38th International Electric Vehicle Symposium and Exhibition (EVS38) Göteborg, Sweden, June 15-18, 2025

Hydrogen-Powered Gensets for EV Infrastructure Optimal Integration

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Executive Summary

This paper investigates an integrated, off-grid energy solution for EV charging infrastructure powered by green hydrogen and renewable energy sources. The proposed system architecture includes a 12 MW solar PV field, an electrolyzer for hydrogen production, hydrogen storage and virtual pipeline transport, an INNIO Jenbacher 1 MW H2-fed engine, and a battery energy storage system. A techno-economic and environmental modelling framework is developed to assess optimal sizing and operational dispatch strategies accounting for EV profiles. The system also exploits cogeneration potential by recovering waste heat to meet ancillary thermal and cooling demands, thereby improving overall efficiency, and lowering the equivalent Levelized Cost of Hydrogen. Results indicate that the system can produce over 200,000 kg of hydrogen annually, offset significant CO_2 by up to 90%, and achieve a payback period of less than 10 years. This study demonstrates the feasibility of hydrogen-based, multi-energy EV charging solutions aligned with net-zero mobility targets.

Keywords: Supply and Value Chain, Energy Management, Sustainable Energy, Modelling and Simulation, Heavy Duty Electric Vehicles & Buses

1 Introduction

The rapid uptake of electric vehicles (EVs) is increasingly recognized as a cornerstone of global transportation decarbonization efforts. According to the International Energy Agency (IEA), worldwide EV sales exceeded 10 million units in 2022, and governments continue to set ambitious targets for the electrification of passenger cars, fleets, and public transport [1]. However, the growth of EVs also places substantial demands on existing electrical infrastructure. Building out scalable, reliable, and low-carbon charging solutions can be challenging, especially in regions with weak grids or high volatility in renewable energy supply.

The global pursuit of net-zero emissions has positioned hydrogen (H_2) as a key enabler of decarbonization strategies due to its versatility and potential to reduce CO2 emissions across energy-intensive sectors. However, the widespread deployment of H2 technologies faces critical challenges related to production scalability, infrastructure development, and integration into existing energy networks. Addressing these barriers is essential to accelerating the energy transition. In this context, the role of H2 transportation technologies and the emerging green NH3 market are crucial to ensuring the viability of H2-based energy solutions. Concurrently, advancements in hydrogen transportation, spanning compressed gas, liquefied hydrogen, liquid organic hydrogen carriers, and ammonia, are essential for reducing costs, improving efficiency, and ensuring regulatory compliance.

In this context, H2 has drawn attention as a versatile energy carrier supporting zero-emission power generation for EV charging. When produced using renewable sources, "*green hydrogen*" offers an opportunity to store surplus renewable electricity and dispatch it later to power fast chargers or provide resilience services [2]. This approach is particularly relevant when distribution network expansions are expensive or delayed. H2-fed generator sets (gensets), namely Internal Combustion Engines (ICE) or alternatively, even if their complete exploitation is still debatable, fuel cell systems can be installed where charging is needed, effectively decoupling charging demand from grid constraints. Multiple European and US demonstration projects have highlighted the feasibility of integrating H2-fed ICE with battery energy storage systems (BESS), forming hybrid solutions for off-grid or weak-grid EV charging [3-5].

Despite notable potential benefits, the value chain for H2-powered EV charging is complex. Indeed, it spans from renewable energy sources (RES), through electrolyzers and battery and H2 energy storage, to H2 distribution (including “virtual pipelines”), and finally to energy conversion systems based on internal combustion engines configured for H2 operation, with the resilient support of already capable ICE to be fed with Natural Gas. The entire chain must be carefully integrated to achieve economic viability, reduced overall emissions, and operational reliability [6,7]. Moreover, the high-quality heat produced by H2 fed ICE can and should be harnessed for additional uses, such as space heating and cooling via absorption chillers, improving system efficiency and optimal operations, especially when integrated into Smart Multi-Energy Systems [8], characterized by the concurrent demand for electricity, cold energy, heat and eventually drinking water. This multi-energy approach, often called combined cooling, heat and power (CCHP) or trigeneration, can help offset fuel and capital costs [3,9].

