cooled via heat exchangers connected to **Wet/Dry Cooling Towers (Pos.6)**.

Cooling pumps designed with redundancy.

5) Compression, HP storage, and distribution (Pos.7–10)

Compression from **~15 bar** to **350–500 bar** by **Pos.7** compressor; storage in HP cascade **Pos.8** (noted as **500 bar** buffer); dispatch via **Pos.9** (two-trailer bay) and **Pos.10 (x2)** filling panels.

6) Wastewater and drains (Pos.12)

Process and sanitary effluent collected in **Pos.12 (x2)** for organised removal/transfer.

5.5.4.5. *Conceptual Block Flow Diagram (BFD): Solution No. 3*

The conceptual block flow diagram below reflects the Solution No. 3 chain by explication positions and the stated process description.

Block Flow Diagram (Solution №3, Stage 2, AWE 20 MW):

- Well field (Stage 1 backbone, expanded if needed) → Iron Removal → (RO/EDI inside Pos.5) → AWE stacks (Pos.5)
- PV Park (Pos.3) + Substation 110 kV + BESS (Pos.4) → indoor rectification (within Pos.5, concept) → AWE stacks (Pos.5)
- AWE stacks (Pos.5) → gas-lye separation + Deoxo + TSA drying (Pos.5) → Compressor (Pos.7) → HP Cascade 500 bar (Pos.8) → Refueling Bay (Pos.9) → Refueling Panels x2 (Pos.10) → Tube Trailers

- Cooling loop ↔ Cooling Towers x2 (Pos.6)
- Wastewater → Wastewater Tanks x2 (Pos.12)

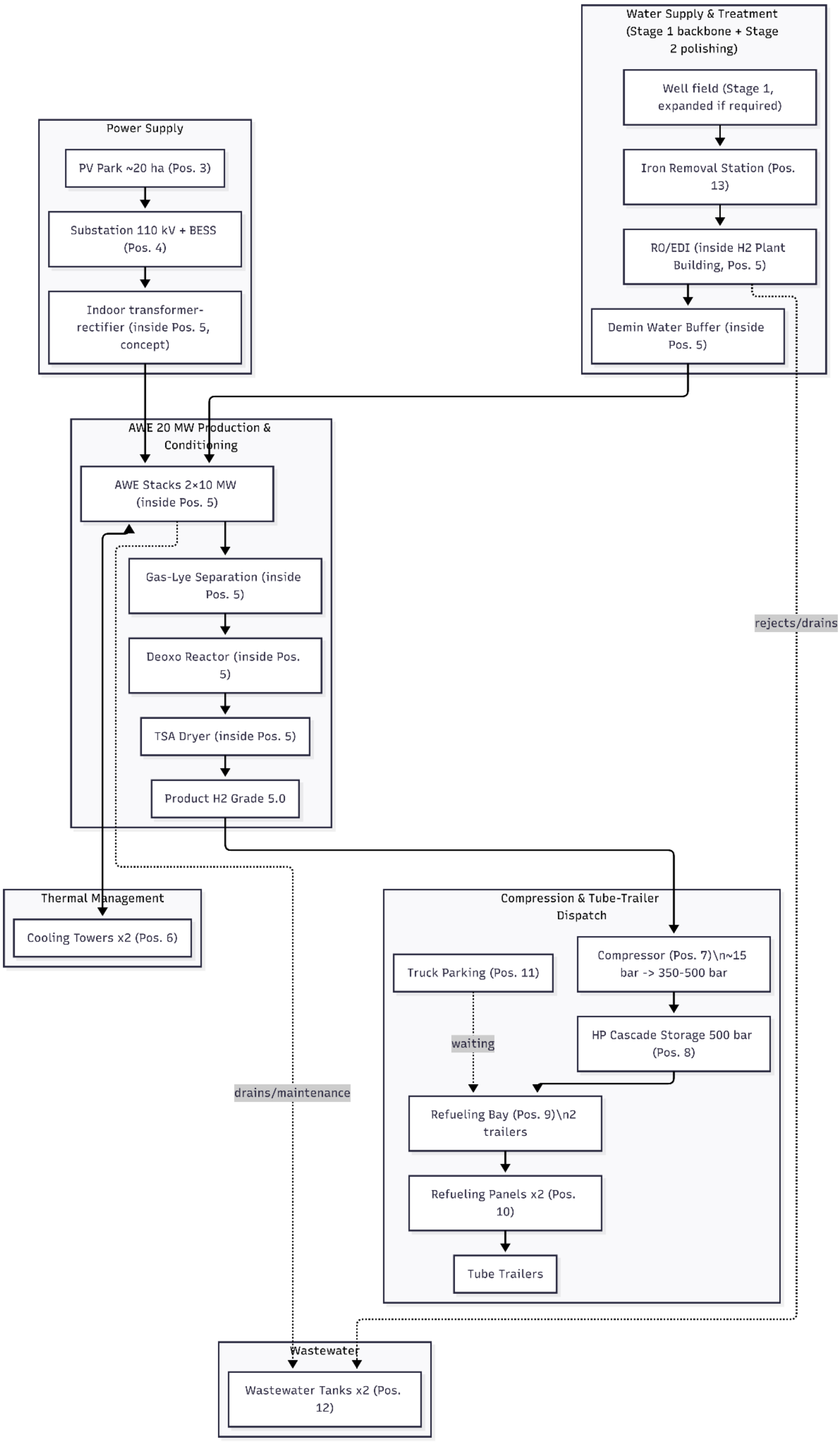


Figure 5-19: Conceptual Block Flow Diagram for Solution N°3 (Alkaline, 20 MW)

5.5.4.6. ATEX & Hazardous Area Summary (Solution №3)

Hazardous area classification (concept) is developed per IEC 60079-10-1 considering (i) higher pressures at Pos.7–10, (ii) credible release sources at valves/seals/couplings, and (iii) explosion-proof ventilation and gas detection inside the H_2 Plant Building stated as safeguards.

HAC summary (concept):

- Pos.5 H_2 Plant Building – Zone 2 concept for perimeter; indoor zoning and ventilation-based zoning to be confirmed at FEED.
- Pos.7 Compressor – Zone 2 around compressor/seals.
- Pos.8 HP cascade – Zone 2 around storage/piping.
- Pos.9 Refueling bay – Zone 2 during dispensing.
- Pos.10 Refueling panels – Zone 1 locally at couplings + Zone 2 in vicinity.

5.5.4.7. Fire Separation Distances (Fire gaps)

For Solution No. 3 (Pre-Design), the following constraints are stated:

- 20.0 m safety distance around the H_2 Plant Building and HP storage areas;
- R = 30.0 m well sanitary exclusion remains applicable;
- hazardous cargo truck flow is separated from personnel/parking.

From (Pos. Nº – Title)	To (Pos. Nº – Title)	Adopted separation	Design intent / comment
Well sanitary zone (Stage 1 well field)	Any permanent building/structure	R30.0 m	Sanitary protection zone retained for expanded well field
5 – H_2 Plant Building	1 – Admin building / 2 – Parking	R20.0 m (baseline)	Stage 2 safety distance; segregate personnel areas
8 – HP Cascade Storage	1 – Admin building / 2 – Parking	R20.0 m (baseline)	Stage 2 safety distance around HP storage
7 – Compressor	2 – Parking	R20.0 m (baseline)	Segregation of compression node from staff areas
10 – Refueling Panels	2 – Parking	R20.0 m (baseline)	Local Zone 1 at couplings; keep non-hazard areas away
9 – Refueling Bay	1 – Admin building	R20.0 m (baseline)	Segregation of dispatch operations

Table 5-18: Fire Separation Distances for Solution Nº3

5.5.4.8. HAZID Summary (Solution №3)

Stage 2 HAZID is qualitative at Pre-Design and is detailed at FEED (HAZOP/LOPA as required). Nodes map to Solution No. 3 explication; AWE-specific risks are included (30% KOH, high heat rejection, indoor process building).

Table 5-19: HAZID Summary Table for Solution №3

Node (Pos. Nº – Title)	Deviation / Hazard	Credible causes	Consequences	Safeguards (assumed at Pre-Design)	Recommendations (FEED)	Priority
5 – H_2 Plant Building	H_2 leak indoors	Flange/seal failure; maintenance error	Explosive atmosphere; flash fire	Gas detection; explosion-proof ventilation; ESD; 20 m separation concept	Confirm ventilation rates; detector mapping/voting; ESD cause & effect	H

Node (Pos. № – Title)	Deviation / Hazard	Credible causes	Consequences	Safeguards (assumed at Pre-Design)	Recommendations (FEED)	Priority
5 – AWE process	KOH leak / caustic exposure	Pipe/valve failure; drain error	Chemical burns; corrosion; secondary failure	Secondary containment; procedures; PPE	Define KOH storage/handling; bunding and neutralisation concept	H
5 – Purification (Deoxo/TSA)	Deoxo overheating / off-spec O_2	Control failure; cooling upset	Hot spots; ignition potential if leak	Monitoring; trips; ESD	Independent HH temperature trip; define O_2 limits and alarm setpoints	H
6 – Cooling towers	Loss of cooling capacity	Pump failure; fouling; power loss	Trip; thermal stress; reduced availability	Pump redundancy	Define winterisation and water chemistry programme	M
7 – Compressor	Seal leak / hot surfaces	Wear; vibration; poor maintenance	Jet fire/flash fire	Gas detection near seals; ESD; hot surface control	Vibration monitoring; maintenance concept; Ex-rated verification	H
8 – HP cascade (500 bar)	Line rupture / impact	Vehicle impact; fatigue; valve failure	Rapid release; jet fire; escalation	Crash protection; access control; ESD segmentation; 20 m distance	Validate crash barriers; isolation points; vent dispersion	H
9–10 – Refueling	Release during coupling	Human error; worn seals; hose fault	Local Zone 1 ignition; injury	E-stop; exclusion zones; bonding/earthing	Interlocks; breakaway couplings; procedural controls	H
4 – Substation/BESS	Electrical fault / battery event	Overcharge; defect; short	Fire; toxic smoke; power loss	Segregated zone; vendor fire safety	Confirm suppression/detection and emergency response plan	M

5.5.4.9. Water / Sewer / Fire philosophy

Solution No. 3 relies on the centralised Stage 1 fire-water backbone: Combined Pump Station and Fire Water Tanks, stated as originally sised for the hub's full expansion envelope.
Stage 2 additionally includes:

- internal safeguards in the H_2 Plant Building: automatic gas detection, explosion-proof ventilation, and local suppression for electrical rooms;
- wastewater collection in Pos.12 (x2);
- process water demand ~4.0–8.0 m³/h with potential well-field expansion.

Hydrogen fire philosophy remains consistent with Stage 1: fast detection, ESD, ventilation, isolation of leak source, controlled venting; water is primarily used for exposure cooling and evacuation path protection (final tactics at FEED).

5.5.5. Stage 2 – Solution №4 – 20 MW Hydrogen Plant – PEM Electrolysis

5.5.5.1. Stage 2 / Solution No. 4: General Concept and Strategic Role in Hub Development

Stage 2 "Scale-up", Solution №4 implements an industrial 20 MW PEM electrolysis configuration in a fully containerised modular arrangement, based on 4 × 5 MW, integrated into the hub's infrastructure backbone established earlier (Stage 1) and expanded for Stage 2.
Role of Solution №4 in the hub strategy:

- serves as a reference industrial PEM configuration for scaling to future phases (≥100 MW) through repeatable modules;

- demonstrates a fully outdoor containerised arrangement for the key PEM hydrogen chain (generation → conditioning → compression → storage → dispatch);
- aligns with the Stage 2 power concept (expanded PV park and a 110 kV substation + BESS as infrastructure core);
- supports core industrial safety principles: zoning, separation distances, fire brigade access, H_2 detection, Emergency Shutdown (ESD), and upward venting.

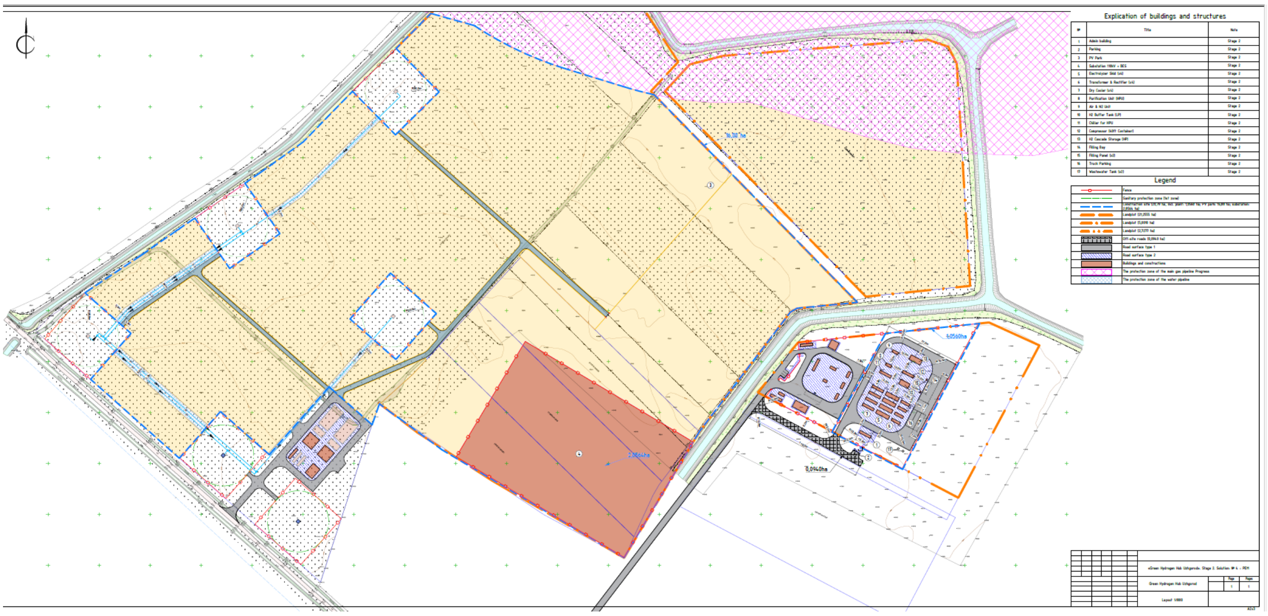


Figure 5-20: General Plan for Green Hydrogen Hub Uzhhorod, Stage 2 -20 MW, Solution №4-PEM

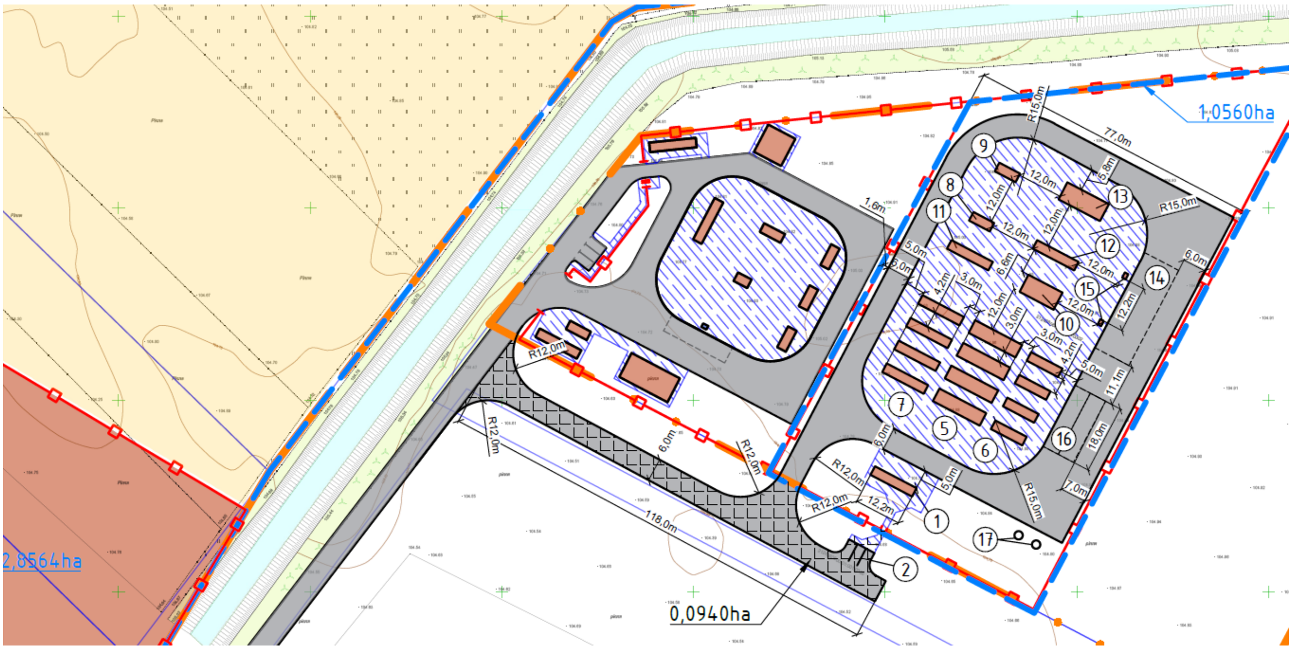


Figure 5-21: Fragment General Plan for Green Hydrogen Hub Uzhhorod, Stage 2 -20 MW, Solution №4-PEM. Plant Area.

5.5.5.2. Spatial Layout, Land Requirements, and Functional Zoning

The layout is developed against the Stage 2 / Solution №4 – PEM general plan (scale 1:1000). The drawing legend records the following areas (used as "as-drawn values" for the Feasibility Study):

- Construction site: 16.7483 ha including:
    - Plant (H_2 process zone): 1.0560 ha
    - PV park: 16.88 ha
    - Substation: 2.8564 ha

Functional zoning in Solution №4 is formed by three major blocks, physically separated on the plot plan:

1. Power block: PV Park (Pos. 3) and Substation 110 kV + BES (Pos. 4).
2. Hydrogen production & BoP block: Electrolyser Skid (Pos. 5), Transformer & Rectifier (Pos. 6), Dry Cooler (Pos. 7), HPU (Pos. 8), Air & N_2 (Pos. 9), H_2 Buffer (Pos. 10), Chiller (Pos. 11).
3. Hydrogen logistics block: Compressor (Pos. 12), Cascade Storage HP (Pos. 13), Filling Bay (Pos. 14), Filling Panel (Pos. 15), Truck Parking (Pos. 16).
   A dedicated wastewater collection node is provided as Wastewater Tank (Pos. 17).

Key Stage 2 / Solution №4 layout principle:

- the end-to-end chain "from molecule to trailer" is arranged linearly and is readable on the plot plan through the sequence 5 → 8 → 10 → 12 → 13 → 14–15 → 16;
- the administrative zone (Pos. 1–2) is separated from the hydrogen zone;
- the energy zone (Pos. 3–4) is separated from the hydrogen zone;
- hub-wide sanitary restriction for water intakes is adopted as R = 30 m as a unified principle for all stages.

5.5.5.3. Explication of buildings and structures

Fire hazard categories follow NAPB B.03.002-2007 (pre-design level; FEED refinement required). ATEX linkage follows IEC 60079-10-1 methodology (pre-design level; FEED refinement based on vendor data and ventilation/leak assessment).

Adopted UA fire hazard categories for feasibility level:

- AN – explosion and fire hazardous outdoor hydrogen installations (gas).
- V – fire hazardous (electrical installations, cable systems, power containers).
- D – non-combustible substances in cold state / auxiliary facilities without handling flammable gases.

Table 5-20: Explication and Safety Matrix for Solution N°4

Pos.	Title (Explication)	Fire Hazard Category (UA)	ATEX / Hazardous Area (concept)	Key role in the layout
1	Admin building Stage 2	D	Non-hazardous	Operator/admin functions, outside H_2 zones
2	Parking Stage 2	N/A	Non-hazardous	Staff/visitor parking
3	PV Park Stage 2	N/A	Non-hazardous	Renewable power generation
4	Substation 110kV + BES Stage 2	V	Non-hazardous (electrical zones)	Grid connection / conversion / energy storage
5	Electrolyser Skid (x4) Stage 2	AN	Zone 2 (outdoor area around containers); inside container to be refined	PEM hydrogen generation, primary separation
6	Transformer & Rectifier (x4) Stage 2	V	Non-hazardous (with separation distances)	Power conversion for PEM modules
7	Dry Cooler (x4) Stage 2	D	Non-hazardous	Heat rejection for closed cooling loops

Pos.	Title (Explication)	Fire Hazard Category (UA)	ATEX / Hazardous Area (concept)	Key role in the layout
8	Purification Unit (HPU) Stage 2	AN	Zone 2	Hydrogen purification and drying
9	Air & N2 Unit Stage 2	D	Non-hazardous	Instrument air and nitrogen for purging/inerting
10	H_2 Buffer Tank (LP) Stage 2	AN	Zone 2	LP buffering to decouple operating modes
11	Chiller for HPU Stage 2	D	Non-hazardous	Cooling for HPU/drying operation
12	Compressor (40ft Container) Stage 2	AN	Zone 2	Hydrogen compression to 350–500 bar
13	H_2 Cascade Storage (HP) Stage 2	AN	Zone 2	HP cascade storage for trailer filling
14	Filling Bay Stage 2	AN	Zone 2 (entire bay)	Drive-through trailer filling pad
15	Filling Panel (x2) Stage 2	AN	Zone 1 (local at connectors) + Zone 2 (surrounding)	Dispensing control and connection points
16	Truck Parking Stage 2	N/A	Non-hazardous (outside zones)	Trailer waiting and manoeuvring
17	Wastewater Tank (x2) Stage 2	N/A	Non-hazardous	Industrial/domestic wastewater collection

5.5.5.4. Hydrogen process chain (PEM 20 MW) and BoP systems

H_2 production: PEM Electrolyser (Pos. 5) and power conversion (Pos. 6)

Hydrogen is produced in four PEM modules (Pos. 5) with a total installed capacity of 20 MW (4 × 5 MW). The containerised concept provides:

- repeatable modular architecture;
- separation of operational risks by "lines";
- potential phased maintenance approach (concept level; FEED defines exact scenarios).

Each PEM module is supplied via its dedicated Transformer & Rectifier (Pos. 6) package. This arrangement:

- reduces internal cable runs within the process area;
- localises electrical risks and improves maintainability;
- supports the "module = PEM + power conversion + cooling" concept.

Thermal management: Dry Cooler Field (Pos. 7) and Chiller for HPU (Pos. 11)

Heat rejection from PEM modules is achieved through closed cooling loops connected to the Dry Cooler (Pos. 7) field. Outdoor dry cooling supports:

- natural heat rejection without generating wet cooling blowdown;
- minimisation of water demand for cooling;
- straightforward access for operation and maintenance.

For hydrogen conditioning and drying stability, Chiller for HPU (Pos. 11) is provided to support controlled temperatures required by purification/drying equipment.

Hydrogen conditioning: Purification Unit / HPU (Pos. 8)

Hydrogen from all Pos. 5 lines is routed into a common header and fed to the HPU (Pos. 8), providing:

- residual oxygen removal (deoxo concept for product specification compliance);
- drying to the required product parameters (final specification is FEED/market dependent);
- quality measurement and control as part of safety and product assurance.

Buffering and compression: H_2 Buffer Tank (Pos. 10), Compressor (Pos. 12), Storage HP (Pos. 13)

After HPU, hydrogen is routed to the H_2 Buffer Tank (Pos. 10) at low pressure. The buffer:

- decouples PV-driven generation variability from compression and dispatch;
- reduces compressor cycling;
- stabilises dispatch capability during short-term demand peaks.

Hydrogen is then compressed in Compressor (Pos. 12) to the logistics pressure range (conceptually 350–500 bar) and stored in H_2 Cascade Storage (Pos. 13). Cascade storage supports:

- rapid trailer filling;
- stepwise pressure management for efficient loading;
- short-term inventory buffering.

H_2 dispatch: Filling Bay (Pos. 14), Filling Panel (Pos. 15), Truck Parking (Pos. 16)

Dispensing is performed at Filling Bay (Pos. 14) in a drive-through arrangement to reduce manoeuvres and time in the hazardous area. Control and connections are provided by Filling Panel (Pos. 15) (two panels). Truck Parking (Pos. 16) is located outside hazardous zones for queueing and logistics management.

Instrument air and nitrogen: Air & N_2 Unit (Pos. 9)

Air & N_2 Unit (Pos. 9) provides:

- instrument air for pneumatic actuators and control valves;
- nitrogen for purging, inerting, and maintenance preparation;
- support for safe start-up/shutdown procedures.

Wastewater: Wastewater Tank (Pos. 17)

Wastewater Tank (Pos. 17) (two tanks) provides:

- collection of process drains linked to water treatment/maintenance flushing and routine operations;
- collection of domestic wastewater where applicable (depending on the hub wastewater concept);
- routing for disposal/treatment as part of the hub infrastructure solution.

5.5.5.5. Conceptual Block Flow Diagram (BFD): Solution No. 4

A. Power Supply Chain

- Grid / Hub power backbone → (Pos. 4 Substation 110kV + BES) → MV/LV distribution → (Pos. 6 Transformer & Rectifier x4) → DC supply → (Pos. 5 Electrolyser Skid x4)

B. Water-to-Hydrogen Process Chain

- Hub water supply & treatment infrastructure (existing within hub; not position-marked in Solution №4) → demin water to process → (Pos. 5 Electrolyser Skid x4) → H_2 wet gas header → (Pos. 8 Purification Unit, HPU) → dry high-purity H_2 → (Pos. 10 H_2 Buffer Tank, LP) → (Pos. 12 Compressor) → (Pos. 13 H_2 Cascade Storage, HP) → (Pos. 15 Filling Panel x2) → (Pos. 14 Filling Bay) → Tube trailer dispatch (via Pos. 16 Truck Parking logistics)

C. Cooling & Thermal Management Chain

- (Pos. 5 Electrolyser Skid x4) heat load → closed-loop cooling → (Pos. 7 Dry Cooler x4) heat rejection to ambient
- (Pos. 8 HPU) temperature control → (Pos. 11 Chiller for HPU) → stable drying/quality operation

D. Utilities & Safety Media Chain

- (Pos. 9 Air & N_2 Unit) → instrument air to valves + N_2 to purging/inerting points (Pos. 5 / 8 / 10 / 12 / 13 / 15)

E. Wastewater / Drainage Chain

- process & service drains → (Pos. 17 Wastewater Tank x2) → further treatment/disposal within hub wastewater concept

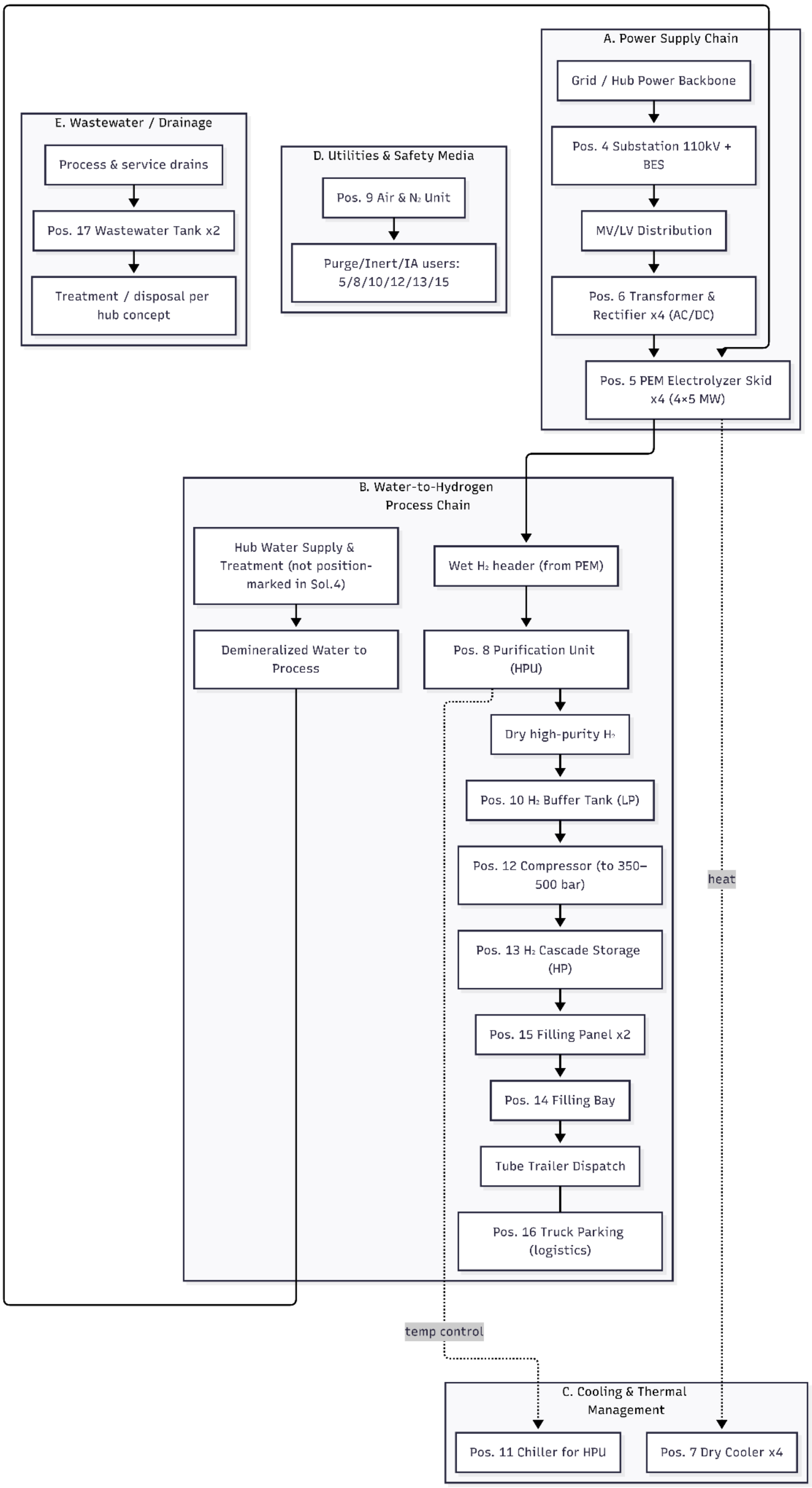


Figure 5-22: Conceptual Block Flow Diagram for Solution №4 (PEM, 20 MW)

5.5.5.6. Water supply, sewerage, and firefighting concept – Solution №4

For Stage 2 / Solution №4, the adopted concept is that the hub provides the heavy water infrastructure backbone, established earlier and expanded progressively. Solution №4 uses water as PEM process medium and as part of utility loops within BoP. Key principles:

- process water for PEM must meet the electrolysis purity requirement (final specification at FEED);
- minimisation of water losses through closed loops and controlled drains;
- hub-wide sanitary restriction for water intakes is adopted as R = 30 m as a unified principle.

Wastewater concept for Stage 2 / Solution №4 (concept level):

- process drains (flushing, maintenance operations) collected in Pos. 17;
- domestic wastewater managed under the hub-wide scheme (temporary or permanent, clarified in utility design);
- stormwater managed under the overall site drainage system, with separation of clean/conditionally contaminated runoff.

Hydrogen-specific principles:

- hydrogen as a gaseous fuel is not extinguished by water; water is used for exposure cooling and preventing escalation;
- key safety measures: ESD, compression stop, isolation valves, safe venting/depressurisation, H_2 detection, alarms, zoning and separation distances;
- outdoor installation supports natural ventilation and reduces accumulation potential.

5.5.5.7. Fire Separation Distances (tabular) + separation philosophy (as per drawing logic)

The Solution №4 drawing indicates R12.0 m as the base separation distance for major hydrogen-related units and R30.0 m as the sanitary reference. Solution №4 implements this principle via a compact H_2 cluster with separations and access roads. Separation philosophy:

- base minimum separation of 12.0 m between AN installations and other objects (concept level);
- localised stricter control near dispensing connections (Zone 1 locally at Pos. 15);
- fire brigade access ensured by loop/through roads and avoiding dead-end access around Pos. 5–15.

Table 5-21: Fire Separation Distances for Solution №4

From	To	Categories (UA)	Required (min), m	Adopted (concept/as-drawn), m	Comment
Pos. 5 Electrolyser Skid	Pos. 1 Admin building	AN – D	12.0	≥12.0	Admin separated from H_2 cluster
Pos. 5 Electrolyser Skid	Pos. 6 Transformer & Rectifier	AN – V	12.0	≥12.0	Electrical zone separated by distances/roads
Pos. 5 Electrolyser Skid	Pos. 7 Dry Cooler	AN – D	12.0	≥12.0	Cooling equipment separated from H_2 sources
Pos. 8 HPU	Pos. 10 H_2 Buffer Tank (LP)	AN – AN	12.0	≥12.0	Separation between conditioning and buffering steps
Pos. 12 Compressor	Pos. 13 H_2 Cascade Storage (HP)	AN – AN	12.0	≥12.0	Compression separated from storage
Pos. 13 H_2 Cascade Storage (HP)	Pos. 14 Filling Bay	AN – AN	12.0	≥12.0	Storage separated from dispensing area
Pos. 14 Filling Bay	Pos. 16 Truck Parking	AN – N/A	12.0	≥12.0	Waiting area outside H_2 zone

From	To	Categories (UA)	Required (min), m	Adopted (concept/as-drawn), m	Comment
Pos. 5–15 H_2 cluster	Boundary / fence	AN – N/A	10.0 (concept)	≥10.0	Controlled perimeter and access

5.5.5.8. ATEX & Hazardous Area Summary (PEM 20 MW)

Hazardous area classification is prepared at pre-design level:

- for outdoor installations with natural ventilation;
- considering typical credible leak points (flanges, fittings, valves, connectors);
- without quantitative risk assessment and without CFD dispersion modelling (FEED scope).

Table 5-22: Fire Separation Distances for Solution №4

Pos. + Title	Gas	ATEX Zone (concept)	Extent (concept)	Comment
Pos. 5 Electrolyser Skid (x4)	H_2	Zone 2	3.0 m around container	Internal zones refined by ventilation/detection
Pos. 8 Purification Unit (HPU)	H_2	Zone 2	3.0 m	Conditioning skid
Pos. 10 H_2 Buffer Tank (LP)	H_2	Zone 2	>12.0 m	LP storage with fittings/valves
Pos. 12 Compressor	H_2	Zone 2	>12.0 m	Critical for seals and dynamic equipment
Pos. 13 H_2 Cascade Storage (HP)	H_2	Zone 2	>12.0 m	HP storage
Pos. 14 Filling Bay	H_2	Zone 2	Entire bay	During filling operations
Pos. 15 Filling Panel (x2)	H_2	Zone 1 (local) + Zone 2	1.0 m local at connectors	Frequent connect/disconnect operations

5.5.5.9. Consolidated table "Explication → Fire Category (UA) → ATEX Zone → Key safeguards" (positions 1–17)

Table 5-23: Hazardous Area Classification for Solution №4

Pos. + Title	Fire Category (UA)	ATEX Zone (concept)	Key safeguards (Pre-Design philosophy)
Pos. 1 Admin building	D	Non-hazardous	Located outside H_2 zones; access control; ESD interface
Pos. 2 Parking	N/A	Non-hazardous	Outside H_2 zones; controlled personnel routes
Pos. 3 PV Park	N/A	Non-hazardous	Fencing; layout separations; electrical protection
Pos. 4 Substation 110kV + BES	V	Non-hazardous	Separation from H_2 area; detection/protection for electrical systems; backup power for critical safety systems
Pos. 5 Electrolyser Skid (x4)	AN	Zone 2	H_2 detection; container ventilation; ESD; upward venting; Ex equipment in zones
Pos. 6 Transformer & Rectifier (x4)	V	Non-hazardous	Electrical protections; cable segregation; ignition source control near H_2 zones
Pos. 7 Dry Cooler (x4)	D	Non-hazardous	Outdoor installation; maintenance access; coolant leak control
Pos. 8 Purification Unit (HPU)	AN	Zone 2	O_2/temperature control; ESD; ventilation; Ex execution
Pos. 9 Air & N_2 Unit	D	Non-hazardous	Pressure control; safe purging; N_2 availability for inerting

Pos. + Title	Fire Category (UA)	ATEX Zone (concept)	Key safeguards (Pre-Design philosophy)
Pos. 10 H_2 Buffer Tank (LP)	AN	Zone 2	PRV to safe discharge; detection; ESD isolation
Pos. 11 Chiller for HPU	D	Non-hazardous	Alarms/redundancy; safe shutdown sequence on cooling loss
Pos. 12 Compressor	AN	Zone 2	Seal-area detection; auto-shutdown on leak; temperature monitoring; ESD
Pos. 13 H_2 Cascade Storage (HP)	AN	Zone 2	Segmented isolation; impact protection; pressure monitoring; ESD
Pos. 14 Filling Bay	AN	Zone 2	Traffic management; emergency stop; ignition source exclusion; bonding/earthing
Pos. 15 Filling Panel (x2)	AN	Zone 1 local	Interlocks; breakaway coupling (FEED); impact barriers; emergency stop
Pos. 16 Truck Parking	N/A	Non-hazardous	Outside zones; routing; signage and speed limits
Pos. 17 Wastewater Tank (x2)	N/A	Non-hazardous	Containment; overfill control; disposal/treatment procedures

5.5.5.10. HAZID Summary (Solution №4)

Priority scale: H / M / L for FEED focus.

Table 5-24: HAZID Summary Table for Solution №4

Node (Pos. + Title)	Deviation / Hazard	Credible Causes	Consequences	Existing / Assumed Safeguards (Pre-Design)	Recommendations (FEED / Next Stage)	Priority
Pos. 5 Electrolyser Skid	Hydrogen leak to atmosphere	Flange/gasket failure, fitting leak, vent misrouting	Explosive atmosphere (Zone 2), ignition → flash fire, injury, damage	Outdoor placement; ATEX zoning; H_2 detection; forced ventilation; ESD; upward venting concept	Define detector setpoints & voting; verify ventilation capacity; confirm vent discharge height/dispersion; finalise Ex equipment list	H
Pos. 5 Electrolyser Skid	Oxygen enrichment / oxygen release	Poor vent location; insufficient separation from H_2 vent; backflow	Oxygen-enriched atmosphere increasing fire severity	Separate vent routing concept	Confirm O_2 vent termination and separation from H_2 vents; add non-return devices where needed	M
Pos. 5 + Pos. 6	Electrical arc/short	Cable fault, insulation failure, moisture ingress	Electrical fire; potential ignition source	Segregated electrical containers; earthing	Verify cable segregation from AN zones; arc-flash protection; smoke detection in Pos. 6	M
Pos. 8 HPU	Deoxo overheating	Elevated O_2, control failure, cooling loss (Pos. 11)	Hot spots, equipment damage, ignition potential if leak	Temperature monitoring; chiller cooling; ESD	Independent high-temp trip; confirm O_2 limits; verify cooling redundancy	H

Node (Pos. + Title)	Deviation / Hazard	Credible Causes	Consequences	Existing / Assumed Safeguards (Pre-Design)	Recommendations (FEED / Next Stage)	Priority
Pos. 11 Chiller	Loss of cooling	Power loss, pump failure	HPU upset, off-spec H_2, trips	Alarms; basic redundancy	Define safe shutdown on cooling loss; consider N+1 pumps if required	M
Pos. 10 Buffer LP	Overpressure	PRV isolation, control valve failure	PRV lift release; rupture if protection fails	PRV to vent; pressure monitoring; ESD	Confirm PRV sizing approach; ensure safe discharge; lock-open critical valves	H
Pos. 12 Compressor	Seal leak	Seal wear, vibration, maintenance error	Jet fire / flash fire	Outdoor; detection; ESD; separation	Add local detectors; auto-shutdown; control hot surfaces; Ex-rated drives	H
Pos. 12 Compressor	Overtemperature / mechanical failure	Cooling loss, overspeed	Fire, catastrophic failure, projectiles	OEM protections; monitoring	Define condition monitoring and vibration trip; consider fragmentation effects for access routes	M
Pos. 13 Storage HP	HP leak / rupture	Valve failure, impact	Jet fire, rapid release	Separation distances; ESD	Add impact barriers; define ESD segmentation and slam-shut valves	H
Pos. 14–15 Filling	Release during coupling	Human error, O-ring wear, hose damage	Local Zone 1 ignition → injury	Procedures; E-stop; zoning	Breakaway couplings; interlocks; driver exclusion zone; bonding/earthing	H
Pos. 14 Filling bay	Vehicle impact	Misalignment, brake failure	Piping/panel damage → major release	Traffic segregation	Install crash barriers/bollards; signage and speed limits	H
Pos. 4 Substation+ BESS	BESS fire	Cell defect, overcharge	Fire, toxic smoke, loss of critical power	Dedicated area; layout separation	Fire detection & suppression per BESS guidance; backup power for ESD/detection	M
Pos. 17 Wastewater	Loss of containment / overflow	Overfill, routing error	Local contamination; slip hazard	Containment; alarms	Overflow management; inspection and maintenance plan	L
Whole site	Lightning/static	Storm; inadequate bonding	Ignition source	Earthing concept assumed	Lightning protection; bonding/earthing for trailers; periodic testing	H
Whole site	Emergency access	Blocked roads, poor signage	Delayed response	Ring road concept	Validate access routes/turning; mark isolation points; emergency maps	M

5.5.6. Stage 3 – Solution №5 – 100 MW Hydrogen Plant – Alkaline Electrolysis (AWE)

5.5.6.1. Stage 3 / Solution №5 General Concept and Role in Hub Development

Stage 3 ("100 MW Scale") marks the transition from early containerised / semi-modular concepts to a **full industrial configuration**, introducing a dedicated engineering interface for **hydrogen transportation into gas distribution / transmission infrastructure** (network injection via metering and control).

Solution №5 delivers a 100 MW hydrogen production facility based on **Alkaline electrolysis**, where:

- a unified **Integrated plant** is formed as the core production block of the stage (Pos. 3),
- a **Compressor Station** is established (Pos. 4), together with a network interface block (Pos. 5),
- a dedicated **Vent Stack** becomes a mandatory element of the industrial safety philosophy (Pos. 6),
- **hydrogen buffering is installed downstream of compression and upstream of GDS** (Pos. 7) in order to smooth pulsations and stabilise the injection interface under dynamic operating conditions.

Therefore, Solution №5 is the "turning point" stage where hydrogen logistics changes from: **"molecule-to-trailer" (earlier stages) → "molecule-to-gas-network" (Stage 3+)**.

5.5.6.2. Plot Structure, Areas and Functional Zoning (as per Solution №5 drawing)

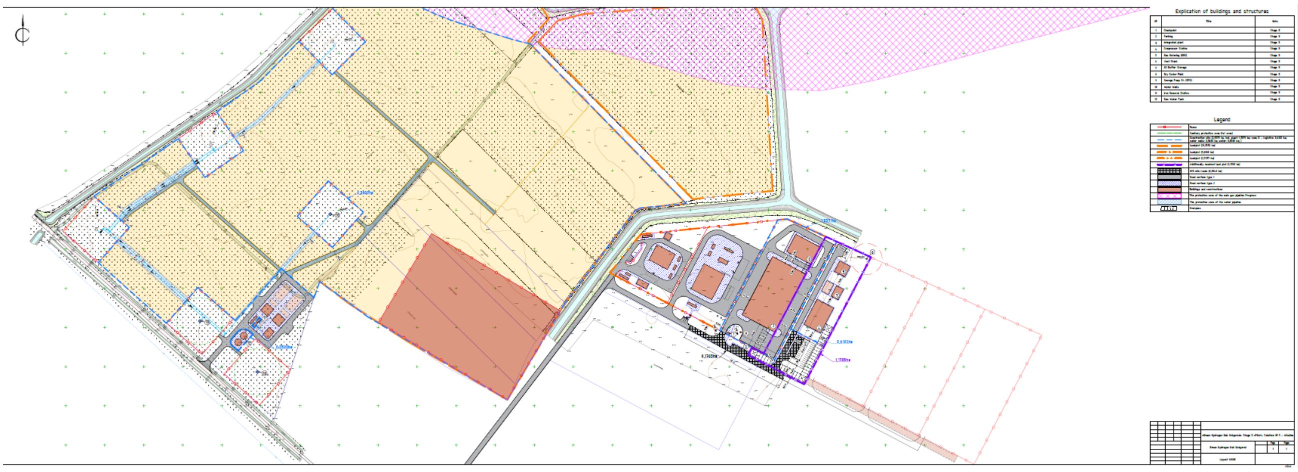


Figure 5-23: General Plan for Green Hydrogen Hub Uzhhorod, Stage 3 – 100 MW, Solution N°5 – Alkaline

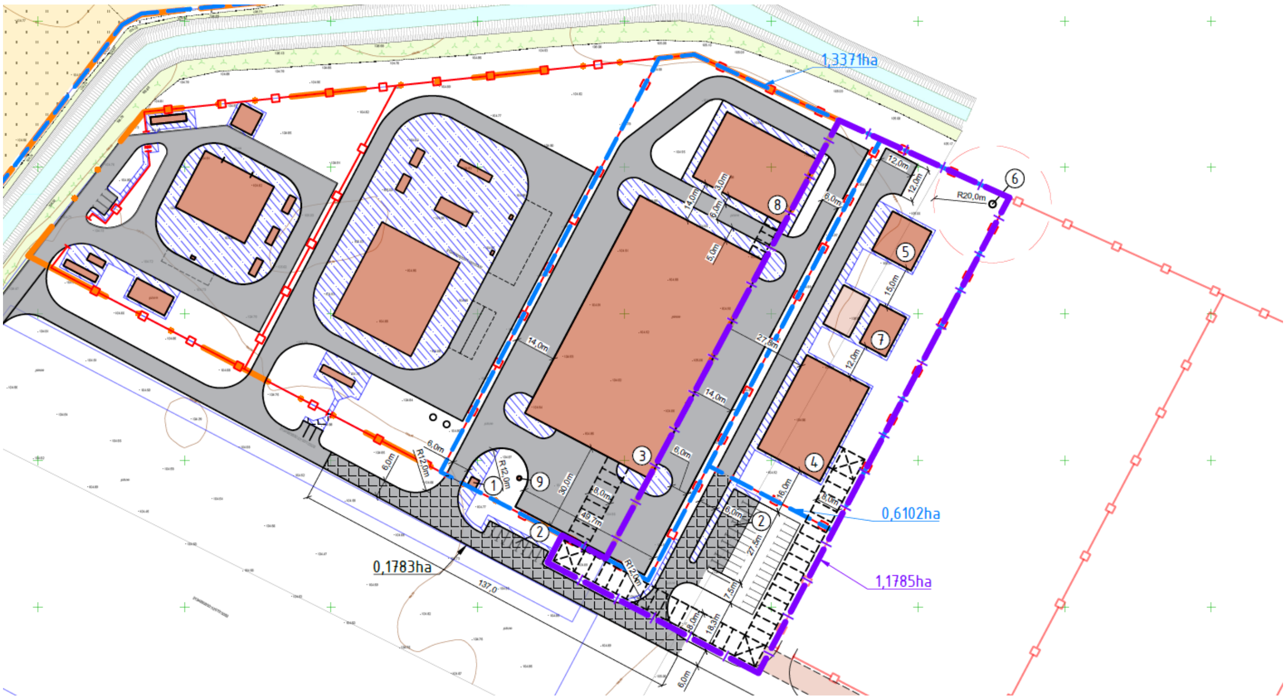


Figure 5-24: Fragment General Plan for Green Hydrogen Hub Uzhhorod, Stage 3 -100 MW, Solution №5-Alkaline. Plant Area.

The layout is strictly aligned with the Stage 3 / Solution №5 general plan (Layout 1:1000). The drawing legend provides the following areas adopted as "as-built-by-drawing" for TEA benchmarking:

- Construction site: 2.3573 ha including:
  - plant: 1.3371 ha
  - zone D – logistics: 0.6102 ha
  - water wells: 0.3600 ha
  - water: 0.0500 ha

The site is divided into four main functional zones:

1. Production zone (plant) – electrolysis core and integrated BoP systems (Pos. 3).

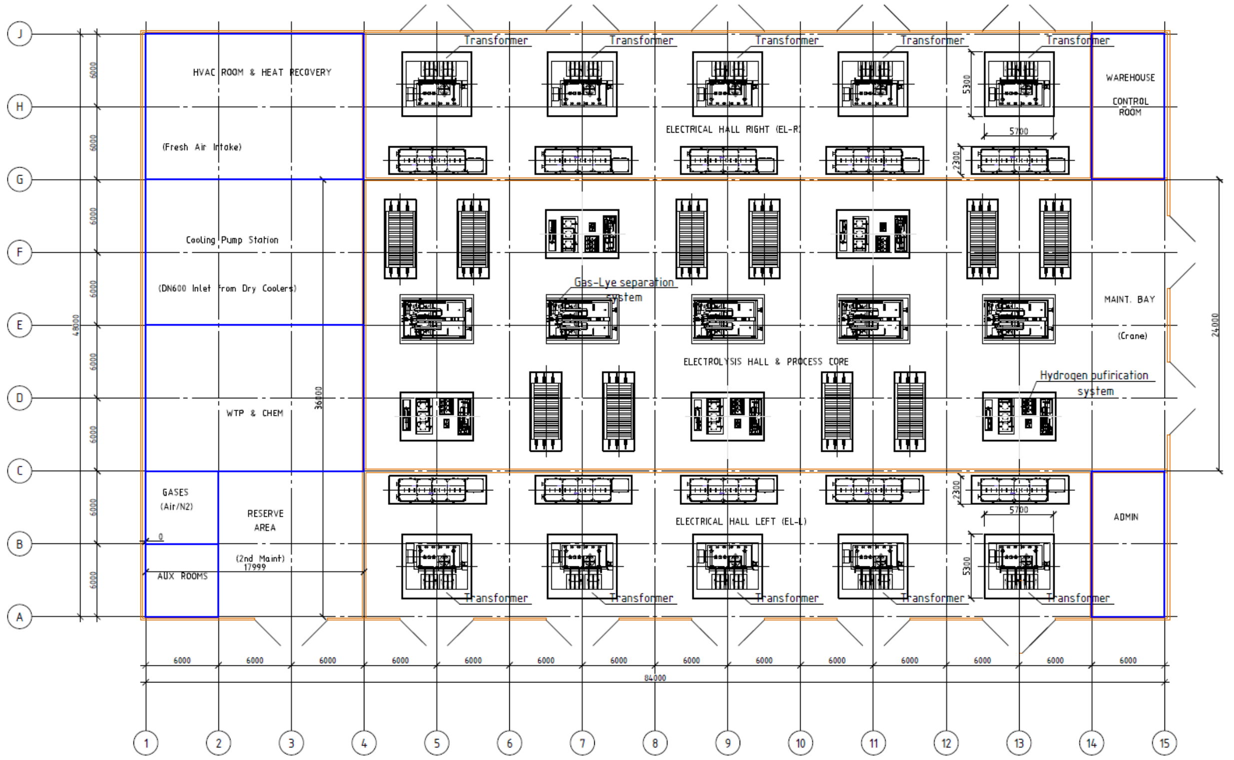


Figure 5-25: H_2 Plant 100 MW Alkaline.

2. Compression / network export zone – compressor station, metering/regulation, vent stack and H_2 buffer (Pos. 4–7).
3. Cooling zone – dry cooler field (Pos. 8).
4. Water and wastewater infrastructure zone – wells, iron removal, raw water storage, SPS/wastewater (Pos. 9–12).

Traffic and safety:

- controlled entry through the checkpoint (Pos. 1) and parking (Pos. 2).
- the logistics area (zone D) is separated, preventing conflict between maintenance/supply traffic and critical hydrogen process areas.
- the project-wide sanitary principle for water intake is R = 30 m, shown on the drawing as R30.0 m.

5.5.6.3. Buildings/Structures Table (Pos. 1–12) + Fire Hazard Category (UA) + ATEX linkage

Fire hazard categories follow NAPB B.03.002-2007 logic at Pre-Design level and are used for ATEX/HAC linkage (IEC 60079-10-1). Internal room-by-room categorisation is to be finalised at the FEED/Design stage.

Table 5-25: Explication and Safety Matrix for Solution №5

Pos. (Explication) – Title	Function	Fire Hazard Category (UA)	ATEX / Hazardous Area linkage (concept)
1 – Checkpoint	Access control, security point	D	Non-hazardous
2 – Parking	Staff/visitor parking	–	Non-hazardous
3 – Integrated plant	Electrolysis building/block + main BoP inside	A/B (local) / V (to be refined)	Internal HAC to be refined; external perimeter typically Zone 2 near potential H_2 sources (if external vents/outlets exist)
4 – Compressor Station	H_2 compression (capital building)	A/B	Zone 2; local Zone 1 at joints/connectors (FEED refinement)

Pos. (Explication) – Title	Function	Fire Hazard Category (UA)	ATEX / Hazardous Area linkage (concept)
5 – Gas Metering (GDS)	Metering/regulation and network interface	A/B	Zone 2; local Zone 1 at valves/joints (FEED refinement)
6 – Vent Stack	Safe vertical vent/depressurisation	AN (outdoor installation)	Zone 2 around outlet and vertically above (FEED refinement)
7 – H_2 Buffer Storage	H_2 buffer after compression and before GDS	AN	Zone 2 around vessel and piping
8 – Dry Cooler Field	Heat rejection (dry coolers)	D	Non-hazardous
9 – Sewage Pump St. (SPS)	Wastewater pumping / handling	V/D	Non-hazardous
10 – Water Wells	Water abstraction wells	–	Non-hazardous; sanitary zone R = 30 m
11 – Iron Removal Station	Deferrisation for raw water	D	Non-hazardous
12 – Raw Water Tank	Raw water reserve	D	Non-hazardous

5.5.6.4. Hydrogen Production Chain (AWE 100 MW) and BoP Systems

Overall principle: the Alkaline electrolysis plant is implemented as an industrial block within the Integrated plant (Pos. 3), while the cooling system is deployed as a separate outdoor field (Pos. 8), and a dedicated "gas export corridor" is formed for compression and network interface (Pos. 4–7).

Water and water preparation (Pos. 10–12, 11)

- Water Wells (Pos. 10) provide raw water to the plant. A project-wide sanitary principle adopts R = 30 m protection around water intake.
- Raw water is treated by Iron Removal Station (Pos. 11) (required for well water under TEA assumptions).
- Treated raw water is stored in Raw Water Tank (Pos. 12) and distributed to consumers. The TEA includes 200 m^3 raw water tanks (2 units) as a stage infrastructure element.

Electrolysis (Integrated plant – Pos. 3)

The Integrated plant includes:

- alkaline electrolyser blocks,
- process solution circulation and make-up systems,
- H_2/O_2 separation systems,
- primary hydrogen drying/purification within the stage plant scope.

The "single Integrated plant" concept creates an industrial production core with controlled indoor conditions, including forced ventilation and monitoring.

Cooling and thermal management (Dry Cooler Field – Pos. 8)

Heat rejection is achieved via Dry Cooler Field (Pos. 8). This is a key decision for Solution №5 because wet cooling towers, often used internationally for Alkaline plants, increase make-up water demand; under the site water balance constraints and the required operating profile, wet cooling introduces a risk of exceeding available abstraction and storage margins.

("Wet vs dry" justification is consolidated in 4.3.6.7.)

Compression, buffering and network export (Pos. 4–7)

- Hydrogen leaving the Integrated plant is routed to Compressor Station (Pos. 4) where pressure is increased to the level required for transport/injection (exact parameters to be defined at FEED).

- Hydrogen then flows to H_2 Buffer Storage (Pos. 7) – buffering is installed downstream of compression and upstream of GDS to smooth pulsations and stabilise the network interface.
- Hydrogen is then routed to Gas Metering (GDS) (Pos. 5) – metering/regulation and the interface to the gas distribution/transmission network.
- Vent Stack (Pos. 6) provides safe vertical depressurisation and controlled discharge.

Wastewater handling (SPS and removal concept)

- SPS (Pos. 9) is included for stage wastewater handling, consistent with the hub infrastructure approach.
- Potential wastewater sources for Alkaline include alkaline wash waters, water treatment concentrates, filter wash waters and others; composition and concentrations must be validated by laboratory testing at later stages.

5.5.6.5. Conceptual Process Scheme (Textual Block Flow Diagram, BFD), Solution №5

Electricity → Power conversion (within Integrated plant) → Alkaline Electrolyser stacks (Integrated plant, Pos. 3)
Raw water (Wells, Pos. 10) → Iron removal (Pos. 11) → Raw water storage (Pos. 12) →
→ Demineralisation / process water preparation (within Integrated plant, Pos. 3) → Electrolysis (Pos. 3)
Hydrogen (from electrolysis, Pos. 3) → Primary gas conditioning (Pos. 3) →
→ Compressor Station (Pos. 4) → H_2 Buffer Storage (Pos. 7) → Gas Metering (GDS) (Pos. 5) → Pipeline / Gas network interface
Safety / depressurisation: H_2 system (Pos. 3/4/5/7) → relief/vent headers → Vent Stack (Pos. 6) → discharge upwards
Wastewater streams (Pos. 3/11/12) → collection / pumping → SPS (Pos. 9) → off-site removal / treatment (per permitting concept)

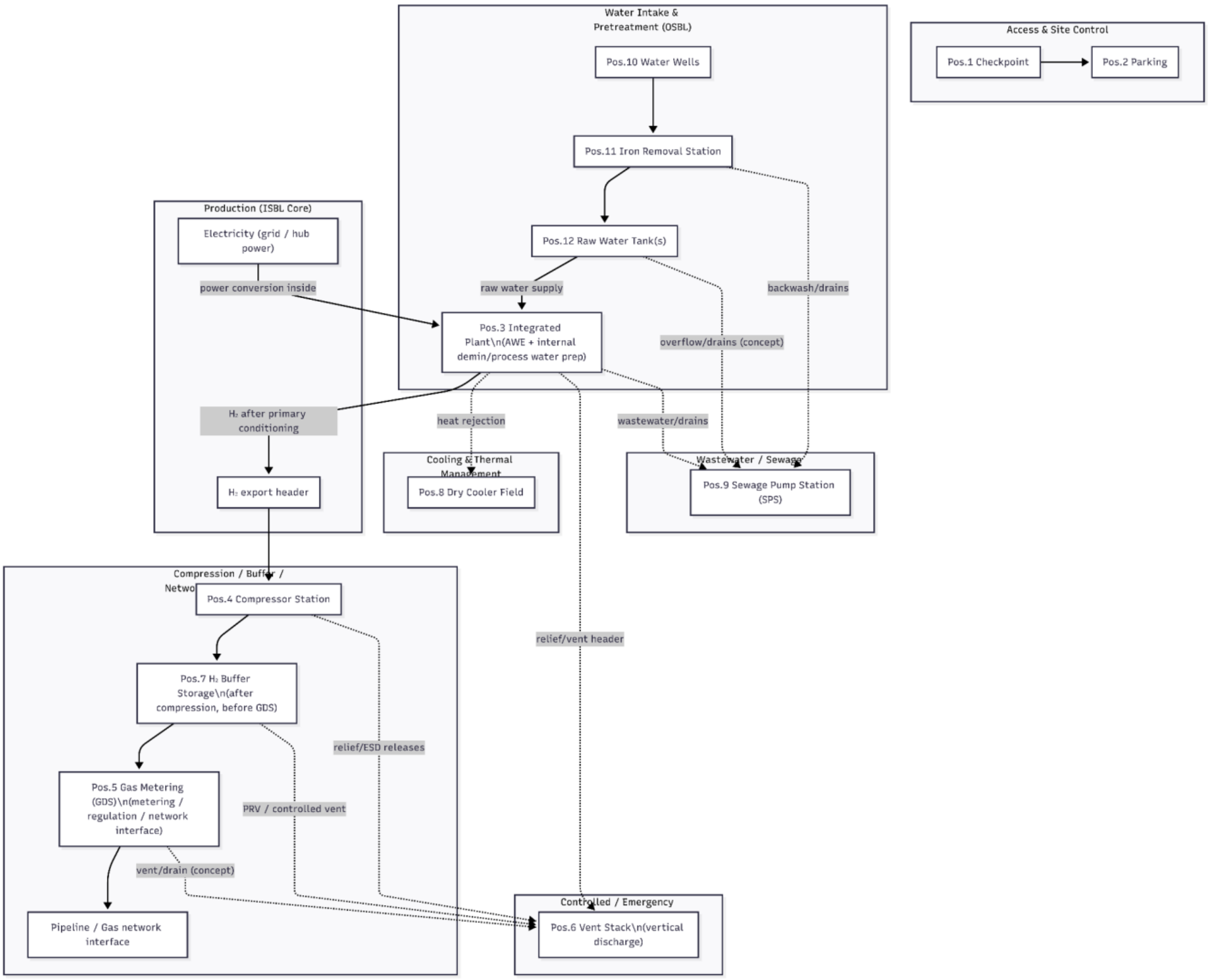


Figure 5-26: Conceptual Block Flow Diagram for Solution Nº5 (Alkaline, 100 MW)

5.5.6.6. Water / Sewer Philosophy and Water Recalculation (63% load = 5519 h/year)

Water TEA baseline assumptions (reference)
The project Water TEA is based on:

- operating mode – one shift,
- shift duration – 7 hours.

For Alkaline technology, the TEA provides production water consumption per stage; for the 3rd stage of construction it states:

- 109.9 m³/h (Alkaline technology, 3rd stage).

This value is used as the baseline for annual recalculation under a different operating profile.
Annual water recalculation for Solution №5 at 63% load
For Stage 3 / Solution №5, the required operating profile is:

- 5519 hours/year, equal to 63% of 8760 hours/year (100%). (Provided by the Client.)

Calculation:

- Production water (Alkaline, Stage 3): 109.9 m³/h
- Annual operating hours: 5519 h/year

Annual water (process/industrial supply):
109.9 m³/h × 5519 h/year = 606,538.1 m³/year
Comparison with TEA "shift mode" (7 hours/day)
Using TEA shift mode as reference:

- 7 h/day × 365 day/year = 2555 h/year

Annual water at TEA shift mode:
109.9 m³/h × 2555 h/year = 280,794.5 m³/year
Therefore, 63% annual operation (5519 h/year) increases annual production water demand by approximately 2.16× versus the TEA shift assumption.
Cooling system implication (why wet cooling becomes problematic)
While wet cooling towers are common internationally for Alkaline plants, they require significant make-up water (evaporation / drift / blowdown), which directly increases the site water demand and the burden on storage and wastewater handling.
For Solution №5, Dry Cooler Field (Pos. 8) is adopted because higher annual utilisation (5519 h/year) makes wet cooling more likely to:

- exceed site water balance margins (wells yield and reserve),
- require larger raw water storage volumes,
- increase chemical treatment and wastewater loads.

The industrial scale also requires early recognition of:

- extensive cooling pipework and pumping systems,
- hydraulic stability and redundancy,
- operational stability under dynamic load.

5.5.6.7. ATEX & Hazardous Area Summary (concept level)

In Solution №5, key H_2 nodes (compression, metering/regulation, buffer, vent stack) constitute the main hazardous corridor. At Pre-Design level, a conceptual IEC 60079-10-1 approach is applied:

- Zone 2: around compression and export equipment (Pos. 4, 5, 7) and associated piping (to be refined at FEED).
- Zone 1 (local): at connectors/joints where frequent operations or higher leak probability may exist (FEED refinement).
- Vent Stack (Pos. 6): Zone 2 around the outlet and vertical development above during discharge (dispersion to be confirmed at FEED).

Principle: minimise personnel presence in hazardous corridors, apply H_2 detection, automatic ESD, forced ventilation inside buildings (compressor, GDS), and safe upward venting.

5.5.6.8. Fire Separation Distances (tabular) + separation philosophy (as per drawing)

The Solution №5 drawing includes control distances and radii, including R12.0 m as the baseline separation principle for technological blocks, and additional as-dimensioned distances more than 12.0 m
Separation philosophy:

- prevent thermal escalation between hydrogen nodes,
- provide dispersion capacity for potential releases,
- secure emergency access and isolation capability,
- protect critical nodes (buffer, GDS, vent) from cascade effects.

Table 5-26: Fire Separation Distances for Solution №5

Pair	Requirement (concept)	Adopted per drawing
Hydrogen process blocks (Pos. 3/4/5/7) between each other	≥12.0 m (baseline stage principle)	R12.0 m indicated as minimum baseline; locally increased (14–28 m)
Water intake (Pos. 10) → capital structures	sanitary protection	R30.0 m shown
Logistics / roads → process blocks	segregated flows + emergency access	ensured by dedicated logistics zone D and site access geometry

5.5.6.9. HAZID Summary (Pre-Design, Solution №5)

Qualitative HAZID is provided to identify major hazards and barriers; quantitative LOPA/HAZOP is assigned to FEED.

Table 5-27: HAZID Summary Table for Solution №5

Node (pos.)	Hazard	Causes	Consequences	Key safeguards (Pre-Design)	Priority
3 – Integrated plant	H_2 leak inside building	loss of tightness, valves, maintenance	explosive mixture, fire/explosion	forced ventilation, H_2 detection, ESD, segmentation, ignition source control	High
4 – Compressor Station	H_2 leak / jet fire	seals, vibration, installation error	jet fire, thermal escalation	H_2 detection, ESD, isolation valves, temperature control, venting to stack	High
5 – Gas Metering (GDS)	leak in regulation/metering	valves, flanges	release inside/outside, ignition risk	ventilation, gas detection, ESD, Ex equipment	High
7 – H_2 Buffer Storage	overpressure / loss of containment	regulator failure, thermal expansion	H_2 release, fire, shutdown	relief devices, discharge to vent stack, isolation	High
6 – Vent Stack	hazardous discharge zone	incorrect height, wind influence	cloud formation, exposure	upward discharge, obstacle-free termination, dispersion modelling at FEED	Medium
8 – Dry Cooler Field	loss of cooling	power loss, fans failure	plant trip, protection actions	sectional redundancy, automated shutdown logic	Medium
9 – SPS / wastewater	uncontrolled discharge	pump failure, overflow	environmental impact	level control, alarms, removal/treatment concept	Medium
Whole site	lightning/static	storms, bonding deficiencies	ignition source	lightning protection, grounding, equipotential bonding	High

5.5.7. Stage 3 – Solution №6 – 100 MW Hydrogen Plant – PEM Electrolysis (HYPRPlant)

5.5.7.1. Baseline input data lock (Stage 3, Solution №6, PEM 100 MW)

Stage 3 / Solution №6 implements a 100 MW PEM electrolyser plant as a single-block integrated HYPRPlant (Explication position 3). In contrast to Solutions №1–4, a major part of ISBL (inside the electrolyser plant battery limits) is delivered as an integrated package; therefore, the plot plan highlights OSBL interface nodes and external infrastructure: nitrogen, compression/metering, vent stack, buffer storage, water intake, raw water tank, sewage pumping / wastewater, and admin/maintenance facilities.

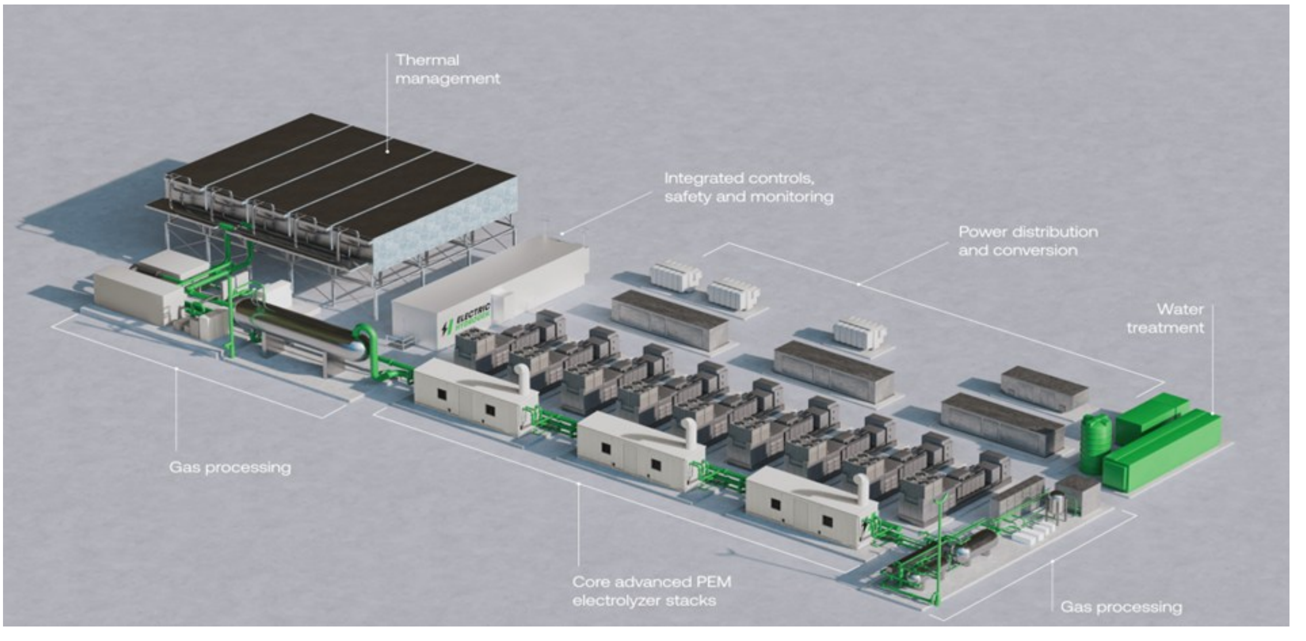


Figure 5-27: H_2 HYPRPlant 100 MW PEM

Key HYPRPlant (100 MW) parameters relevant for plot plan and interfaces:

- Hydrogen production (specific operating case): 1900 kg/h.
- Hydrogen outlet pressure from the electrolyser complex: 30 barg.
- Operating range: 18–100% (100 MW configuration).
- Ambient temperature range: -20°C to 50°C, including freeze protection requirements.
- Plot plan footprint reference (including setback and maintenance allowances): < 5000 m².

Scope delineation / responsibilities (critical for layout boundaries): ISBL (supplier scope) includes electrolyser stacks, power electronics (MV transformers & rectifiers), pressure vessels, heat exchangers, water pumps, polishing beds, reverse osmosis deionisation system, instrument air system, etc. OSBL (buyer/site scope) includes foundations and civil works, site lighting, external substations/transformers, upstream water processing to meet the water standard at the plant interface, and downstream hydrogen processing/storage/piping outside OSBL.

5.5.7.2. Layout structure, areas and functional zoning (as per Solution №6 drawing)

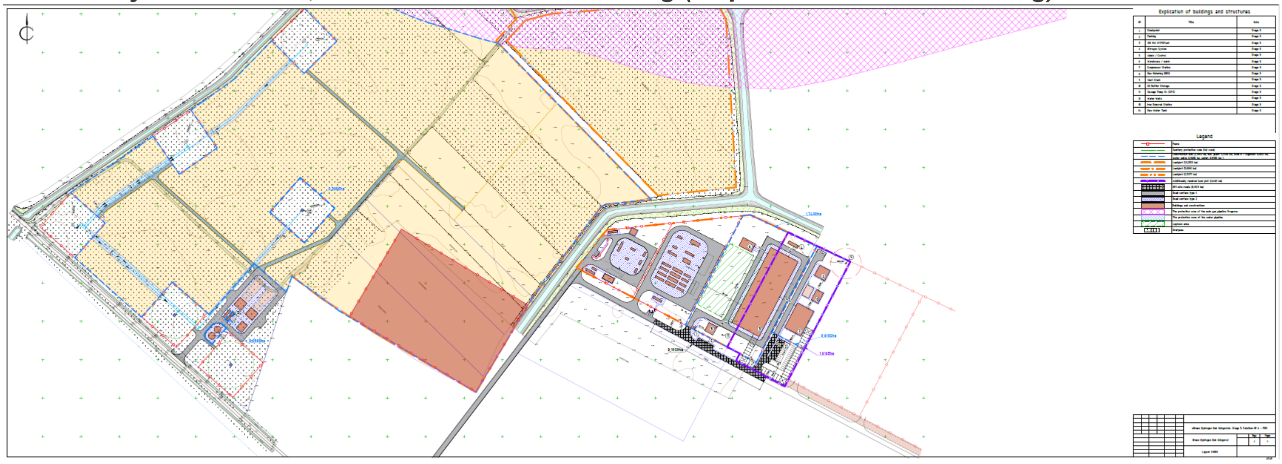


Figure 5-28: General Plan for Green Hydrogen Hub Uzhhorod, Stage 3 - 100 MW, Solution №6 - PEM

The plot plan is developed in direct alignment with the Stage 3 / Solution №6 General Arrangement. The drawing legend fixes the following areas used as "as-drawn references" for the Feasibility Study:

- Construction site: 2.4879 ha (including: Plant 1.7777 ha; Water supply 0.7102 ha).
- Total PV park: 15 ha.
- A 30 m sanitary zone around water wells is adopted across all hub stages.

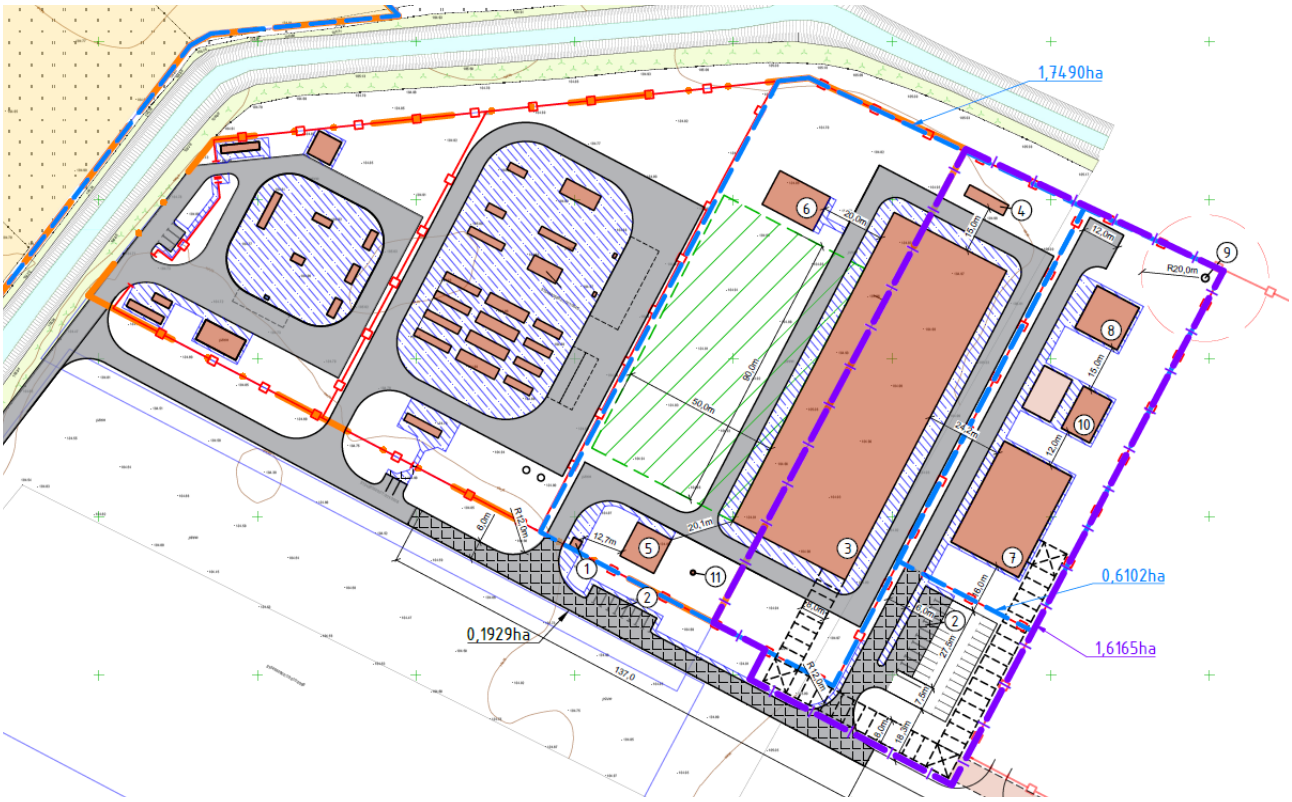


Figure 5-29: Fragment General Plan for Green Hydrogen Hub Uzhhorod, Stage 3 -100 MW, Solution №5-Alkaline. Plant Area.

Functional zones (layout logic):

1. Electrolyser production zone (Plant / HYPRPlant ISBL) – Pos. 3: integrated plant building/complex with forced ventilation and internal process infrastructure (including water treatment, power conversion, gas processing, thermal management, dry cooling, compressed air, integrated controls, safety and monitoring – as part of the integrated supply).
2. External hydrogen interface zone (OSBL H_2 handling) – Pos. 7–10: compressor station, gas metering (GDS), vent stack, buffer storage.
3. Nitrogen support zone – Pos. 4: external nitrogen supply system for commissioning and limited operational purge scenarios (major ESD and major maintenance).
4. Administrative & O&M zone – Pos. 5–6: control/admin and warehouse/maintenance.
5. Water intake & OSBL water zone – Pos. 12–14: wells, iron removal, raw water tank.
6. Wastewater zone – Pos. 11 and associated collection/handling within site limits.

5.5.7.3. Explication table (Solution №6) + Fire Hazard Category (UA) + ATEX linkage + Key safeguards

Fire hazard categories follow NAPB B.03.002-2007 logic at Pre-Design level; hazardous area linkage is conceptually aligned with IEC 60079-10-1 and refined at FEED.

Table 5-28: Explication and Safety Matrix for Solution №6

Explication position – Name	Fire Hazard Category (UA)	ATEX / Hazardous Area (concept)	Key safeguards (concept)
1 – Checkpoint Stage	D	Non-hazardous	Access control, ESD/emergency response instructions at entry
2 – Parking Stage	D / N/A	Non-hazardous	Parking outside hazardous zones, evacuation and access routes
3 – 100 MW HYPRPlant (Integrated plant)	A	Inside: Zone 2 (local Zone 1 at disconnections/vents if applicable); outside: Zone 2 at vent outlets	Forced ventilation, H_2 detection, automatic ESD, interlocks, upward venting, integrated controls and monitoring
4 – Nitrogen System	D	Non-hazardous	Isolation/purging capability, pressure regulation, safe connection points
5 – Admin / Control	D	Non-hazardous	Located outside hazardous areas; ESD interface; resilient power for safety systems
6 – Warehouse / maint.	D	Non-hazardous	Segregated storage, ignition source control, permit-to-work regime
7 – Compressor Station	A / AN (to be confirmed)	Zone 2 around equipment; inside building/container – Zone 2	H_2 detection, ESD, Ex equipment, hot surface control, ventilation per design
8 – Gas Metering (GDS)	A / V (to be confirmed)	Zone 2 around metering/valve manifolds	Isolation valves, parameter monitoring, quality/moisture control, ESD integration
9 – Vent Stack	AN	Zone 2 at stack tip/outlet region	Vertical discharge, ignition exclusion, lightning protection, restricted access zone
10 – H_2 Buffer Storage	AN	Zone 2 around vessel and piping	ESD isolation, PRV to safe vent, vehicle impact protection, pressure monitoring
11 – Sewage Pump St. (SPS)	D	Non-hazardous	Sealing, spill control, instrumentation and alarms
12 – Water Wells	N/A	Non-hazardous	30 m sanitary zone, controlled access, pollution prevention

Explication position – Name	Fire Hazard Category (UA)	ATEX / Hazardous Area (concept)	Key safeguards (concept)
13 – Iron Removal Station	D	Non-hazardous	Water quality control, redundancy aligned with hub water concept
14 – Raw Water Tank	N/A / D	Non-hazardous	Raw water reserve, level control, contamination prevention, bunding philosophy

Note on Pos. 7–8: final UA fire category (A/V/AN) is FEED-dependent (container vs building, ventilation regime, hydrogen inventory and valve/piping arrangement). A conservative Pre-Design approach is applied: if hydrogen equipment is within a confined volume, the design basis follows explosion-hazard building logic (Category A) and ATEX requirements.

5.5.7.4. Hydrogen production chain (PEM 100 MW) and BoP systems (mapped to explication)

Solution №6 is based on PEM electrolysis integrated into HYPRPlant (Pos. 3). At plot plan level, the description focuses on flow chain, OSBL interfaces, and utility systems that define zoning, separations, access, and routing corridors.

Water and water preparation (OSBL → ISBL interface)

- Water is sourced from wells (Pos. 12), pre-treated via iron removal (Pos. 13), buffered in the raw water tank (Pos. 14), and supplied to the HYPRPlant water interface (Pos. 3).
- HYPRPlant includes integrated RODI as part of the ISBL supply scope, producing process-quality water for electrolysis and cooling circuits.

Power supply and conversion (site/OSBL → ISBL)

- HYPRPlant requires MV power 30–34.5 kV and includes internal power conversion equipment within ISBL (MV transformers & rectifiers).
- Plot plan implications: protected MV routing corridors, segregation from hydrogen zones, and resilient power supply for safety-critical systems (detection/ESD/communications).

PEM electrolysis, separation and thermal management (within Pos. 3)

- The block flow includes anode/cathode separation, dry cooling, electrolysers, power conversion, and hydrogen cooling within the integrated plant boundary.
- Heat rejection relies on dry cooling as a key layout driver (placement, wind consideration, maintenance access).

Hydrogen: from HYPRPlant outlet to Stage 3 OSBL nodes (Pos. 7–10)

- Hydrogen is produced and exported at approximately 30 barg from the integrated plant boundary.
- OSBL nodes as per explication:
    - Compressor Station (Pos. 7) – pressure boost for downstream requirements.
    - Gas Metering (GDS) (Pos. 8) – fiscal/technical metering and quality/safety interface.
    - Vent Stack (Pos. 9) – controlled safe vertical hydrogen release aligned with ESD logic.
    - H_2 Buffer Storage (Pos. 10) – smoothing production variability and stabilizing downstream operation.

Nitrogen and instrument air (Pos. 4 and within Pos. 3)

- Nitrogen supply (Pos. 4) supports commissioning and limited operational purge scenarios; ongoing nitrogen provision is on the buyer/site side, while the supplier provides tie-in information.
- Instrument air is included as an integrated system within ISBL (HYPRPlant).

5.5.7.5. Conceptual process scheme (Textual Block Flow Diagram, BFD), Solution №6

Scheme limits: OSBL water intake and utilities up to Stage 3 hydrogen OSBL nodes (compression/metering/buffer/vent) and off-take interface.

Textual BFD (arrow format):

Water Wells (Pos. 12) → Iron Removal Station (Pos. 13) → Raw Water Tank (Pos. 14) → HYPRPlant Water Interface (Pos. 3; upstream processing to EH_2 water standard) → Integrated RODI (inside Pos. 3) → PEM Electrolysers & Separation (inside Pos. 3) → Hydrogen Cooling / Thermal Management (inside Pos. 3; dry cooling concept) → Hydrogen Output Header (Pos. 3) → Compressor Station (Pos. 7) → H_2 Buffer Storage (Pos. 10) → Gas Metering (GDS) (Pos. 8) → Hydrogen to Off-take (pipeline / consumer interface)

Emergency / controlled releases: HYPRPlant / OSBL reliefs → Vent Stack (Pos. 9) (vertical discharge)

Oxygen stream (process): HYPRPlant separation → Oxygen to vent (controlled discharge per OEM design).

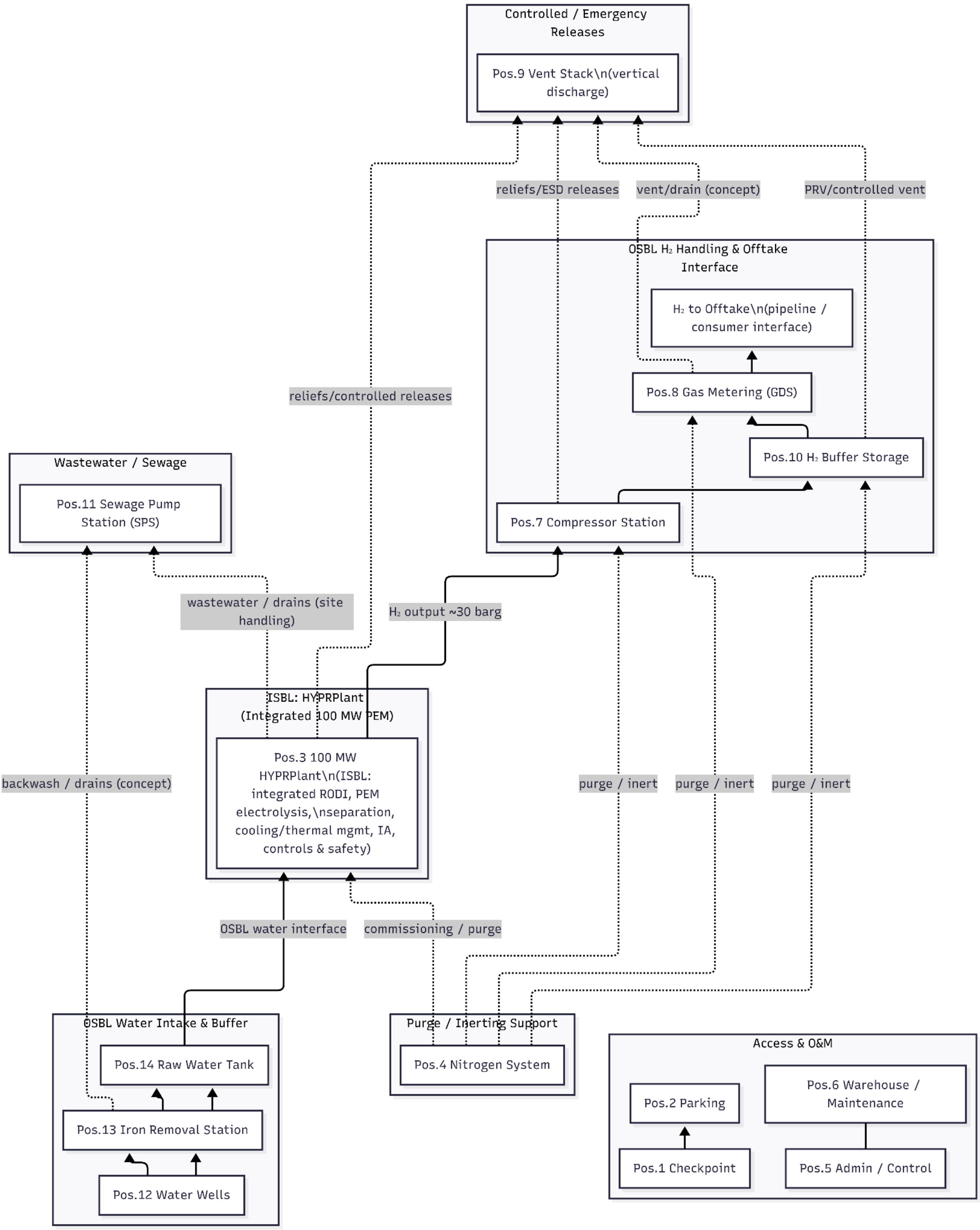


Figure 5-30: Conceptual Block Flow Diagram for Solution N°6 (PEM, 100 MW)

5.5.7.6. Water / Sewer Philosophy

For Solution №6, water consumption calculations are intentionally excluded (as agreed). The layout-level principles are fixed as follows:

Well sanitary zone: R = 30 m adopted across all hub stages; no contamination sources within the zone.

OSBL water train: wells (Pos. 12) → iron removal (Pos. 13) → raw water tank (Pos. 14) → HYPRPlant interface (Pos. 3).

ISBL internal water treatment and water flows: integrated RODI, electrolysis process water and cooling circuits, and reject/wastewater streams as part of integrated plant operation.
Wastewater handling: Sewage Pump Station (Pos. 11) is provided; OSBL scope includes handling/disposal of contaminated waters (including instrument air oily water and glycol-related streams), aligned with site design requirements.

5.5.7.7. ATEX & Hazardous Area Summary (concept), Solution №6

Hazardous area classification is conceptually aligned with IEC 60079-10-1. Core logic:

- hydrogen leak sources typically create Zone 2 in normal operation;
- Zone 1 may apply locally at frequent disconnections/operations (if applicable);
- for buildings with hydrogen equipment, ventilation and explosion protection requirements apply and zones are refined at FEED.

Mapping to explication (concept):

- Pos. 3 HYPRPlant: internal Zone 2 (local Zone 1 where applicable); external Zone 2 at vent outlets.
- Pos. 7 Compressor: Zone 2 around equipment; inside – Zone 2.
- Pos. 8 GDS: Zone 2 around metering/valve manifolds.
- Pos. 9 Vent stack: Zone 2 at outlet region; final extents by dispersion study at FEED.
- Pos. 10 Buffer: Zone 2 around vessel and piping.

5.5.7.8. Fire Separation Distances (as per drawing) + separation philosophy

Separation philosophy for Solution №6 is based on:

- segregation of admin/O&M areas from process hydrogen areas;
- provision of fire brigade access and turning;
- separation of hydrogen nodes from ignition sources;
- sanitary separation of the wellfield.