According to the complexity proposed by the challenge of switching toward advanced H2-fed EV charging infrastructure in the holistic transition towards highly integrated Smart Multi-Energy systems, by leveraging on a well-structured techno-economic analysis carried out thanks to the house-developed digital platform NxPlan [10], it is possible to solve Master-Planning & Optimal Dispatching Problem in the multi-energy system decarbonization framework.

The results of the investigation carried out by the author in this study demonstrate how H2-fed ICE can effectively support EV fast charging infrastructure in a configuration where grid capacity is not always available. By optimally selecting a 1 MWe H2-Ready ICE alongside BESS, the study highlights that while BESS excels at short-term buffering, its capital-intensive nature makes it less economical for extended backup. Conversely, relying on a full H2 value chain based on an advanced H2 Virtual Pipeline, H2-fed ICE offers both scalable power and cost advantages, particularly in highly integrated scenarios, characterized by RES intermittency. A hybrid configuration combining batteries for rapid fluctuation control with H2-fed ICE for more extended outages yields improved reliability and lower infrastructure costs. The results of the environmental assessment show substantial (up to 90%) CO_2 reductions when using green H2. The papers present results that also integrate details of a complete environmental techno-economic assessment for accounting for CO2 tax, incentivization mechanism, and related costs, both at CAPEX and OPEX. The computational tool adopted and developed by the authors allows future efforts to target system optimization, supportive policy frameworks, and alternative H2 carriers such as ammonia to enhance sustainability and economic viability.

2 Technical Background

In the technical background sections, the authors present details on each stage of this H2-to-EV value chain in sequence: (1) the role of renewables in producing green H2, (2) BESS for complementary, short-term buffering, (3) truck-based H2 supply (“virtual pipelines”), (4) on-site energy conversion systems, and (5) the final EV charging infrastructure. A discussion on insights on heat recovery and the broader multi-energy integration that can elevate system efficiency and economics is also presented.

Accordingly, H2-powered EV charging systems offer a promising alternative when grid capacity is limited, or upgrades are prohibitively expensive, integrating renewables for green H2 production, battery storage for short-term demand buffering, truck-based deliveries (“virtual pipelines”) for flexible supply, and on-site conversion via H2-fed ICE or, less commonly, with fuel cell. Solar farms, based on large-scale PV, can, similarly to large-scale wind farms, generate H2 at a Levelized Cost of Hydrogen (LCOH) ranging between \$4–\$10/kg, depending on geographical locations and investment policies. LCOH, in specific areas, though current demonstration projects often see \$7–\$15/kg [11], when all the BOP costs are included and integrating strategy with the national grids is accounted for too. Accordingly, to make H2 production more attractive for the electrification process and support the EV infrastructure, industry targets aim to reduce delivered costs to below \$ 3/kg by 2030.

Electrolyzers and fuel cells are commercially mature (TRL near 7–9) but still require cost reductions, while H2-fed ICE, already commercially available [3], has competitive electrical efficiency (>40%) compared to fuel cells (45–60%) yet benefit from combined heat and power, which can raise global efficiency above 80%. Primary electrolyser technologies include alkaline, proton-exchange membrane (PEM), and solid oxide electrolysers (SOECS) [12,13]. Currently, alkaline and PEM systems are the most commercially established, converting electricity to H2 at efficiencies of around 60-70%, with specific consumption of about 50-60 kWh/kg of H2. SOECs, which operate at high temperatures, can reach 80% or more efficiencies but remain in the early stages of commercial deployment. The choice of technology is typically guided by factors such as desired efficiency, operating conditions, and integration requirements.

Accordingly, BESS help smooth spikes in EV charging or electrolyzer load, though their cost and limited duration make H2 storage more economical for multi-day power. Indeed, electrolyzers operate most efficiently under steady, high loads, whereas solar PV output is inherently variable. Using BESS to buffer solar energy allows electrolysers to run continuously near optimal conditions, maximizing H2 production efficiency per kWh. BESS also prevent solar energy waste by storing excess PV generation or briefly supporting EV chargers during sudden drops in solar output until fuel cells ramp up. This integrated approach, demonstrated in a solar-H2-battery EV charging station [14], ensures reliable, near-100% renewable-powered EV charging: solar provides primary energy, batteries enhance power quality and reduce downtime, and H2 storage extends energy availability during nights or cloudy periods. It is essential to highlight that the H2 storage system is often linked to the H2 transportation infrastructure. Indeed, while BESS can only be operated as a hardware energy storage solution, H2 is an energy carrier that can be seen as a storage system, but simultaneously also as a tradable asset that can be exchanged, transported, and converted into electricity and heat. To do so, especially when the distance between the production site and the utilization site is relevant, virtual H2 pipelines, primarily truck-based delivery systems, are currently the main approach for transporting H2 from production sites to EV charging stations, as permanent pipeline infrastructure remains limited. H2 is typically delivered either as compressed gas in tube trailers carrying around 350–1,100 kg per load [6-15] or as liquid H2 in cryogenic tankers with capacities of 3,000–4,000 kg, offering higher payloads but at increased energy and handling costs due to liquefaction. Truck-based supply provides flexibility, allowing H2 deliveries from renewable-rich regions to sites without existing infrastructure, making it an attractive near-term option for EV charging installations before more extensive pipeline networks emerge. Virtual pipelines based on tube trailers carrying 350–1,000 kg of compressed gas or liquid tankers up to 4,000 kg are the primary distribution method in early markets, although liquefaction and trucking add to costs. Capital expenses for a containerized 200 kW fuel cell generator typically range from $300k to over $1 million, while recurring costs hinge on H2's price and, in the case of H_2-fed ICE, NO_x control measures. Despite these barriers, including ongoing concerns around logistics, infrastructure, and technology costs, real-world pilots increasingly demonstrate H2's technical feasibility and highlight its potential to provide reliable, zero-emission power for fast-charging EV stations, especially when coupled with advanced control systems, heat recovery solutions, and opportunities to include additional revenue, through grid ancillary services, in the holistic H2-EV infrastructure value chain.

2.1 EV infrastructure challenges and requirements

The global electric vehicle (EV) market is poised for significant expansion, driven by rising EV sales, evolving policy mandates [16], and increased battery production, yet the scaling of EV charging infrastructure, especially with integrated energy storage, remains challenging. Below are key trends, taken from the IEA, 2023 report [1] presented in bullet points:

- **EV Market Growth:** Rapidly increasing sales, projected to reach nearly one-fifth of the overall car market in 2023.
- **Impact on Energy Sector:** By 2030, at least five million barrels of oil per day could be displaced by EV adoption, signalling a historic shift in energy consumption.
- **Key Markets:** China leads global sales (60% in 2022), with Europe and the United States also commanding notable shares.
- **Policy Initiatives:** Measures like the EU's Fit for 55 package and the US Inflation Reduction Act are expected to boost EV uptake further.
- **Battery Production and Supply Chains:** Strong growth in associated industries, though manufacturing remains highly concentrated in China.
- **Emerging Markets:** Sales more than tripled in India and Indonesia in 2022, with significant growth in Thailand.
- **Public Charging Points:** A 55% global increase from 2021 to 2022 brought the total to 2.7 million, with China leading in slow charger installation.
- **Fast Chargers:** Added 330,000 globally 2022, primarily in China, while Europe surpassed 70,000.
- **Electricity Demand for EVs:** Reached about 110 TWh in 2022 and is projected to rise to over 950 TWh by 2030 under the Stated Policies Scenario.

Despite these positive trends, EV charging infrastructure expansion faces hurdles: peak electricity charges can undermine profitability, grid operators grapple with supply chain constraints, and the cost-effectiveness of battery storage, while potentially transformative, varies by region due to different demand charge policies and environmental regulations. Although lower peak charges in parts of Europe have limited storage deployment, operators increasingly seek prime charging locations, potentially accelerating infrastructure growth. With ongoing grid investments and maturing BESS technologies, energy storage is expected to play a pivotal yet evolving role in meeting rising EV charging demands. To tackle these issues, integrating the Green H2 energy carrier as an equivalent energy storage medium allows the exploitation of commercially competitive and sustainable solutions. Indeed, thanks to H2-fed ICE, it is possible to plan ahead and cover intermittency and peak demands, disconnect from the national grid, and support reliable operations thanks to smart integration and demand response. To do so, it is essential to couple the technology with the EV infrastructure requirements.