The Solution №6 drawing shows the following factual distance references used as Feasibility Study layout controls: 12.0 m and more, and a sanitary zone R = 30.0 m.

Table 5-29: Fire Separation Distances for Solution №6

From (position – name)	To (position – name)	Separation purpose	Adopted at Feasibility	As-drawn reference controls
3 100 MW HYPRPlant	5 Admin / Control	Process vs admin segregation	≥ 12.0 m (concept)	Drawing indicates ≥ 12.0 m controls
3 100 MW HYPRPlant	6 Warehouse / maint.	Ignition source control / work segregation	≥ 12.0 m (concept)	12–18 m controls present
7 Compressor Station	8 Gas Metering (GDS)	Node separation + access	≥ 12.0 m (concept)	12–16 m controls present
7 Compressor Station	10 H_2 Buffer Storage	Leak/jet fire escalation control	≥ 12.0 m (concept)	15–20 m controls present
9 Vent Stack	Any buildings/structures	Safe dispersion and ignition exclusion	FEED dispersion study + restricted zone	Larger 50–90 m references present as layout controls
12 Water Wells	Any buildings/structures	Sanitary zone	R = 30.0 m	R = 30.0 m

Note: FEED will refine separations using thermal radiation and hydrogen dispersion studies, and will finalise fencing/impact barriers requirements.

5.5.7.9. HAZID Summary (Pre-Design), Solution №6

The following is a Pre-Design HAZID (no LOPA/Project HAZOP), mapped to Solution №6 explication positions. Priority: H/M/L for FEED focus.

Table 5-30: HAZID Summary Table for Solution №6

Node (position – name)	Hazard / Deviation	Credible causes	Consequences	Key safeguards (Pre-Design)	FEED actions	Priority
3 – 100 MW HYPRPlant	H_2 leak inside building / via ventilation exhaust	Valve/fitting leak, seal failure	Explosive atmosphere, flash fire/explosion, building damage	Forced ventilation, H_2 detection, automatic ESD, Ex equipment, upward venting (concept)	Finalise IEC 60079 zones, ventilation calculation, detection/ESD voting & setpoints, explosion relief concept	H
3 – 100 MW HYPRPlant	Loss of cooling (thermal management upset)	Fan/pump failure, freezing, fouling	Overtemperature, trip, equipment damage	Integrated monitoring and protections; freeze protection to -20°C	Confirm redundancy and safe shutdown sequence	M
7 – Compressor Station	H_2 leak / jet fire	Seal wear, vibration, maintenance error	Jet fire, escalation to adjacent nodes	H_2 detection, ESD, separations, Ex equipment	Add local detectors at seals, vehicle impact barriers, hot surface control	H
8 – Gas Metering (GDS)	Metering/control abnormality	Meter/valve failure, misconfiguration	Commercial losses; unsafe operation outside limits	Isolation valves, parameter monitoring, ESD integration	Redundant metering, QA/QC analysers and logic	M
9 – Vent Stack	Unsafe venting / ignition	Poor siting, lightning, nearby ignition source	Ignition at vent, personnel and asset impact	Vertical discharge, lightning protection, restricted access	Dispersion study, height and exclusion zone, earthing/bonding	H
10 – H_2 Buffer Storage	Overpressure / PRV release	Regulator failure, wrong setpoints	H_2 release; escalation potential	PRV to safe vent; ESD isolation; pressure monitoring	Confirm setpoints, PRV routing to vent stack, loss-of-power scenarios	H
4 – Nitrogen System	Purge error / wrong connection	Human error, procedural gaps	Incomplete inerting; mixture risk	Procedures, keyed connections, pressure control	Interlocks; training and operational discipline	M
11 – SPS	Wastewater upset / overflow	Pump failure, high level	Sanitary impact; O&M disruption	Level alarms, sealing	Confirm disposal/haulage scheme and redundancy	L
Whole site	Lightning / static	Storm, inadequate grounding	Ignition source	Lightning protection, equipotential bonding	Lightning risk study, grounding resistance testing regime	H
Whole site	Emergency access / ESD interface	Blocked roads, poor marking	Delayed response; escalation	Plot plan access and	Validate routes/turning;	M

Node (position – name)	Hazard / Deviation	Credible causes	Consequences	Key safeguards (Pre-Design)	FEED actions	Priority
				separations; checkpoint	mark isolation points; emergency maps	

5.5.8. Stage 4 – Solution №7 – 300 MW Hydrogen Plant – Alkaline Electrolysis (AWE)

5.5.8.1. Stage 4 / Solution №7 General Concept and Role in Hub Development

Stage 4 is the final step in establishing the industrial Green Hydrogen Hub, transitioning from pilot and scale-up solutions (Stages 1–3) to full-scale production and industrial hydrogen logistics.

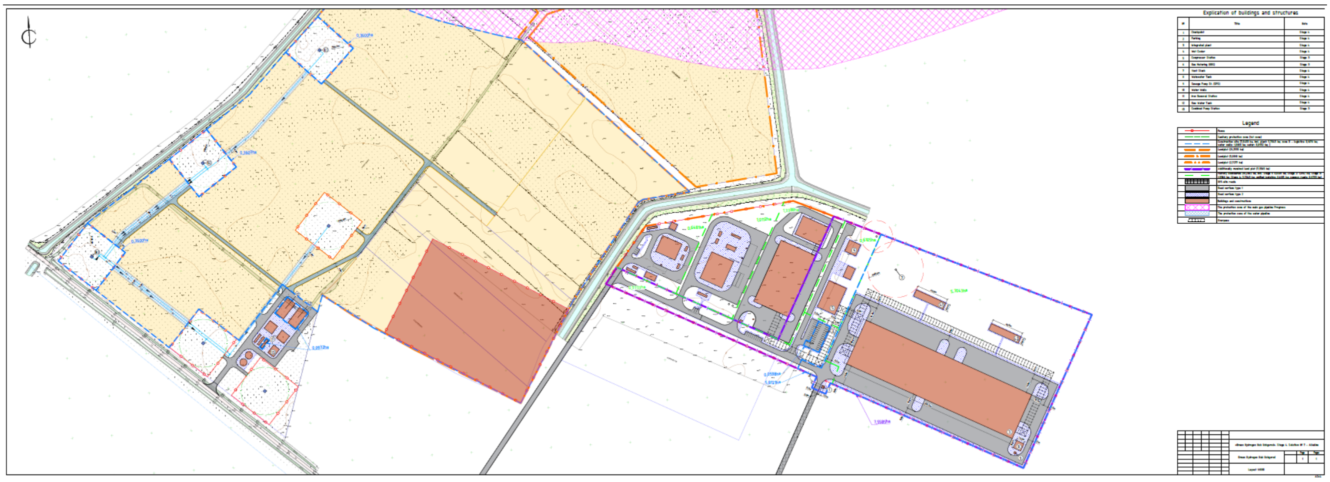


Figure 5-31: General Plan for Green Hydrogen Hub Uzhhorod, Stage 4 – 300 MW, Solution N°7 – Alkaline

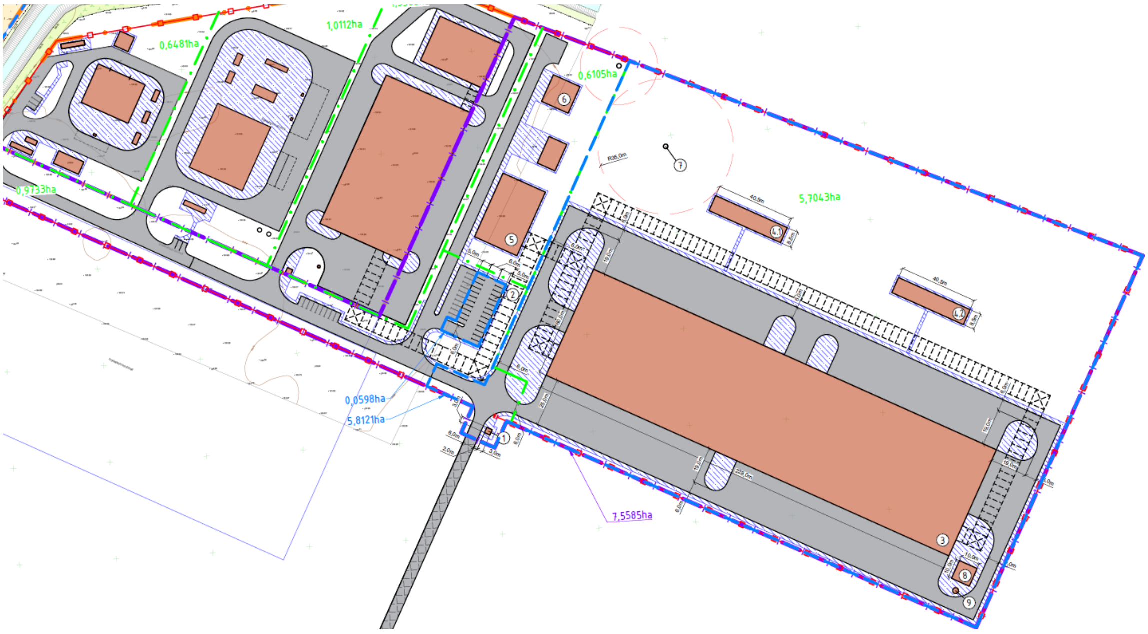


Figure 5-32: Fragment of General Plan for Green Hydrogen Hub Uzhhorod, Stage 4 - 300 MW, Solution №7 - Alkaline. H_2 HUB Area

Solution №7 (AWE, 300 MW) delivers:

- an industrial integrated plant as the Stage 4 production core (item 3),
- hydrogen infrastructure at industrial readiness level (including venting, cooling, water and wastewater facilities as per explication),
- full integration of Stage 4 into the unified hub boundaries with common roads and logistics framework.

The drawing provides "as-per-plot-plan" reference figures for techno-economic comparisons:

- Construction site: 7.0453 ha, including:
  - plant: 5.7043 ha
  - zone D – logistics: 0.1678 ha
  - water wells: 1.0800 ha
  - water: 0.0932 ha
- Additionally received land plot: 7.5585 ha
- Factory boundaries: 10.2862 ha, including Stage contributions: Stage 1 (0.6481 ha), Stage 2 (1.0112 ha), Stage 3 (1.3388 ha), Stage 4 (5.7043 ha), unified logistics (0.6105 ha), common roads (0.9733 ha).

Therefore, Solution №7 defines the final hub configuration: unified territory, common utility corridors and logistics, and a consistent safety-first zoning and staging philosophy.

5.5.8.2. Spatial Layout and Land Requirements (Stage 4 – Solution №7)

The layout is developed strictly according to the Stage 4 / Solution №7 – Alkaline plot plan (1:1000). The explication lists items 1–13:

Functional zones (layout logic):

- Access & administration zone:
  - (1) Checkpoint – access control and perimeter regime;
  - (2) Parking – staff/visitor parking.
- Stage 4 hydrogen production zone (core):
  - (3) Integrated plant – main Stage 4 production building/complex containing AWE hydrogen production and major BoP systems within the integrated envelope.
- Cooling zone:
  - (4) Wet Cooler – wet cooling towers / wet cooling system for Stage 4, as a key differentiator versus dry-cooling-oriented solutions.
- High-pressure hydrogen and network interface infrastructure (some nodes are inherited from Stage 3 per explication):
  - (5) Compressor Station (Stage 3) – compression (hub infrastructure node);
  - (6) Gas Metering (GDS) (Stage 3) – metering/regulation for export interface;
  - (7) Vent Stack – controlled venting/purging to a safe elevated discharge.
- Wastewater and sanitary infrastructure:
  - (8) Wastewater Tank – wastewater accumulation;
  - (9) Sewage Pump Station (SPS) – wastewater transfer;
  - (10) Water Wells – water intake (30 m sanitary radius is applied as a unified hub rule);
  - (11) Iron Removal Station – raw water pre-treatment;
  - (12) Raw Water Tank – raw water storage;
  - (13) Combined Pump Station (Stage 3) – hub combined pumping station (infrastructure backbone).

5.5.8.3. Buildings/Structures Table (Pos. 1–13) + Fire Hazard Category (UA) + ATEX linkage

Categorisation is provided per NAPB B.03.002 logic at Pre-Design level. For hydrogen equipment located inside the integrated plant (item 3), internal fire category and HAC zoning are to be finalised at FEED based on the final indoor arrangement, ventilation rates, and identified release sources; external interfaces (compression, metering, vent stack) are treated conservatively at concept stage.

Table 5-31: Explication and Safety Matrix for Solution N°7

Item (Explication) – Title	Fire Hazard Category (UA)	ATEX / HAC linkage (concept)	Key safeguards (concept, Pre-Design)
1 – Checkpoint (Stage 4)	D	Non-hazardous	Access control, perimeter regime, emergency maps and ESD interface at checkpoint
2 – Parking (Stage 4)	–	Non-hazardous	Located outside hazardous zones; signage; fire truck routes not obstructed
3 – Integrated plant (Stage 4)	A (indoor premises) / AN (outdoor vents and interfaces)	Indoor: Zone 2 locally (near sources), to be confirmed; Outdoor: Zone 2 around ventilation/exit points	Forced ventilation, H_2 detection, ESD, segmentation, upward venting, ignition source control
4 – Wet Cooler (Stage 4)	D	Non-hazardous	Electrical safety, drift/blowdown drainage, anti-icing operating modes if required
5 – Compressor Station (Stage 3)	A / AN (as-built)	Zone 2 around compressor skids and valves; indoor zoning to be confirmed	H_2 detection, ESD on leak/fire, ventilation, hot surface control, impact protection for piping
6 – Gas Metering (GDS) (Stage 3)	A / V (as-built)	Zone 2 at valve/bleed/vent points	Instrument redundancy, isolation valves, purge/inert procedures, tightness control
7 – Vent Stack (Stage 4)	AN	Zone 2 around the vent outlet corridor (concept)	Vertical discharge upward, ignition source exclusion in vent sector, ESD linkage to production
8 – Wastewater Tank (Stage 4)	–	Non-hazardous	Segregated collection, overflow control, containment, maintenance without crossing AN zones
9 – Sewage Pump Station (Stage 4)	V / D	Non-hazardous	Automation and alarms, redundancy, flooding prevention of critical areas
10 – Water Wells (Stage 4)	–	Non-hazardous	30 m sanitary radius, fencing, controlled access, contamination source exclusion
11 – Iron Removal Station (Stage 4)	D	Non-hazardous	Filter/backwash control, routing of backwash waters into wastewater system
12 – Raw Water Tank (Stage 4)	D	Non-hazardous	Raw water buffer, level/leak control, make-up connections
13 – Combined Pump Station (Stage 3)	V	Non-hazardous	Pump redundancy, power reliability per hub design, fire-related operating modes for common needs

5.5.8.4. Hydrogen Production Chain (Alkaline 300 MW) and BoP Systems (per explication)

Solution №7 is based on industrial Alkaline electrolysis within (3) Integrated plant, supported by (4) Wet Cooler, and connected to hub export/interface infrastructure via (5) Compressor Station, (6) Gas Metering (GDS) and (7) Vent Stack for controlled purges/reliefs.

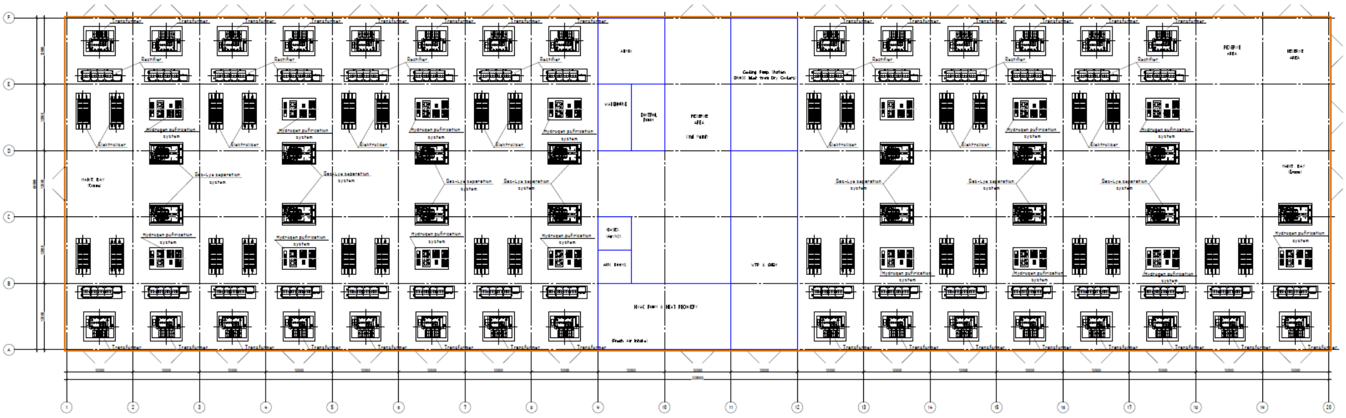


Figure 5-33: H_2 Plant 300 MW Alkaline.

Process chain (BFD logic):

Water / raw water / pre-treatment

- (10) Water Wells → (11) Iron Removal Station → (12) Raw Water Tank → raw water routed to (3) Integrated plant for internal polishing WTP (demineralisation/polishing) → treated water supplied to electrolysis.
- Stage 4 engineering intent: stable flow/quality for electrolysis + cooling make-up, with wet cooler blowdown control and routing to wastewater handling (see 4.3.8.6).

Power supply (hub-level interface)

- Stage 4 power supply via hub infrastructure → conversion/distribution inside (3) Integrated plant (rectification, sectional distribution to electrolysis) → AWE power feed.

Hydrogen production (Alkaline)

- Treated water + electrical power → AWE electrolysis inside (3) Integrated plant → H_2 and by-product O_2 streams.

Hydrogen processing and export interface

- Primary separation/purification/quality conditioning within (3) Integrated plant → export to hub infrastructure:
  - (5) Compressor Station (compression to export/interface parameters),
  - (6) GDS (metering/control/regulation),
  - (7) Vent Stack for operational purges/reliefs (vertical controlled discharge along a safe corridor).

Oxygen handling (O_2)

- Controlled discharge from (3) Integrated plant via a dedicated route (preventing mixing with H_2) → atmospheric release per safe scheme (to be finalised at FEED).

F) Cooling / thermal management

- Heat from electrolysis and auxiliaries → circulating cooling loop → (4) Wet Cooler → return of cooled medium to (3) Integrated plant.

Wastewater / sewer

- WTP backwash + process/service wastewater → (8) Wastewater Tank → pumping/transfer (9) SPS → further routing per hub scheme (final interface at the next stage).

Integrated plant (item 3) explanation as the production core:
A single industrial building/complex hosting AWE electrolysis sections, process water treatment, H_2 conditioning (separation/drying/quality conditioning), and station-wide BoP (power distribution, instrumentation/control, safety: detection/ESD/ventilation, headers/isolation). This is a key distinction vs containerised solutions at higher capacities. [126]

5.5.8.5. Block Flow Diagram (BFD) – Solution №7 (AWE 300 MW)

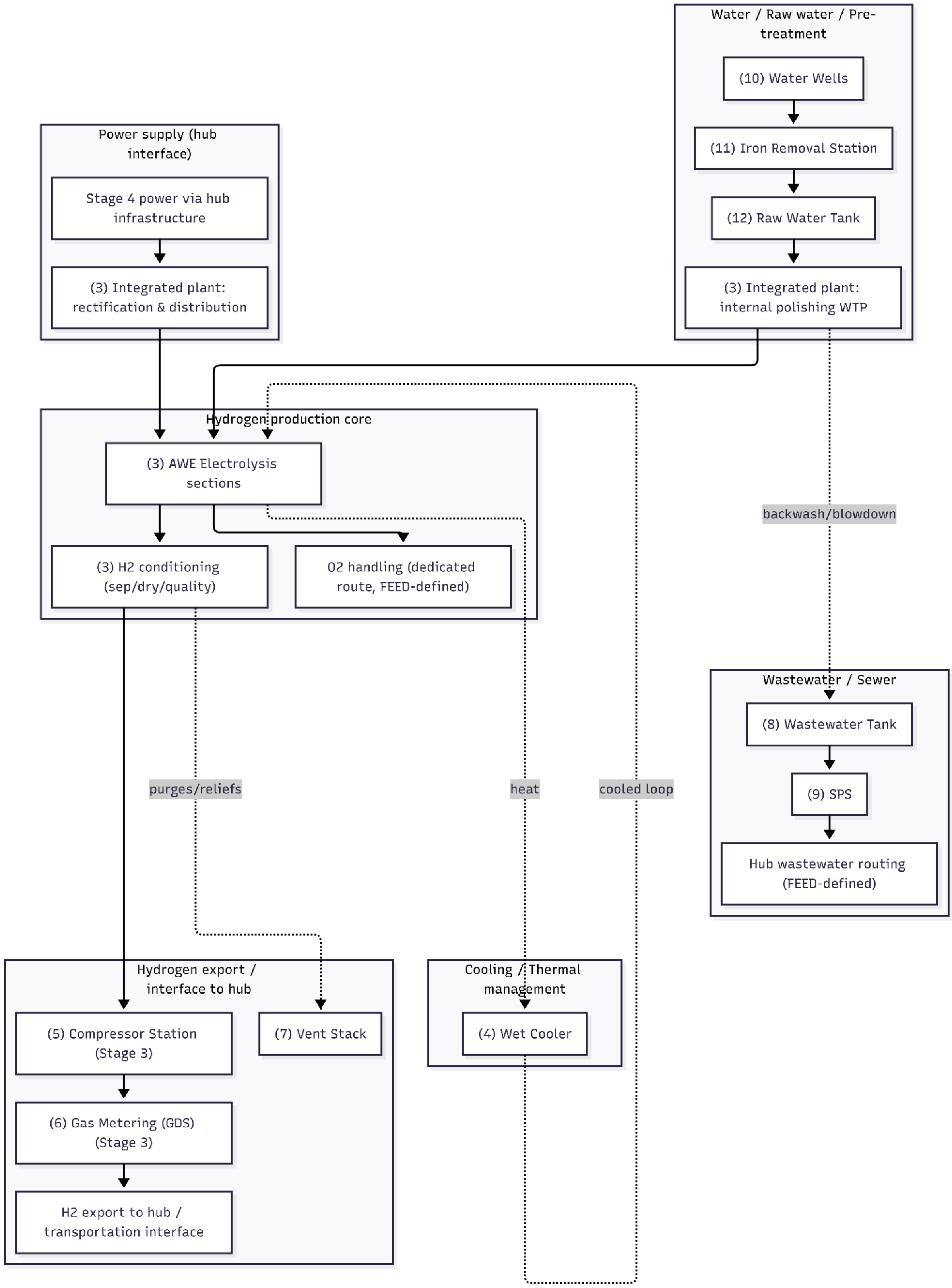


Figure 5-34: Conceptual Block Flow Diagram for Solution №7 (Alkaline, 300 MW)

5.5.8.6. Water / Sewer / Fire philosophy (Stage 4 – Solution №7)

Water supply (items 10–13)

Stage 4 water supply is based on the water intake and water infrastructure reflected in the explication:

- (10) Water Wells – water source; a 30 m sanitary radius is applied as a unified hub rule.
- (11) Iron Removal Station – raw water pre-treatment.
- (12) Raw Water Tank – raw water buffering to smooth demand fluctuations and ensure stable operation, including cooling make-up and process needs.
- (13) Combined Pump Station (Stage 3) – hub pumping backbone supplying water to process circuits.

For Solution №7, the main water consumer is the wet cooling system (4) Wet Cooler, therefore the concept explicitly includes:

- cooling make-up supply,
- blowdown control and routing to wastewater handling,
- redundancy and operational stability under variable load profiles.

Sewerage / wastewater (items 8–9)

- (8) Wastewater Tank – collection of process and wash waters (including cooling tower blowdown and WTP backwash).
- (9) SPS – wastewater transfer/pumping within the hub scheme.

Principle: segregated collection of industrial and potentially contaminated waters with controlled discharge; avoidance of maintenance routes crossing hydrogen hazardous areas.

Fire philosophy (concept)

For hydrogen systems, the priorities are:

- preventing formation of an explosive mixture (detection, ventilation, tightness),
- rapid isolation and safe shutdown (ESD, isolation valves),
- ignition source control within HAC,
- in a fire scenario: not “extinguishing hydrogen with water”, but exposure cooling, protection of adjacent assets, and enabling emergency response.

Within Stage 4 explication, special attention is placed on:

- fire-related operating modes of the pumping backbone (item 13 as part of the hub infrastructure),
- preserving access routes and emergency approach to (3), (5), (6), (7), and (4).

5.5.8.7. ATEX & Hazardous Area Summary (Stage 4 – Solution №7)

Hazardous Area Classification is developed conceptually per IEC 60079-10-1 at Pre-Design level. For Solution №7 the core logic is:

- potential H_2 release sources are concentrated at processing/export/compression and the venting system;
- inside the integrated plant (item 3), indoor HAC depends on architecture, ventilation and routing; at plot plan level a conservative link “A + local Zone 2 indoors / Zone 2 at outdoor interfaces” is applied.

HAC summary (concept):

- (3) Integrated plant – Zone 2 at outdoor interfaces (ventilation/outlet points, process inlets/outlets); indoor local Zone 2 near sources to be confirmed at FEED.
- (5) Compressor Station – Zone 2 around compressor skids, valves and headers; indoor zoning finalised at FEED.
- (6) Gas Metering (GDS) – local Zone 2 at valves and purge/bleed points.
- (7) Vent Stack – Zone 2 around the vent outlet and its operational corridor.
- (4) Wet Cooler, (8–13) water/wastewater – typically non-hazardous regarding H_2 provided routing segregation is maintained and no H_2 sources are present.

5.5.8.8. Fire Separation Distances (Fire gaps)

Separation philosophy for Solution №7:

- separation distances combine DBN/NAPB mandatory requirements with hydrogen reference practice (ISO/IEC concept): segregation of H_2 release sources, escalation prevention, dispersion support, and guaranteed emergency access;
- the Stage 4 differentiator is a large integrated plant (item 3) combined with wet cooling (item 4), which strengthens requirements for access corridors, maintenance routes, and controlled ventilation/venting areas.

As-per-drawing linear dimensions (representative distances and access corridors): The plot plan includes representative dimension callouts (including 5.0 m; 6.0 m; 8.5 m; 10.0 m; 19.0 m; 40.5 m) reflecting adopted corridors/roads/setbacks in the Stage 4 area; these are treated as factual layout values at TEO level.

Table 5-32: Fire Separation Distances for Solution №7

From (item) → To (item)	Purpose of separation	As-per-drawing value where dimensioned, m	Compliance principle
(3) Integrated plant → access corridors/roads	fire & service access, evacuation	6.0 / 10.0 (representative roads)	FEED to confirm minimum fire access widths and turning radii
(3) Integrated plant → (4) Wet Cooler	segregation of cooling/water systems from production core	19.0 (representative setback)	FEED to confirm no adverse recirculation/icing and HAC impacts
(5) Compressor Station → (6) GDS	export interface safety and maintainability	10.0 / 19.0 (representative)	FEED to confirm isolation valve arrangement and maintenance zones
(7) Vent Stack → surrounding areas	safe vent sector and ignition source exclusion	40.5 (representative linkage)	FEED to confirm vent sector and siting restrictions

Note: at TEO/Pre-Design stage the table records the dimensions explicitly shown on the drawing as representative. Detailed point-to-point separations between specific equipment items and building façades are finalised at FEED using the final equipment model and HAC/dispersion verification.

5.5.8.9. HAZID Summary (Stage 4 – Solution №7, AWE 300 MW)

The Pre-Design HAZID captures key hazards and safety focus areas for Solution №7 (without quantitative risk analysis).

Table 5-33: HAZID Summary Table for Solution №7

Node (item)	Deviation / Hazard	Credible causes	Consequences	Key safeguards (concept)	Actions for FEED
(3) Integrated plant	H_2 leak inside building	leaks at flanges/valves, seal failures, maintenance errors	explosive mixture, flash fire/explosion, building damage	forced ventilation, H_2 detection, ESD, segmentation, ignition control	finalise indoor HAC, sise ventilation, define ESD cause&effect
(3) Integrated plant	O_2 enrichment	improper O_2 routing, backflow	increased fire severity	segregated discharge routes, prevention of mixing with H_2	confirm O_2 routing and discharge points
(4) Wet Cooler	Loss of cooling / hydraulic instability	pump failure, icing, fouling	derate/trip, abnormal modes	redundancy, temperature/pressure monitoring	define redundancy, safe shutdown scenarios
(5) Compressor station	H_2 leak / jet fire	seal wear, vibration, line rupture	jet fire, escalation to GDS/vent	detection, ESD, isolation valves, controlled zones	compression HAZOP, verify valve siting
(6) GDS	purge/regulation malfunction	procedure error, instrument failure	H_2 release, hazardous area, export shutdown	purge procedures, interlocks, tightness control	refine procedures and interlocks
(7) Vent stack	abnormal venting	wrong command, valve failure	release into unsafe sector, ignition risk	vertical discharge, ESD linkage, ignition exclusion sector	verify vent sector and site constraints
(8–9) Wastewater/SPS	overflow / contamination	automation failure, overfill	environmental impact, flooding	alarms, redundancy, procedures	finalise modes and discharge routing

Node (item)	Deviation / Hazard	Credible causes	Consequences	Key safeguards (concept)	Actions for FEED
(10–12) Wells/WTP/Raw water	water shortage	well yield drop, station outage	loss of cooling/process make-up	redundancy, storage buffers, operating modes	Stage 4 water balance and resilience verification

5.5.8.10. Summary of Alkaline Hub Evolution (Stage 1 to 4)

The development of the Alkaline (AWE) production complex follows a centralised industrial scaling model, culminating in a 422 MW "Integrated Plant" configuration designed for high-capacity export.

- Stage 1-2 (2 MW to 20 MW): Initial pilot phase using containerised AWE units. By 20 MW (Solution 3), the infrastructure transitions from decentralised modules to the first "H_2 Plant Building," establishing the foundation for water treatment and KOH (potassium hydroxide) handling systems.
- Stage 3 (100 MW): Industrial breakthrough. Construction of a large-scale electrolysis hall. Integration with the Gas Transmission System (GTS) via the Chaslivtsi interconnection point begins. Introduction of multi-stage centrifugal compressors to raise pressure from 15 bar to 70 bar.
- Stage 4 (422 MW Target - Solution 7): Final hub maturity. The site hosts a massive integrated electrolysis building. Cooling is managed via heavy-duty Wet Cooling Towers, requiring a peak water supply of 420.5 m3/hr. This stage cements the hub as a primary supplier for the Central European Hydrogen Corridor (CEHC).

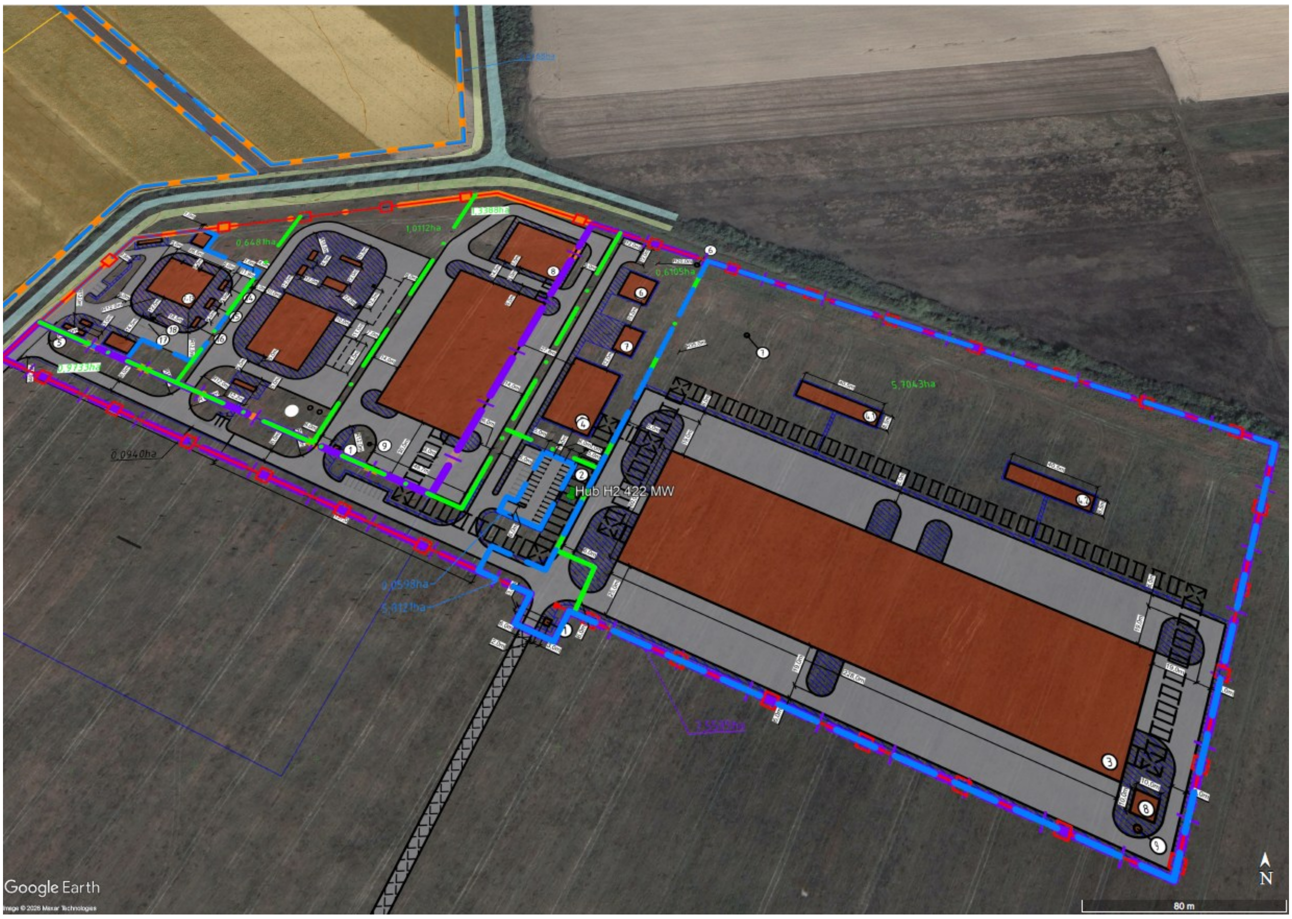


Figure 5-35: Hydrogen Hub Alkaline technological solution 422 MW Site Layout (Google Earth Visualisation)

The following table provides a technical evaluation of the 422 MW Alkaline configuration compared to the fundamental project requirements and export standards

Table 5-33: Technical Specification Analysis for 422 MW Alkaline Configuration

Parameter	Project Requirement	Alkaline Offer (Sol. 7)	Status	Technical Remarks
Output Capacity	84,400 Nm3/h	84,400 Nm3/h	Match	Meets Stage 4 export targets.
Cooling Method	High Efficiency	Wet Cooling Towers	Match	Requires stable 240+ m3/h water debit.
Power Density	Max footprint opt.	Centralised Building	Match	Industrial-grade durability.
Load Range	20–100%	20–100%	Clarification	Risk of gas crossover at <20% load from PV.
H_2 Delivery P	70 bar (GTS)	15 bar (at stack)	Gap	Requires significant 3-stage compression.

5.5.9. Stage 4 – Solution №8 – 300 MW Hydrogen Plant – PEM Electrolysis (HYPRPlant)

5.5.9.1. Stage 4 / Solution №8 General Concept and Role in Hub Development

Solution №8 represents the final scale-up of the hub to an industrial 300 MW PEM configuration implemented as a cluster of three independent 100 MW trains, aligned by a common site philosophy and shared utility/connection corridors (common pipe racks and standardised tie-in points).

Role of Solution №8 within the unified hub strategy:

- demonstrates phased capacity growth while preserving the "infrastructure backbone" established in earlier stages;
- formalises PEM industrial scaling logic "module → train → cluster";
- maximises integration of Stage 2–3 infrastructure (power, water, and hydrogen transport interfaces), while Stage 4 adds production capacity and expands internal flow distribution.

Key layout principles of Solution №8:

3×100 MW cluster with parallel trains and common utility corridors.
Functional zoning: hydrogen production, utilities/infrastructure, logistics/transport, and administrative/support zone.
Safety-driven arrangement: separation distances, ventilation, upward venting, hydrogen detection, emergency shutdown (ESD), and segregation of traffic routes from hazardous zones.
Phased commissioning: sequential train start-up with controlled construction zones and minimal disturbance to operating facilities.

5.5.9.2. Layout Structure, Areas and Functional Zoning (as per Solution №8 drawing)

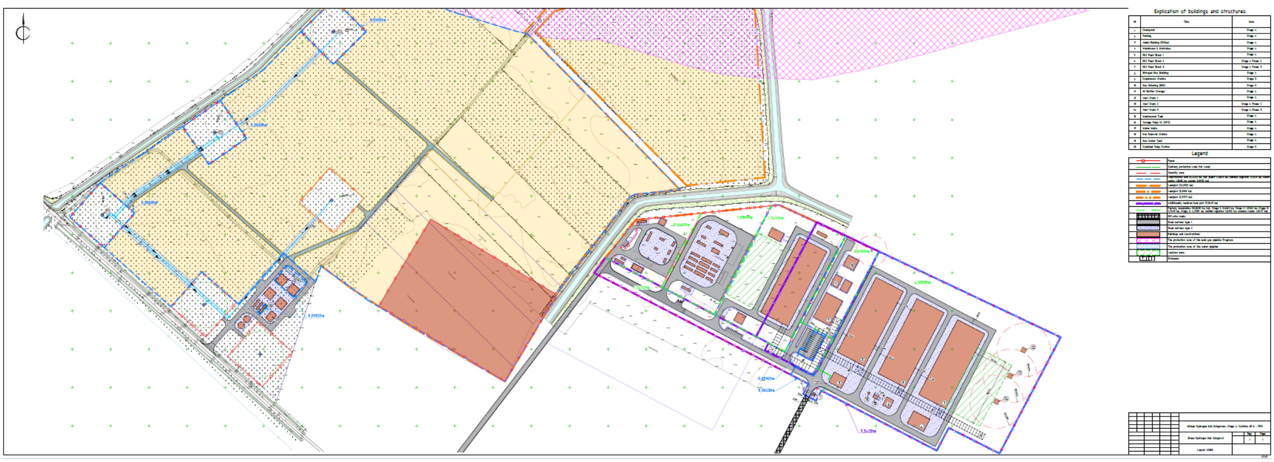


Figure 5-36: General Plan for Green Hydrogen Hub Uzhhorod, Stage 4 - 300 MW, Solution №8 - PEM

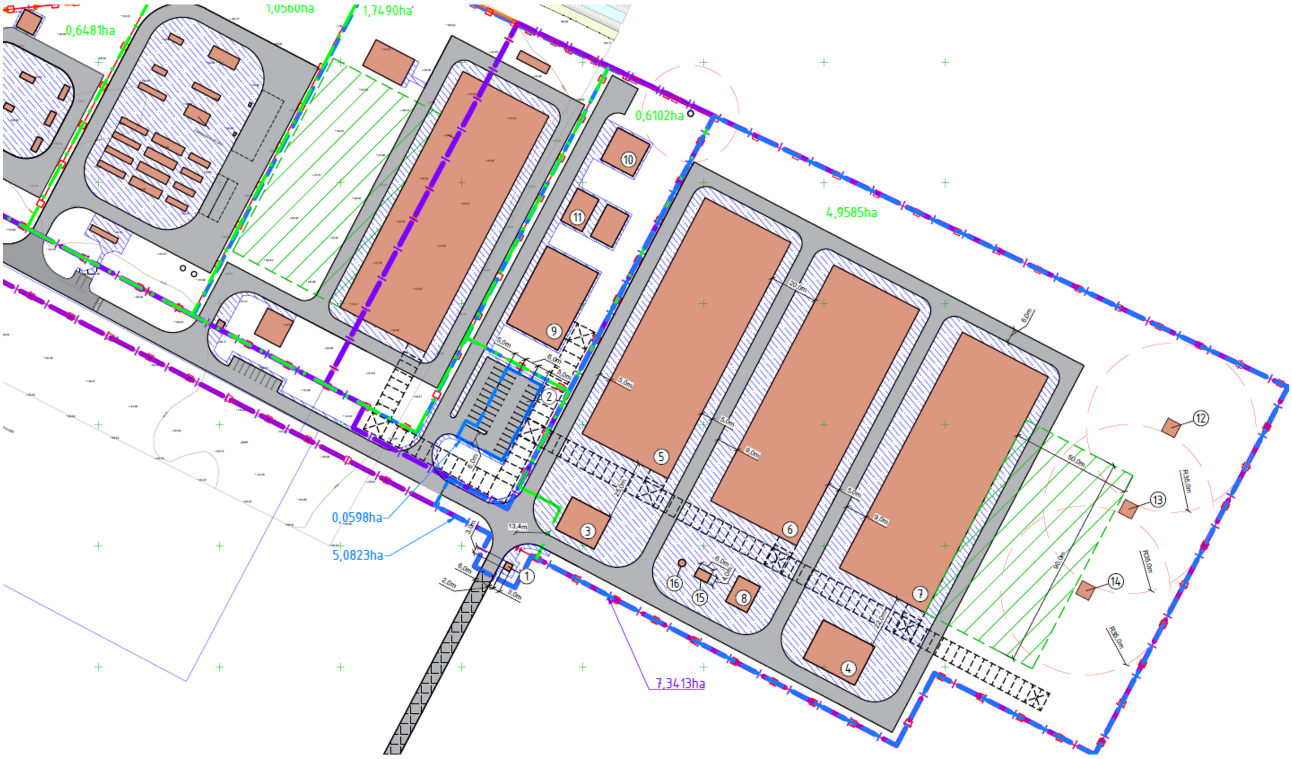


Figure 5-37: Fragment of General Plan for Green Hydrogen Hub Uzhhorod, Stage 4 - 300 MW, Solution №8 - PEM. HUB Area

The layout is developed in accordance with the Stage 4. Solution: № 8 – PEM general plan. The drawing legend provides the following TFS baseline ("as per drawing") area figures:

- Construction site: 6.4233 ha, incl.:
  - plant: 5.0823 ha
  - unified logistics: 0.1678 ha
  - water wells: 1.0800 ha
  - water: 0.0932 ha
- Additionally shown on the drawing:
  - Additionally received land plot: 7.3413 ha
  - Factory boundaries: 10.0690 ha, incl. the split between stages and common zones (unified logistics, common roads).

Stage 4 (Solution №8) functional zones within the unified hub:

1. Controlled access and logistics zone: Checkpoint (Pos. 1), Parking (Pos. 2), controlled traffic scheme.
2. Administrative and O&M zone: Admin Building (Pos. 3), Warehouse & Workshop (Pos. 4).
3. Hydrogen production zone (PEM): Plant blocks (Pos. 5–7) and nitrogen supply (Pos. 8).
4. Hydrogen network export zone: Compressor Station (Pos. 9), Gas Metering (GDS) (Pos. 10), Buffer Storage (Pos. 11), Vent Stacks (Pos. 12–14).
5. Water and wastewater infrastructure: Wastewater Tank (Pos. 15), Sewage Pump Station (Pos. 16), Water Wells (Pos. 17), Iron Removal (Pos. 18), Raw Water Tank (Pos. 19), Combined Pump Station (Pos. 20).

The water intake sanitary protection is shown as Sanitary protection zone (1st zone) and the project adopts R = 30 m (unified hub rule).

5.5.9.3. Buildings/Facilities Table (Solution №8 explication)

Fire hazard categorisation follows NAPB B.03.002-2007. ATEX/HAC follows IEC 60079-10-1. The table below is the TFS consolidated cross-reference: "position → function → fire category → ATEX → key safeguards".

Fire hazard categories:

- AN – outdoor hydrogen installations (explosion/fire hazard).
- V – power-related fire hazard (electrical/cables/energy).
- D – non-combustible in cold state / low fire hazard.
- N/A – roads/fences/areas (category not applicable).

Table 5-34: Explication and Safety Matrix for Solution N°8

Pos. (Explication)	Facility (as per drawing)	Fire Hazard Category (UA)	ATEX / HAC linkage (concept)	Key safeguards (Pre-Design / design intent)
1 – Checkpoint Stage 4	Controlled access checkpoint	D	Non-hazardous	Perimeter control, controlled access, emergency notification
2 – Parking Stage 4	Parking	–	Non-hazardous	Located outside HAC, traffic routing without crossing process areas
3 – Admin Building (Office) Stage 4	Administration building	D	Non-hazardous	Outside HAC, protected access, dispatch/communications
4 – Warehouse & Workshop Stage 4	Warehouse and workshop	V	Non-hazardous	Separated from H_2 zones, ignition source control
5 – EH_2 Plant Block 1 Stage 4	PEM production block 1	A (preliminary)	Zone 2 (outdoor tie-ins); internal zoning to be defined	Forced ventilation (building design), H_2 detection, ESD, Ex equipment, upward venting
6 – EH_2 Plant Block 2 Stage 4 Phase 2	PEM production block 2 (Phase 2)	A (preliminary)	Zone 2 (concept)	Same as Pos. 5; phased build-out without changing backbone
7 – EH_2 Plant Block 3 Stage 4 Phase 3	PEM production block 3 (Phase 3)	A (preliminary)	Zone 2 (concept)	Same as Pos. 5; repeatable module scaling
8 – Nitrogen Gen. Building Stage 4	Nitrogen generation building	D	Non-hazardous	Purging/inerting for start-up/shutdown and maintenance support
9 – Compressor Station Stage 3	Hydrogen export compressor station	A / AN (to be confirmed)	Zone 2 (leak sources); locally Zone 1 at connectors	H_2 detection, ESD isolation, temp/vibration monitoring, ventilation, Ex equipment
10 – Gas Metering (GDS) Stage 3	Gas metering/regulation (GDS)	AN (preliminary)	Zone 2 around the metering/regulation skid	Isolation valves, pressure/flow control, emergency venting to stacks
11 – H_2 Buffer Storage Stage 4	Hydrogen buffer storage	AN	Zone 2 around vessel and manifolds	Network pulsation damping, PRVs to safe vent, ESD
12 – Vent Stack 1 Stage 4	Vent stack 1	AN	Zone 2 near outlet	Upward discharge, ignition source exclusion, safe positioning
13 – Vent Stack 2 Stage 4 Phase 2	Vent stack 2 (Phase 2)	AN	Zone 2	Same as Pos. 12 (phased expansion)
14 – Vent Stack 3 Stage 4 Phase 3	Vent stack 3 (Phase 3)	AN	Zone 2	Same as Pos. 12 (phased expansion)

Pos. (Explication)	Facility (as per drawing)	Fire Hazard Category (UA)	ATEX / HAC linkage (concept)	Key safeguards (Pre-Design / design intent)
15 – Wastewater Tank Stage 4	Wastewater tank	–	Non-hazardous	Collection of process drains/backwash, spill control, disposal scheme
16 – Sewage Pump St. (SPS) Stage 4	Sewage pump station	V	Non-hazardous	Reliable pumping, redundancy, alarms
17 – Water Wells Stage 4	Water wells	–	Non-hazardous	R = 30 m sanitary zone, quality monitoring
18 – Iron Removal Station Stage 4	Iron removal station	D	Non-hazardous	Raw water pre-treatment protecting downstream RO/EDI
19 – Raw Water Tank Stage 4	Raw water tank	–	Non-hazardous	Water buffering for stability and peak coverage
20 – Combined Pump Station Stage 3	Combined pump station	V	Non-hazardous	Process/domestic/fire water supply within hub backbone

Note on categories: the final category for Pos. 5–7 and Pos. 9 depends on the final building architecture, ventilation, and how hydrogen equipment is split between indoor/outdoor installations. At pre-design level, a conservative A-category approach is adopted for indoor hydrogen process buildings.

5.5.9.4. Hydrogen Production and Export Process Chain (PEM 300 MW) and BoP Systems

Scope boundary for Solution №8:
End-to-end process intent from water intake and raw water handling (Pos. 17–19) with pumping (Pos. 20) → PEM production (Pos. 5–7) → network export chain via compression (Pos. 9), buffering (Pos. 11), metering/regulation (Pos. 10) → safe venting via stacks (Pos. 12–14).
Stage 4 key feature: hydrogen is exported **to the gas network**, which drives requirements for:

- stable delivery pressure/flow,
- metering and commercial/technical accounting,
- coordinated compression/regulation control,
- robust venting and emergency scenarios at the plant-to-network interface.

Water supply and water preparation (Positions 17–20, 18–19)

Water intake (Pos. 17 – Water Wells Stage 4)
Wells supply raw water to electrolysis and utilities. A **R = 30 m sanitary zone** is adopted and shown on the plan.

Pre-treatment (Pos. 18 – Iron Removal Station Stage 4)
Iron removal reduces fouling risks and protects downstream deep purification steps (RO/EDI as typical for electrolysis projects).

Raw water buffering (Pos. 19 – Raw Water Tank Stage 4)
The tank stabilises supply, covers intake fluctuations, and improves resilience to short disruptions.

Pumping and distribution (Pos. 20 – Combined Pump Station Stage 3)
Provides:

- process water delivery to plant blocks,
- domestic/utility water,
- fire water supply as part of the hub infrastructure backbone.

PEM electrolysis and integrated BoP (Positions 5–7)
Stage 4 production is implemented as three phased blocks:

- Pos. 5 – EH_2 Plant Block 1

- Pos. 6 – EH_2 Plant Block 2 (Phase 2)
- Pos. 7 – EH_2 Plant Block 3 (Phase 3)

Each block conceptually contains:
- **PEM electrolysis**,
- **power distribution and conversion** (rectification, controls),
- **product gas conditioning** (oxygen/moisture removal to required export quality),
- **thermal management** (cooling circuits and air heat rejection as part of the block),
- **controls, safety and monitoring** (ESD, H_2 detection, interlocks, telemetry).

From a layout standpoint, the block approach:
- localises risk within repeatable modules,
- supports phased build-out (Phase 1 → Phase 3),
- keeps the infrastructure backbone unchanged (water, wastewater, roads, security zones, export node).

Nitrogen (Position 8)
Pos. 8 – Nitrogen Gen. Building supplies nitrogen for:
- inerting and purging of hydrogen equipment,
- start-up/shutdown operations,
- safe maintenance of gas processing and export interfaces.

Network export: compression → buffering → metering/regulation → vent stacks (Positions 9–14, 11–14)
Pos. 9 – Compressor Station Provides pressure matching to the gas network requirements. Specific duty points are finalised at FEED.
Pos. 11 – H_2 Buffer Storage (located after compression and before GDS)
Buffering is arranged **after the compressor station and before the GDS** in order to:
- damp network pulsations and transient behaviour,
- stabilise delivery pressure/flow at the network interface,
- improve controllability during transitions (switching, fast load changes).

Pos. 10 – Gas Metering (GDS) Performs:
- commercial/technical metering,
- regulation and stabilisation of export parameters,
- protective isolation at the "plant ↔ network" boundary.

Pos. 12–14 – Vent Stacks (phased) Provide safe hydrogen relief:
- for emergencies (isolation, overpressure),
- for operational switching and purging,
- for maintenance when sections are taken out of service. Principle: **upward discharge**, exclusion of ignition sources near the outlet, safe positioning.

5.5.9.5. Conceptual Block Flow Diagram – Solution №8 (PEM 300 MW)

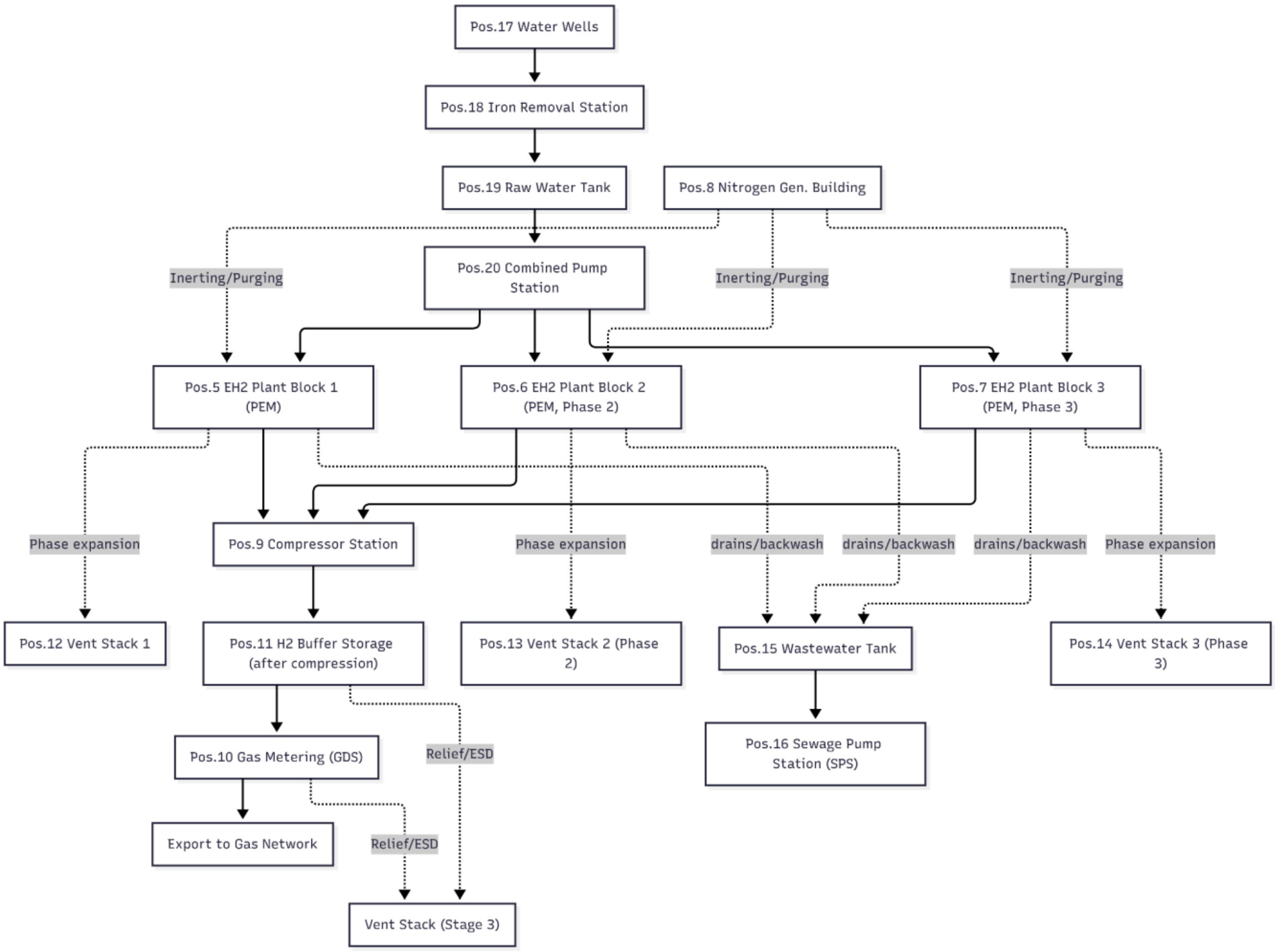


Figure 5-38: Conceptual Block Flow Diagram for Solution №8 (PEM, 300 MW)

5.5.9.6. ATEX & Hazardous Area Summary (PEM 300 MW) – concept

Hazardous area classification follows IEC 60079-10-1 at pre-design level. Solution №8 combines:

- indoor/process buildings with forced ventilation (Pos. 9 depending on architecture),
- outdoor tie-ins and installations (Pos. 5–7, Pos. 11, Pos. 10, Pos. 12–14).

Conceptual HAC by position:

- Pos. 5–7: Zone 2 at outdoor tie-ins/manifolds; internal zoning depends on ventilation/leak sources.
- Pos. 9: Zone 2 around leak sources; locally Zone 1 at connectors (if applicable).
- Pos. 10: Zone 2 around metering/regulation equipment.
- Pos. 11: Zone 2 around buffer vessel/manifolds.
- Pos. 12–14: Zone 2 near vent outlet and termination.

Electrical equipment in HAC shall be Ex-rated per IEC 60079; H_2 detection, alarms and ESD logic are mandatory.

5.5.9.7. Fire Separation Distances (tabular) + separation philosophy – Solution №8

Fire separation philosophy for Solution №8:

Separation distances reduce escalation likelihood and ensure fire brigade operability.

Hydrogen nodes rely on "distance + upward venting + ESD", and administration functions are excluded from HAC and thermal impact zones.

The adopted configuration is taken from the Solution №8 general plan; FEED confirms final distances against DBN/NAPB. The Solution №8 drawing shows characteristic radii/distances (including R = 30 m sanitary zone, and roadway/offset dimensions shown on the plan).

Table 5-35: Fire Separation Distances for Solution №8

From (position + facility)	To (position + facility)	UA categories	Principle / criterion	Adopted per Solution №8 plan
Pos. 5 – EH_2 Plant Block 1	Pos. 3 – Admin Building	A → D	Admin outside HAC and escalation zones	Functionally separated (per plan)
Pos. 5 – EH_2 Plant Block 1	Pos. 4 – Warehouse & Workshop	A → V	Warehouse functions outside H_2 process cluster	Functionally separated (per plan)
Pos. 9 – Compressor Station	Pos. 10 – Gas Metering (GDS)	A/AN → AN	Export interface as one technological cluster with ESD segmentation	Export cluster formed (per plan)
Pos. 9 – Compressor Station	Pos. 11 – H_2 Buffer Storage	A/AN → AN	Buffer **after compression** for flow stabilisation	Linear export chain (per plan)
Pos. 12–14 – Vent Stacks	Personnel/general areas (Pos. 3–4)	AN → D/V	Upward venting; stacks positioned away from general areas	Separated (per plan)
Pos. 17 – Water Wells	Any construction	–	**R = 30 m** sanitary zone	**R = 30 m** shown

5.5.9.8. HAZID Summary (Stage 4 / Solution №8 – PEM 300 MW)

Table legend (concept, pre-FEED):

- HAZID is qualitative and intended to fix the major hazards, key barriers, and FEED actions.
- Safeguards reflect the layered barrier philosophy: process control & detection → ESD levels → active fire protection → passive safety (venting/blast relief, blast walls, etc.).
- ATEX/HAC concept used in Solution №8: indoor forced-ventilation process buildings (architecture-dependent Pos. 9) + outdoor tie-ins (Pos. 5–7;Pos. 10–14, 11). [101]

Table 5-36: HAZID Summary Table for Solution №8

Node (position + facility)	Deviation / Hazard	Credible causes	Consequences	Existing / assumed safeguards (Pre-Design)	Recommendations (FEED / next stage)
Pos. 5–7 – EH_2 Plant Blocks 1–3 (PEM production buildings)	Loss of containment (H_2 leak) inside building or at outdoor tie-ins	Flange/gasket leak; instrument fitting leak; vibration fatigue; maintenance error; inadequate tightening	H_2 accumulation at ceiling; explosive atmosphere; ignition → deflagration / jet fire; injury; building damage	Forced ventilation concept; ceiling-mounted H_2 detectors; alarm/trip logic with emergency ventilation; ESD shutdown of affected train / whole production as required; blast relief / deflagration venting concept for hydrogen hall; Ex equipment in classified zones	Confirm ventilation performance (air change rates) by calculation; define detector placement & setpoints (alarm / trip); define building explosion relief philosophy and duct routing; finalise Ex equipment schedule per IEC 60079; confirm ESD voting logic and UPS supply for safety systems

Node (position + facility)	Deviation / Hazard	Credible causes	Consequences	Existing / assumed safeguards (Pre-Design)	Recommendations (FEED / next stage)
Pos. 5–7 – EH_2 Plant Blocks 1–3	Oxygen enrichment / oxygen release in unsafe location	O_2 vent misrouted; discharge near intakes/doors; inadequate separation from H_2 vents; backflow	Oxygen-enriched atmosphere increasing fire intensity; accelerated ignition; higher escalation potential	Dedicated venting philosophy, separation of vent terminations; building ventilation concept; procedural controls	Fix O_2 vent termination locations at safe elevated discharge; confirm separation between O_2 and H_2 vent outlets; add non-return devices where required; confirm that O_2 discharge does not impact occupied areas or air intakes
Pos. 5–7 – EH_2 Plant Blocks 1–3	Electrical hazard (DC arc flash / short circuit) as ignition source	Cable insulation failure; busbar fault; moisture ingress; poor earthing; incorrect isolation	Electrical fire; ignition of leaked H_2; personnel injury; extended outage	Electrical protection concept; segregation of electrical rooms; insulation monitoring for DC systems and grounding concept; ESD hierarchy	Perform arc-flash studies for DC systems; specify insulation monitoring devices (IMD) and trip philosophy; confirm earthing/bonding scheme for hydrogen service; ensure cable routing segregation from hydrogen piping
Pos. 5–7 – EH_2 Plant Blocks 1–3	High temperature / thermal runaway of electrolysis equipment	Cooling loop pump failure; heat exchanger fouling; control fault; loss of utilities	Membrane damage; gas release; potential fire; forced shutdown	Flow monitoring on cooling loop; high-temperature trip; safe shutdown sequence; ventilation and gas detection remain active during trip	Define N+1 philosophy for critical cooling pumps; define safe shutdown sequencing and interlocks; confirm emergency ventilation remains powered on loss of normal supply
Pos. 8 – Nitrogen Generation Building	Loss of inerting / purging capability	Nitrogen system outage; compressor failure; storage depletion	Unsafe start-up/shutdown; inability to purge; increased likelihood of forming explosive mixtures during maintenance	Nitrogen system provided for inerting/purging of hydrogen equipment (start-up/shutdown/maintenance)	Define minimum nitrogen availability and storage/backup philosophy; implement low-pressure alarms and permissives for maintenance and restart; confirm interface points to each train
Pos. 9 – Compressor Station (export)	H_2 leak at seals / packing; ignition (jet fire)	Seal wear; vibration; maintenance error;	Jet fire; escalation to adjacent export equipment; injury; plant/network trip	HAC concept Zone 2 around sources, local Zone 1 at connectors; H_2 detection; ESD isolation;	Add local detectors at seal areas; specify auto-shutdown thresholds

Node (position + facility)	Deviation / Hazard	Credible causes	Consequences	Existing / assumed safeguards (Pre-Design)	Recommendations (FEED / next stage)
		compressor upset		Ex equipment; monitoring of temperature/vibration; ventilation for enclosed compressor areas	(vibration/temp/gas detection); confirm hot surface control; define physical protection against vehicle impact and maintenance access routing
Pos. 9 – Compressor Station (export)	Overpressure / surge / mechanical failure	Control failure; blocked discharge; sudden network demand change; compressor trip/restart	Rupture of piping; major release; cascading ESD; downtime	ESD segmentation at export chain; pressure monitoring; relief philosophy to vent stacks; compressor protective controls	Confirm relief sizing and blowdown routing; verify ESD valve placement and closure times; perform dynamic review of network interface transients and compressor control philosophy
Pos. 11 – H_2 Buffer Storage (post-compression, before GDS)	Loss of containment / manifold failure	Valve failure; flange leak; fatigue; impact	Jet fire; major H_2 release; escalation to GDS; risk to personnel	Buffer is intentionally located **after compression and before GDS** to stabilise export and damp pulsations; PRVs to safe vent; ESD isolation; zoning and separation philosophy	Confirm buffer vessel design basis and PRV sizing; define ESD segmentation (block valves both sides); install impact barriers; confirm safe distances to occupied zones and roadways
Pos. 10 – Gas Metering (GDS)	Regulation/metering upset; unstable export; leak in metering skid	Regulator failure; instrument impulse leak; incorrect setpoints; blocked filters	Off-spec export pressure/flow; release; plant-network emergency shutdown	Protective isolation at "plant ↔ network" boundary; regulation and stabilisation function; ESD valves; relief to vent stacks	Define metering redundancy (as required); implement differential pressure monitoring; confirm ESD shutdown logic at network boundary; finalise hazardous area extent around GDS skid
Pos. 12–14 – Vent Stacks (phased)	Unsafe vent discharge / ignition at outlet	Low discharge velocity; downwash; outlet near ignition sources; poor stack height	Ignition at outlet; flame impingement; hazardous radiation	Dedicated vent stack concept with upward discharge; exclusion of ignition sources near outlet; location away from general areas; PRVs discharge to vent stacks	Verify vent stack sizing/height and dispersion; confirm clear vertical release without obstructions; implement ignition source control zone; confirm vent routing from PRVs and blowdown valves

Node (position + facility)	Deviation / Hazard	Credible causes	Consequences	Existing / assumed safeguards (Pre-Design)	Recommendations (FEED / next stage)
Pos. 12–14 – Vent Stacks (phased)	Inadequate safety zone management around stacks	Encroachment by roads/working areas; expansion conflicts	Personnel exposure during venting; inability to evacuate safely	Safety zone requirement applied around stacks (planning requirement); siting intent excludes permanent workplaces and evacuation routes near stacks	Freeze “no permanent workplace” and “no evacuation route overlap” constraints in FEED; confirm safe access control and signage; implement event-based area isolation procedures
Pos. 15 – Wastewater Tank	Uncontrolled discharge / contamination	Tank overflow; improper segregation of streams; leak	Environmental impact; corrosion/ground contamination; regulatory non-compliance	Collection of drains/backwash routed to wastewater tank; controlled disposal scheme in hub infrastructure philosophy	Define wastewater stream segregation and capacity; implement high-level alarms; confirm lining/bunding and leak detection; confirm removal/treatment route per permits
Pos. 16 – Sewage Pump Station (SPS)	Loss of pumping / flooding	Pump failure; power loss; blockage	Local flooding; hygiene hazard; equipment access issues	SPS included with reliability intent; alarms and redundancy concept implied	Define duty/standby arrangement and emergency power philosophy; confirm overflow prevention; maintenance access and odor control
Pos. 17–19 – Water Wells / Iron Removal / Raw Water Tank	Insufficient water supply / quality deterioration	Reduced well yield; seasonal variability; iron removal malfunction; tank contamination	Water treatment failure; reduced production; membrane/stack damage; unplanned shutdown	R = 30 m sanitary zone adopted; iron removal protects downstream purification; raw water buffering stabilises intake and resilience	Define water quality monitoring and sampling plan; confirm redundancy strategy for wells; define tank hygiene and inspection; verify iron removal performance and backwash disposal
Pos. 20 – Combined Pump Station	Insufficient delivery for process/fire/utility duties	Pump failure; power loss; hydraulic mismatch at expanded Stage 4	Loss of utilities; impaired safety barriers relying on water (cooling/exposure cooling)	Pump station is part of hub backbone supplying process/domestic/fire duties	Confirm pump duty/standby and power classification; confirm ring main hydraulic capacity for Stage 4; define test and maintenance regime
Whole export chain (Pos. 9–11–10 + interface)	Plant-to-network interface rupture / external interference	Third-party excavation; sabotage; ground movement	Full-bore rupture; jet fire; VCE; major escalation	Passive: deep burial, warning tape, slabs; Active: leak detection/monitoring; Active: ESD valves at boundary/compressor	Fix pipeline corridor protection measures; define boundary ESD valve locations and closure time;

Node (position + facility)	Deviation / Hazard	Credible causes	Consequences	Existing / assumed safeguards (Pre-Design)	Recommendations (FEED / next stage)
				station; check valves; DP monitoring to prevent reverse flow	implement patrol/monitoring philosophy; confirm reverse-flow protection and isolation logic
Whole site	Lightning / static electricity ignition source	Storm events; inadequate bonding; insufficient lightning protection	Ignition of a leak; equipment damage	Earthing/bonding and lightning protection philosophy required; Ex equipment selection in HAC	Design lightning protection system and equipotential bonding; define bonding for all skids/pipe racks; periodic testing
Whole site	Emergency response access impaired	Blocked roads; poor turning radii; unclear isolation points	Delayed response; escalation	Separation philosophy and zoning; access control at checkpoint; general plan includes controlled traffic scheme	Validate fire appliance routes, turning circles, and hardstandings; mark isolation valves and ESD points on emergency maps; define muster points outside hazard zones

Fixed alignment note (important for this HAZID table)

- This HAZID is **explicitly aligned** to the Solution №8 layout and chain: **Pos. 5–7 → Pos. 9 → Pos. 11 (buffer after compression) → Pos. 10 (GDS) → export**, with vent stacks **Pos. 12–14** supporting relief/purging in staged expansion.

5.5.9.9. Summary of PEM Hub Evolution (Stage 1 to 4)

The PEM (Proton Exchange Membrane) pathway utilises a "HYPRPlant" modular architecture, prioritizing high dynamic flexibility for integration with volatile renewable energy sources (RES).

- **Stage 1-2 (2 MW to 20 MW):** Rapid deployment is achieved through standardised 5 MW PEM containers. Logistics focus on a "Virtual Pipeline" strategy involving tube-trailer loading at 350–500 bar to supply local industrial and mobility partners.
  +2
- **Stage 3 (100 MW):** The plant transitions to an integrated cluster architecture. A 100 MW PEM block is commissioned with integrated power electronics and separators. Native H_2 output at 30 bar significantly reduces the energy penalty for future GTS injection.
  +2
- **Stage 4 (422 MW Target - Solution 8):** The hub is completed as a cluster of three independent 100 MW PEM trains plus an expansion block. Cooling is managed via **Adiabatic Dry Coolers**, which reduces annual water consumption by 50% compared to the Alkaline pathway. The system is capable of operating between 0% and 160% load to capture solar peaks.

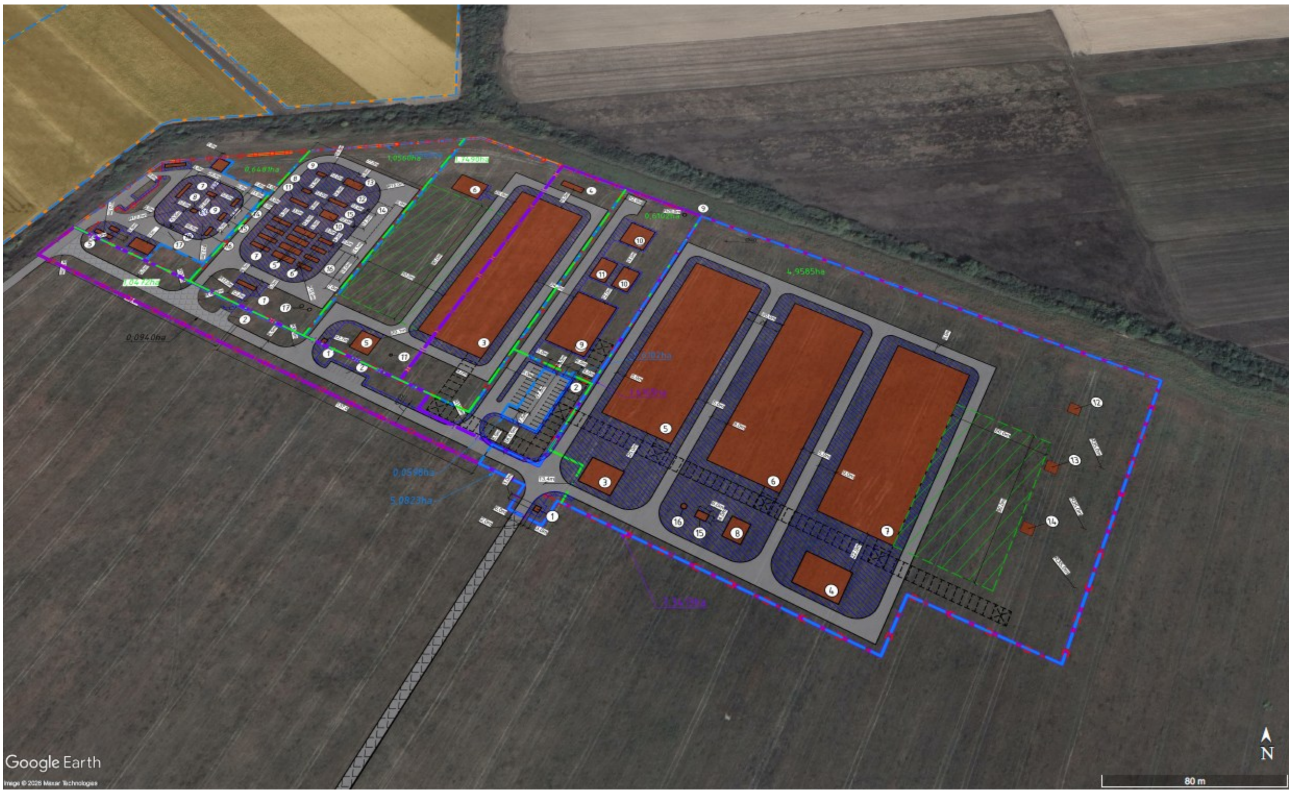


Figure 5-39: Hydrogen Hub PEM technological solution 422 MW Site Layout (Google Earth Visualisation)

The table below details the technical alignment of the 422 MW PEM configuration with the site's environmental and operational constraints.

Table 5-37: Technical Specification Analysis for 422 MW PEM Configuration

Parameter	Project Requirement	PEM Offer (Sol. 8)	Status	GIP Comment
Output Capacity	84,400 Nm3/hr	84,400 Nm3/hr	Match	Full compliance with export volume.
Cooling Method	Water-Smart	Dry Coolers	Match	Optimal for regions with water limits.
Operational Flex	Fast Frequency Res.	0–160% load	Match	Best-in-class for solar integration.
Footprint	Modular/Compact	Containerised Clusters	Match	Allows for phased CAPEX deployment.
H_2 Delivery P	70 bar (GTS)	30 bar (at stack)	Match	Lower compression OPEX vs Alkaline.

5.6. Overall Hydrogen Hub Mass Balance

The overall mass balance of the Uzhhorod Hydrogen Hub delineates the key inputs (raw water, ultra-pure water, electricity) and outputs (hydrogen, oxygen, and wastewater/reject water) required across all stages of project scaling, from the 2 MW pilot up to the 422 MW final configuration.

A critical factor in the mass balance is the raw water quality. Depending on the chemical composition and total dissolved solids (TDS) of the incoming water, the reverse osmosis and demineralisation processes may require higher rejection rates. As a result, the technical water consumption (excluding cooling water) can increase up to 20–25 liters of water per 1 kg of produced hydrogen to ensure the ultra-pure water (UPW) meets the strict requirements of the electrolysis stacks.

5.6.1 Alkaline Technology Mass Balance

For the Alkaline (AWE) technological pathway, the water consumption profile changes significantly as the plant scales. Starting from Stage II (20 MW), the system transitions to utilizing wet cooling towers for thermal management.

The calculation for the cooling system's make-up water from 20 MW onwards is strictly based on the equipment manufacturer's data to compensate for evaporation and blowdown losses. This reliance on evaporative cooling substantially increases the overall water footprint of the Alkaline solution at industrial scales. The specific energy consumption remains flat at 56 kWh/kg H_2.

Table 5-38: Mass Balance for Alkaline Technology (Stage I to 422 MW HUB)

Stage	Capacity	Tech Water (m3/h)	Cooling Make-up (m3/h)	Total Water (m3/h)	UPW (m3/h)	H_2 Output (Nm3/h)	H_2 Output (kg/h)	O2 Byproduct (kg/h)	Reject Water + Drain (m3/h)	Power (kWh/kg H_2)
I	2 MW	0.7	0.0	0.7	0.4	400	35.8	286	0.3	56.0
II	20 MW	6.8	13.8	20.6	3.9	4,000	358.0	2,860	6.2	56.0
III	100 MW	34.0	69.0	103.0	18.0	20,000	1,790.0	14,300	32.45	56.0
IV	300 MW	101.3	207.0	308.3	54.0	60,000	5,370.0	42,900	96.65	56.0
HUB	422 MW	142.8	289.8	432.6	76.3	84,400	7,553.8	60,346	135.59	56.0

Note: Reject water includes drain volumes from the wet cooling system starting from Stage II.

5.6.2 PEM Technology Mass Balance

The Proton Exchange Membrane (PEM) solution utilises a fundamentally different thermal management strategy. Across all stages of development, the PEM configuration exclusively utilises dry air cooling systems. Because there is no evaporative cooling involved, the cooling system make-up water requirement remains at zero.

This characteristic makes the PEM pathway significantly more water-efficient at the Hub scale (saving over 289 m3/h of water compared to AWE). Furthermore, the PEM systems demonstrate a slight improvement in energy efficiency as they scale, dropping from 57 kWh/kg H_2 at the pilot stage to 52.8 kWh/kg H_2 at the 422 MW Hub stage.

Table 5-39: Mass Balance for PEM Technology (Stage I to 422 MW HUB)

Stage	Capacity	Tech Water (m3/h)	Cooling Make-up (m3/h)	Total Water (m3/h)	UPW (m3/h)	H_2 Output (Nm3/h)	H_2 Output (kg/h)	O2 Byproduct (kg/h)	Reject Water (m3/h)	Power (kWh/kg H_2)
I	2 MW	0.7	0.0	0.7	0.4	400	35.0	286	0.3	57.0
II	20 MW	7.0	0.0	7.0	3.9	4,000	358.0	2,860	3.1	56.0
III	100 MW	36.7	0.0	36.7	19.0	21,130	1,900.0	15,200	17.7	52.6
IV	300 MW	110.0	0.0	110.0	57.0	63,390	5,700.0	45,600	53.0	52.6
HUB	422 MW	154.4	0.0	154.4	80.3	88,920	7,993.0	63,946	74.1	52.8

6. Water Resource Analysis and Management Strategy

6.1. Water Supply Objectives and Purity Standards

6.1.1. The Critical Role of Water in the Hydrogen Value Chain

For the "H_2 Hub Uzhhorod" project, water is not merely a utility but the primary feedstock. The reliability, quality, and security of the water supply directly influence the **Levelised Cost of Hydrogen (LCOH)**, the operational lifetime of the electrolyser stacks, and the overall bankability of the asset.
With a target terminal capacity of 422 MW, the facility must secure a sustainable supply capable of meeting two distinct demands:

- Feedstock for Electrolysis: Water is split into hydrogen and oxygen. This requires ultrapure water (UPW) to prevent catalyst poisoning and membrane fouling.
- Thermal Management (Cooling): Water is required for heat rejection from electrolysis stacks, gas-liquid separators, and compressors.

The project adopts a "Water-First" engineering philosophy, prioritizing **Operational Autonomy** to mitigate risks associated with external utility providers.

6.1.2. Quality Standards: PEM vs. Alkaline Requirements

The choice of electrolysis technology – Proton Exchange Membrane (PEM) or Alkaline Water Electrolysis (AWE) – dictates the stringency of water treatment. The project design anticipates both scenarios (8 Technical Solutions) and sets the baseline water quality to the highest common denominator (PEM standards) to ensure future-proofing.

Table 6-1: Comparative Water Quality Requirements (Input to Cell)

Parameter	Unit	Alkaline (AWE) Requirement	PEM Requirement (Critical)	Project Design Standard (Grade 5.0)
Standard	-	ISO 14687 / Manufacturer Specs	ASTM D1193 Type II / ISO 3696	ISO 14687 Grade 5.0
Conductivity (at 25°C)	µS/cm	< 5.0	< 0.1	< 0.056 (18.2 MOhm-cm)
Total Organic Carbon (TOC)	ppb	< 200	< 100	< 50
Silica (SiO2)	ppb	< 100	< 50	< 20
Iron (Fe)	ppb	< 50	< 5	< 1
Chlorides (Cl-)	ppb	< 50	< 5	< 1

Impact on Engineering: While Alkaline technology is more tolerant of impurities, PEM stacks are highly sensitive to cationic contamination (Fe, Cu, Al). Even trace amounts can permanently damage the membrane electrode assembly (MEA). Therefore, the Water Treatment Plant (WTP) is designed with a double-pass Reverse Osmosis (RO) + Electrodeionisation (EDI) configuration to guarantee resistivity > 16 MOhm-cm, satisfying the strictest PEM OEM requirements (e.g., Electric Hydrogen, Plug Power, Siemens). [55]

6.2. Strategic Option Comparison: Autonomous vs. Municipal Supply

A rigorous feasibility analysis (TEA 01/02-WPG/56) evaluated two potential sources for the industrial water supply.
Two principal sourcing options were screened at PFS level: (1) autonomous groundwater wells on the project land plot; and (2) sourcing from the existing Mynai municipal water intake. Option 1 is selected as the base case.

6.2.1. Option 1: Autonomous Well-Field (Selected)

The selected concept is to develop a dedicated wellfield on Land Plot No. 1. Stage-4 envelope concept: 5–6 production wells with individual flow of 40–60 m³/h, design depth up to 105 m, and a Tier I SPZ radius of 30 m around each well.

Water intake infrastructure elements (conceptual): wells with above-ground pavilion / first-lift pumping station, raw water tanks, deferrisation station, fire water reserve tanks, and a combined second-lift pumping station.
Rationale: The geological survey confirmed a stable aquifer with a high filtration coefficient, ensuring sufficient debit for the 422 MW capacity.

6.2.2. Option 2: Municipal Grid Connection (Rejected)

Connection to the "Minaj" water intake, operated by the Uzhhorod Utility Company "Vodokanal," located approximately 7 km from the site.
The Mynai water intake was reviewed using available documents and open information sources. The assessment concluded that its reserves are limited and primarily intended to meet drinking and domestic needs; industrial abstraction could create a risk of shortages and social tension. In addition, industrial use increases the risk of secondary pollution and may require additional treatment to meet industrial specifications. Therefore, Mynai sourcing is not recommended for the project base case.

- Engineering Concept: Construction of a 7-km pipeline, booster pumping stations, and extensive reconstruction of municipal infrastructure.
- Rationale for Rejection: The existing municipal infrastructure is aged (>60% wear), prone to frequent ruptures, and cannot guarantee the uninterrupted flow required for industrial safety.

6.2.3. Comparative Matrix and Investment Decision

Table 6-2: Strategic Comparison of Water Supply Options

Assessment Criteria	Option 1: Autonomous Well-Field (Selected)	Option 2: Municipal Grid (Rejected)
Operational Reliability	**High.** Full control over the entire supply chain (source-to-stack). No dependency on third-party maintenance schedules.	**Low.** Vulnerable to municipal grid failures, pressure drops, and pipe bursts common in the region.
Water Chemistry Stability	**Stable.** Groundwater composition is constant, allowing for precise WTP calibration and lower reagent consumption.	**Variable.** Fluctuates with seasonal changes and municipal treatment variations (e.g., shock chlorination).
Social Impact (ESG)	**Positive.** Utilises deep aquifers unconnected to local residential shallow wells. Prevents competition for drinking water.	**Negative.** Industrial withdrawal of 237 m3/h could create drinking water deficits for Uzhhorod city residents during summer peaks.
CAPEX (Initial Investment)	**High.** Costs for drilling, pumps, and WTP pre-treatment are borne by the project.	**High.** Costs for 7 km pipeline and grid reinforcement are comparable to drilling.
OPEX (Running Costs)	**Low.** Only electricity for pumps and subsoil use taxes (< 0.5 EUR/m3).	**High.** Commercial tariffs (> 1.5 EUR/m3) are subject to inflationary and political escalation.
Time to Deployment	**6–9 Months.** Controlled execution of drilling and licensing.	**18–24 Months.** Complex land allocation for the 7 km pipeline route and bureaucratic delays.

Decision: The project proceeds with **Option 1**. This secures **Independence from Tariff Volatility** and mitigates **Operational Risks**, directly enhancing the project's bankability.

6.3. Integrated Water Balance (Stages 1–4)

The water balance varies significantly depending on the selected electrolysis technology (PEM vs. Alkaline). Alkaline systems typically have higher cooling demands due to lower stack efficiency and higher operating temperatures, whereas PEM systems allow for dry-cooling solutions in temperate climates.

6.3.1. Water Balance for Alkaline (AWE) Technology

- Assumptions: Wet cooling towers are used for heat rejection.
- Process: Includes water for electrolyte preparation (KOH mixing) and hydrogen washing.

Table 6-3: Alkaline Water Consumption Forecast (Stages 1–4)

Category	Unit	Stage 1 (Pilot)	Stage 2 (Scale-up)	Stage 3 (Industrial)	Stage 4 (industrial)	Hub H_2
Installed Capacity	MW	2	20	100	300	422
Hydrogen Output	Nm3/h	400	4000	20000	60000	84400
1. Process Feed (Electrolysis)	m3/h	0.4	4	20	60	84.4
2. Process Waste (RO Reject)	m3/h	0.3	2.7	13.5	40.5	57
3. Cooling Makeup (Evaporation)	m3/h	0	0	69	207	276
4. Sanitary & Aux	m3/h	0.1	0.5	1	1.5	3.1
TOTAL PEAK DEMAND	m3/h	0.8	7.2	34.5	102	144.5
TOTAL	m3/h	0.8	7.2	103.5	309	420.5
Annual Volume (8000h)	m3/yr	6400	57600	634800	1892400	2591200
Annual Volume (4000h)	m3/yr	3200	28800	317400	946200	1295600
Annual Volume (2000h)	m3/yr	1600	14400	158700	473100	647800

6.3.2. Water Balance for PEM Technology

- Assumptions: Closed-loop Dry Cooling systems (Adiabatic Coolers) are used, drastically reducing evaporation losses.
- Process: Higher purity requirements lead to slightly higher RO reject rates, but overall consumption is lower.

Table 6-4: PEM Water Consumption Forecast (Stages 1–4)

Category	Unit	Stage 1 (Pilot)	Stage 2 (Scale-up)	Stage 3 (Industrial)	Stage 4 (Industrial)	Hub H_2
Installed Capacity	MW	2	20	100	300	422
Hydrogen Output	Nm3/h	400	4000	20000	60000	84400
1. Process Feed (Electrolysis)	m3/h	0.4	4	20	60	84.4
2. Process Waste (RO Reject)	m3/h	0.3	3.2	16.1	48.3	67.9
3. Cooling Makeup option* (Adiabatic)	m3/h	0	0	20	60	80
4. Sanitary & Aux	m3/h	0.1	0.5	1	1.5	3.1
TOTAL PEAK DEMAND without cooling	m3/h	0.8	7.7	37.1	109.8	155.4
Annual Volume (8000h)	m3/yr	6400	61600	320544	902144	1290688
Annual Volume (4000h)	m3/yr	3200	30800	160272	474336	668608
Annual Volume (2000h)	m3/yr	1600	15400	80136	237168	334304

Strategic Insight: The PEM pathway reduces water consumption by approximately **45-50% lower** compared to Alkaline at utility scale. This is a significant ESG advantage and reduces the environmental footprint of the facility.

6.3.3. Climatic Impact and Seasonality Coefficients (K_seas)

To ensure accurate OPEX modeling for the Uzhhorod location, specific Seasonality Coefficients (K_seas) have been applied to the water consumption calculations. The region features a temperate continental climate with hot summers (influence of the Pannonian Plain) and mild winters, which creates a distinct disparity in water usage between Wet and Dry cooling technologies.

A. Alkaline Technology (Wet Cooling Towers)

- Operating Principle: Constant evaporation and blowdown required to reject heat. Consumption correlates with the wet-bulb temperature.
- Annual Average Load: Estimated at 65% of the peak design flow (K_avg = 0.65).

B. PEM Technology (Adiabatic Dry Coolers)

- Operating Principle: The system operates in "Dry Mode" (air-only) for the majority of the year. Water spray (Adiabatic Mode) is activated only when the ambient temperature exceeds the setpoint of +25°C.
- Annual Average Load: Estimated at ~10% of the peak spray flow (K_avg = 0.10), as night-time temperatures in Uzhhorod typically drop below the activation threshold even in summer.

Table 6-5: Seasonal Water Consumption Coefficients for Uzhhorod

Season	Months	Ambient Temp (T_amb)	K_seas Alkaline (Wet Tower)	K_seas PEM (Adiabatic)	Operational Context (PEM)
Winter	Dec – Feb	-5°C ... +5°C	**0.30**	**0.00**	**Dry Mode.** Zero water consumption.
Spring / Autumn	Mar – May, Oct – Nov	+10°C ... +20°C	**0.60**	**0.05**	**Mixed Mode.** Spray active only during peak noon hours on warm days.
Summer	Jun – Aug	+25°C ... +35°C	**1.00**	**0.40 – 0.60**	**Adiabatic Mode.** Spray active during day (10:00–19:00); Dry mode at night.
September	Sep	+18°C ... +25°C	**0.80**	**0.20**	Transition period.

Strategic Impact on Stage 4 (422 MW):
Applying these coefficients reveals a massive reduction in the **Annual Water Footprint** for cooling:

- **Alkaline:** approx. 1,565,000 m3/year (Continuous evaporation).
- **PEM:** approx. 45,000 m3/year (Peak shaving only).

Conclusion: The adoption of PEM technology with adiabatic cooling reduces the annual cooling water demand by factor of **~35x**, significantly lowering the load on the Water Treatment Plant and minimizing wastewater discharge (Zero Liquid Discharge for cooling).