2.2 Internal Combustion Engine for Green Hydrogen EV infrastructure supply

According to the above, H2-fed ICE integration with EV infrastructure allows for gaining flexibility and resiliency. Indeed, manufacturers like INNIO (Jenbacher) [3] have commercial engines in the range of 1.0 MWe that can run - today - on 100% hydrogen, with almost unchanged performance when compared with traditional CH4 fuel feeding [3]. While the main advantage is cost-effective scaling and reliability, an equally compelling benefit is heat recovery for additional energy services. By capturing jacket water heat and exhaust heat, an H2-fed ICE can achieve global system efficiencies of up to 80% or even higher, with respect to the application, when concurrently to electricity, heat and eventually cold energy are required. The integration of H2-ready ICE is attractive for extensive commercial or industrial facilities that require steam, hot water, or space heating [6], since the integration of an absorption chiller can convert engine waste heat into cooling, enabling tri-generation (power, heat, cooling), valuable for data centres or large buildings near the EV fast charging site.

Given that EV charging demand can be intermittent, the cogeneration or tri-generation approach helps keep the CCHP running at or close to optimal load, improving its overall efficiency and reducing overall emissions. The captured heat offsets building heating costs or powers cooling loads, enhancing economic viability [3,9]. If the EV charging station is located near a commercial or industrial complex, it may allow the sale of the heat directly or use it for associated processes. This synergy plays a key role in justifying the mitigation of the capital expense of the Green H_2 ICE value chain, allowing a short payback time, and maximizing the benefit for the end-user and the technology provider.

3 Methods

In the paper the authors have provided, based on an existing digital platform called NxPLAN [10], the modelling and simulation of a highly integrated multi-energy system mainly based on PV, BESS and an electrolyzer for green H2 production, leveraging on advanced H2-fed ICE with optional heat recovery for cogeneration or trigeneration applications to supply green electrons to EV infrastructure, focusing on fast charging market segment, where typically contingency issues can occur when only supported by the national grid. Accordingly, in this section, the authors present a well-structured procedure developed to simulate and optimize these hybrid systems, aiming to maximize renewable energy utilisation, minimize primary energy consumption, and reduce CO_2 emissions in the context of EV infrastructure, both during planning and operational phases. The modelling framework follows a lumped-parameter, steady-state 0-D, approach, whereby each component is defined by boundary surfaces and representative control volumes, in line with the discretization methodology previously established in [17]. Mass, energy, momentum, and entropy balances are implemented for every system element, supported by constitutive and auxiliary equations where necessary. A custom component library – in the form of a Database - has been assembled, featuring commercially available and custom-defined technologies relevant to the system architecture. This includes H2-fed ICE, Solar PV, BESS, absorption chillers, and modular electrolysers and many others.

The components were first modelled and validated individually using manufacturer data or available experimental datasets. Subsequently, they were integrated into a modular simulation environment capable of representing the full-cycle performance, including design-point analysis, off-design operation, and load-dependent performance mapping. The approach follows the methodology introduced by Mazzoni et al. [8], where to address optimal dispatch and techno-economic planning, a Mixed-Integer Linear Programming (MILP) solver has been implemented and benchmarked against heuristic approaches (e.g., genetic algorithms). The simulation tool is designed to serve as a master-planning instrument—for identifying the optimal system configuration (namely, nominal capacities, sizes, and CAPEX) from a database of potential components—and as an operational optimizer—capable of managing multi-vector dispatch across electricity, heat, and cooling demands, allowing for OPEX & CO2 emission minimization, and concurrently evaluating asset management basic control rules.

In the present study, the primary objective is to enhance EV system-wide cost-effectiveness while minimizing CO_2 emissions associated with EV charging and auxiliary loads. The optimization platform also includes routines for evaluating CAPEX and OPEX, enabling its use in cost-optimal system design when economic constraints are imposed. Given the topic of H2 penetration in EV infrastructure, the LCOH is also included in the optimization framework.

For the purpose of this conference paper, the fully detailed description of the equations characterizing all the components is not presented, given the limitation of 12 pages, while the authors present the functional diagram adopted to set up the simulations, following an advanced modular approach of components. In order to allow the evaluation of the environmental techno-economic assessment, the authors present the power flow equations, together with emissions computation and finally with LCOH and NPV assessment.