6.4. Water Supply System, Engineering Solution

According to the technical specifications, to meet the needs of the hydrogen plant in water, the following water supply systems must be designed:

- household and drinking water;
- production;
- fire protection.

For the specified systems, on the designed land plot of the hydrogen plant site, a water intake is organised as part of the following structures:

- wells with a surface pavilion – first-stage pumping station;
- source water tanks;
- iron removal station ;
- fire water supply tanks;
- combined pumping station of the second lift.

Description of the water supply schematic diagram

The output water from the wells is supplied to the site by submersible pumps in two streams:

- source water to meet firefighting needs enters the fire water supply tanks (FWST) without prior purification;
- he source water for production and domestic drinking needs is supplied to the iron removal station , where it is cleaned of excess iron to regulatory standards in accordance with DSanPiN 2.2.4-171-10 [2], and then either to the combined second-lift pumping station (ONS-II) or to the source water tanks (RVV). [77]

From the RPZ, fire pumps pump water to the plant site for internal and external fire extinguishing needs.

Purified water after the iron removal station (or after the RBB) is pumped to the plant site for production and drinking needs by the appropriate pumping groups in the ONS -II and is then sent for the needs of the plant.

The schematic diagrams of the water supply of the hydrogen plant for Alkaline and PEM technologies by construction phase is given down

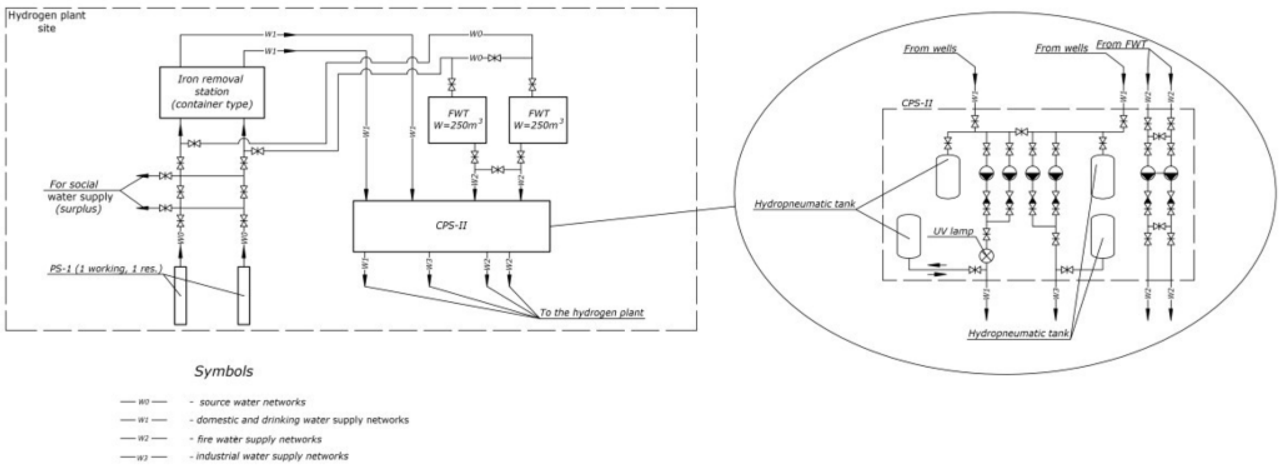


Figure 6-1: Water supply scheme. Stage 1-2. PEM Technology

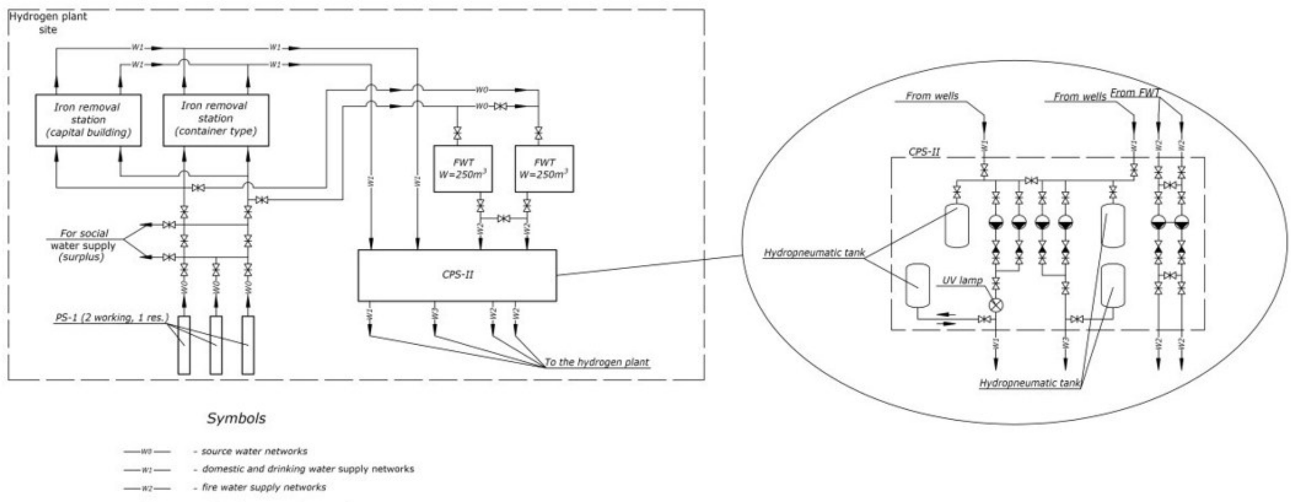


Figure 6-2: Water supply scheme. Stage 3. PEM Technology

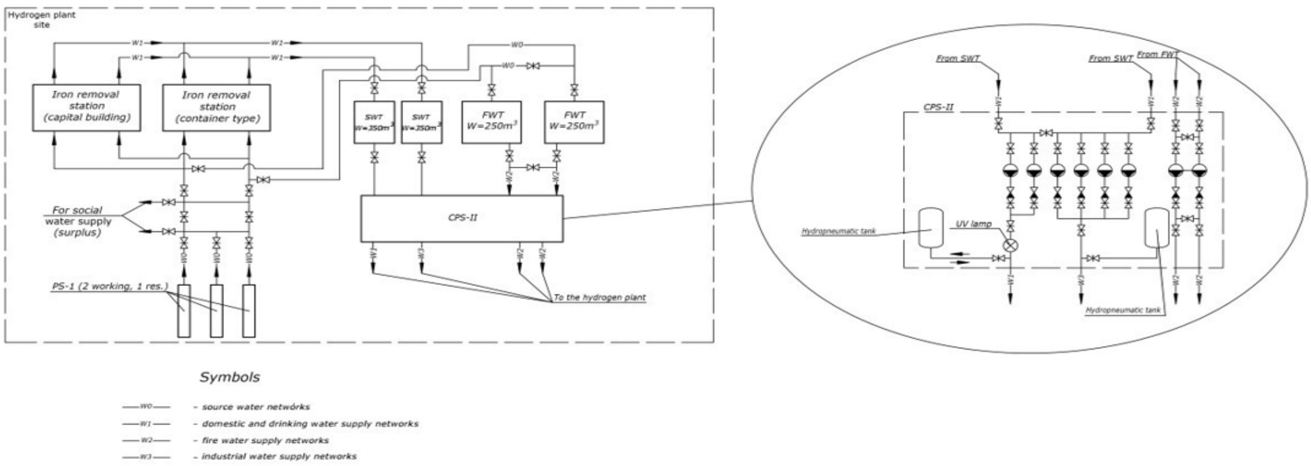


Figure 6-3: Water supply scheme. Stage 4. PEM Technology

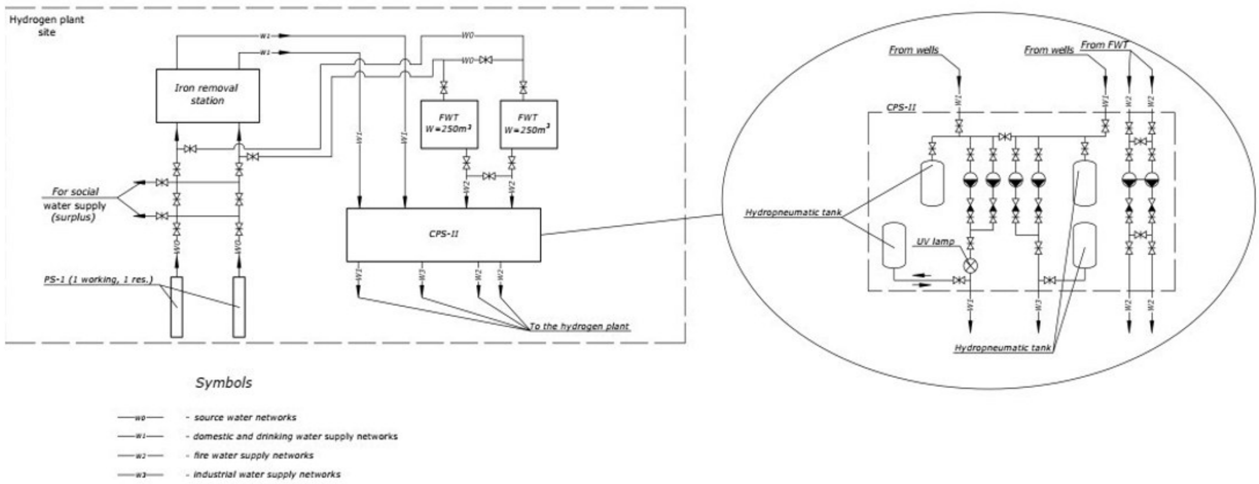


Figure 6-4: Water supply scheme. Stage 1-2. Alkaline Technology

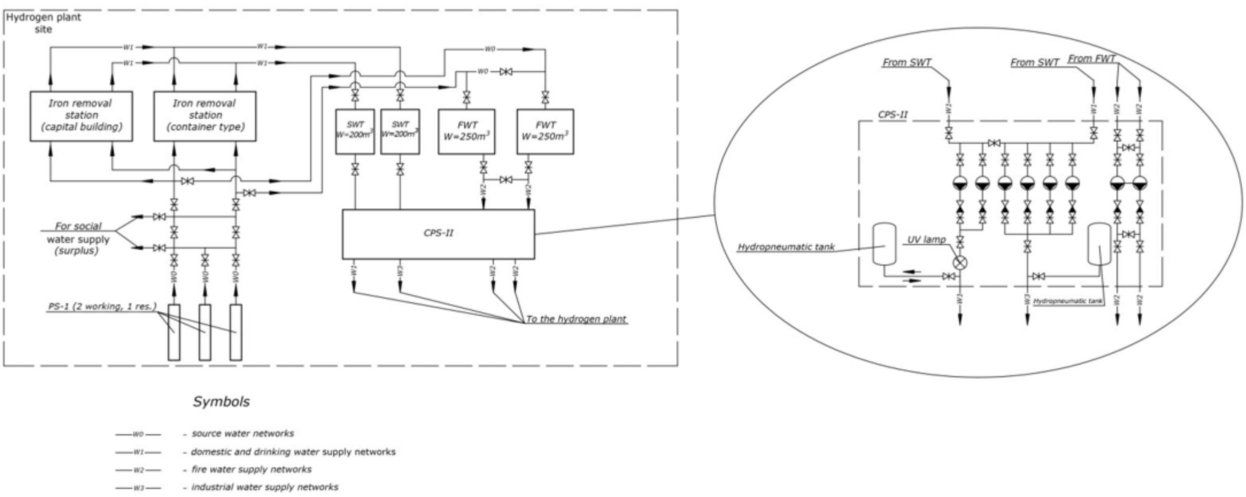


Figure 6-5: Water supply scheme. Stage 3. Alkaline Technology

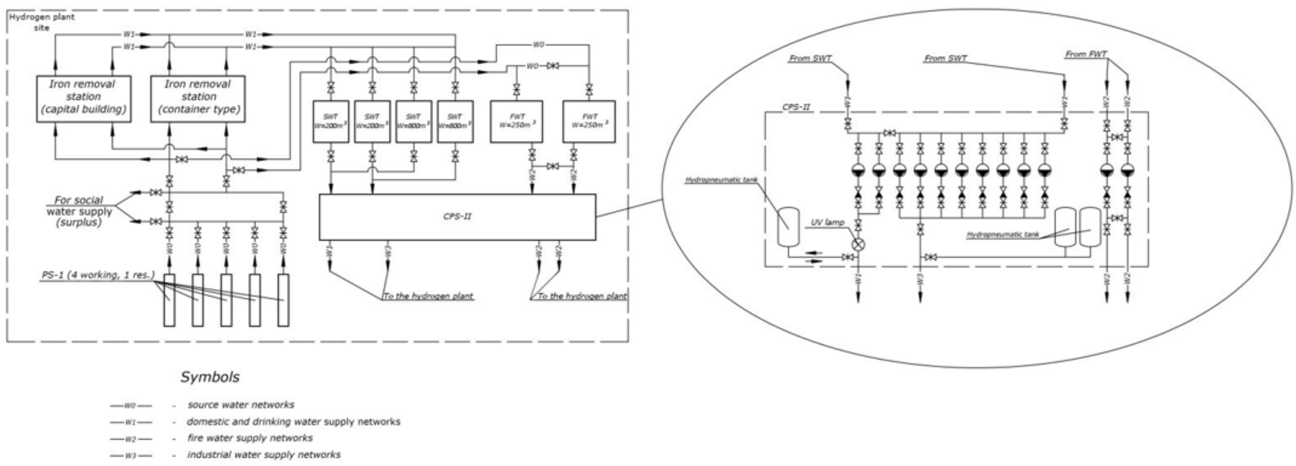


Figure 6-6: Water supply scheme. Stage 4. Alkaline Technology

First lift pumping station

A first-lift pumping station is installed above each well at the water intake site. Deep well pump with a flow rate of 46 m3/h is installed to supply water to the site.
A ground pavilion is provided above the wells to protect against precipitation, contamination of the aquifer and equipment, and unauthorised access.
In accordance with DBN V.2.5-74:2013 [4], wells are equipped with a metering unit.

Iron removal station

The quality of the source water (according to archival materials) does not meet drinking quality, as well as the requirements for water for production needs in terms of iron content, according to DSanPiN 2.2.4-171-10 [2]. In order to bring the source water to regulatory requirements, it is planned to organise an iron removal station on the site . The complete supply installation is located:

- 1st, 2nd stages of construction – in containers;
- 3rd, 4th stage of construction – in a stationary building or containers.

Source water tanks

Source water tanks (SWT) are made of monolithic reinforced concrete:

- 1, 2 construction phases – no tanks are planned;
- Phase 3 of construction – two tanks with a capacity of 150 m3 each;
- Phase 4 of construction – two additional tanks with a capacity of 800 m3 each.

Tanks are equipped with pipes: supply, outlet, overflow, drain, ventilation. Breathing valves are installed on the ventilation pipe.

Fire water storage tanks

Fire water storage tanks (FWS) are made of monolithic reinforced concrete, the number of tanks is two, with a capacity of 250 m 3 each.
Tanks are equipped with pipes: supply, outlet, ventilation.

Combined second-stage pumping station

Three groups of pumps are installed in the combined second-stage pumping station:

- pumping group for domestic and drinking water supply;
- fire-fighting water supply pumping group;
- pumping group for industrial water supply.

hydropneumatic tanks on the supply pipelines of domestic, drinking and industrial water supply pumps . For phases 3 and 4, these tanks will be dismantled.
hydropneumatic tanks on pressure pipelines for domestic, drinking and industrial water supply for all construction phases.

Also, for domestic and drinking water supply, it is provided to install UV lamps in accordance with clause 10.18.24 of DBN V.2.5-74:2013 [4] for water disinfection, which are installed after domestic and drinking water supply pumps.

External water supply networks
To provide the hydrogen plant site with water, external water supply networks are planned:

- source water (B0)
- household and drinking (B1);
- fire-fighting water supply (B2);
- production (B3).

Functional segregation
The water system is designed as three functional networks: (I) potable/domestic water, (II) industrial/service water, and (III) firefighting water. Industrial water is further split into treated raw water (utility) and demineralised water for electrolysers (process).

Intake, buffering and pre-treatment
Raw groundwater is pumped by submersible pumps. Two streams are foreseen: (1) firefighting stream routed directly to fire water storage tanks without treatment; and (2) production/domestic stream routed through iron removal (deferrisation) to meet drinking/utility standards and then to treat raw water tanks / second-lift pumping.

Demineralised water production (for electrolysis)
Demineralised (RODI) water is produced from pre-treated groundwater using a modular polishing package (e.g., filtration + RO + EDI / mixed bed). Each stage adds containerised/skid modules sised for the stage peak demand, providing expandability and redundancy. The final technology and redundancy philosophy shall be confirmed once the electrolyser OEM is selected.

Based on the commercial proposal, the following treatment steps are implemented:
Pre-Treatment (Iron Removal):

- Aeration: Saturation of water with oxygen to oxidise Fe(2+) to Fe(3+).
- Catalytic Filtration: Passage through columns filled with catalytic media (e.g., Birm or Greensand) to trap precipitated iron and manganese.
- Result: Iron content < 0.1 mg/L.

Softening (Hardness Removal):

- Ion Exchange: Sodium-cation exchange columns remove Calcium (Ca) and Magnesium (Mg) ions to prevent scaling on RO membranes.
- Result: Hardness < 0.1 mEq/L.

Reverse Osmosis (RO):

- Configuration: Two-pass RO system.
- Pass 1: Removes 98% of dissolved salts (TDS reduction).
- Pass 2: Polishing step to lower conductivity below 5 µS/cm.
- Efficiency: Recovery rate set at 75% to optimise water usage.

Electrodeionisation (EDI) – For PEM technology:

- Process: Continuous removal of residual ionised species using an electric field and ion-exchange membranes. This replaces mixed-bed resins and eliminates the need for chemical regeneration.
- Result: Conductivity < 0.056 µS/cm (Resistivity 18.2 MOhm).

Distribution, metering and resilience
Key resilience measures at concept level include: N+1 well capacity at the stage envelope, raw water and treated water buffering tanks, duty/standby pumps at critical stations, online monitoring (conductivity, pH, temperature; plus iron/manganese where relevant), and clear segregation of wastewater streams to avoid cross-contamination.

6.5. Wastewater and Brine Management

Wastewater streams

Wastewater streams are expected to include: RO concentrate (brine), filtration backwash / membrane cleaning waters, and (depending on technology) alkaline wash waters and spent electrolyte solutions (KOH/NaOH) for AWE. Domestic sewage and stormwater runoff are managed separately.

Treatment and disposal concept

At PFS level, the recommended approach is controlled collection, segregation and treatment (as required) followed by disposal via a permitted route. Where connection to a municipal sewer system is feasible (subject to technical conditions and acceptance criteria), it is generally the preferred long-term route. For early stages, interim solutions (collection tanks and tanker removal) may be used to de-risk schedule while permits and connections are being finalised.

AWE technology introduces additional wastewater complexity due to alkaline wash waters/electrolyte replacement and therefore requires dedicated neutralisation and possibly precipitation/filtration prior to discharge or off-site disposal. PEM technology wastewater streams are primarily related to water treatment and are generally simpler to permit and treat.

Stormwater, spill control and environmental protection

Stormwater shall be managed using a separate drainage network with oil-water separation where required. Bunding/secondary containment is required around chemical dosing stations, electrolyte storage/handling areas and wastewater tanks. A spill response plan, monitoring programme and periodic sampling shall be incorporated into the Environmental & Social Management System (ESMS).

Table 6-6: Wastewater stream register and indicative management route

Stream	Typical origin / notes	Indicative treatment & disposal (concept)
RO concentrate (brine)	RO/EDI polishing; elevated salinity and conductivity	Collect in industrial wastewater system → assess acceptance for municipal sewer; if not acceptable, treat (neutralisation/dilution) or remove by licensed contractor
Filter / membrane backwash & CIP	Iron removal filters, UF/RO cleaning, media/ion exchange regeneration	Equalisation tank → neutralisation if required → sewer (subject to TU) or off-site removal
AWE alkaline wash water / spent electrolyte	Only for alkaline: maintenance wash waters and periodic electrolyte replacement (KOH/NaOH)	Dedicated segregated tank → neutralisation (pH control) + possible precipitation/filtration → permitted discharge or off-site hazardous waste route
Cooling blowdown (if wet cooling used)	Only if wet cooling selected; may contain inhibitors/biocide residues	Prefer dry cooling to minimise make-up water; if wet cooling, treat to meet discharge/sewer criteria
Domestic sewage	Sanitary wastewater from staff facilities	Sewage pumping station → connection to municipal sewer where feasible; interim packaged treatment for early stage if required
Stormwater runoff	Roofs/hardstands; potential contamination near chemical areas	Separate drainage network; oil-water separators where required; bunding/containment in chemical and electrolyte areas

In accordance with the technical specifications and taking into account the design limits, the following sewage systems are planned to be organised to meet the needs of the hydrogen plant:

- household;
- production;
- rain, including those contaminated with petroleum products.

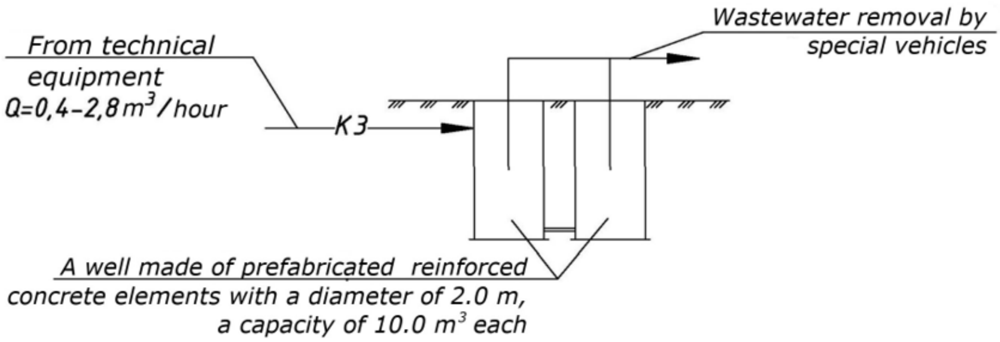


Figure 6-7: Sewerage scheme for Alkaline and PEM technologies for 1-2 stages of construction

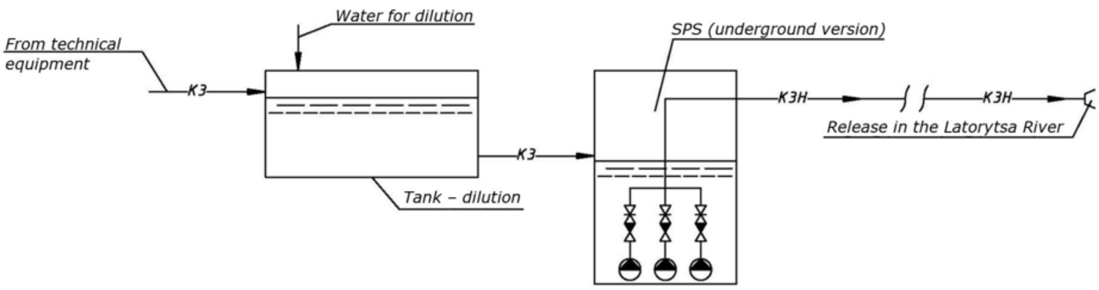


Figure 6-8: Sewerage scheme for Alkaline and PEM technologies for 3-4 stages of construction

Domestic sewage

Wastewater from the internal domestic sewage systems (K1) of buildings is discharged into the external network of the same name and then sent by gravity to local treatment plants such as OrganicBase. with a capacity of 0.6 m3/day , where mechanical and biological treatment takes place. The treated domestic wastewater is expected to be used to dilute industrial wastewater or removed by a sewage truck.

Industrial sewage

Wastewater from technological equipment is discharged into the external network of industrial sewage K3. Then the wastewater enters the averaging tank , where the dilution process to the MPC standards takes place. For dilution, it is possible to use treated rainwater and household wastewater, as well as technical water from a well.
For construction phases 1 and 2, it is possible to organise the removal of undiluted production wastewater by tanker truck to special storage tanks under a separate permit.
Diluted, uncontaminated wastewater is sent via gravity networks to the wastewater treatment plant, from where it is discharged into the Latorytsia River under pressure .

Storm sewer

The stormwater drainage system on the site is intended to collect and drain rainwater and meltwater from the roof of the building and driveways around the buildings to the gravity-fed external stormwater drainage network (K2). Rainwater from external drains and roads enters the K2 network through stormwater wells. Conditionally clean wastewater from the premises of buildings is also periodically drained into the K2 external network. Rainwater and meltwater are directed through the pipes of the gravity-fed K2 network to local stormwater treatment plants (STPs), where they are treated.

6.6. Regulatory Roadmap and Water Permitting

Legalisation of water abstraction and wastewater disposal requires an integrated administrative cycle. Key steps include: (1) Geological and Economic Assessment (GEO) including drilling of an exploration/production well and GKZ defence; (2) obtaining a special subsoil use permit (Derzhgeonadra) if abstraction exceeds 300 m³/day; and (3) obtaining a permit for special water use (Derzhvodahentstvo) for withdrawal limits and discharge conditions.
For wastewater discharge into a surface water body, a Maximum Permissible Discharge (MPD) project and an EIA procedure are required, followed by a special water use permit for discharge. This route is typically more time- and documentation-intensive than sewer connection and should be considered as a contingency only if municipal acceptance is not achievable.

Table 6-7: Key permits, authorities and indicative lead times

Permit / deliverable	Authority / interface	Indicative lead time	Notes
Geological & Economic Assessment (GEO) + GKZ defence	GKZ / licensed geology contractor	6–8 months	Includes drilling of first exploration-production well and pumping tests
Special subsoil use permit (groundwater extraction)	Derzhgeonadra (State Service of Geology and Mineral Resources)	3–4 months	Required if abstraction >300 m³/day
Sanitary Protection Zone (SPZ) establishment	Sanitary authorities + design institute	In parallel	Tier-I SPZ radius 30 m per well assumed at PFS
Special water use permit (withdrawal limits + discharge conditions)	Derzhvodahentstvo (State Agency of Water Resources)	~30 days	Integrated with EIA / environmental conclusion
Sewer connection TU + discharge contract	Local Vodokanal / utility	Case-dependent	Preferred long-term route where feasible
MPD project + EIA for discharge to surface water (contingency)	Ministry of Environment / authorised body	Several months	Required if discharging treated wastewater to a water body
Waste disposal contracts (sludge, spent chemicals)	Licensed waste contractors	1–2 months	Define hazardous/non-hazardous routes; integrate into ESMS

6.7. Social-Economic Impact and Community Engagement

The decision to develop an autonomous water supply (Option 1) generates significant positive externalities for the host community, the Syurtivska Territorial Community (TG).

- **Elimination of Resource Conflict:** By tapping into deep artesian aquifers (105m), the project avoids depleting the shallow groundwater table used by local residential wells and agriculture.
- **Infrastructure Contribution:** The confirmed debit of the aquifer (>240 m3/h) exceeds the early-stage needs of the plant. N1 Power has engineered the WTP with potential excess capacity. This allows for a future "Social Line" – a connection to supply purified, iron-free potable water to the village of Syurte, addressing a chronic regional issue of poor water quality.
- **Monitoring and Safety:** The project includes a network of observation wells. Data on groundwater levels will be shared with the local administration to ensure transparency and trust.

6.8. Chapter Conclusions and Recommendations

Based on the hydrogeological surveys, technical-economic analysis (TEA 01/02-WPG/56), and vendor specifications, the following conclusions define the water strategy for the **green H_2 project in Zakarpattia.**

1. **Strategic Security Secured:** The decision to develop an **Autonomous Well-Field (Option 1)** is the only viable path for a utility-scale facility. It eliminates exposure to municipal infrastructure risks, guarantees price stability (OPEX control), and ensures physical security of supply for the critical 237 m3/h demand.
2. **PEM as the "Water-Smart" Choice:** The comparative analysis of water balances definitively favors **Proton Exchange Membrane (PEM)** technology. By enabling the use of high-temperature adiabatic cooling, PEM reduces the annual cooling water requirement by a factor of **~35x** compared to Alkaline systems (Wet Towers). This drastically lowers the environmental footprint and wastewater treatment costs.
3. **Treatment Sufficiency:** The designed multi-stage Water Treatment Plant (Aeration -> RO -> EDI) is fully capable of treating the local iron-rich groundwater to **ISO 14687 Grade 5.0** standards. The inclusion of Electrodeionisation (EDI) ensures the removal of trace ions, safeguarding the longevity of the expensive catalyst-coated membranes.
4. **ESG Compliance:** The project demonstrates high social responsibility by utilizing deep aquifers (105m) that are hydrologically separated from local residential wells. Furthermore, the excess capacity of the well-field creates a tangible social benefit opportunity – supplying clean potable water to the Syurtivska community.
5. **Permitting Readiness:** The regulatory pathway is clearly defined. No "fatal flaws" have been identified in the hydrogeology. The critical path now shifts to the practical execution of the **Exploratory Drilling (Q2 2025)** and the defense of reserves at the State Commission (GKZ).

7. Electrical Infrastructure and H_2 Logistics

This section details the critical infrastructure and logistical chains necessary to connect the project to its essential inputs (power and water) and its primary output market (the EU hydrogen grid). A robust and resilient infrastructure plan is fundamental to the project's operational success and bankability.

7.1. Power Supply and Grid Interconnection

The project's power supply strategy is a sophisticated hybrid model designed not merely to source renewable electricity, but to do so in a way that maximises the electrolyser's annual operating hours (capacity factor) while strictly adhering to the EU's green hydrogen criteria. A higher capacity factor is essential for lowering the LCOH, as it spreads the high capital cost of the electrolyser over a larger volume of hydrogen production. [57]

7.1.1. Project Expansion Strategy and Grid Connection Requirements

The project is structured in four progressive development stages with increasing generation capacities. Table 8-1 outlines the design capacity at each stage for hydrogen (H_2) production, solar photovoltaic (PV) generation, and battery energy storage systems (BESS):

Table 7-1: Project Phases and Power Capacities

Stage	H_2 Plant Capacity (MW)	PV Capacity (MW)	BESS Capacity (MW/MWh) (option)
1	2	4	2 / 2
2	20	40	20 / 20
3	100	PPA	option
4	300	PPA	option

Considering these planned expansions, the long-term electricity demand will significantly increase, making the choice of transformer and grid connection strategy critical for cost-efficiency and reliability. [63]

7.1.2. Grid Connection Constraints and Impact on Design

Initially, the project evaluated a non-standard connection at 35 kV voltage level, which would be applicable for the Uzhhorod region under the third reliability category. The estimated cost of such a connection was approximately €780,000, which included around 2.5 km of power line infrastructure, either in underground cable or overhead format. This pricing is consistent with market rates for cable-based solutions and slightly elevated for overhead lines.

Interestingly, the expected cost of connection at 110 kV was estimated to be nearly half that, at around €368,000. However, the overall budget impact is likely to be similar in both cases, since a 110/35 kV step-down transformer and related high-voltage equipment would be required in the 110 kV option.

Considering this trade-off, the 110 kV connection was eventually chosen as the more viable long-term solution and is treated as the primary design path.

Initially, the project intended to connect to the local distribution network at 35 kV. However, the regional operator (Oblenergo) clarified that connection is only permissible at the 110 kV level in the designated area. This resulted in a fundamental change to the infrastructure design and increased overall project costs.

7.1.3. Transformer Selection

Based on the intermediate capacity requirements of the project and the phased development strategy, a step-up transformer with a voltage level of 110/35 kV is envisaged to ensure reliable and stable operation of the hydrogen production facility under continuous base-load conditions. The transformer is designed to support long annual operating hours and to accommodate future operational flexibility within the defined grid connection parameters.

Conductor Material: Aluminium vs. Copper

For the 110/35 kV transformer, two conductor material options were assessed: aluminium and copper windings. The comparison was performed from a technical and operational reliability perspective rather than on procurement cost, as the final equipment selection will be subject to a separate EPC and supplier tendering process.

Aluminium-wound transformers offer advantages in terms of lower weight and reduced mechanical stress on the transformer structure. However, for applications characterised by high annual utilisation, stable base-load operation, and limited tolerance for thermal cycling, aluminium windings exhibit higher sensitivity to long-term thermal ageing and joint resistance.
Copper-wound transformers, by contrast, provide superior electrical conductivity, lower winding losses, and improved thermal performance under continuous load conditions. These characteristics translate into enhanced operational reliability, reduced hotspot temperatures, and improved long-term stability, which are critical for a hydrogen production facility expected to operate for several thousand hours per year with limited operational interruptions.
Given the project's emphasis on long-term reliability, operational robustness, and reduced technical risk during continuous operation, a copper-wound transformer configuration is considered the technically preferred solution for the 110/35 kV interface.

Tap Changer Configuration: OLTC vs. DETC
Conventional transformer solutions at the 110 kV level are typically equipped with On-Load Tap Changers (OLTC) to allow voltage regulation under varying grid conditions. However, for the present project, the necessity of an OLTC has been reassessed in the context of the plant's operational profile and grid connection characteristics.
The hydrogen production facility represents a predominantly stable and predictable electrical load, with limited rapid fluctuations at the point of common coupling. Voltage regulation at the 110 kV level is primarily managed by the upstream transmission system operator, while fine voltage control on the 35 kV side can be addressed through downstream equipment and plant-level electrical design.
In this context, the use of a transformer without OLTC – equipped instead with an Off-Circuit Tap Changer (DETC) or fixed tap configuration – is considered technically sufficient. This approach offers several advantages:

- increased mechanical simplicity and reduced failure risk,
- lower maintenance requirements and improved availability,
- elimination of OLTC-related oil systems and control components,
- improved long-term reliability under continuous base-load operation.

Tap settings can be optimised during commissioning to match the agreed grid voltage conditions, with limited need for subsequent adjustment over the operational lifetime.

7.1.3.1. Conclusion
The 110/35 kV transformer concept for the project is therefore based on a copper-wound transformer design with a non-OLTC tap configuration. This solution aligns with the project's operational philosophy of stable, long-duration operation, minimises technical complexity, and reduces lifecycle risk, while remaining fully compatible with transmission-level voltage control strategies and future project scaling.

7.1.4. Connection Cost Breakdown
Two alternative connection schemes to the 110 kV grid were analysed:

- Option 1: Basic Connection – with a dedicated feeder cell at the utility substation
- Option 2: Extended Connection – involving a full transit through the 110 kV switchyard with an entry/exit scheme

Table 7-2: Option 1 - Connection via dedicated feeder cell at the utility substation

Equipment Description	Quantity	Unit Cost (EUR)	Total (EUR)
Power transformer 110/35 kV without OLTC	1	390,000	390,000
110 kV circuit breaker	–	–	0
110 kV disconnector	1	16,000	16,000
Protection, automation, SCADA, remote metering systems	1	25,000	25,000
Total cost (Option 1)			431,000

Table 7-3: Option 2 – Full transit connection via 110 kV switchyard with loop-in/loop-out scheme

Equipment Description	Quantity	Unit Cost (EUR)	Total (EUR)
Power transformer 110/35 kV without OLTC	1	390,000	390,000
110 kV circuit breakers	3	25,000	75,000
110 kV disconnectors	7	16,000	112,000
110 kV voltage transformers	2	25,000	50,000
Protection, automation, SCADA, remote metering systems	2	25,000	50,000
Total cost (Option 2)			677,000

7.1.5. Cost and Scope Comparison

- The basic scheme is estimated at €431,000, excluding the installation of breakers, as it assumes integration into an existing bay with minimal upgrades.
- The full transit scheme with full bay replication and entry/exit topology is €677,000, nearly 60% more expensive. However, it provides increased operational independence, redundancy, and improved control architecture for future expansions.

While the basic connection appears more affordable, it is highly dependent on substation layout and availability. The extended scheme is considered technically preferable and more aligned with the project's long-term scalability goals, particularly under Stage 3 (up to 400 MW installed capacity).

7.1.6. Primary Power Source (On-site PV)

The foundation of the power supply is the co-located, 400 MWp solar PV plant, which will be directly wired to the electrolysis facility. This direct connection minimises grid fees and transmission losses. The study will analyse the optimal coupling strategy (AC vs. DC). While AC coupling is more conventional, DC coupling, which connects the PV panels directly to the electrolyser's DC bus via a converter, can improve overall system efficiency by 5-10% by avoiding the double inversion losses (DC-AC from PV, then AC-DC to electrolyser).

7.2. Photovoltaic Power Plant (PV) Design for Stage I 4000 kWp

7.2.1. General Description

The current project has been prepared based on a design assignment from the client, with the aim of constructing a photovoltaic installation for electricity production with an installed capacity of 4,000 kWp and a maximum output power of 3,660 kW (AC).

The installation will convert solar radiation into electrical energy through monocrystalline photovoltaic modules. To achieve the installed capacity of 5 350.8 kWp, a total of 7644 photovoltaic modules with a power of 700 W each will be installed. To increase the overall efficiency of the system, the photovoltaic modules will be connected in series into strings. These strings will be grouped into 14 three-phase string inverters, each with a capacity of 350 kW. The inverters will convert the DC voltage from the strings into AC at 800 V. The AC outputs of the inverters will be collected into low-voltage switchboards (LVS) in a newly constructed compact transformer station.

The compact transformer station will consist of two low-voltage switchboards, each with 8 inputs (7 for inverters and one spare). The low-voltage side inputs will be equipped with the necessary switching and protection devices in accordance with the provided diagrams and drawings.

The two low-voltage switchboards will be connected to the 0.8 kV low-voltage winding of a transformer. The transformer will have a rated power of 5,000 kVA and a voltage ratio of 0.8/35 kV.

The medium-voltage switchgear will be equipped with a transformer protection cell, metering cell and one outgoing feeder.

A monitoring system will be implemented at the photovoltaic power plant to track parameters and energy production. In the 35 kV medium-voltage switchgear, which connects to the BESS local utility grid, remote control, telemetry, and line switching equipment will also be installed, operating at the point of synchronisation. The possibility of further expansion (connection) of PV+BESS equipment of the first stage to the 35 kV power grids of the second and subsequent stages and further parallel operation with the power system is envisaged.

The photovoltaic modules will be mounted on supporting steel structures, arranged in parallel rows. The structures will consist of standard mounting tables with a 25° tilt angle, each holding two rows of vertically positioned modules. There will be two types of structures:

- A table with two rows, each row holding 28 modules.
- A table with two rows, each row holding 14 modules.

7.2.2. Electrical Safety

For the purposes of electrical safety, each individual structural unit supporting the photovoltaic modules will be grounded to a common earthing system, in full compliance with all applicable standards and electrical safety regulations. During the installation of the supporting structures, all technical safety requirements explicitly stated in the technical documentation must be strictly observed.

7.2.3. Direct Current Section

The total number of strings is 273. The strings have been designed to meet the technical specifications of the selected inverters. The number of modules connected in series has been determined so that the resulting voltage is optimal for the maximum efficiency of the inverters.
The strings are connected to the inverter inputs according to a manufacturer-specified configuration, ensuring that the voltage and current values do not exceed the limits set by the manufacturer.
The photovoltaic power plant includes 14 high-efficiency three-phase inverters. Each inverter is equipped with DC disconnect switches (ESS) on the PV module side. The ESS switch ensures safe operation of the DC circuits by disconnecting the PV generator during maintenance of the inverter unit.

7.3. Modules technical data

Figure 7-1: Photovoltaic module Hanersun HN21N-66HT700W – technical representation

Figure 7-2: Photovoltaic Inverter Sungrow SG350HX-20 – technical representation

Table 7-4: Photovoltaic Module Hanersun HN21N-66HT700W Technical Specifications

Parameter	Value
Nominal Power (Wp)	700
MPPT Voltage (V)	40.4
MPPT Current (A)	17.33
Open-Circuit Voltage (Voc)	48.20 V
Short-Circuit Current (Isc)	18.34 A
Module Dimensions (mm)	2384 × 1303 × 33

7.4. Inverter technical data

Table 7-5: Inverter Technical Specifications – Sungrow SG350HX-20

Parameter	Value
DC Voltage	1500 V
Input Current per MPPT	75 A
Short Current per MPPT	125 A
MPP Voltage Range	500–1500 V
Number of MPPT	6 pcs
Max. Number of Inputs per MPPT	5 pcs
AC Power	350,000 W
Max Current (@ 800V, 3P+PE)	254 A
Voltage	800 V
Grid Frequency	50 Hz
THD (Total Harmonic Distortion)	<1%

Table 7-6: Electrical Parameters of the Photovoltaic System

Parameter	Value
Maximum AC Power	4900 kW
Maximum DC Power	5350,8 kW
MV Grid Voltage	35 kV
Frequency	50 Hz
Power Factor (Cos φ)	0.99 (leading) – 0.8 (lagging)

7.5. Electrical parameters

7.5.1. Installation of Photovoltaic Modules

The electrical terminals of the photovoltaic modules are located on their rear side and are insulated. From the insulated junction box on the back of each module, insulated solar cables extend, terminating with **MC4-type connectors**. The connectors have a **protection rating of IP67**.
The modules are connected in series to form strings without the need for additional cables. The cables integrated into each module are of sufficient length and are equipped with **male and female connectors**, allowing for direct series connection. **Additional solar cable** is required to extend both ends of the assembled string to the distribution boards. These **single-core flexible solar cables with rubber insulation** feature:

- Class 5 flexible copper conductor;
- PVC plastisol insulation for the core;
- PVC plastisol outer sheath;
- Operating temperature range: -40°C to +90°C;
- UV resistance.

7.6. Cabling

7.6.1. DC Cabling

The interconnection of the modules within each string is performed using the factory-installed cables and connectors. The extension of the end cables of the strings is carried out with **special UV-resistant double-insulated DC solar cable**.
Each string is connected to the inverters using **solar cables 2x1x4mm² or 2x1x6mm²**, as per the provided wiring diagrams. The solar cables are routed along the supporting structures of the modules and are **mechanically secured**. As the PV installation is outdoors and subject to direct atmospheric exposure, the securing of cables must provide sufficient mechanical strength. All cables, cable trays, paths, and fixing elements must be resistant to environmental factors (dust, wind, high humidity, rain, snow, and solar radiation).
DC wiring will be laid in **trenches of varying depths**, depending on the number of cables, for the part of the plant located on the ground. For the rooftop part of the plant, DC cables will be routed in **metal cable trays**.
Cable ends must have extra length reserved:

- **Up to 1 meter** on the inverter side (formed into a loop);
- **0.5 meters** on the module side.
  The **minimum bending radius** of the cable must be **no less than 15 times the outer diameter** of the cable.
  It is mandatory to follow the rule: "Cable bending radius must not be less than the manufacturer's minimum allowed value." Special attention must be paid to **contact points** between cables and any objects or structures.
  Direct contact with surfaces that could damage cable insulation is not permitted.

7.6.2. AC Cabling

The electrical connections between the 350 kWp inverters and the LV switchgear will be made using NAYY 4x300mm² cables from each inverter. These cables will be laid in cable ducts, as shown in the respective drawings. The 35kV connection between the compact transformer station and the distribution grid will be carried out using a 35kV 3x1x95mm² cable. This cable will be laid in a cable trench from the compact transformer station to an existing steel lattice tower. From there, the connection to the existing network will be made via overhead line. The total cable length is approximately max. 800 meters. Cables will be selected with double insulation made from flame-retardant materials. For additional protection, if deemed necessary by the client, the cables will be installed in conduits along the metal structure and cable trays. All installers must be qualified and certified to carry out this type of work.

7.6.3. Equipotential Bonding and Grounding Installation

To protect the photovoltaic system from **overvoltages**, strict adherence to the specified grounding and equipotential bonding system must be ensured.

All **metal structural elements** and **mounting structures** must be connected to an **internal grounding loop**, including flexible connections to doors and grilles. These connections must be **electrically reliable**. Multiple loops will be created and connected in a **star configuration** to a **common grounding busbar**. The inverter enclosures and external metallic parts (PV module frames and mounting structures) will also be connected to this common grounding bar.

A **grounding loop** will be constructed around the **roof-mounted sections** of the plant using **galvanised steel wire Ø8 mm**. This wire will connect all metallic components of the plant and will be grounded using **rods driven into the ground near the buildings**.

Grounding loops around **Compact Transformer Station 01 and 02** will be constructed using **40x4 mm galvanised steel strips** and **L 63/63/6 mm galvanised grounding rods**. The connection to the internal grounding system will also use a 40x4 mm galvanised strip.

The described star-shaped equipotential bonding system, which is both grounded and neutralised, ensures voltage equalisation and a reliable overvoltage protection concept.

All non-current-carrying metal parts of the photovoltaic modules, inverters, and distribution/control panels will be connected to the grounding system.

After the grounding installation is completed, the **resistance value must be measured**, and a **compliance protocol** must be prepared.

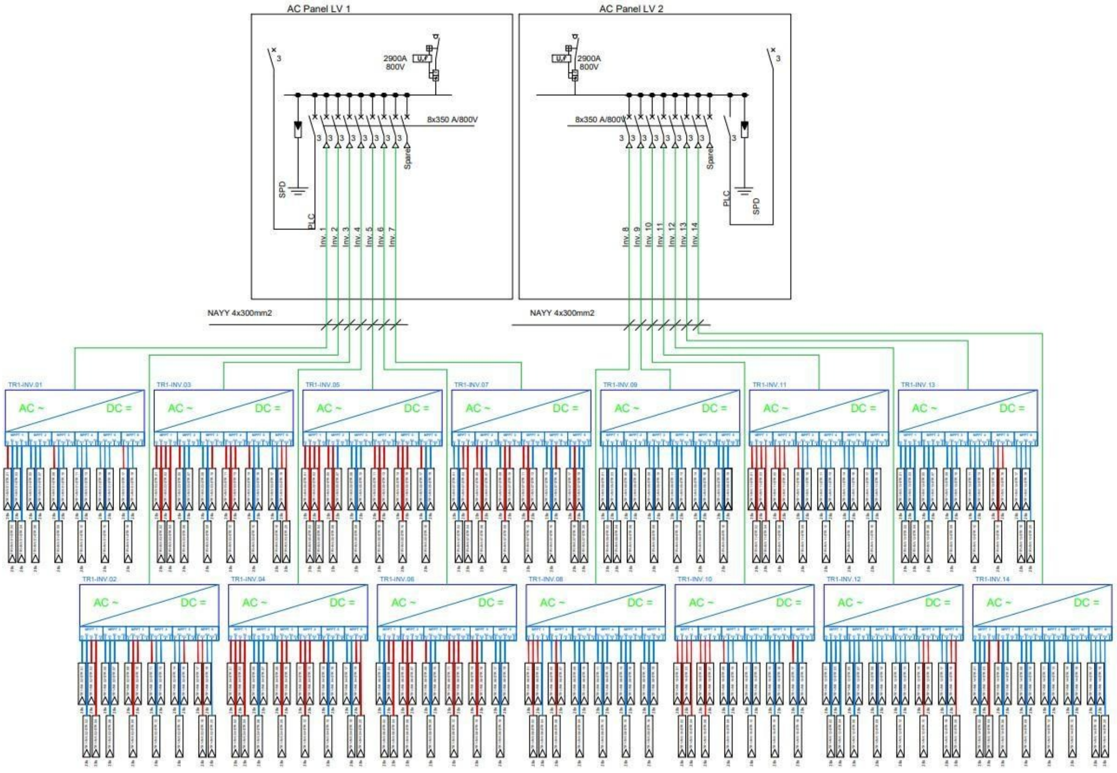


Figure 7-3: DC and AC Circuit Diagram LV

This diagram shows the connections between the **inverters** and **modules** in the photovoltaic system for both DC and AC circuits. It outlines the **parallel connections** between different panels and inverters. Each **inverter** is connected to the **AC panels** for the conversion of DC into AC."

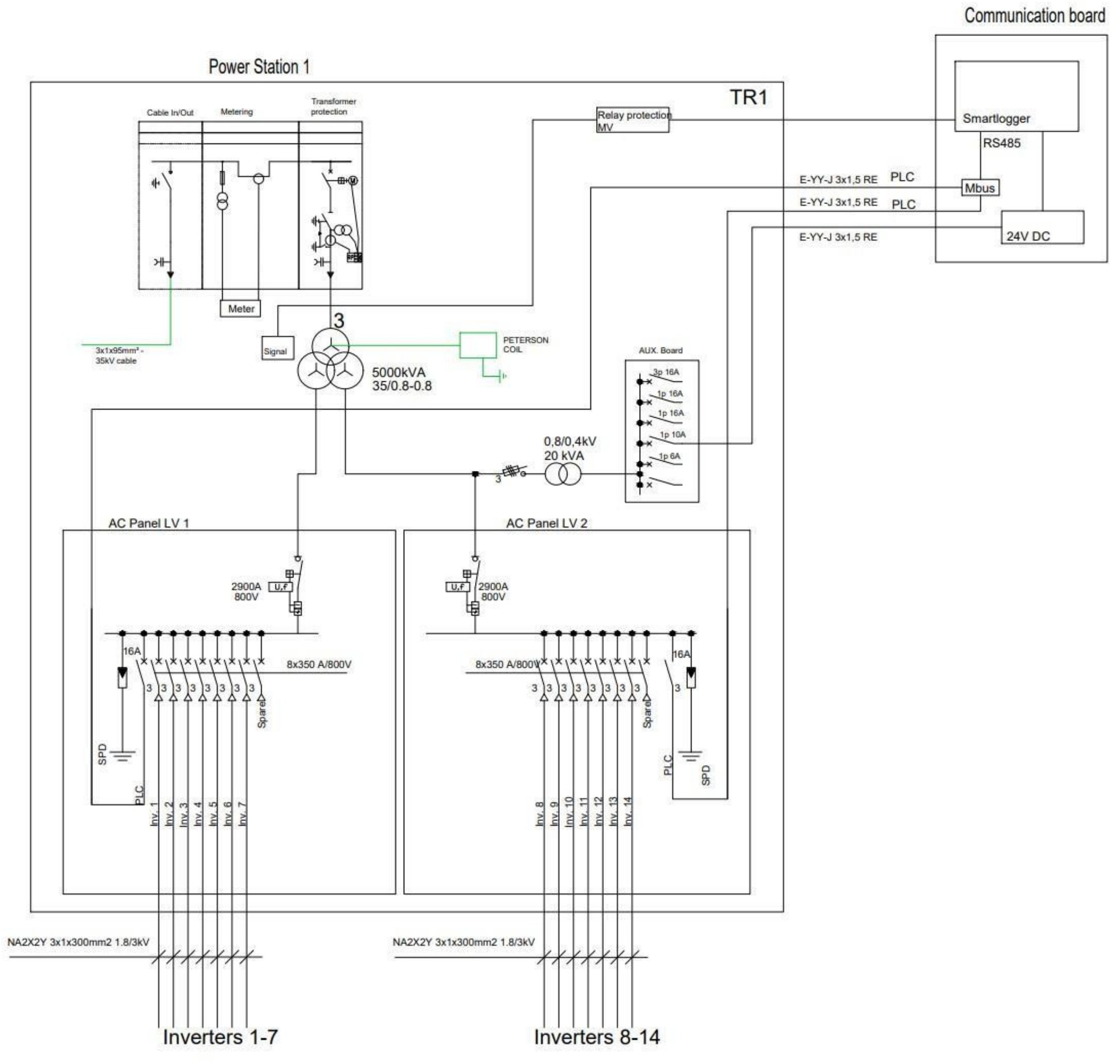


Figure 7-4: Compact Transformer Substation Scheme 35/0.8/0.8 kV

This diagram illustrates the compact transformer substation that is responsible for converting and transmitting electrical energy. The transformer has a capacity of **5000 kVA**, with input at **35 kV** and output at **0.8 kV**. It also displays the connections to **inverters**, the **AC panel**, and the **SmartLogger** communication system used for monitoring and control.

7.7. PV project with installed power Stage II 40000 kWp

7.7.1. Description

The current project has been prepared based on a design assignment from the client, with the aim of constructing a photovoltaic installation for electricity production with an installed capacity of 42800 kWp and a maximum output power of 39200 kW (AC).

The installation will convert solar radiation into electrical energy through monocrystalline photovoltaic modules. To achieve the installed capacity of 42800 kWp, a total of 61152 photovoltaic modules with a power of 700 W each will be installed. To increase the overall efficiency of the system, the photovoltaic modules will be connected in series into strings. These strings will be grouped into 112 three-phase string inverters, each with a capacity of 350 kW. The inverters will convert the DC voltage from the strings into AC at 800 V. The AC outputs of the inverters will be collected into low-voltage switchboards (LVS) in a newly constructed compact transformer station pass-through type in total number of 8 pcs.

The compact transformer station will consist of two low-voltage switchboards, each with 8 inputs (7 for inverters and one spare). The low-voltage side inputs will be equipped with the necessary switching and protection devices in accordance with the provided diagrams and drawings.
The two low-voltage switchboards will be connected to the 0.8 kV low-voltage winding of a transformer. The transformer will have a rated power of 5,000 kVA and a voltage ratio of 0.8/35 kV.
The medium-voltage switchgear pass-through type will be equipped with a transformer protection cell, metering cell and one outgoing feeder.
A monitoring system will be implemented at the photovoltaic power plant to track parameters and energy production. In the 35 kV medium-voltage switchgear, which connects to the BESS local utility grid, remote control, telemetry, and line switching equipment will also be installed, operating at the point of synchronisation. The possibility of further expansion (connection) of PV+BESS equipment of the first stage to the 35 kV power grids of the second and subsequent stages and further parallel operation with the power system is envisaged.
The photovoltaic modules will be mounted on supporting steel structures, arranged in parallel rows. The structures will consist of standard mounting tables with a 25° tilt angle, each holding two rows of vertically positioned modules.
There will be two types of structures:

- A table with two rows, each row holding 28 modules.
- A table with two rows, each row holding 14 modules.

7.7.1.1. Electrical Safety

For the purposes of electrical safety, each individual structural unit supporting the photovoltaic modules will be grounded to a common earthing system, in full compliance with all applicable standards and electrical safety regulations. During the installation of the supporting structures, all technical safety requirements explicitly stated in the technical documentation must be strictly observed.

7.7.1.2. Direct Current Section

The total number of strings is **2184**. The strings have been designed to meet the **technical specifications of the selected inverters**. The number of modules connected in series has been determined so that the resulting voltage is optimal for the **maximum efficiency** of the inverters.
The strings are connected to the inverter inputs according to a **manufacturer-specified configuration**, ensuring that the **voltage and current values** do not exceed the limits set by the manufacturer.
The photovoltaic power plant includes **112 high-efficiency three-phase inverters**. Each inverter is equipped with **DC disconnect switches (ESS)** on the PV module side. The ESS switch ensures safe operation of the DC circuits by disconnecting the PV generator during maintenance of the inverter unit.
Inverters and PV Modules are the same for both Stages I and II.

7.7.2. Electrical parameters

Table 7-9: Electrical Parameters of the Photovoltaic System

Parameter	Value
Maximum AC Power	4900 kW
Maximum DC Power	5350,8 kW
MV Grid Voltage	35 kV
Frequency	50 Hz
Power Factor (Cos φ)	0.99 (leading) – 0.8 (lagging)

7.7.2.1. Installation of Photovoltaic Modules

The electrical terminals of the photovoltaic modules are located on their rear side and are insulated. From the insulated junction box on the back of each module, insulated solar cables extend, terminating with MC4-type connectors. The connectors have a protection rating of IP67.
The modules are connected in series to form strings without the need for additional cables. The cables integrated into each module are of sufficient length and are equipped with male and female connectors, allowing for direct series connection.

Additional solar cable is required to extend both ends of the assembled string to the distribution boards. These single-core flexible solar cables with rubber insulation feature:

- Class 5 flexible copper conductor;
- PVC plastisol insulation for the core;
- PVC plastisol outer sheath;
- Operating temperature range: -40°C to +90°C;
- UV resistance.

7.7.3. Cabling

7.7.3.1. DC Cabling

The interconnection of the modules within each string is performed using the factory-installed cables and connectors. The extension of the end cables of the strings is carried out with special UV-resistant double-insulated DC solar cable.
Each string is connected to the inverters using **solar cables 2x1x4mm² or 2x1x6mm²**, as per the provided wiring diagrams. The solar cables are routed along the supporting structures of the modules and are **mechanically secured**. As the PV installation is outdoors and subject to direct atmospheric exposure, the securing of cables must provide sufficient mechanical strength. All cables, cable trays, paths, and fixing elements must be resistant to environmental factors (dust, wind, high humidity, rain, snow, and solar radiation).
DC wiring will be laid in **trenches of varying depths**, depending on the number of cables, for the part of the plant located on the ground. For the rooftop part of the plant, DC cables will be routed in **metal cable trays**.
Cable ends must have extra length reserved:

- **Up to 1 meter** on the inverter side (formed into a loop);
- **0.5 meters** on the module side.
  The **minimum bending radius** of the cable must be **no less than 15 times the outer diameter** of the cable. It is mandatory to follow the rule: "Cable bending radius must not be less than the manufacturer's minimum allowed value." Special attention must be paid to **contact points** between cables and any objects or structures. **Direct contact** with surfaces that could damage cable insulation is not permitted.

7.7.3.2. AC Cabling

The electrical connections between the 350 kWp inverters and the LV switchgear will be made using NAYY 4x300mm² cables from each inverter. These cables will be laid in cable ducts, as shown in the respective drawings.
The **35kV connection** between the compact transformer station and the distribution grid will be carried out using a **35kV 3x1x95mm² cable**. This cable will be laid in a cable trench from the first compact transformer station to the next compact transformer station **in a ring pattern and then to the 35 kV switchgear** . The total cable length is approximately max. **6400 meters**.
Cables will be selected with **double insulation** made from **flame-retardant materials**. For additional protection, if deemed necessary by the client, the cables will be **installed in conduits** along the **metal structure and cable trays**.
All installers must be **qualified and certified** to carry out this type of work.

7.7.4. Equipotential Bonding and Grounding Installation

To protect the photovoltaic system from **overvoltages**, strict adherence to the specified grounding and equipotential bonding system must be ensured.
All **metal structural elements** and **mounting structures** must be connected to an **internal grounding loop**, including flexible connections to doors and grilles. These connections must be **electrically reliable**. Multiple loops will be created and connected in a **star configuration** to a **common grounding busbar**. The inverter enclosures and external metallic parts (PV module frames and mounting structures) will also be connected to this common grounding bar.
A **grounding loop** will be constructed around the **roof-mounted sections** of the plant using **galvanised steel wire Ø8 mm**. This wire will connect all metallic components of the plant and will be grounded using **rods driven into the ground near the buildings**.
Grounding loops around **Compact Transformer Station 01 and 02** will be constructed using **40x4 mm galvanised steel strips** and **L 63/63/6 mm galvanised grounding rods**. The connection to the internal grounding system will also use a 40x4 mm galvanised strip.

The described star-shaped equipotential bonding system, which is both grounded and neutralised, ensures voltage equalisation and a reliable overvoltage protection concept.
All non-current-carrying metal parts of the photovoltaic modules, inverters, and distribution/control panels will be connected to the grounding system.
After the grounding installation is completed, the **resistance value must be measured**, and a **compliance protocol** must be prepared.

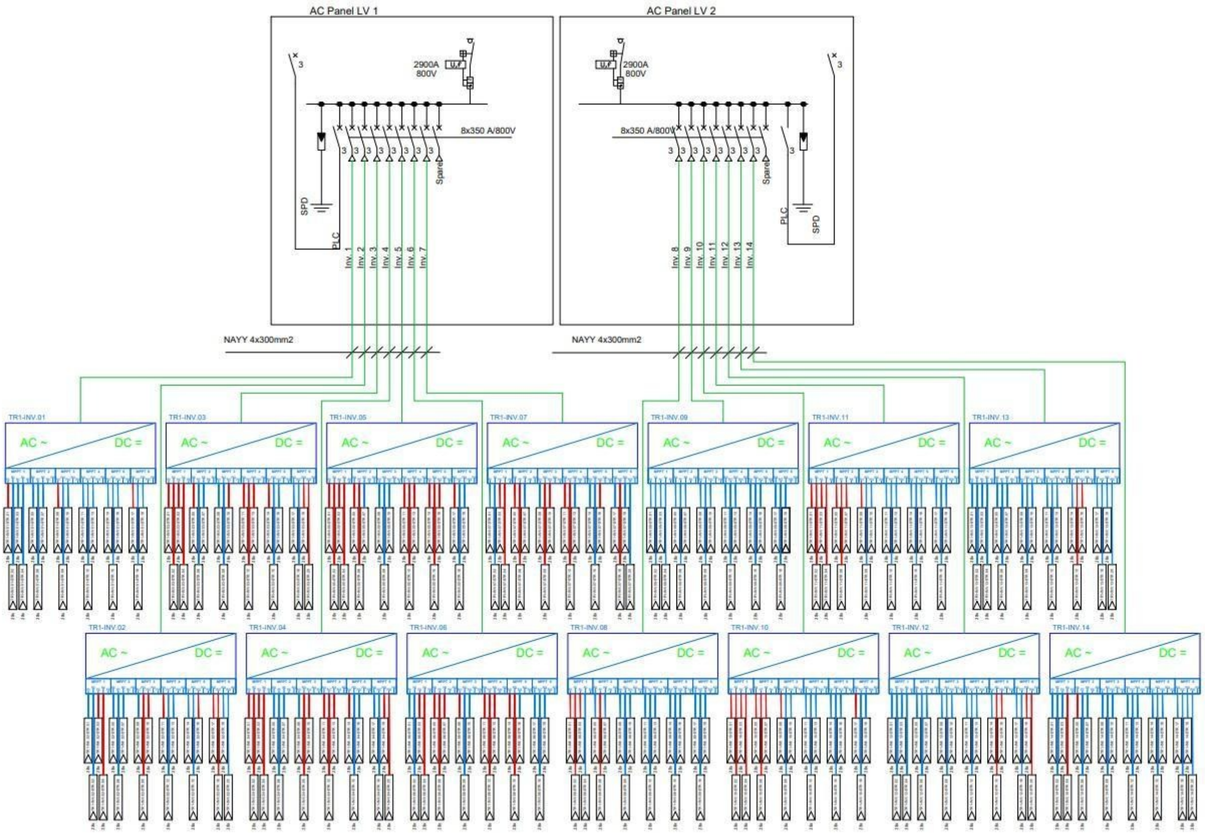


Figure 7-5: Diagram of direct current and alternating current circuits for low voltage (LV) (the same applies to the other 7 KTPs)

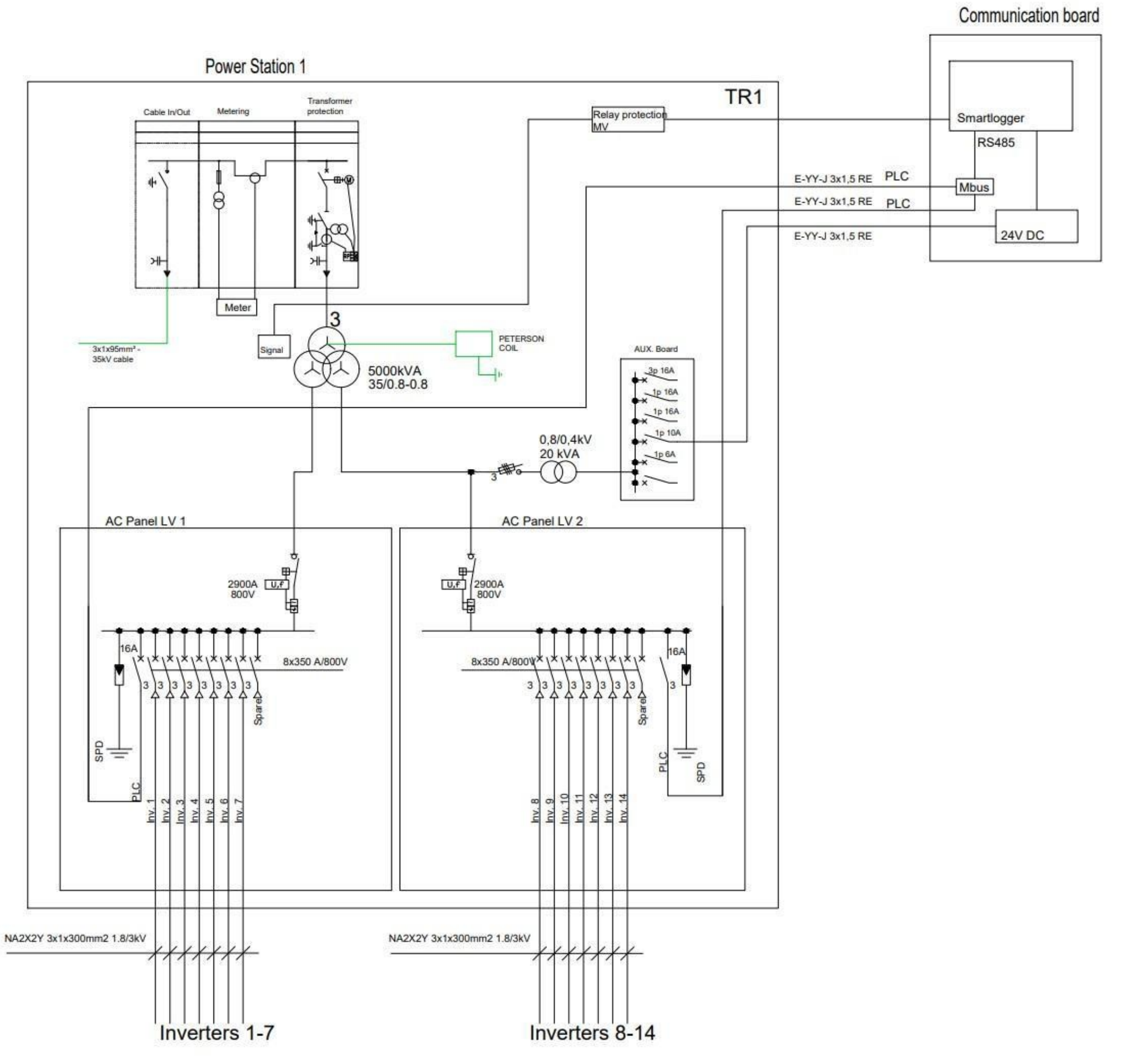


Figure 7-6: Diagram of a compact transformer substation 35/0.8/0.8 kV (the same applies to the other 7 KTPs)

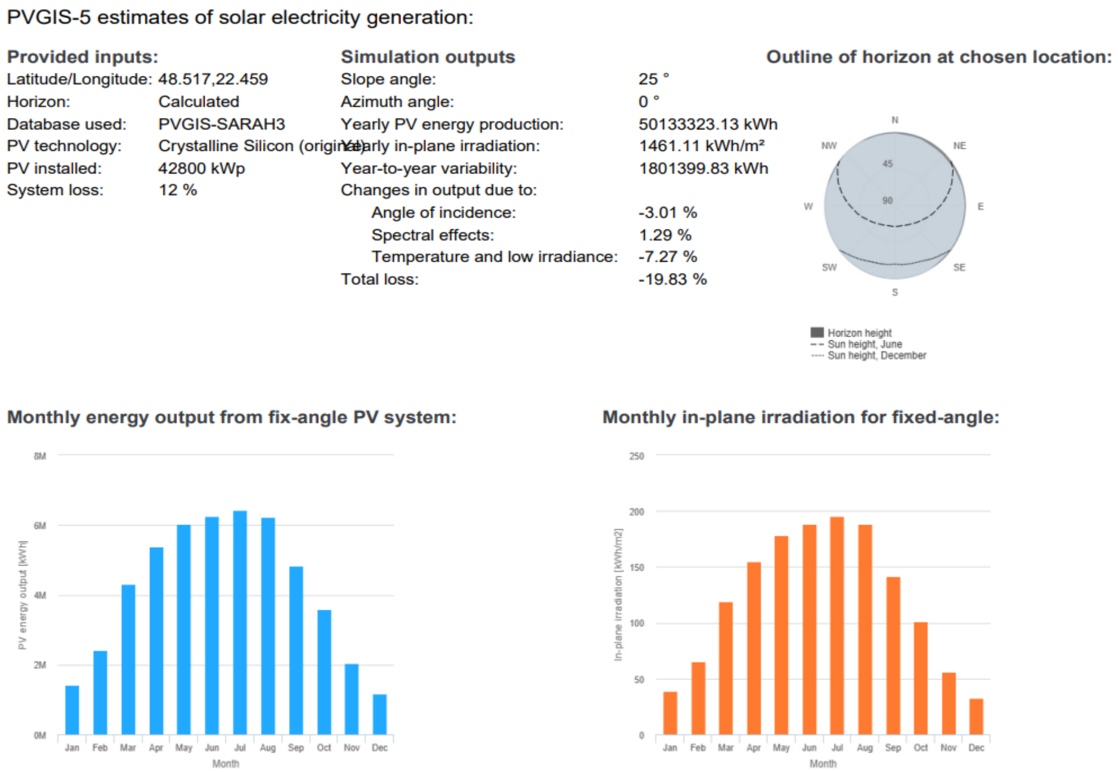


Figure 7-7: Results of the calculation of average annual electricity production volumes

Table 7-10: Delivery and Execution Timelines

No.	Item	Execution Time (months)
1	Equipment delivery	9-12 months
2	Design and construction works	Up to 12 months

7.7.4.1. Supplemental Power (Grid & PPAs)

To increase the electrolyser's utilisation beyond the hours of peak solar generation, the project will source additional renewable power through two RED II-compliant mechanisms:

- **Power Purchase Agreements (PPAs):** N1C will leverage its broader renewable energy portfolio by signing internal PPAs with its other new-build wind and solar projects, such as those under development in the Odessa Oblast. Sourcing power from wind assets, which have a different generation profile from solar, is particularly valuable for enabling production during nighttime hours and winter months.
- **Grid Purchases:** The project will be designed to draw power from the grid during specific periods when there is a surplus of renewable energy generation across the Ukrainian system, thereby helping to reduce grid-wide curtailment. This mode of operation is explicitly permitted under the RED II Delegated Acts and turns the electrolyser into a valuable source of flexible demand for the grid operator. The financial model will factor in the cost of this grid electricity, based on current Ukrainian business tariffs (approximately 0.177 USD/kWh or ~0.16 EUR/kWh as of early 2025), which will influence the operational strategy.

7.8. BESS Project with Installed Power of 2 MW / 2 MWh

The Battery Energy Storage System (BESS) foreseen for the first stage of the project is designed as a pilot-scale storage unit fully integrated with the photovoltaic (PV) power plant and the hydrogen production system.

The BESS parameters are optimised to fulfill the following functions:

- Daily energy shifting of PV generation, enabling limited nighttime operation of the electrolysers and improving the overall efficiency of utilisation of electrical energy (KIE) from renewable sources.
- Ensuring power supply to critical technological subsystems of the hydrogen plant in island mode, allowing short-term autonomous operation without connection to the external power grid.
- Operational smoothing and stabilisation of the electrolyser load during short-term PV fluctuations, reducing stress on power electronics and auxiliary systems.

7.8.1. Electrical Configuration – Stage 1

The schematic solution for the first stage of the project includes the following configuration:

- A 35 kV cable line from the PV station is connected to an integrated SF_6-insulated medium-voltage (MV) switchgear of pass-through type.
- The 35 kV BESS connection is implemented at the MV level, supplying power directly to the electrolysers.

Figure 7-8: Site Plan for PV+BESS Layout – First and Second Stages

This configuration enables simple integration of the pilot BESS while maintaining a compact layout and minimizing MV equipment complexity.

The MV-side power supply scheme is designed with scalability in mind, allowing future expansion of the number of electrolysers and a progressive increase of PV+BESS capacity in subsequent project stages.

7.9. BESS project with installed power 20 MW / 20 MWh

For the second stage of the project, the BESS capacity is increased to 20 MW / 20 MWh, reflecting the transition from pilot operation to an early commercial-scale hydrogen production system. At this stage, the BESS plays a more pronounced role in system flexibility, grid interaction, and operational reliability.

The BESS parameters are optimised for:

- **Daily energy storage of PV generation**, enabling extended electrolyser operation beyond daylight hours and further improving the electrolyser's capacity utilisation factor (KIUM).
- **Provision of auxiliary and backup power** to the hydrogen plant's technological subsystems in island mode.

- **Enhanced load management and peak shaving** at the MV/HV interface, supporting stable operation during dynamic operating conditions.

7.9.1. Electrical Configuration – Stage 2

The schematic solution for the second stage includes a reinforced and more resilient electrical architecture:

- The **35 kV switchgear of the PV station (KTP)** is connected via overhead lines to the **35 kV section of the 110/35 kV substation**, arranged in a **ring configuration**.
- Two independent electrical rings are envisaged, each connected to separate 35 kV bus sections, providing a high level of redundancy and operational flexibility.
- Each ring includes multiple PV station KTPs with a normally open circuit breaker located at the electrical center of the ring.
- The **35 kV overhead lines from the BESS container switchgear (ZRU)** are connected to the same ringed MV network.
- Power supply to one or more electrolysers is provided from the 35 kV bus sections, depending on the selected project configuration.

This MV-side power supply scheme ensures high reliability and maintainability, enables operational continuity during maintenance or fault conditions, and allows for future expansion of both electrolyser capacity and PV+BESS infrastructure. The configuration is fully compatible with the project’s long-term development pathway, considering a potential total installed capacity growth up to 400 MW.

7.9.1.1. HV Grid Connection

The project requires a robust connection to the high-voltage transmission network operated by NEC Ukrenergo. An interconnection feasibility study was initiated in September 2023 for a connection to the new 400kV Baranyntsi substation, located just 1 km from the site. This study will determine the final technical specifications, cost, and timeline for the construction of the short high-voltage line and the required switchgear at the substation. The analysis will incorporate Ukraine's latest grid connection regulations, including requirements for advance payments and capacity reservation.

7.10. Technical description of equipment and solution

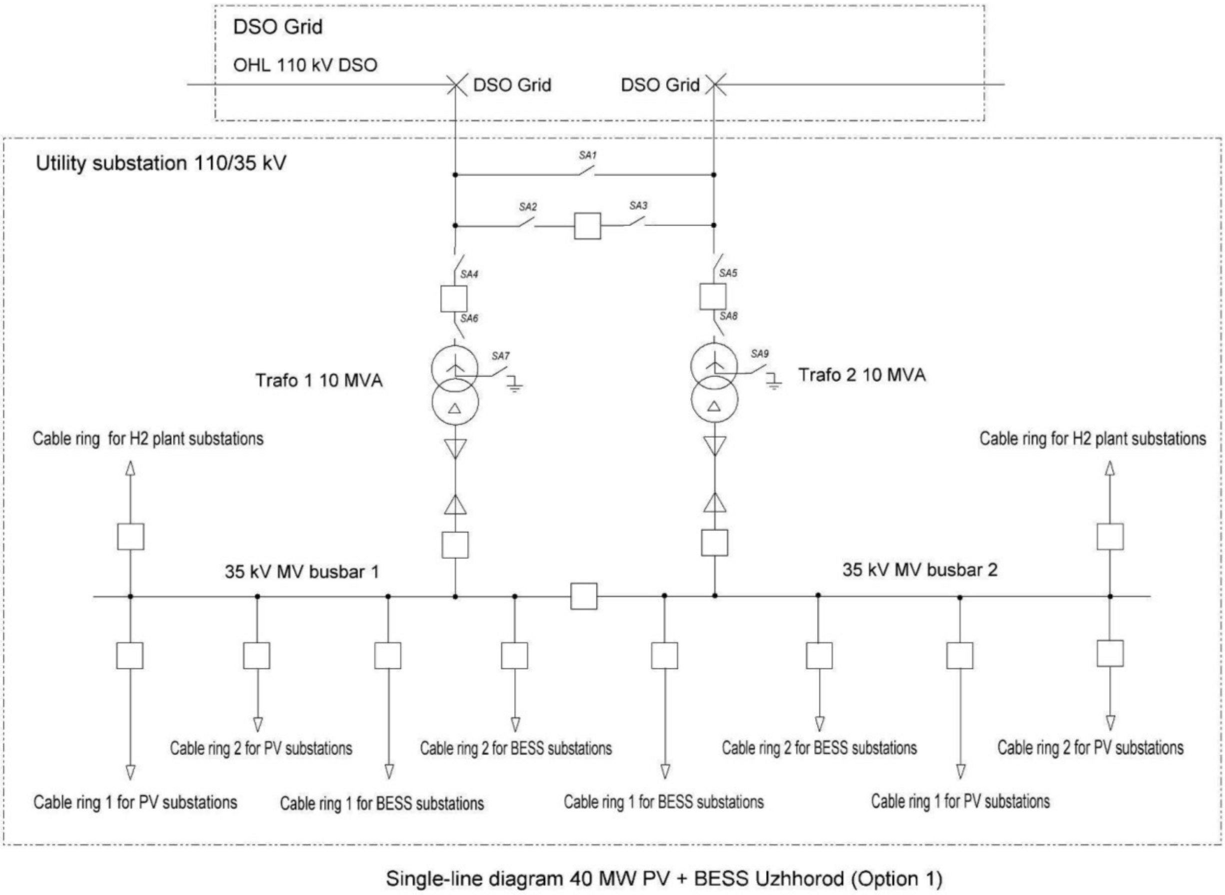


Figure 7-9: Single-line diagram of the connection of the PV+BESS+H_2 plant second stage (option for six electrolysers with a unit capacity of 3 MW and a connection scheme of the MV through-type connection

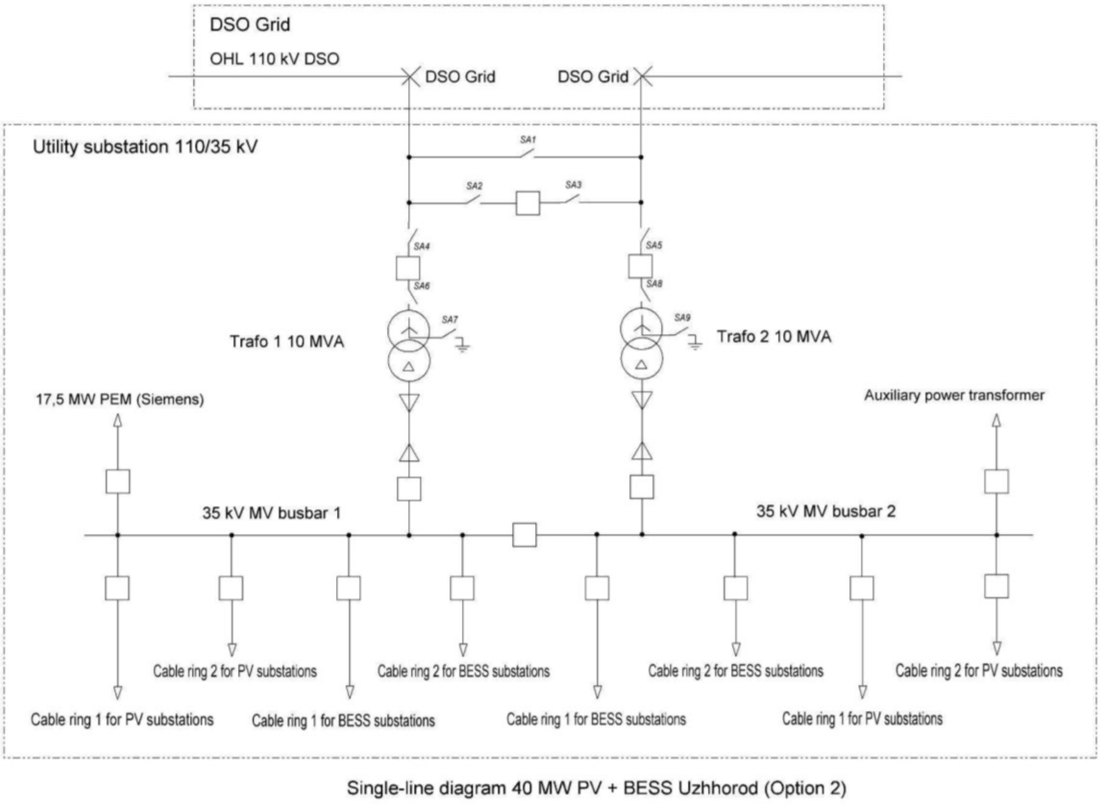


Figure 7-10: Single-line diagram of the connection of the PV+BESS+H_2 plant second stage (option for one Siemens electrolyser with a capacity of 17.5 MW and a radial connection scheme)

General Provisions

This section defines the technical composition, main parameters, and completeness of the equipment supplied under the project for the 35/0.4 kV Outdoor Prefabricated Switchgear Unit (KRPZ-35/0.4 kV). All equipment is manufactured in accordance with applicable technical specifications, complies with ISO 9001:2015 and ISO 14001:2015 standards, is tested in an electrical laboratory, and is ready for installation and commissioning at the Customer's site.

Table 7-10: Power Transformer

Type	Dry-type
Rated power	3200 kVA
Voltage	35/0.4 kV
Winding connection	Δ / Yn-11
Energy efficiency class	not lower than ECO-2
Quantity	1 pcs

Final Provisions

The supplied equipment is intended for use as part of an industrial energy complex and ensures reception, distribution, and metering of electrical energy at voltage levels of 35 kV and 0.4 kV. The system provides reliable power supply to consumer facilities, including a hydrogen electrolysis plant (2.5 MW) and an energy storage system (2 MW). All components are technically compatible, have appropriate insulation levels, and comply with electrical safety standards.

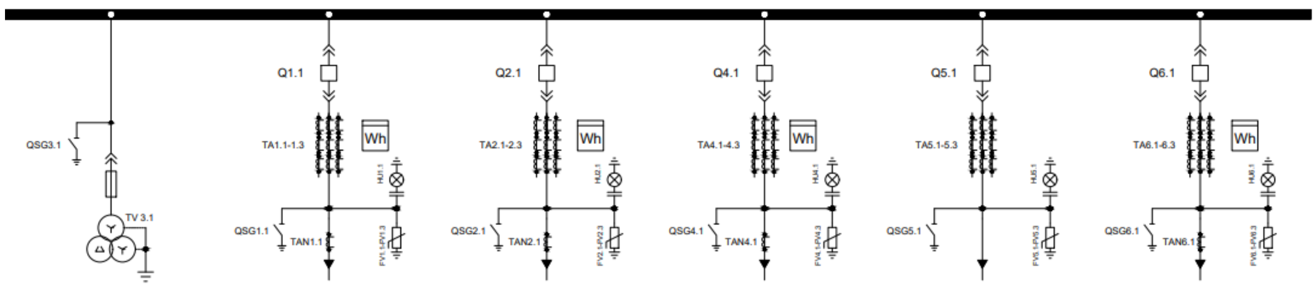


Figure 7-11: High-Voltage Switchgear and Transformer Interface – Single-Line Diagram

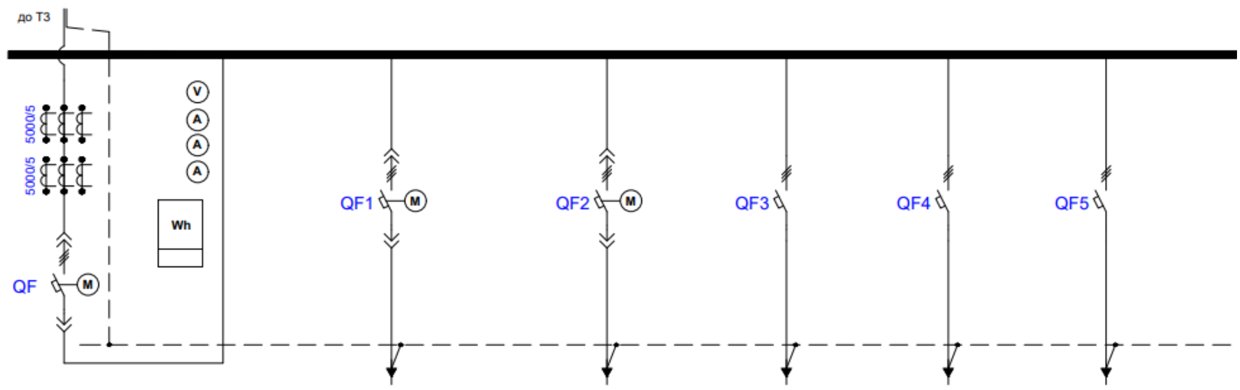


Figure 7-12: LV Main Distribution Panel (MDP) – Electrical Single-Line Diagram

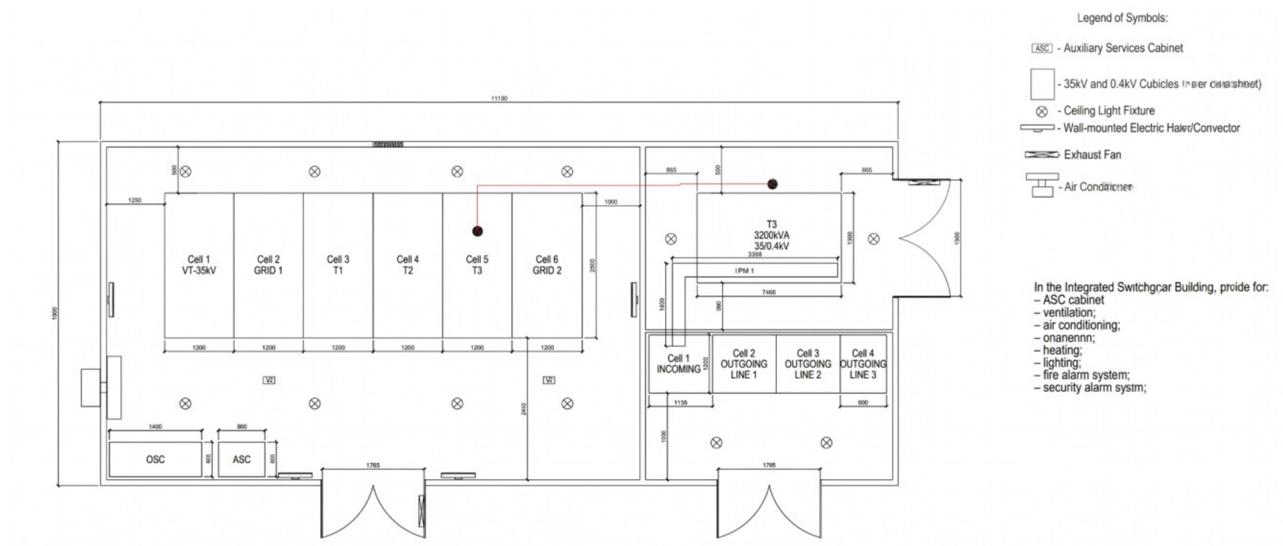


Figure 7-13: Floor Plan of the Electrical Distribution Room (Switchgear Layout)

7.10.1. Grid Services Potential

The PEM electrolyser's ability to rapidly modulate its power consumption makes it an ideal asset for providing ancillary services to the electricity grid. The study will analyse the potential for the project to participate in Ukraine's ancillary services market, offering services such as frequency response and demand-side management. This would not only create an additional, non-hydrogen-based revenue stream but also contribute to the stability and resilience of the Ukrainian power system, a national priority, especially in the context of its integration with the ENTSO-E network.

7.10.2. Hydrogen Transport and Offtake Logistics

Hydrogen transport and offtake logistics for the Project are developed within the framework of existing Ukrainian gas transmission legislation, EU cross-border interconnection practices, and emerging hydrogen-specific regulatory instruments. While the detailed legal analysis is addressed in a dedicated regulatory section, this chapter focuses on those regulatory elements that directly affect technical feasibility, infrastructure design, and implementation timelines.

The Project benefits from a rare alignment of technical feasibility and regulatory permissibility, stemming from:

- the physical availability of transmission infrastructure,
- the applicability of existing gas transmission procedures to hydrogen on an interim basis,
- and the openness of relevant transmission system operators (TSOs) to pilot hydrogen transmission projects.

7.10.2.1. Project Site Location and Physical Interface with the Gas Transmission System

The hydrogen production facility is located approximately **500 meters from the Chaslivtsi Gas Compressor Station**, an operational asset of the **Gas Transmission System Operator of Ukraine (GTSOU)**.

Under Ukrainian legislation, compressor stations form part of the **Unified Gas Transmission System of Ukraine (UGTS)**, regulated primarily by:

- the **Gas Transmission System Code of Ukraine** (approved by NERC, Resolution No. 2493),
- and the **Law of Ukraine "On the Natural Gas Market" (No. 329-VIII)**.

From an infrastructure standpoint, the proximity of the Project site to the Chaslivtsi station allows the hydrogen connection to be treated as a **short dedicated branch pipeline**, rather than a mainline transmission asset. This distinction materially reduces both engineering complexity and approval timelines.