3.1 Modelling Approach and Simulation Framework

The authors have developed the simulation tool on the basis of a modular approach of elementary components. Indeed, by ensuring conservation of mass and energy on the cross-boundary of each component, by matching them, it has been possible to build up the entire system. The proposed approach, according to the schematic layout given in Figure 1, divided the entire simulation into three conceptual "*islands*":

1. Renewable Island
    - Power Balance: The model first solves a power balance for the PV output, battery charge/discharge rates, and the electrolyzer load. In each time step, the PV generation P_{PV} must match the electrolyser demand P_{ELZ} plus any direct export to the grid (or import from the grid, if needed, even if in the proposed paper, the authors, looking at decarbonised Green H2, have set the constraints that no import is allowed).
    - Mass Balance for H2 Production: H2 mass flow from the electrolyser, $\mathrm{m_{H2}}$, is computed based on the electrolyser specific consumption and the power input $\mathrm{P_{ELZ}}$. An optional equation for curtailed PV power (if the battery is full and the electrolyser is at max capacity) can be introduced.

2. Supply/Transport Island
    - Virtual Pipeline Logistics: The proposed model accounts for H2 compression and storage in the H2 inventory in the storage tank (in kg), ensuring that at any time step, the stock does not exceed tank capacity nor fall below zero.
    - Transport Emissions and Costs: The proposed transport relies on truck transportation, the mass of H2 delivered per trip is accounted for, along with associated transport cost (€/km or $/km) and, if applicable, CO_2 emissions from the truck. According to GHG protocols, these emissions can be estimated via an emissions factor for diesel or other fuels, multiplied by the distance travelled and the number of trips.

3. Smart Multi Energy District Island
    - H2-fed ICE and CCHP operations: The model takes the H2 (and, in case required, emergency CH4 backup) from Virtual Pipeline as the main fuel to feed the ICE in CCHP configuration. Accordingly, the H2-fed engine power output P_{ICE} is calculated based on the fuel LHV, expressed in kJ/kg and the electrical efficiency η_{ICE}. When CCHP operations are accounted for, global efficiency is instead used, and the useful outputs are P_{ICE} and H_{ICE}. Heat can be used to feed the heat bus, or when trigeneration solutions are proposed, the H2-fed ICE coupled with Absorption Chillers allows for cooling production. Accordingly, thanks to thermal Energy Storage (TES) and an Absorption Chiller, the recovered heat is circulated through a TES buffer. An absorption chiller can convert some thermal energy into cooling, which can be mapped onto cooling loads (e.g., air conditioning) or process refrigeration needs. The coefficient of performance (COP) and heat demand/cooling demand equations govern how much heat is used or stored.
    - EV Charging Demand: The H2-fed ICE (and if available, the national grid) supplies the EV charging load P_{EV}. The model ensures electrical demand, through energy conservation equations, for each time step:

$$P_{\mathrm{ICE}} + P_{\mathrm{grid}} - P_{\mathrm{AC/CH}} + P_{B_-} - P_{B_+} - P_{EL} = P_{\mathrm{EV}} \qquad (1)$$