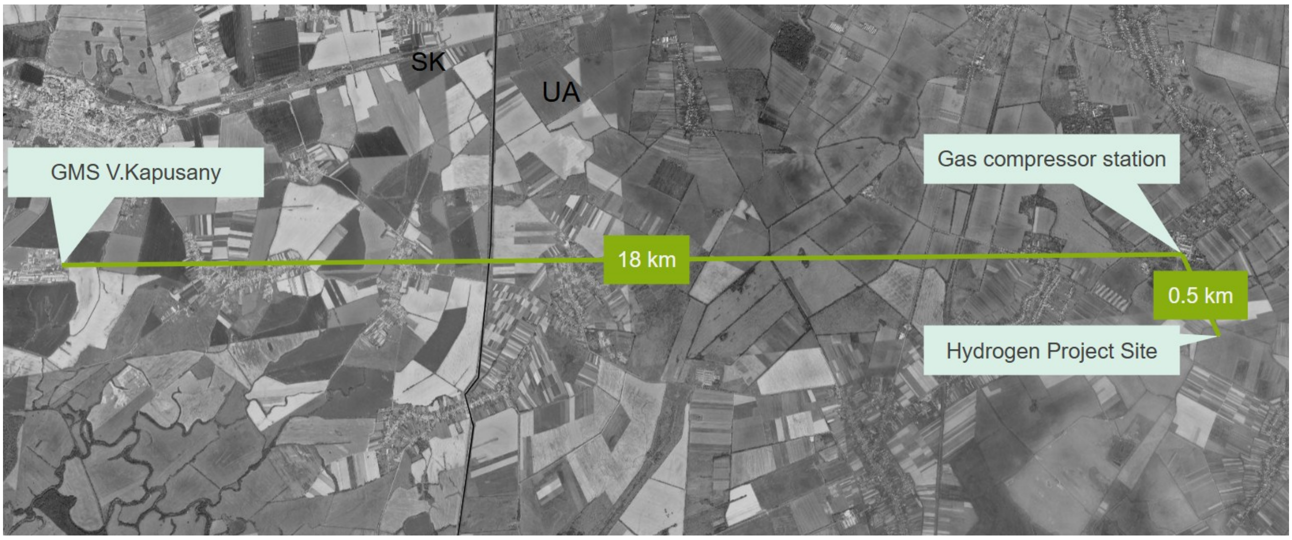


Figure 7-14: H_2 Cross-Border Gas Connection in Close Proximity to the Project Site

7.10.2.2. Applicable Regulatory Instruments for Hydrogen Pipeline Injection

Interim Regulatory Basis for Hydrogen Transmission in Ukraine

Ukraine does not yet have a fully hydrogen-specific transmission code. However, hydrogen pilot projects may be implemented under the existing gas regulatory framework through **project-specific Technical Conditions (TU – Technical Specifications)** issued by the TSO.Key applicable instruments include:

- **Gas Transmission System Code of Ukraine**
  Governs pressure regimes, connection procedures, metering, and quality control for gas transmission assets.
- **DSTU ISO 14687**
  Ukrainian adoption of ISO standards defining hydrogen quality requirements, including purity, moisture content, and contaminant limits. [36]

- **Technical Conditions (TU) Procedure**
  A legally established mechanism allowing non-standard gas compositions or pilot configurations to be approved on a case-by-case basis by the TSO. [134]

This mechanism has been confirmed by GTSOU as the **primary practical pathway for pilot hydrogen injection projects** prior to the formal adoption of a hydrogen transmission code. [152]

7.10.2.3. Cross-Border Context and TSO Coordination

The Project's logistics concept is reinforced by active engagement with neighboring EU transmission system operators, particularly:

- **Eustream a.s. (Slovakia)** – gas TSO operating the Slovak transmission network,
- **GTSOU (Ukraine)** – operator of the Ukrainian transmission system. [132]

Memoranda of Understanding (MoUs) concluded in December 2025 between:

- GTSOU and Eustream, [133]
- and between Ukrainian and Slovak gas authorities, explicitly recognise hydrogen transmission as a future use case for the existing cross-border infrastructure. These MoUs support technical feasibility studies, pressure regime assessments, and quality alignment for hydrogen transport from Ukraine into Eastern Slovakia.

While current commercial gas flows between Uzhhorod and Slovakia are limited, the physical interconnection remains operational, preserving the hydraulic and technical capability for future hydrogen transmission.

7.10.2.4. Phased Hydrogen Transport Strategy

Road-Based Hydrogen Logistics

For the pilot and early commercial stages, hydrogen transport will rely on **compressed gaseous hydrogen (CGH_2)** logistics. [99]

Key parameters:

- On-site compression to **350–500 bar**
- Loading into certified tube trailers compliant with ADR regulations
- Typical payload: **250–1,000 kg H_2 per trailer**, depending on configuration [115]

This approach is consistent with:

- EU ADR transport regulations,
- standard industrial hydrogen supply practices,
- and early offtake volumes expected during pilot deployment.

Road transport enables rapid market entry without dependency on pipeline commissioning.

7.10.2.5. Transition Threshold to Pipeline Transport

Economic and operational modeling indicates that road-based logistics become inefficient once hydrogen production exceeds several thousand tonnes per year, corresponding to electrolyser capacities above approximately 100 MW. [125]

Key limiting factors include:

- exponential increase in truck movements,
- escalating logistics OPEX,
- site congestion and safety management complexity.

At this scale, pipeline transport becomes the only viable long-term solution, both technically and economically.

7.10.2.6. Pipeline Injection Concept and Operating Parameters

Injection Pressure and Flow Regime

Based on preliminary hydraulic assessments and operator input, the indicative injection pressure at the GTS interface is expected to be in the range of 50–70 bar, depending on downstream operating conditions.

Compression Implications by Electrolyser Technology

- **PEM Electrolysis**
  Typical outlet pressure: 30–40 bar
  → single-stage booster compression sufficient
- **Alkaline Electrolysis**
  Typical outlet pressure: 1–15 bar
  → multi-stage compression required, resulting in:
    - higher CAPEX,
    - increased OPEX,
    - additional electrical losses

These differences are directly reflected in the infrastructure layout and energy balance of the Project.

7.10.2.7. Dedicated Hydrogen Connection Pipeline

The dedicated hydrogen pipeline connecting the plant to the Chaslivtsi compressor station will have:

- length: **<1 km**,
- design pressure aligned with transmission requirements,
- materials selected in accordance with hydrogen compatibility standards,
- integrated isolation valves and monitoring instrumentation.

Due to its limited length, the pipeline is expected to:

- avoid complex routing constraints,
- fall outside major environmental impact thresholds,
- be constructed within standard project timelines.

7.10.2.8. Implementation Timeline and Permitting Sequence

The hydrogen connection infrastructure will be implemented under the following sequence:

1. Issuance of Technical Conditions (TU) by GTSOU
2. Detailed engineering of connection pipeline and metering interface
3. Construction and installation
4. Commissioning and acceptance testing

Given the limited scope and proximity to existing assets, the hydrogen connection is **not expected to constitute a critical path item** for overall project delivery.

7.10.3. Site Infrastructure and Logistics

7.10.3.1. Water Infrastructure

Based on the selected water sourcing strategy (municipal connection or on-site wells), the necessary infrastructure will be designed. This will include intake pipelines, on-site raw water storage tanks to ensure a buffer for continuous operation, and a wastewater discharge system compliant with local environmental regulations.

7.10.3.2. Construction and O&M Logistics

The project's location in Western Ukraine, bordering four EU member states, is a significant logistical advantage that de-risks the construction phase.

- **Inbound Logistics:** Heavy and specialised equipment, such as electrolyser stacks and transformers, can be imported via secure EU ports (e.g., Gdansk in Poland or Constanta in Romania) and transported overland by truck or rail, bypassing potential risks associated with Ukrainian seaports.
- **Labor and Services:** The project will prioritise sourcing construction labor and operational staff from the local Zakarpattia region, contributing to the local economy. A detailed plan for operations and maintenance (O&M) will be developed, outlining requirements for spare parts inventory, routine maintenance schedules, and specialised technical support.

8. Environmental, Social, and Governance (ESG) Compliance

Adherence to the highest international standards of Environmental, Social, and Governance (ESG) performance is not an optional extra; it is a core requirement for securing financing from International Financial Institutions (IFIs) and a central tenet of the H2Uppp program's commitment to sustainable development. This section details the project's framework for ESG compliance, which is designed to meet and exceed both Ukrainian national law and the stringent requirements of the EBRD and IFC.

8.1. Environmental and Social Management System (ESMS)

The project will develop and implement a comprehensive Environmental and Social Management System (ESMS) based on the "plan-do-check-act" cycle. This ESMS will serve as the overarching framework for managing all ESG risks and impacts throughout the project's lifecycle, from construction to decommissioning. It will be designed in full alignment with the requirements of IFC Performance Standard 1 (Assessment and Management of Environmental and Social Risks and Impacts) and EBRD Performance Requirement 1, ensuring a systematic and auditable approach to ESG management. [41]

8.2. Environmental Impact Assessment (EIA)

8.2.1. Scope and Methodology

A full-scope Environmental Impact Assessment (EIA) will be conducted, serving as the primary tool for identifying, evaluating, and mitigating the project's environmental footprint. While the EIA will follow the procedural requirements of Ukrainian law, its scope and methodology will be expanded to satisfy the more comprehensive requirements of the EBRD's Environmental and Social Policy (2019) and the IFC Performance Standards. This ensures the project's bankability and adherence to good international practice. The assessment will cover direct, indirect, and cumulative impacts across the project's area of influence. [44]

8.2.2. Key Impact Areas

The EIA will focus on several key potential impact areas specific to a large-scale electrolysis and solar PV project:

- **Water Resources:** The assessment will analyse the potential impact of water abstraction on local surface and groundwater resources, particularly if on-site wells or aquifer abstraction is chosen. It will model the potential for drawdown and impacts on other water users and aquatic ecosystems, proposing mitigation measures to ensure sustainable use. [52] [54]
- **Biodiversity:** In line with EBRD PR6 (Biodiversity Conservation and Sustainable Management of Living Natural Resources), the EIA will include a comprehensive biodiversity baseline study of the 37-hectare site and surrounding area. It will assess potential impacts on habitats and species from land clearing for the PV plant and construction activities. A mitigation hierarchy will be applied, prioritizing avoidance of sensitive areas, followed by minimisation, restoration, and, if necessary, offsetting of residual impacts.
- **Construction Impacts:** The temporary impacts during the construction phase, including noise from machinery, dust generation, and increased traffic on local roads, will be assessed. A detailed Construction Environmental and Social Management Plan (CESMP) will be developed to manage these impacts through specific mitigation measures (e.g., work hour limitations, dust suppression techniques, traffic management plans).
- **Resource Efficiency and Pollution Prevention:** The project's design will be assessed against EBRD PR3 (Resource Efficiency and Pollution Prevention), ensuring the use of Best Available Techniques (BAT) to minimise energy and water consumption and prevent pollution.

8.2.3. Deliverable: EIA Template

As a key deliverable for the H2Uppp program, a standardised, IFI-compliant EIA template is provided in Appendix E. This template serves as a best-practice guide for future hydrogen developers in Ukraine, outlining the necessary scope, structure, and content to meet the due diligence requirements of international lenders.

8.2.4. Social Impact and Stakeholder Engagement

As a key deliverable of the H2Uppp program, a standardised Environmental Impact Assessment (EIA) Template has been developed to ensure full compliance with Ukrainian environmental legislation while aligning with European Union directives and international financial institution (IFI) requirements.
The template is designed as a replicable framework for hydrogen projects in Ukraine, covering the full lifecycle from pilot stage to utility-scale deployment. It integrates:

- Law of Ukraine "On Environmental Impact Assessment" No. 2059-VIII
- EU EIA Directive 2011/92/EU (as amended by 2014/52/EU)
- EBRD Performance Requirement 1 [68]
- IFC Performance Standard 1

The template ensures that future hydrogen projects are legally compliant, technically robust, and finance-ready.

8.2.4.1. Project Definition, Legal Framework and Baseline Conditions

The template consolidates all regulatory, technical, and baseline inputs into a unified structure covering:

- Detailed project description (location, coordinates, land status, capacity by stage, hydrogen output in t/year)
- Technological configuration (electrolysis type, compression, storage, auxiliary systems)
- Associated infrastructure (water abstraction, wastewater systems, grid connection, pipeline interface)
- Applicable Ukrainian environmental legislation and sectoral standards (DSTU, DBN)
- International conventions and EU alignment considerations
- Required permits and approval sequence
- Sanitary protection zone (SPZ) justification

In addition, the template requires comprehensive documentation of baseline environmental conditions, including:

- Meteorology and climate
- Air quality
- Soil and land use
- Hydrogeology and groundwater
- Surface water bodies
- Biodiversity and protected areas
- Existing background noise levels

This baseline establishes the reference scenario against which all project impacts are assessed.

8.2.4.2. Environmental Impact Assessment and Risk Analysis

The EIA Template structures impact assessment across all environmental components in an integrated manner, including:

- Air emissions during construction and operation
- Noise propagation modeling (in accordance with DBN V.1.1-31:2013)
- Water abstraction volumes and wastewater discharge
- Soil disturbance and restoration measures
- Waste classification and management
- Biodiversity and habitat disturbance

It also incorporates structured risk assessment for:

- Hydrogen leakage and explosion scenarios
- ATEX zoning and hazardous area classification
- Fire safety systems and emergency response planning
- Seismic and extreme weather resilience

The template applies the mitigation hierarchy (avoid–minimise–mitigate–monitor) and requires quantification wherever feasible.

8.2.4.3. Environmental Management and Monitoring System

The template includes a fully structured Environmental Management Plan (EMP), integrating:

- Mitigation measures by impact category

- Defined monitoring indicators
- Assignment of responsibilities
- Monitoring frequency and reporting obligations
- Compliance verification procedures

Monitoring programs typically include:

- Groundwater sampling
- Air quality monitoring
- Noise measurements at SPZ boundary
- Waste tracking documentation
- Occupational exposure monitoring

The template is designed to be directly integrated into the Project's Environmental and Social Management System (ESMS), ensuring operational continuity beyond permitting.

8.2.4.4. Stakeholder Engagement, Cumulative Effects and IFI Alignment

The EIA Template embeds stakeholder engagement requirements under Ukrainian law, including:

- Publication of EIA notification
- Public hearings
- Structured response to comments
- Disclosure of the final EIA conclusion

In parallel, it incorporates IFI-compatible documentation standards, including:

- Risk categorisation methodology
- Gap analysis between Ukrainian and EU standards
- Corrective Action Plan (if required)
- Cumulative impact assessment

Cumulative assessment covers:

- Regional industrial development
- Grid infrastructure expansion
- Water resource competition
- Potential cross-border environmental implications

A Non-Technical Summary (NTS) is included as a mandatory component to ensure transparency and accessibility for local communities and international financiers.

8.2.5. Stakeholder Identification and Analysis

A systematic process of stakeholder mapping will be undertaken to identify all individuals, groups, and organisations that could be affected by the project or have an interest in its outcomes. This includes local communities in and around the Chaslivtsi municipality, landowners, local and regional government authorities, Ukrainian TSOs (Ukrenergo, GTSOU), and civil society organisations.

8.2.6. Stakeholder Engagement Plan (SEP)

Based on the stakeholder analysis, a formal Stakeholder Engagement Plan (SEP) will be developed, in line with the principles of EBRD PR10 (Information Disclosure and Stakeholder Engagement) and IFC PS1. The SEP, a draft of which is included in the Appendices, will be a living document that guides the project's communication and consultation activities. It will outline a clear process for:

- **Information Disclosure:** Proactively sharing relevant and understandable project information with stakeholders at key project milestones.
- **Meaningful Consultation:** Organizing public meetings and targeted consultations to solicit feedback from affected communities and other stakeholders, ensuring their views are considered in project design and decision-making.
- **Inclusive Engagement:** Ensuring that vulnerable or marginalised groups have the opportunity to participate in the consultation process. [43]

8.2.7. Community Benefits

The project is expected to generate significant positive impacts for the local community and the country. These benefits, which will be quantified and highlighted in communications with stakeholders, include:

- **Local Revenue:** Rent payments for the land will provide a stable income source for local municipalities and landowners.
- **Tax Contributions:** The project company, registered locally, will contribute corporate taxes that directly benefit the local community's budget.
- **Job Creation:** The project will create new, skilled jobs during both the construction and long-term operational phases, supporting the region's economic development.

8.2.8. Grievance Mechanism

A formal, transparent, and accessible grievance mechanism will be established, as required by IFI standards. This mechanism will allow affected individuals and communities to raise concerns or complaints about the project's environmental or social performance and receive a timely response. The process will be designed to resolve issues at the local level where possible, reducing the potential for conflict and project delays.

8.3. Governance and Permitting

8.3.1. Corporate Governance

The project's special purpose vehicle (SPV) will be structured to meet the high standards of corporate governance and transparency required by IFIs. This includes establishing a clear organisational structure, implementing robust financial controls and reporting mechanisms, and adopting policies on anti-corruption and ethical conduct.

9. Economic and Financial Analysis

This section provides a rigorous and transparent assessment of the project's financial viability. It details the capital and operational cost estimates, presents the outputs of a comprehensive financial model, and outlines a robust financing strategy designed to make the project bankable in the complex Ukrainian investment climate.

9.1. Cost Estimation (CAPEX and OPEX)

9.1.1. Methodology

The cost estimates presented in this study are prepared to a Class 4 standard, as defined by the Association for the Advancement of Cost Engineering (AACE International). This level of estimate is appropriate for a feasibility study and is expected to have an accuracy range of +/- 15% to 30%. The estimates are based on a combination of preliminary engineering designs, budgetary quotes from major equipment suppliers, and cost data from analogous renewable energy and industrial gas projects. Basic project configurations for different scenarios are illustrated in the table below.

Table 9-1: Basic Project Configurations for Different Stages

Scenario	Electrolyser capacity	PV plant capacity	BESS capacity / energy	Imported RES capacity
1	2 MWel	4 MWp	2 MW / 2 MWh	4 MW (Wind) 4 MWp (PV)
2	20 MWel	40 MWp	20 MW / 20 MWh	40 MW (Wind) 40 MWp (PV)
3	100 MWel	-	-	150 MW (Wind) 150 MWp (PV)
4	300 MWel	-	-	450 MW (Wind) 450 MWp (PV)
Total (Hub)	**422 MWel**	**44 MWp**	**22 MW / 22 MWh**	**644 MW (Wind) 644 MWp (PV)**

9.1.2. CAPEX Breakdown

The total installed cost (TIC), or capital expenditure (CAPEX), for the recommended 422 MW Hub is meticulously broken down to ensure transparency. The major cost centers include:

- **Electrolyser System:** This is the largest single cost component, comprising the PEM stacks and the associated Balance of Plant (BOP) equipment (e.g., power electronics, purification). Current estimates for manufactured PEM systems are in the range of 700-1,500 EUR/kW for PEM and 340-740 EUR/kW for AEL, with cost reductions expected by 2030.
- **On-site PV Plant:** The capital cost for the 40 MWp solar facility, including modules, inverters, mounting structures, and installation.
- **Water Treatment System:** The cost of the UF/RO/EDI system required to produce ultrapure water.
- **Infrastructure and Interconnections:** Includes the costs for the high-voltage grid connection to the Baranyntsi substation and the short pipeline to the Chaslivtsi gas compressor station.
- **Civil Works and Buildings:** Costs for site preparation, foundations, the main electrolysis building, and administrative facilities.
- **EPC and Owner's Costs:** Includes Engineering, Procurement, and Construction (EPC) contractor fees, project management costs, development fees, and permitting expenses.
- **Contingency:** A contingency allowance is included to account for unforeseen costs and risks during project execution.

Table 9-2: CAPEX breakdown (totals) - 4 PEM stages

Type of costs	Unit	2 MWel	20 MWel	100 MWel	300 MWel	422 MWel
1. Development	**t EUR**	**240 €**	**1,680 €**	**4,035 €**	**10,835 €**	**16,790 €**
2. Equipment	**t EUR**	**7,021 €**	**48,875 €**	**86,374 €**	**249,150 €**	**391,420 €**
Electrolysers stack & balance of stack	t EUR	2,973 €	21,827 €	63,552 €	189,928 €	278,280 €
Interconnection	t EUR	415 €	2,410 €	9,000 €	20,000 €	31,825 €
Solar PV plant	t EUR	1,600 €	16,000 €	- €	- €	17,600 €
BESS	t EUR	240 €	2,400 €	- €	- €	2,640 €
3. Civil Works, Installation & Commissioning	**t EUR**	**726 €**	**5,439 €**	**15,750 €**	**37,800 €**	**59,715 €**
Capital building	t EUR	- €	- €	- €	- €	- €
Total CAPEX	**t EUR**	**7,987 €**	**55,994 €**	**106,159 €**	**297,785 €**	**467,925 €**

Table 9-3: CAPEX breakdown (per kW) - 4 PEM stages

Type of costs	Unit	2 MWel	20 MWel	100 MWel	300 MWel	422 MWel
Development	**EUR/kWel**	**120 €**	**84 €**	**40 €**	**36 €**	**40 €**
Equipment	**EUR/kWel**	**3,511 €**	**2,444 €**	**864 €**	**831 €**	**928 €**
Electrolysers stack & balance of stack	EUR/kWel	1,486 €	1,091 €	636 €	633 €	659 €
Interconnection	EUR/kW	104 €	96 €	72 €	63 €	68 €
Solar PV plant	EUR/kWp	400 €	400 €	- €	- €	400 €
BESS	EUR/kWh	120 €	120 €	- €	- €	120 €
Civil Works, Installation & Commissioning	**EUR/kWel**	**363 €**	**272 €**	**158 €**	**126 €**	**142 €**
Capital building	EUR/kWel	- €	- €	- €	- €	- €
Total CAPEX	**EUR/kWel**	**3,994 €**	**2,800 €**	**1,062 €**	**993 €**	**1,109 €**

Table 9-4: CAPEX breakdown (totals) - 4 AEL stages

Type of costs	Unit	2 MWel	20 MWel	100 MWel	300 MWel	422 MWel
Development	**t EUR**	**240 €**	**1,680 €**	**4,035 €**	**10,835 €**	**16,790 €**
Equipment	**t EUR**	**5,429 €**	**33,510 €**	**55,233 €**	**154,818 €**	**248,990 €**
Electrolysers stack & balance of stack	t EUR	1,478 €	7,400 €	33,880 €	99,843 €	142,601 €
Interconnection	t EUR	415 €	2,410 €	9,000 €	20,000 €	31,825 €
Solar PV plant	t EUR	1,600 €	16,000 €	- €	- €	17,600 €
BESS	t EUR	240 €	2,400 €	- €	- €	2,640 €
Civil Works, Installation & Commissioning	**t EUR**	**352 €**	**2,536 €**	**10,943 €**	**33,714 €**	**47,545 €**
Capital building	t EUR	- €	703 €	2,625 €	8,905 €	12,233 €

Type of costs	Unit	2 MWel	20 MWel	100 MWel	300 MWel	422 MWel
Total CAPEX	t EUR	6,021 €	37,726 €	70,211 €	199,367 €	313,325 €

Table 9-5: CAPEX breakdown (per kW) - 4 AEL stages

Type of costs	Unit	2 MWel	20 MWel	100 MWel	300 MWel	422 MWel
Development	**EUR/kWel**	**120 €**	**84 €**	**40 €**	**36 €**	**40 €**
Equipment	**EUR/kWel**	**2,715 €**	**1,676 €**	**552 €**	**516 €**	**590 €**
Electrolysers stack & balance of stack	EUR/kWel	739 €	370 €	339 €	333 €	338 €
Interconnection	EUR/kW	104 €	96 €	72 €	63 €	68 €
Solar PV plant	EUR/kWp	400 €	400 €	- €	- €	400 €
BESS	EUR/kWh	120 €	120 €	- €	- €	120 €
Civil Works, Installation & Commissioning	**EUR/kWel**	**176 €**	**127 €**	**109 €**	**112 €**	**113 €**
Capital building	EUR/kWel	- €	35 €	26 €	30 €	29 €
Total CAPEX	**EUR/kWel**	**3,011 €**	**1,886 €**	**702 €**	**665 €**	**742 €**

9.1.3. OPEX Breakdown

The annual operational expenditure (OPEX) is broken down into its key components:

- **Electricity Costs:** The cost of supplemental electricity purchased from the grid or via PPAs to achieve the 5,200 - 6500 full load hours. This is a significant variable cost.
- **Maintenance:** Includes planned and unplanned maintenance for the electrolyser, PV plant, and BOP. This is typically modeled as a percentage of CAPEX or based on supplier service agreements.
- **Water Costs:** The cost of raw water purchased from the municipal supplier or the cost of operating on-site wells.
- **Staffing:** Salaries and benefits for operational and administrative personnel.
- **Insurance, Taxes, and Fees:** Includes property taxes, operational insurance, and fees for certification and regulatory compliance.

Table 9-6: OPEX breakdown (per kg) - 4 PEM stages

Type of costs	Unit	2 MWel	20 MWel	100 MWel	300 MWel	422 MWel
Energy costs	EUR/MWh	66.1 €	65.7 €	84.0 €	83.8 €	82.5 €
Energy costs	EUR/kg H_2	4.3 €	4.3 €	5.2 €	5.2 €	5.1 €
Maintenance & other OPEX	EUR/oph	42.5 €	224.1 €	930.0 €	2,699.4 €	3,771.8 €
Maintenance & other OPEX	EUR/kg H_2	1.3 €	0.7 €	0.5 €	0.5 €	0.5 €
Total OPEX	**EUR/kg H_2**	**5.6 €**	**5.0 €**	**5.7 €**	**5.7 €**	**5.6 €**

Table 9-7: OPEX breakdown (per kg) - 4 AEL stages

Type of costs	Unit	2 MWel	20 MWel	100 MWel	300 MWel	422 MWel
Energy costs	EUR/MWh	65.8 €	65.5 €	83.8 €	83.7 €	82.2 €
Energy costs	EUR/kg H_2	4.1 €	4.1 €	5.2 €	5.2 €	5.1 €
Maintenance & other OPEX	EUR/oph	39.8 €	168.3 €	858.6 €	2,451.1 €	3,283.5 €

Maintenance & other OPEX	EUR/kg H_2	1.2 €	0.5 €	0.5 €	0.5 €	0.5 €
Total OPEX	**EUR/kg H_2**	**5.3 €**	**4.6 €**	**5.7 €**	**5.7 €**	**5.5 €**

9.2. Financial Modeling

9.2.1. Model Structure

A comprehensive, dynamic financial model has been developed using Microsoft Excel. The model integrates the Profit & Loss Statement and Cash Flow Statement over a 25-year project lifetime. It is designed to be flexible, allowing for detailed sensitivity and scenario analysis.

9.2.2. Key Assumptions

The financial projections are based on a transparent set of key assumptions, including:

- **Capacity Factor:** 60% - 75%, based on achieving 5,200 - 6500 full load operating hours per year through the hybrid power supply strategy.
- **Electrolyser Degradation:** A performance degradation rate is applied over the life of the electrolyser stack, with a full stack replacement assumed after a defined operational period (e.g., 80,000 hours).
- **Hydrogen Selling Price:** Based on a combination of negotiated offtake prices for the initial phases and long-term forecasts for the EU hydrogen market.
- **Taxation:** Based on current Ukrainian corporate tax law and depreciation schedules.

9.2.3. Core Outputs

- **Levelised Cost of Hydrogen (LCOH):** This is the most critical metric for assessing the project's cost-competitiveness. The LCOH is the break-even price at which the project repays its lifetime costs, including capital, O&M, and financing. The model calculates the LCOH in EUR/kg at the plant gate ("ex works"). Within the pre-feasibility study a discount rate was excluded from LCOH calculations ("undiscounted LCOH") given the currently very high and war related WACC in Ukraine.
- **Upside potential:** Conservative scenario includes revenues only from directly sold RFNBO grade H_2. Low-carbon H_2 sales, BESS, electricity trading, grid services and heat utilisation (central heating in the city and the agricultural sector) could be considered as a potential upside, bringing down H_2 production costs and/or improving the commercial viability of the model (this can result in <5 EUR/kg LCOH).

Table 9-8: Undiscounted LCOH (year 5) - 4 PEM stages & Hub

Type of costs	Unit	2 MWel	20 MWel	100 MWel	300 MWel	422 MWel
CAPEX (Depreciation)	EUR/kg H_2	3.8 €	2.6 €	1.1 €	1.1 €	1.1 €
Energy costs	EUR/kg H_2	4.3 €	4.3 €	5.2 €	5.2 €	5.1 €
Maintenance & other OPEX	EUR/kg H_2	1.3 €	0.7 €	0.5 €	0.5 €	0.5 €
LCOH	**EUR/kg H_2**	**9.4 €**	**7.5 €**	**6.8 €**	**6.7 €**	**6.7 €**

Table 9-9: Undiscounted LCOH (year 5) - 4 AEL stages & Hub

Type of costs	Unit	2 MWel	20 MWel	100 MWel	300 MWel	422 MWel
CAPEX (Depreciation)	EUR/kg H_2	2.8 €	1.7 €	0.8 €	0.7 €	0.8 €
Energy costs	EUR/kg H_2	4.1 €	4.1 €	5.2 €	5.2 €	5.1 €
Maintenance & other OPEX	EUR/kg H_2	1.2 €	0.5 €	0.5 €	0.5 €	0.5 €
LCOH	**EUR/kg H_2**	**8.1 €**	**6.3 €**	**6.4 €**	**6.4 €**	**6.3 €**

9.2.4. Project Stages Overview

Table 9-10: Stages & Hub overview - PEM

Capacity of H_2 installation	MWel	2	20	100	300	422 (Hub)
CAPEX						
H_2 Electrolyser & Balance of Stack	t EUR	2,973 €	21,827 €	63,552 €	189,928 €	278,280 €
Total equipment	t EUR	7,021 €	48,875 €	86,374 €	249,150 €	391,420 €
Total CAPEX	t EUR	7,987 €	55,994 €	106,159 €	297,785 €	467,925 €
Total CAPEX	EUR/kWel	3,994 €	2,800 €	1,062 €	993 €	1,109 €
OPEX						
Energy costs	EUR/kg H_2	4.3 €	4.3 €	5.2 €	5.2 €	5.1 €
Maintenance & other OPEX	EUR/kg H_2	1.3 €	0.7 €	0.5 €	0.5 €	0.5 €
Total OPEX	EUR/kg H_2	5.6 €	5.0 €	5.7 €	5.7 €	5.6 €
Stage outputs (year 1)						
H_2 output p.a.	t	224	2,296	9,917	29,047	42,839
EL full load hours	-	6,316	6,465	5,271	5,146	5,397
Stage results						
Undiscounted LCOH (year 5)	EUR/kg H_2	9.4 €	7.5 €	6.8 €	6.7 €	6.7 €
Undiscounted IRR (15 years)	%	7.6%	9.1%	14.7%	14.9%	14.1%

Table 9-11: Stages & Hub overview - AEL

Capacity of H_2 installation	MWel	2	20	100	300	422 (Hub)
CAPEX						
H_2 Electrolyser & Balance of Stack	t EUR	1,478 €	7,400 €	33,880 €	99,843 €	142,601 €
Total equipment	t EUR	5,429 €	33,510 €	55,233 €	154,818 €	248,990 €
Total CAPEX	t EUR	6,021 €	37,726 €	70,210 €	199,367 €	312,325 €
Total CAPEX	EUR/kWel	3,011 €	1,886 €	702 €	665 €	742 €
OPEX						
Energy costs	EUR/kg H_2	4.1 €	4.1 €	5.2 €	5.2 €	5.1 €
Maintenance & other OPEX	EUR/kg H_2	1.2 €	0.5 €	0.5 €	0.5 €	0.5 €
Total OPEX	EUR/kg H_2	5.3 €	4.6 €	5.7 €	5.7 €	5.5 €
Stage outputs (year 1)						
H_2 output p.a.	t	229	2,330	9,704	29,052	41,753

EL full load hours	-	6,438	6,562	5,454	5,443	5,562
Stage results						
Undiscounted LCOH (year 5)	EUR/kg H_2	8.1 €	6.3 €	6.4 €	6.4 €	6.3 €
Undiscounted IRR (15 years)	%	8.7%	11.7%	18.7%	20.5%	18.5%

9.3. Sensitivity Analysis

To understand the project's vulnerability to key variables, a sensitivity analysis has been performed. The results, presented in a heat table, demonstrate that the project's LCOH is most sensitive to:

1. **Electricity Price:** The cost of supplemental power has a significant impact on OPEX.
2. **Number of full load hours (capacity factor):** Demonstrates the profound impact of the planned electrolyser load on project viability.
3. **Total CAPEX:** Highlights the need for rigorous cost control during the EPC phase (especially in case of low capacity factor).

Table 12-9: Undiscounted LCOH (year 5) - 422 MWel PEM Hub sensitivity analysis

Load factor	Full load hours p.a.		Electricity price (incl. TSO & DSO fees), EUR/MWh						
		Change	*-15%*	*-10%*	*-5%*	*0%*	*5%*	*10%*	*15%*
	Change	Total	70	74	78	**82**	86	90	95
31%	*-50%*	2,698	7.6	7.8	8.1	8.3	8.6	8.8	9.1
37%	*-40%*	3,238	7.0	7.3	7.5	7.8	8.0	8.3	8.5
43%	*-30%*	3,777	6.6	6.9	7.1	7.4	7.6	7.9	8.1
49%	*-20%*	4,317	6.3	6.6	6.8	7.1	7.4	7.6	7.9
55%	*-10%*	4,856	6.1	6.4	6.6	6.9	7.1	7.4	7.6
62%	*0%*	**5,396**	6.0	6.2	6.5	**6.7**	7.0	7.2	7.5
68%	*10%*	5,936	5.8	6.1	6.3	6.6	6.8	7.1	7.3
74%	*20%*	6,475	5.7	6.0	6.2	6.5	6.7	7.0	7.2
80%	*30%*	7,015	5.6	5.9	6.1	6.4	6.6	6.9	7.2
86%	*40%*	7,554	5.5	5.8	6.1	6.3	6.6	6.8	7.1
92%	*50%*	8,094	5.5	5.7	6.0	6.3	6.5	6.8	7.0

Table 12-10: Undiscounted LCOH (year 5) - 422 MWel AEL Hub sensitivity analysis

Load factor	Full load hours p.a.		Electricity price (incl. TSO & DSO fees), EUR/MWh						
		Change	*-15%*	*-10%*	*-5%*	*0%*	*5%*	*10%*	*15%*
	Change	Total	70	74	78	**82**	86	90	94
32%	*-50%*	2,780	6.7	7.0	7.2	7.5	7.7	8.0	8.2
38%	*-40%*	3,336	6.3	6.6	6.8	7.1	7.3	7.6	7.8
44%	*-30%*	3,892	6.0	6.3	6.5	6.8	7.0	7.3	7.5
51%	*-20%*	4,448	5.8	6.1	6.3	6.6	6.8	7.1	7.3
57%	*-10%*	5,004	5.7	5.9	6.2	6.4	6.7	6.9	7.2

63%	*0%*	**5,560**	5.5	5.8	6.1	**6.3**	6.6	6.8	7.1
70%	*10%*	6,116	5.5	5.7	6.0	6.2	6.5	6.7	7.0
76%	*20%*	6,672	5.4	5.6	5.9	6.1	6.4	6.7	6.9
83%	*30%*	7,228	5.3	5.6	5.8	6.1	6.3	6.6	6.9
89%	*40%*	7,784	5.3	5.5	5.8	6.0	6.3	6.6	6.8
95%	*50%*	8,341	5.2	5.5	5.8	6.0	6.3	6.5	6.8

9.4. Financing Strategy

The project's financing strategy is fundamentally shaped by the high-risk perception of investing in Ukraine. A purely commercial financing approach is likely unfeasible due to the prohibitively high cost of capital (WACC). A high WACC would inflate the LCOH, rendering the project's hydrogen uncompetitive in the EU market. Therefore, the core of the financing strategy is to systematically de-risk the project to attract a blend of concessional and commercial capital.

This de-risking is achieved through several key project attributes demonstrated in this study: its strong alignment with EU strategic objectives (REPowerEU), its contribution to Ukraine's sustainable reconstruction, and its adherence to the highest IFI environmental and social standards. This positioning makes the project a prime candidate for a blended finance structure.

9.4.1. Funding Requirements

The total funding required for the recommended 422 MW project will be determined by the final CAPEX estimate. The proposed capital structure will target a debt-to-equity ratio typical for infrastructure projects in the region, adjusted for the specific risks.

9.4.2. Sources of Finance

The financing plan will target a combination of sources:

- **IFI/DFI Engagement:** The primary target for debt financing will be IFIs like the EBRD, the European Investment Bank (EIB), and the IFC. These institutions have mandates to support projects that promote sustainable development and energy transition in countries like Ukraine and can offer longer tenors and more favorable interest rates than commercial banks. [69]
- **Public Funding and Risk Mitigation:** The project will actively seek support from public funding mechanisms. This includes applying for grants from EU facilities (e.g., the Ukraine Investment Framework, Connecting Europe Facility) and participating in auctions run by the European Hydrogen Bank, which can provide a fixed premium per kg of hydrogen produced, effectively de-risking the revenue side. Furthermore, the project will seek political risk insurance and investment guarantees from agencies like the Multilateral Investment Guarantee Agency (MIGA) or national development finance institutions (e.g., Germany's KfW, U.S. DFC), which is critical for attracting private capital. [72]
- **Commercial Debt and Equity:** The participation of IFIs and the securing of risk guarantees are expected to "crowd in" private investment by reducing the perceived risk for commercial banks and equity investors.

The financial model will explicitly quantify the reduction in LCOH achieved through this blended finance structure, demonstrating the path from a high-risk, uncompetitive project to a bankable, strategically important asset.

10. Risk Assessment and Mitigation

A systematic and proactive approach to risk management is essential for the successful implementation of a complex, first-of-its-kind project in a challenging environment. This section identifies the principal risks facing the **green H_2 project in Zakarpattia** and outlines specific, actionable mitigation strategies for each.

10.1. Risk Management Framework

The project will adopt a formal risk management framework based on a standard risk matrix, which assesses risks based on their **Likelihood** of occurrence and their potential **Impact** on project objectives (cost, schedule, quality). This allows for the categorisation of risks (e.g., Low, Medium, High, Critical) and the prioritisation of mitigation efforts on the most significant threats.

10.2. Key Risk Categories and Mitigation Strategies

10.2.1. Geopolitical and Security Risks

- **Risk:** Direct military action, sabotage, or civil unrest impacting the project site, key infrastructure (e.g., substations, pipelines), or personnel. While Zakarpattia is the least war-affected region, this remains the overriding risk for any investment in Ukraine.
- **Mitigation:**
  - **Strategic Location:** The selection of Zakarpattia Oblast, hundreds of kilometers from active combat zones, is the primary mitigation measure.
  - **Physical Security:** Implementation of robust on-site physical security protocols, including controlled access, surveillance, and hardened infrastructure for critical components.
  - **Insurance:** Securing comprehensive political risk and war risk insurance is non-negotiable. This coverage is available from specialised multilateral agencies like MIGA and national DFIs (e.g., U.S. DFC, German and French export credit agencies), which have active programs for Ukraine.
  - **Resilient Supply Chains:** Designing inbound logistics for major equipment to flow through secure EU ports and overland routes, avoiding higher-risk maritime corridors.

10.2.2. Regulatory and Permitting Risks

- **Risk:** Delays in the permitting process due to bureaucratic inefficiencies, evolving legislation, or a lack of established procedures for hydrogen projects. Specific risks include delays in land use re-designation (DPT) and obtaining a positive conclusion for the EIA.
- **Mitigation:**
  - **Proactive Stakeholder Engagement:** Early and continuous engagement with all relevant authorities at the local (Chaslivtsi municipality), regional (Zakarpattia Oblast), and national levels (ministries, regulators).
  - **Leveraging Partnerships:** Actively using the support networks of GIZ, the German-Ukrainian Energy Partnership, and H_2-diplo to facilitate dialogue with key public stakeholders.
  - **High-Quality Submissions:** Utilizing the IFI-compliant templates (DPT, SEA, EIA) developed in this study to ensure submissions are comprehensive and of high quality, reducing the likelihood of rejection or requests for additional information.
  - **Parallel Processing:** Initiating the time-consuming studies required for IFI due diligence in parallel with the national permitting processes to avoid a sequencing bottleneck where national permits are obtained but the project is not yet bankable.

10.2.3. Commercial and Market Risks

- **Risk:** Failure to convert the LoI with Orlen into a binding, long-term, bankable Power Purchase Agreement (PPA). Volatility in the future EU hydrogen market price, potentially falling below the project's LCOH.
- **Mitigation:**
  - **Prioritise Offtake Agreements:** Dedicate significant commercial resources to finalizing a binding offtake agreement for the pilot phases. This is the most critical near-term milestone for de-risking the project.
  - **Diversify Offtakers:** For the utility-scale phases, pursue a portfolio of offtakers in different sectors (e.g., refining, mobility, industry) and regions (Slovakia, Austria, Germany) to reduce dependence on a single customer. [129]

- **Utilise EU Support Mechanisms:** Actively pursue revenue-side support through mechanisms like the European Hydrogen Bank's competitive auctions, which offer a fixed price premium (a form of Contract for Difference) for a set period, providing long-term revenue certainty.

10.2.4. Construction and Technology Risks

- **Risk:** EPC contractor cost overruns or schedule delays. Supply chain disruptions for critical, long-lead-time equipment like electrolyser stacks. Technology underperformance or higher-than-expected degradation rates.
- **Mitigation:**
  - **Experienced EPC Partner:** Select a reputable EPC contractor with a proven track record in delivering large-scale renewable energy or industrial gas projects, preferably with experience in the region.
  - **Secure Supply Chain:** Place orders for critical equipment early and structure contracts with robust delivery guarantees and penalties.
  - **Proven Technology:** Select electrolyser technology from established, bankable manufacturers that can provide strong performance warranties and long-term service agreements.
  - **Modular Design:** The modular architecture inherently mitigates construction risk by allowing for parallel manufacturing and phased commissioning.

10.2.5. Financial Risks

- **Risk:** Inability to reach financial close due to the high perceived risk profile of Ukraine, leading to an unacceptably high WACC. Fluctuation in the UAH/EUR exchange rate.
- **Mitigation:**
  - **Blended Finance Strategy:** The core mitigation is the blended finance strategy detailed in Section 9.4, which is designed to lower the WACC by attracting concessional debt and risk guarantees from IFIs and DFIs.
  - **Euro-Denominated Contracts:** Structure key contracts, including the offtake agreement and debt financing, in Euros. This creates a natural hedge, as revenues and major costs/debt service will be in the same currency, minimizing exposure to exchange rate volatility.

10.3. Hazard Analysis & Safety Concept (HAZID/HAZOP)

10.3.1. Executive Summary of Process Safety

The implementation of the **N1Capital Green Hydrogen Production Facility** in Uzhhorod, Zakarpattia, represents a significant engineering undertaking that introduces specific high-consequence process risks into the regional energy infrastructure. This chapter articulates a rigorous, multi-dimensional **Process Safety Management (PSM)** framework designed to govern the facility's lifecycle from the pilot phase (2 MW) through to full utility-scale operation (400 MW). The safety concept is predicated on a strategic shift from a traditional compliance-based posture – often termed "Planning for Order" – to a resilience-based philosophy defined as **"Preparing for Chaos."** This paradigm acknowledges that First-of-a-Kind (FOAK) integrated energy systems, which couple intermittent solar generation with complex electrochemical processes, possess inherent uncertainties and "non-obvious" failure modes that require systems designed for graceful degradation rather than catastrophic collapse. [122]

The facility's design prioritises the hierarchy of controls, embedding **Inherently Safer Design (ISD)** principles to minimise hazardous inventories and simplify process complexity. A comprehensive **Hazard Identification (HAZID)** study has isolated the critical physicochemical properties of hydrogen – specifically its wide flammability range (4–75%), low minimum ignition energy (0.02 mJ), and unique susceptibility to the Joule-Thomson heating effect – as the primary drivers for the engineering safety barriers. Furthermore, the production of up to 200,000 tonnes per annum of high-purity oxygen introduces a parallel major accident hazard related to oxygen enrichment and material compatibility, necessitating distinct segregation and materials selection protocols. [95]

A core component of this safety architecture is the **Node-Based Hazard Analysis**, which scrutinises the interface between the variable 400 MW solar PV generation profile and the electrolyser's operational envelope. This analysis has identified the **Gas Crossover** phenomenon – the migration of hydrogen into the oxygen stream – as a critical safety differentiator between Alkaline (AEL) and Proton Exchange Membrane (PEM) technologies. The selection of PEM technology is validated not only by its dynamic response capabilities but by its superior safety profile under the frequent start-stop cycling inherent to solar-powered operations, mitigating the explosion risks associated with low-load Alkaline operation.

Crucially, the protection of the facility's energy buffer – the Battery Energy Storage System (BESS) – is addressed through the deployment of advanced **Perfluorohexanone ($C_6F_{12}O$)** fire suppression systems. This choice reflects a nuanced

understanding of lithium-ion thermal runaway mechanisms, utilizing a clean, electrically non-conductive agent capable of providing both rapid flame extinction and significant cooling to prevent propagation. [96] [112]
The conclusion of this hazard assessment is that the residual risk profile of the Uzhhorod Hydrogen Hub can be maintained as **As Low As Reasonably Practicable (ALARP)**. This is achieved through a holistic integration of Safety Instrumented Systems (SIS), rigorous zoning of explosive atmospheres (ATEX) utilizing Group IIC-certified equipment, and a proactive emergency response architecture aligned with the strategic importance of the Central European Hydrogen Corridor (CEHC). [153]

10.3.2. Regulatory Compliance & Standards Framework

The legal and normative foundation for the project's safety concept is a dual-layered framework that harmonises strict European Union directives – prerequisites for export market access and international financing – with mandatory Ukrainian national legislation. This alignment is critical for obtaining the "Permit for the Performance of High-Risk Works" from the State Labor Service of Ukraine and ensuring the bankability of the project with International Financial Institutions (IFIs) such as the EBRD. [42]

10.3.2.1. European Union Directives and Norms

As a project designated for the export of Renewable Fuels of Non-Biological Origin (RFNBO) to the EU, the facility is designed to meet the safety standards required of a European Tier-1 industrial asset. The following directives form the backbone of the safety compliance strategy:

1. Seveso III Directive (2012/18/EU): Control of Major Accident Hazards

The Seveso III Directive is the principal EU instrument for the prevention of major industrial accidents involving dangerous substances. It imposes tiered obligations on operators based on the quantity of hazardous substances present on site.

- **Classification:** Hydrogen is classified as a hazardous substance under Part 2 of Annex I (Entry 15) of the Directive.
- Thresholds:
  - **Lower-tier requirements** apply if the hydrogen inventory exceeds **5 tonnes**.
  - **Upper-tier requirements** apply if the hydrogen inventory exceeds **50 tonnes**.
- Project Application:
  - **Pilot Phase (2-20 MW):** The on-site inventory (including buffer storage at 30-50 bar and piping volume) will likely remain below 50 tonnes, potentially categorizing the site as a Lower-Tier establishment or below the threshold entirely depending on the buffer sizing strategy.
  - **Full Scale (400 MW):** With a daily production capacity potentially exceeding 80 tonnes and significant buffer storage required for pipeline injection stability, the facility will unequivocally trigger **Upper-Tier Seveso** obligations. This mandates the preparation of a **Safety Report (MAPP - Major Accident Prevention Policy)**, a Safety Management System (SMS), and comprehensive internal and external emergency plans.[9] The project must demonstrate to competent authorities that all necessary measures have been taken to prevent major accidents and limit their consequences for human health and the environment.

2. ATEX Directives (Explosive Atmospheres)

The management of explosion risks is governed by two complementary directives that address the equipment and the workplace respectively.

- **ATEX 114 (2014/34/EU) - Equipment:** This directive applies to equipment and protective systems intended for use in potentially explosive atmospheres. All electrolysers, compressors, sensors, and valves installed in hazardous zones must carry the Ex marking. For hydrogen, equipment must be certified for **Group IIC**, the most stringent gas group due to hydrogen's extremely low ignition energy and high flame transmission speed. [100]
- **ATEX 153 (1999/92/EC) - Workplace:** This directive sets out the minimum requirements for improving the safety and health protection of workers potentially at risk from explosive atmospheres.[8] It places the obligation on the operator (N1Capital) to:
  - Assess explosion risks.
  - Classify the plant into Zones (0, 1, 2) based on the frequency and duration of explosive atmospheres.
  - Produce an Explosion Protection Document (EPD).
  - Take technical and organisational measures to prevent the formation of explosive atmospheres or, where that is not possible, to avoid their ignition and mitigate the effects of an explosion.

3. Machinery Directive (2006/42/EC) & Pressure Equipment Directive (PED 2014/68/EU)

- **PED:** The hydrogen processing system involves pressures up to 50 bar. Electrolyser stacks, gas-liquid separators, buffer tanks, and piping fall under the PED. Equipment must be designed, manufactured, and assessed for conformity (CE marking) based on the stored energy product (Pressure times Volume). Hydrogen causes specific material degradation issues (embrittlement) which must be accounted for in the Essential Safety Requirements (ESR) analysis under the PED.
- **Machinery Directive:** Applies to the assembly of the electrolyser BOP (pumps, compressors) to ensure safety against mechanical hazards, guarding of moving parts, and functional safety of control systems.

10.3.2.2. International Standards (ISO/IEC)

The technical design relies on specific ISO/IEC standards that represent the global state-of-the-art for hydrogen technologies:

- ISO 22734:2019 (and 2025 Draft): Hydrogen generators using water electrolysis.
  This is the definitive standard for electrolyser safety. It defines requirements for venting, material compatibility, and, crucially, **gas crossover detection**. The 2025 revision introduces enhanced requirements for **functional safety** (referencing IEC 61508/61511) and **cybersecurity** (ISO/IEC 27001), addressing risks of remote interference with safety systems. Adherence to ISO 22734 ensures that the electrolyser package itself is inherently safe and validated against thermal, mechanical, and chemical hazards.
- ISO 14687: Hydrogen Fuel Quality.
  While primarily a quality standard, it has safety implications. Impurities (e.g., sulfur, CO, water) can degrade fuel cell catalysts downstream or cause corrosion/ice formation in cryogenic parts of the supply chain. Ensuring compliance with **Grade D** purity is a safety function to protect the integrity of the offtaker's assets.
- IEC 61508 / IEC 61511: Functional Safety. [114]
  These standards govern the **Safety Instrumented Systems (SIS)**. The HAZOP process will determine the **Safety Integrity Level (SIL)** required for critical loops (e.g., High-High Pressure Trip, LEL Detection Trip). Typically, hydrogen H_2-O2 crossover protection requires SIL 2 or SIL 3 reliability due to the catastrophic consequences of failure. [94]
- NFPA 2: Hydrogen Technologies Code (USA).
  Although an American standard, NFPA 2 is referenced globally for its scientifically derived **separation distances** (setbacks) and detailed requirements for **Hydrogen Equipment Enclosures (HEE)**. It provides a more prescriptive alternative to the performance-based approach of some EU norms, particularly regarding fire barriers and ventilation rates.

10.3.2.3. Ukrainian Regulatory Alignment

The project operates under the jurisdiction of Ukrainian law, which is currently undergoing rapid harmonisation with EU norms (UA-REACH, UA-CLP):

- Law of Ukraine "On High-Risk Facilities" (HRF):
  This law mandates the identification of HRFs based on the mass of hazardous substances. Hydrogen is listed as a hazardous substance.
  Category 1: Threshold mass aligns with Seveso Upper Tier (typically 50 tonnes).
  Category 2: Threshold mass aligns with Seveso Lower Tier (typically 5 tonnes).
  Implication: The project will be registered in the **State Electronic Register of High-Risk Facilities**. N1Capital must develop a **PLAS (Plan for Localisation and Liquidation of Accidents)** and perform a quantitative risk assessment (QRA). The classification impacts the frequency of state inspections and the required level of civil liability insurance. [106]

- Chemical Safety (UA-REACH):
  Entering into force in January 2025, the Technical Regulation on the Safety of Chemical Products (UA-REACH) requires registration of substances manufactured or imported in quantities >1 tonne/year.
  Implication: The potassium hydroxide (KOH) electrolyte required for the Alkaline electrolyser option is a hazardous chemical that must be registered. Furthermore, the hydrogen product itself may require registration as a chemical substance placed on the market. The pre-registration period opens in January 2025, creating an immediate compliance action item for the project team. [107]

- Occupational Safety (NPAOP):
  The facility must adhere to NPAOP 0.00-1.81-18 "Rules for Labor Protection during Operation of Equipment Working under Pressure" and DBN V.2.5-20:2018 regarding gas supply systems. These national codes dictate specific requirements for pipeline marking, pressure testing, and personnel certification.

10.3.3. Hazard Identification (HAZID) - Primary Risks

The HAZID workshop serves as the foundation of the safety concept. It identifies the inherent physical and chemical properties of the substances handled that could lead to a loss of containment or loss of control. The project team adopts the **"Preparing for Chaos"** philosophy, acknowledging that in a complex, novel system like a solar-hydrogen hub, "non-obvious" failure modes are inevitable.

10.3.3.1. Physicochemical Properties of Hydrogen

Hydrogen poses a unique "Risk Triad" that differentiates it from natural gas (methane) and requires specialised engineering controls.

- Wide Flammability Range (4% – 75%):
  Unlike natural gas (5–15%) or gasoline vapor (1–7%), hydrogen can burn in very lean and very rich mixtures. This implies that a leak inside the Electrolyser Hall becomes dangerous almost immediately upon release and remains dangerous even at high concentrations.
  Implication: Ventilation strategies must be aggressive. The "safe" limit is typically 25% of the Lower Explosive Limit (LEL), which is 1% by volume. Detection systems must react extremely fast (seconds) to cut power before this concentration is reached.

- Low Minimum Ignition Energy (MIE = 0.017 mJ):
  Hydrogen's MIE is an order of magnitude lower than natural gas (0.29 mJ) and gasoline vapor (0.24 mJ). A spark from static electricity on a person's finger, a standard light switch, or even particle friction in a high-velocity vent is sufficient to ignite it.
  Implication: Strict bonding and grounding (earthing) of all equipment is mandatory to prevent static buildup. Personnel must wear anti-static clothing and footwear. All electrical equipment in classified zones must be intrinsically safe (Ex ia) or flameproof (Ex d), as standard industrial waterproofing (IP ratings) is insufficient to prevent ignition of hydrogen.

- Joule-Thomson (JT) Inversion Effect:
  A critical and often overlooked hazard. At ambient temperatures, hydrogen has a **negative Joule-Thomson coefficient**. This means that when it expands rapidly (e.g., through a leaking valve or a relief valve lifting) from high pressure to low pressure, it **heats up** rather than cools down (unlike natural gas or air).
  Implication: A high-pressure leak (e.g., from the 50 bar pipeline interface) can **auto-ignite** purely due to the heat generated by expansion, without any external spark source. This phenomenon creates a risk of spontaneous jet fires from PRVs or flange leaks. This necessitates "fire-safe" valve designs and remote-operated isolation valves (ROIV) that do not require personnel approach during a leak event.

- High Buoyancy and Diffusivity:
  Hydrogen is 14 times lighter than air and rises at a speed of approximately 20 m/s.
  Implication: It will not accumulate at ground level (like propane or gasoline vapors) but will collect in "dead zones" at the apex of roofs or ceiling pockets. The Electrolyser Hall design must avoid structural pockets (inverted beams) and place gas detectors at the absolute highest points. Outdoor storage designs should avoid roofs or canopies that could trap gas.

- Hydrogen Embrittlement:
  Atomic hydrogen can diffuse into the crystal lattice of steel, causing a loss of ductility, reduction in tensile strength, and catastrophic brittle fracture (Hydrogen Induced Cracking - HIC). [130]
  Implication: Standard carbon steel pipelines are unsuitable. Materials must be selected per ISO 11114-4. Austenitic stainless steels (e.g., 316L, 304L) are preferred for plant piping. Pipeline steels (API 5L X42/X52) for the CEHC

connection must be verified for hydrogen service suitability, often requiring specific hardness limits and heat treatments.

10.3.3.2. Oxygen Enrichment Risks

The production of 200,000 tonnes/year of high-purity oxygen is a major process hazard often overshadowed by hydrogen risks:[3]

- **Enrichment:** Air containing >23.5% oxygen significantly lowers the ignition energy of combustible materials and increases flame temperature and velocity. Materials that are fire-retardant in air (e.g., certain plastics, lubricants, asphalt) can burn fiercely or explode in oxygen-enriched atmospheres.
- **Oil/Grease Incompatibility:** Standard hydrocarbon greases will spontaneously ignite in high-pressure oxygen atmospheres.
- **Implication:** All oxygen service piping and equipment must be strictly "Oxygen Clean" (free of organics/particles) per EIGA/CGA standards. Lubricants for oxygen compressors must be fluorinated (e.g., PFPE). Oxygen vents must be located carefully, away from air intakes and hydrogen vents, to prevent the creation of oxygen-enriched zones where personnel or equipment are present.

10.3.3.3. Electrical Hazards (High-Current DC)

The 400 MW capacity implies massive DC currents (tens of kA) flowing to the electrolyser stacks:

- **DC Arc Flash:** DC arcs do not have a zero-crossing point like AC, making them significantly harder to extinguish. They generate immense heat and UV radiation.
- **Stray Currents:** Leakage currents from the electrolyser stack (which is a conductive liquid path in Alkaline systems) can cause rapid electrolytic corrosion of ground grids, rebar in concrete, and piping.
- **Implication:** Arc flash studies are required for the DC busbars. Insulation monitoring devices (IMD) must be installed to detect ground faults in the floating DC system. The grounding system must be designed to handle potential stray currents without compromising structural integrity.

10.3.4. Node-Based Hazard Analysis (Preliminary HAZOP)

The Preliminary Hazard and Operability Study (HAZOP) applies guidewords (NO, MORE, LESS, REVERSE, CONTAMINATION) to specific process nodes to identify deviations. This analysis focuses on the interaction between the variable renewable power supply and the process equipment.

Node 1: Electrolyser Hall (Technology Specifics: PEM vs. AEL)
Overview: This node covers the electrolyser stacks, gas-liquid separators, and immediate piping. The hazards differ significantly between technologies, particularly regarding gas crossover.

Table 10-1: Process Hazard Analysis (HAZOP) – Electrolyser Hall

Scenario ID	Deviation	Cause	Consequence	Safeguards (Layers of Protection)
N1-01	Contamination (Gas Crossover): High H_2 in O2 stream	**AEL Specific:** Operation below minimum load (e.g., <20%) due to sudden cloud cover dropping PV power. Reduced current density allows dissolved gas diffusion across the porous diaphragm.	Formation of explosive mixture inside the anode separator. Explosion rupture of vessel.	1. **Process Control:** Minimum load interlock (stop H_2 production if power <20%). 2. **SIS Trip:** Online gas analyser (H_2 in O2) trips rectifiers at 2% concentration (50% LEL). 3. **Design:** Use **PEM** technology which has a solid membrane preventing crossover even at 0% load.

Scenario ID	Deviation	Cause	Consequence	Safeguards (Layers of Protection)
N1-02	High Temperature (Thermal Runaway)	Cooling water pump failure; Heat exchanger fouling; Rectifier control fault overloading stack.	Membrane damage (PEM) or diaphragm melting (AEL). Loss of containment. Potential fire.	1. **Process Control:** Flow monitoring on cooling loop. 2. **SIS Trip:** High-Temperature Trip (Safety Cut-out) on stack outlet. 3. **Passive:** Electrolyser stacks rated for over-temperature survivability for short duration.
N1-03	Loss of Containment (H_2 Leak)	Gasket failure (AEL stacks have hundreds of gaskets); Fitting leak; Vibration fatigue.	H_2 released into Hall. Buoyant gas accumulation at ceiling. Ignition -> Explosion / Jet Fire.	1. **Active:** Ceiling-mounted H_2 detectors (Logic: 10% LEL = Alarm + High Vent; 25% LEL = Trip + ESD). 2. **Active:** Emergency Ventilation (Air change rate >12/hr). 3. **Passive:** Blast relief panels / deflagration venting on hall roof.
N1-04	Chemical Release (AEL Specific)	KOH piping rupture; Maintenance error.	Release of hot, corrosive lye (30% KOH). Chemical burns to operators.	1. **Design:** Bunding/diking around AEL electrolyte tanks. 2. **Procedural:** PPE requirements (chem suits). 3. **Design:** Selection of **PEM** eliminates bulk liquid electrolyte hazard (uses water).

Strategic Insight: The HAZOP highlights a critical safety advantage for **PEM technology** in this specific project context (Solar PV). The Alkaline (AEL) requirement to maintain >20% load to prevent explosive gas crossover creates a complex safety reliance on the BESS during solar transients. PEM, being inherently resistant to crossover at low loads due to its solid polymer electrolyte, removes this failure mode, representing a higher level of **Inherently Safer Design (ISD)**.

Node 2: Hydrogen Processing & Compression (30-50 bar)
Overview: This node includes the DeOxo units, dryers, buffer tanks, and diaphragm compressors.

Table 10-2: HAZOP Risk Assessment Matrix – Hydrogen Processing & Compression (30–50 bar)

Scenario ID	Deviation	Cause	Consequence	Safeguards (Layers of Protection)
N2-01	High Pressure (Overpressure)	Compressor discharge blockage; Control valve failure; Thermal expansion in blocked liquid H_2 line.	Pipeline/Vessel rupture. Large H_2 release.	1. **Process Control:** Pressure transmitters with high alarm. 2. **SIS Trip:** High-High Pressure Safety Switch (hardwired) trips compressor.

Scenario ID	Deviation	Cause	Consequence	Safeguards (Layers of Protection)
				3. **Passive:** Mechanical Pressure Relief Valves (PRVs) routed to vent stack.
N2-02	Vibration / Mechanical Failure	Diaphragm failure in compressor; Loose mounting bolts; Liquid ingress.	H_2 leaks into the compressor crankcase (if diaphragm breaks); Catastrophic compressor failure.	1. **Monitoring:** Vibration monitoring sensors (trip on high vibration). 2. **Design:** Triple-diaphragm compressors with leak detection ports between diaphragms. 3. **Active:** H_2 detector in compressor distance piece/crankcase vent.
N2-03	Impure H_2 (Moisture breakthrough)	Dryer saturation; Regeneration cycle failure.	Pipeline corrosion/embrittlement downstream; Off-spec product rejected by CEHC TSO.	1. **Process Control:** Online Dew Point meters. 2. **Procedural:** Automatic switchover to standby dryer bed. 3. **Active:** Automatic isolation valve at pipeline interface (Off-spec diversion).

Node 3: Battery Energy Storage System (BESS)
Overview: The project utilises a significant BESS (15 MWh / 27.6 MWh) to buffer solar power. The primary risk is thermal runaway of the Li-ion cells.

Table 10-3: HAZOP Risk Assessment Matrix – Battery Energy Storage System (BESS)

Scenario ID	Deviation	Cause	Consequence	Safeguards (Layers of Protection)
N3-01	Thermal Runaway (Single Cell)	Internal short circuit; Manufacturing defect; Overcharging; External heat.	Rapid heat release; Propagation to adjacent cells; Venting of toxic/flammable gases (CO, H_2, HF). Fire/Explosion.	1. **Design:** Cell-to-cell thermal barriers. 2. **Process Control:** BMS (Battery Management System) monitoring voltage/temp of every cell. 3. **Active: Perfluorohexanone** Fire Suppression System.
N3-02	Gas Accumulation in Container	Venting from batteries during runaway; HVAC failure.	Explosive atmosphere inside container.	1. **Active:** Gas detection (H_2, CO, electrolyte vapors). 2. **Active:** Deflagration venting panels. 3. **Active:** Emergency exhaust ventilation activation.

Deep Dive: Perfluorohexanone Effectiveness:
The selection of Perfluorohexanone ($C_6F_{12}O$), commercially known as Novec 1230, as the fire suppression agent for the BESS is a critical safety decision. Unlike traditional agents, Perfluorohexanone functions through a dual mechanism:

1. **Cooling Effect:** It is stored as a liquid but vaporises immediately upon discharge. This phase change absorbs a massive amount of heat energy from the fire zone (heat of vaporisation), rapidly lowering the temperature below the fire point. This is crucial for Li-ion fires where cooling is needed to stop the exothermic runaway reaction.
2. **Chemical Inhibition:** It chemically interrupts the combustion chain reaction. [123] Research indicates that Perfluorohexanone is highly effective in extinguishing Li-ion battery fires and preventing reignition, often outperforming agents like HFC-227ea. It is electrically non-conductive, protecting the high-voltage BESS assets, and leaves no residue, simplifying cleanup. The system design will utilise "pack-level" injection, delivering the agent directly into the battery modules for the fastest possible response. [110]

Node 4: Pipeline Interface (Plant to Chaslivtsi Station - 500m)
Overview: The high-pressure connection to the CEHC/GTSOU network.

Table 10-4: HAZOP Risk Assessment Matrix – High-Pressure Pipeline Interface (Plant to CEHC/GTSOU)

Scenario ID	Deviation	Cause	Consequence	Safeguards (Layers of Protection)
N4-01	Loss of Containment (External Interference)	Third-party excavation (backhoe strike); Sabotage.	Full bore rupture; Jet fire; Vapour Cloud Explosion (VCE).	1. **Passive:** Deep burial (>1.2m); Warning tape; Concrete slabs. 2. **Active:** Fiber optic leak detection / Acoustic monitoring. 3. **Active:** ESD valve at plant boundary and compressor station (check valve).
N4-02	Reverse Flow	Plant pressure drops below pipeline pressure; Compressor trip.	Natural gas (from the grid) flows back into the H_2 plant (contamination/safety risk).	1. **Passive:** Non-Return Valves (Check Valves). 2. **Active:** Differential pressure monitoring and automated isolation valves.

10.3.5. Safety Zones & Explosion Protection (ATEX)

The facility layout utilises separation distances and zoning to manage explosion risks, compliant with ATEX 153 and IEC 60079-10-1.

10.3.5.1. ATEX Zoning Classification

The classification defines areas based on the probability of an explosive atmosphere being present.

Zone 0 (Continuous Hazard):

- **Definition:** Place in which an explosive atmosphere consisting of a mixture with air of flammable substances in the form of gas, vapour or mist is present continuously or for long periods or frequently (>1000 hours/year).
- **Locations:** Inside hydrogen piping, separators, buffer tanks, and the headspace of water tanks where H_2 might degas.
- **Equipment:** Category 1G (Ex ia - Intrinsic Safety) only.

Zone 1 (Likely Hazard):

- **Definition:** Place in which an explosive atmosphere is likely to occur in normal operation occasionally (10-1000 hours/year).
- Locations:
  - **Compressor Enclosures:** Due to the likelihood of seal leakage.
  - **Vent Stack Outlets:** A radius of 3–5 meters around the discharge point.
  - **Electrolyser Valve Skids:** Immediate vicinity of flanges and valves.

- **Equipment:** Category 2G (Ex d - Flameproof, Ex e - Increased Safety, Ex ib - Intrinsic Safety).

Zone 2 (Unlikely/Short Duration):

- **Definition:** Place in which an explosive atmosphere is not likely to occur in normal operation but, if it does occur, will persist for a short period only (<10 hours/year).
- Locations:
- **Electrolyser Hall Ceiling:** The top 10-20% of the room volume, assuming adequate ventilation is proven.
- **Outdoor Piping:** 1–3 meters around flanged connections, safety valves, and instrument fittings.
- **BESS Containers:** The interior of BESS containers is typically classified as Zone 2 due to potential battery venting gases (H_2), requiring Ex-rated detection and ventilation equipment. [111]
- **Equipment:** Category 3G (Ex n - Non-sparking, Ex ic).

10.3.5.2. Safety Distances (Separation)

Safety distances are crucial for preventing "domino effects" (cascade failures). We apply the conservative criteria from **NFPA 2** and **EIGA Doc 75**.

Table 10-5: Safety Separation Distances in Accordance with NFPA and EIGA Standards

Source	Object	Target	Recommended Distance	Rationale
NFPA 2 / EIGA	Electrolyser Building	Control Room / Offices	20–30 meters	Protection of personnel from thermal radiation (jet fire) and overpressure (blast). Can be reduced with blast walls.
NFPA 855	BESS Container	Electrolyser Hall	10–15 meters	Separate the fire load of the batteries from the explosion hazard of the hydrogen.
NFPA 855	BESS Container	BESS Container	3 meters (10 ft)	Prevent thermal runaway propagation from one unit to another.
NFPA 2	H_2 Vent Stack	HVAC Air Intakes	15 meters (50 ft)	Prevent recycling of vented hydrogen or oxygen back into building air supply.
EIGA	O2 Storage/Vents	H_2 Storage/Vents	Min. 5-10 meters	Prevent interaction of oxidant and fuel leaks.

10.3.6. Mitigation & Safety Barriers (Layers of Protection)

The safety concept relies on Independent Protection Layers (IPLs).

10.3.6.1. Process Control & Detection (Layer 1)

- **SCADA System:** Continuous monitoring of cell voltages, temperatures, pressures, and flow rates.
- Gas Detection Matrix:
  - **Hydrogen (Indoor):** Ceiling-mounted sensors. Technology combination: **Catalytic Bead** (0-100% LEL) for general leaks + **Ultrasonic** (acoustic) for high-pressure leaks which are instant.
  - **Hydrogen (Outdoor):** Point detectors at potential leak sources (flanges, compressors).
  - **Oxygen (Indoor):** Sensors at breathing height (to detect enrichment or displacement/asphyxiation).
  - **Flame Detection: UV/IR (Ultraviolet/Infrared)** detectors are mandatory because hydrogen flames are invisible to the naked eye and emit low radiant heat.

10.3.6.2. Emergency Shutdown (ESD) Levels (Layer 2)

The ESD system is hierarchically structured to minimise disruption while ensuring safety.

- **ESD-0 (Local Unit Trip):** Stops a specific electrolyser stack or compressor train. Triggered by local vibration, high temp, or minor leak.
- **ESD-1 (Production Shutdown):** Stops all electrolysis and compression. Isolates buffer storage. Triggered by confirmed gas detection (2oo3 voting) in the hall or critical process upset.

- **ESD-2 (Total Plant Emergency):** "Site Blackout" (except UPS safety systems). Isolates grid connection, PV arrays, and BESS. Closes pipeline interface valves. Triggered by fire detection, manual call point, or seismic event.

10.3.6.3. *Active Fire Protection (Layer 3)*

The strategy differentiates between the Hydrogen Hall and the BESS.

- Electrolyser Hall (Hydrogen Fire):
  - **Strategy: DO NOT EXTINGUISH** a hydrogen jet fire until the source is isolated. Extinguishing a leak that is still flowing creates an explosive cloud (vapor cloud explosion risk).
  - **System:** High-rate Emergency Ventilation (dilution) + Water Mist (cooling of adjacent structures/vessels to prevent BLEVE). No gas suppression (ineffective against H_2 supply). [157]
- BESS Containers (Lithium Fire):
  - **Strategy:** Immediate suppression and cooling to stop thermal runaway.
  - Agent: Perfluorohexanone (C6F12O).
  - **Effectiveness:** As detailed in Section 8.3.4 (Node 3), Perfluorohexanone is superior for this application. It effectively extracts heat, inhibiting the thermal runaway process, and is safe for electrical components.
  - **Application:** Automated system triggered by smoke/heat detection or BMS signal. [98]

10.3.6.4. *Passive Safety (Layer 4)*

- **Blast Walls:** Reinforced concrete walls separating the high-pressure storage area from the control room and public roads.
- **Venting System:** All safety relief valves (PRVs) discharge to a dedicated vent stack designed to disperse H_2 upwards to a safe location (high velocity, unhindered vertical release).
- **Material Selection:** Rigorous use of hydrogen-compatible materials (e.g., austenitic stainless steel 316L) to prevent embrittlement. [158]

10.3.7. Risk Matrix and Conclusion

The following qualitative risk matrix summarises the residual risk profile after the implementation of the defined safeguards.

Table 10-6: Residual Risk Matrix After Implementation of Safeguards

Risk Scenario	Severity (Unmitigated)	Probability (Unmitigated)	Mitigation Measures (Barriers)	Residual Risk
Electrolyser Gas Crossover (Explosion)	Catastrophic (5)	**Medium (3)** (AEL at low load)	PEM Technology Selection (Design), LEL Interlocks (SIS), Membrane Monitoring.	Low (Acceptable)
BESS Thermal Runaway (Fire)	Major (4)	**Medium (3)** (Li-ion inherent)	BMS monitoring, Cell spacing, **Perfluorohexanone Suppression**, Fire rated container.	Low (Acceptable)
Hydrogen Leak & Jet Fire	Major (4)	**Medium (3)** (Fittings/Seals)	Leak detection, UV/IR sensors, Auto-isolation (ESD), Blast walls, Zoning.	Low (Acceptable)
Pipeline Interface Rupture	Catastrophic (5)	Low (2)	Deep burial, Warning tape, ESD valves, Patrols.	Low (ALARP)

The hazard analysis confirms that the proposed **Green Hydrogen Plant in Uzhhorod** presents specific, high-consequence risks inherent to hydrogen and oxygen production. However, these risks are well-understood and fully manageable through the application of the **"Preparing for Chaos"** philosophy.

The strategic selection of **PEM technology** significantly de-risks the primary hazard of gas crossover during solar-driven operation, providing an inherently safer operational profile compared to Alkaline alternatives. The integration of **Perfluorohexanone** fire suppression provides a state-of-the-art safeguard for the critical BESS assets. By strictly adhering to **Seveso III, ATEX, and ISO 22734**, and by implementing the defined layers of protection (LOPA), the project meets the **ALARP (As Low As Reasonably Practicable)** criteria required by EU regulations and international investors. The facility is designed not just for compliance, but for resilience, ensuring safe operation within the critical energy infrastructure of Ukraine and the European Union. [97] [113]

10.4. Cybersecurity Concept: Unified Industrial Resilience

10.4.1. Purpose, Scope, and Critical Digital Assets

This section defines the comprehensive cybersecurity concept for the utility-scale hydrogen production hub (422 MW capacity) in Zakarpattia. The objective is to identify key cybersecurity risks, define security architecture principles, and ensure the absolute resilience of Industrial Control Systems (ICS), IT infrastructure, and operational processes against cyber-physical disruptions.

To achieve this, the following **Critical Digital Assets** have been identified and fall strictly under this protection framework:

- SCADA and Distributed Control System (DCS) platforms.
- Programmable Logic Controllers (PLC) and Remote Terminal Units (RTU).
- Hydrogen electrolyser control systems.
- Compressor and hydrogen storage control systems.
- Grid interface equipment (inverters, switchgear controllers).
- Dispatch and Energy Management Systems (EMS).

Protection of these assets is governed by core **Secure Design Principles**:

- Comprehensive threat modeling during the detailed engineering phase.
- Zero Trust architecture for all logical access.
- Principle of least privilege (PoLP) applied across all systems.
- Strict separation of duties for operators, engineers, and administrators.
- "Secure by default" configuration for all procured equipment.

10.4.2. Critical Infrastructure Classification & Regulatory Framework

The hydrogen hub is a strategically vital energy asset.

- Classification Status: The facility is expected to be classified as a critical infrastructure facility in accordance with the Resolution of the Cabinet of Ministers of Ukraine No.1109 concerning the categorisation of critical infrastructure objects. Considering the scale of energy consumption and integration with national energy systems, the facility will likely fall into Category I or Category II of criticality. Final categorisation must be determined during the detailed design phase with the competent authorities.
- Applicable Standards and Regulatory Requirements:
  - Order of the Ministry of Energy of Ukraine No.403 (07.10.2025): Establishing cybersecurity requirements for the fuel and energy sector.
  - IEC 62443: Industrial control systems security.
  - ISO/IEC 27001: Information security management systems.
  - ISO/IEC 27019: Information security controls for the energy utility industry.
  - NIST SP 800-82: Guide to Industrial Control Systems (ICS) protection.

10.4.3. Unified Threat Landscape (Physical & Cyber Integration)

Energy infrastructure in Ukraine faces elevated, highly complex cybersecurity risks. The security philosophy acknowledges that cyber threats are often precursors to, or combined with, kinetic impacts. The primary threat vectors include:

- State-sponsored cyber operations targeting energy infrastructure.
- Destructive malware and wiper attacks specifically engineered for industrial disruption (e.g., similar to Industroyer or NotPetya), aiming to halt electrolysis or compromise gas storage parameters.
- Combined cyber-physical attacks, including coordinated cyber blinding (disabling monitoring systems) preceding missile strikes or drone attacks.
- Ransomware affecting IT and operational visibility.
- Supply-chain compromises of industrial equipment (e.g., PLCs, network devices).
- Insider misuse or credential compromise (engineering access).

10.4.4. Secure Network Architecture & Supply Chain Security

To mitigate advanced threats, a strict Defense-in-Depth (DiD) network architecture is mandated.
Secure Network Architecture entails 4 mandatory segmentation zones:

- Corporate IT Network.
- Industrial OT Network.
- Security Systems Network (CCTV, Access Control, Fire Alarms).
- External Connections Zone.
- Boundary Protection: Implementation of an Industrial DMZ (Demilitarised Zone) is mandatory to ensure strictly controlled communication between the IT network and SCADA environments.
- Data Transmission: Utilisation of VPN gateways for all external routing and mandatory encryption of transmitted data via TLS-based protocols.
- Supply Chain Security Controls:
  All EPC contractors and OEMs must comply with:
  - Cybersecurity requirements embedded in all procurement contracts.
  - Rigorous equipment integrity verification prior to installation.
  - Secure, authenticated firmware update mechanisms.
  - Strict control and monitoring of vendor remote access.

10.4.5. Monitoring, Incident Response, and Operational Resilience

Continuous visibility and the ability to operate under duress are critical for the hydrogen hub.

I Monitoring and Incident Response:
- Deployment of SIEM (Security Information and Event Management) and SOAR (Security Orchestration, Automation, and Response) platforms.
- Comprehensive log collection from all network infrastructure, servers, and controllers.
- Deployment of OT-specific intrusion detection systems for real-time anomaly detection in technological processes.

II Operational Resilience and Business Continuity measures include:
- Redundant control systems (DCS/SCADA) isolated physically and logically.
- Backup communication channels for dispatch and emergency shutdown.
- Secure, offline, and immutable data backups.
- Formally tested disaster recovery procedures.
- Full integration of cyber anomaly detection and physical security systems into a unified SOC.

10.4.6. Cybersecurity Implementation Roadmap

The integration of this framework follows a structured project lifecycle approach:

1. Cybersecurity risk assessment (Preliminary in Pre-FS, detailed in FEED).
2. Security architecture design (IT/OT blueprints).
3. Technology selection (Firewalls, SIEM, IDS, Endpoint protection).
4. Implementation during engineering and construction (EPC phase).
5. Continuous monitoring and improvement during Operations & Maintenance (O&M).

Table 10.6. Preliminary Cybersecurity Risk Assessment

Threat Scenario	Affected Systems	Likelihood	Impact	Mitigation Measures
Targeted cyber attack on SCADA / OT environment	SCADA, PLC, DCS	High	Very High	Network segmentation, OT IDS/IPS, strict access control
Compromise of remote vendor access	Engineering workstations, OT network	High	High	MFA, PAM, jump servers, access monitoring
Supply-chain compromise of industrial equipment	PLC, network devices	Medium	High	Vendor security requirements, equipment integrity verification, firmware validation
Ransomware affecting IT infrastructure	Corporate IT systems	Medium	High	Backups, endpoint protection, monitoring
Insider misuse or credential compromise	Admin accounts, engineering access	Medium	High	RBAC, logging, PAM

11. Project Implementation Plan

This section outlines a high-level but credible execution plan, providing a roadmap with key phases, governance structures, and strategic activities required to move the project from the current feasibility stage to commercial operation.

11.1. Project Governance and Team

A dedicated Special Purpose Vehicle (SPV), "Green H_2 Uzhhorod," will be the legal entity that owns and operates the project. The project governance will be overseen by a Steering Committee comprising representatives from N1Capital and, upon investment, key equity partners and lenders. A dedicated Project Management Unit (PMU) will be established, led by an experienced Project Director, with key roles including a Commercial Manager (offtake, financing), Technical Manager (engineering, EPC), Permitting and ESG Manager, and a Construction Manager.

11.2. Phased Development Timeline

The project will be executed in a phased manner to manage risk and align with market and infrastructure development. The following timeline outlines the critical path and key milestones for the recommended 422 MW Hub development, which includes the initial pilot phases.

Phase 1: Development and Pilot (Current – Q4 2027):

- Pre-Feasibility Study Completion & Dissemination (Q4 2025): Finalise and publish this study, fulfilling H2Uppp requirements.
- Financing and Offtake Finalisation (Q1 2026 – Q2 2026): Secure binding term sheets from IFIs and other lenders based on this study.
- Pre-FEED and Permitting (Q2 2025 – Q2 2026): Commence Front-End Engineering Design (Pre-FEED). Submit applications for all key permits (DPT, EIA, Grid/Gas Connection).
- EPC Tendering and Award (Q3 2026): Select and contract the EPC partner.
- Financial Close (Q4 2026): Finalise and sign all financing agreements.
- Construction – 2 MW Pilot (Q1 2027 – Q4 2027): Construction, installation, and commissioning of the initial 2 MW pilot plant.
- Milestone: Commercial Operation Date (COD) for 2 MW Pilot (End of 2027).

Phase 2: 20 MW Commercial Demonstration Plant (Q1 2028 – Q4 2028):

- Construction – 20 MW Plant (Q1 2028 – Q4 2028): Construction and commissioning of the next 20 MW.
- Milestone: COD for 20 MW Plant (End of 2028).
- Final Investment Decision (FID) for 100 MW Scale-up (Mid-2028): Based on successful pilot operation and CEHC progress.

Phase 3: 100 MW Pre-Utility Scale Plant (Q1 2029 – Q4 2030):

- Construction – 100 MW Plant (Q1 2029 – Q4 2030): Construction and commissioning of the next 100 MW stage.
- Milestone: COD for 100 MW Plant (End of 2030).
- Final Investment Decision (FID) for 300 MW Scale-up (Mid-2030): Based on successful 100 MW operation and CEHC progress.

Phase 4: 300 MW Utility Scale Plant (Q1 2031 – Q4 2032):

- Construction – Full 300 MW Plant (Q1 2031 – Q4 2032): Construction and commissioning of the remaining 300 MW capacity, completing the full 422 MW H_2HUB configuration.
- Milestone: COD for Full 422 MW Plant (End of 2032).

11.3. Procurement Strategy

The procurement strategy will prioritise bankability, reliability, and cost-effectiveness.

- **Electrolysers & PV Modules:** Key equipment will be sourced from Tier-1, internationally recognised manufacturers with a strong track record and the ability to provide robust performance warranties and long-term service agreements. A competitive bidding process will be used to select suppliers.
- **EPC Contractor:** The project will be delivered via a lump-sum, turnkey EPC contract to provide cost and schedule certainty. The selection process will involve pre-qualification of experienced international and local firms, followed by a competitive tender. The EPC contractor will be responsible for detailed engineering, procurement, construction, and commissioning of the entire facility.

11.4. H2Uppp Dissemination and Stakeholder Engagement Plan

Fulfilling the knowledge-sharing mandate of the H2Uppp grant is a key project objective. Following the finalisation of this study, the PMU will execute a detailed dissemination plan:

- **Publication:** The non-confidential versions of this study and the developed templates (DPT, SEA, EIA, ToR) will be made publicly available through the H2Uppp and GIZ platforms.
- **Developer Workshops:** Organise and participate in at least two workshops in Ukraine, presenting the study's findings, methodologies, and templates to other project developers, industry associations (e.g., Ukrainian Hydrogen Council), and private sector stakeholders. The goal is to share lessons learned and facilitate the uptake of best practices.
- **Public Stakeholder Engagement:** Conduct dedicated briefings and meetings with key public stakeholders, including the Ministry of Energy, the national energy regulator (NEURC), Ukrenergo, and the GTSOU. The objective is to present the policy recommendations on lifting regulatory barriers and to provide technical input for the development of new standards. [149]
- **Local Community Dialogue:** Organise at least two dialogue events with the local community and civil society in the Zakarpattia region to maintain transparency, provide project updates, and continue the stakeholder engagement process initiated during the EIA.

12. Conclusions and Recommendations

This feasibility study has conducted a comprehensive, multi-faceted analysis of the proposed utility-scale green hydrogen project in Zakarpattia, Ukraine. The findings confirm that the project is strategically aligned with both Ukrainian and European energy objectives, technically sound, and commercially viable under a structured, de-risked implementation plan.

12.1. Summary of Project Viability

The project's viability is underpinned by a confluence of positive factors: a strategic location with excellent proximity to critical energy infrastructure; access to sufficient renewable energy and water resources; a clear and cost-effective export route via the planned Central European Hydrogen Corridor; and a strong market pull from the EU's legally mandated decarbonisation targets. The primary challenges are not technical but are concentrated in the financial and regulatory spheres, namely Ukraine's high-risk investment climate and its nascent legal framework for hydrogen. However, as detailed in this report, these challenges are surmountable through a targeted mitigation strategy centered on blended finance, adherence to IFI standards, and proactive engagement to shape the regulatory environment.

12.2. Recommended Scenario for Implementation

Based on the detailed technical and economic analysis, this study formally recommends that N1Capital and its partners proceed with the full project development of up to 422 MW Proton Exchange Membrane (PEM) electrolyser configuration. This is recommended for the following reasons:

- **Technical Suitability:** PEM technology's superior flexibility and rapid response rate are optimally suited for integration with the project's primary variable power source, solar PV, maximizing energy capture and hydrogen output.
- **Economic Performance:** While requiring higher initial CAPEX than AEL, the 422 MW PEM Hub benefits from higher efficiency and flexibility, and a more compact footprint, leading to a competitive LCOH and robust long-term financial returns.
- **Scalability and Risk Management:** The 422 MW scale achieves significant economies of scale beyond the pilot phases while providing a platform to prove the utility-scale operational and commercial model before replicating it in the Ukrainian market.

12.3. Strategic Recommendations for N1Capital

To maintain momentum and advance the project towards a Final Investment Decision (FID), the following actions are recommended as immediate priorities:

- **Secure Binding Offtake:** Convert the current LoI with Orlen for the 2 MW + 20 MW pilot phases into a binding, long-term offtake agreement. This is the single most critical step to unlock project financing. Simultaneously, initiate commercial discussions with other potential offtakers in Slovakia, Austria, and Germany for the 100 MW scale-up.
- **Advance Interconnection Agreements:** Work closely with Ukrenergo and the GTSOU to finalise the technical studies and move towards signing binding grid and gas connection agreements. This will solidify cost estimates and timelines for critical infrastructure.
- **Initiate IFI Engagement:** Formally approach the EBRD, EIB, and IFC with this feasibility study as the basis for financing discussions. The primary objective is to secure concessional debt and explore risk mitigation instruments (e.g., MIGA guarantees) to structure a bankable, blended finance package. [70]

12.4. Policy Recommendations for Ukrainian Stakeholders

This study, funded under the H2Uppp program, provides a unique, investor-grade perspective on the needs of the emerging hydrogen sector. The following policy recommendations are offered to the Government of Ukraine, the Ministry of Energy, and relevant regulatory bodies to accelerate market development:

- **Enact a Dedicated Hydrogen Law:** Prioritise the finalisation and adoption of a comprehensive legal framework for hydrogen. This law should formally define "renewable" and "low-carbon" hydrogen in line with EU directives, establish a clear system for Guarantees of Origin, and create a predictable permitting process. [117]
- **Develop Grid Injection Standards:** Task the GTSOU and the national regulator (NEURC) with developing and formalizing the technical standards and tariff methodologies for injecting pure hydrogen into the transmission network, using the templates and analysis from this study as a starting point.
- **Align Environmental Permitting with IFI Standards:** Consider integrating key requirements of the EBRD/IFC Performance Standards into the national EIA regulations for large-scale energy projects. This would streamline the due diligence process for projects seeking international finance and enhance the overall investment attractiveness of Ukraine's energy sector.

12.5. Concluding Remarks

The **green H_2 project in Zakarpattia** represents more than a standalone investment opportunity. It is a pioneering venture with the potential to serve as a catalyst for Ukraine's transformation into a major European green energy hub. By successfully navigating the complexities of its development, the project will not only deliver clean energy to Europe and generate economic value for Ukraine but will also create a proven, replicable blueprint for a new generation of sustainable infrastructure. Its implementation will be a tangible symbol of Ukraine's resilience, its commitment to a green future, and its irreversible integration into the European community. [45]

Appendices

- **A.** Preliminary Equipment List
- **B.** Stakeholder Engagement Plan (SEP)
- **C.** Works Cited

Attached separately:

- **D.** H2Uppp Deliverable: Standardised Detailed Plan of Territory (DPT) Template
- **E.** H2Uppp Deliverable: Standardised Strategic Ecological Analysis (SEA) Template
- **F.** H2Uppp Deliverable: Standardised Environmental Impact Assessment (EIA) Template (IFI-Compliant)
- **G.** H2Uppp Deliverable: Template Terms of Reference for Gas Grid Interconnection

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