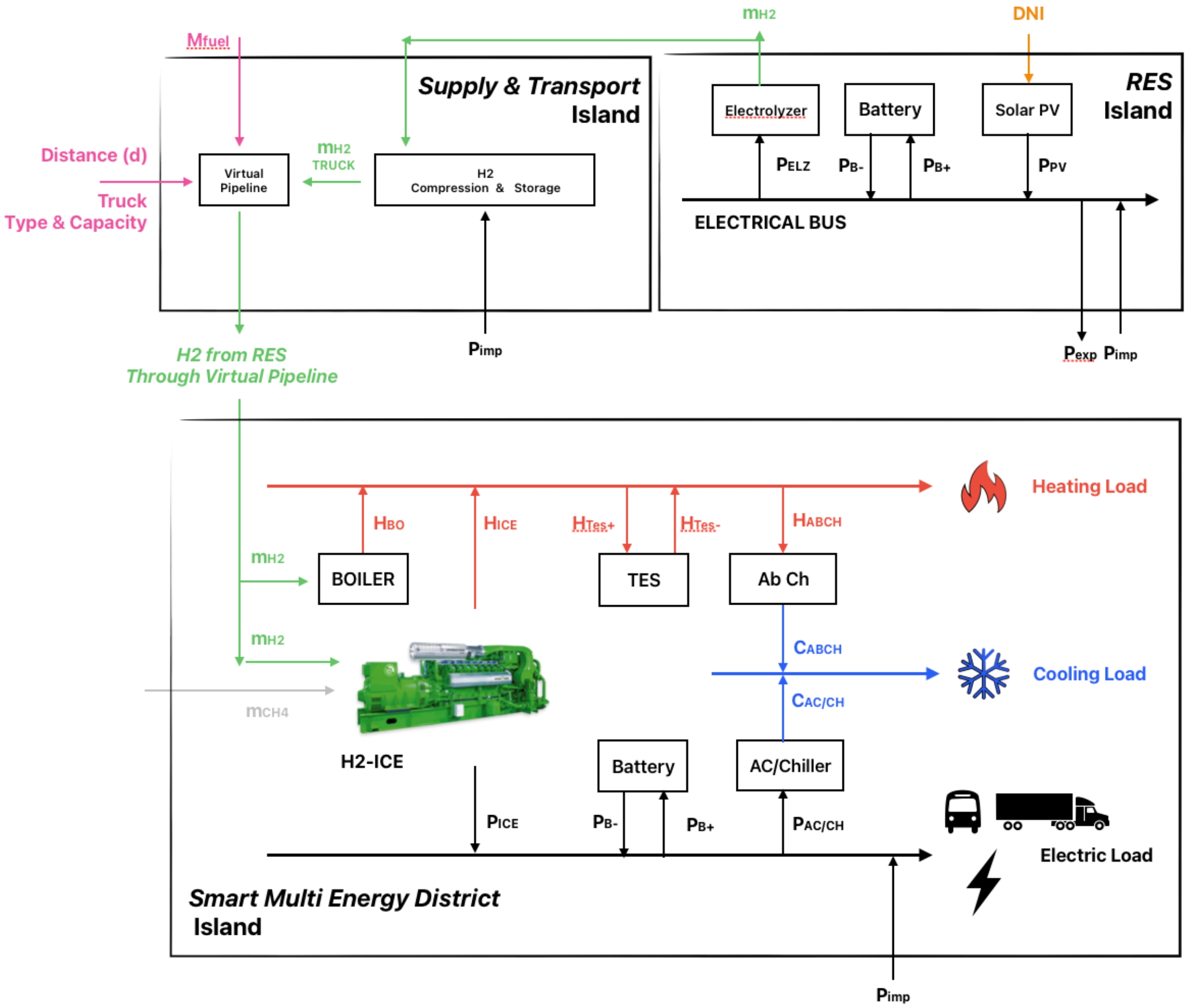

Figure 1: Modular Approach for Simulating the Smart Multi-Energy System Integrated with RES and H2 Virtual Pipeline

The purpose of the proposed methodology is to account for energy and mass conservation equations balances across all components ranging from Solar PV, BESS, electrolyser, H2-storage, truck distribution to H2-ICE, and thermal subsystems, ensuring capacity constraints, efficiency parameters, and that demand profiles (both EV charging and heat/cooling loads) are satisfied. By running NxPlan Digital Platform for the entire year of operation, it is possible to evaluate the optimal system design together with the optimal dispatching profiles for maximising the benefit of integrating H2-fed ICE in CCHP configuration, while drastically reducing CO2 emissions in the EV fast Charging infrastructure. In the following section, details related to case studies, assumptions and results are given.

To account for the system viability, the evaluation of CAPEX, expressed as the sum of the various components, and of OPEX is fundamental for accounting LCOH and Net Present Values (NPV). Indeed, the scope of the LCOH is to estimate the specific cost ($/$kg_{H2}$) of electricity that can be produced by a certain plant configuration. To evaluate the two quantities, it is required to evaluate:

- Capital Expenditure (C_{APEX})
- Operating Costs (O_{PEX})
- Lifetime span of the plant equipments (N = years)
- Interest Rate (I = %)
- Net H2 Production per Annum (H2 = kg_{H2})
- Assumption: In the current formulation, the residual value of plant equipment has not been taken into account.

The formulation of the LCOH, is given in equation 2, where *j* is the year *j-th*.

$$LCOH = \frac{\sum_{j=1}^{N} \frac{C_{APEX_j} + O_{PEX_j}}{(1+i)^j}}{\sum_{j=1}^{N} \frac{H2_j}{(1+i)^j}} \quad (2)$$

In equation 2, the numerical values of the C_{APEX} and O_{PEX} are different for each plant configuration tested by the optimiser for each iteration step, since the number & type of equipment involved in the H2-EV value chain can change during the optimization procedure. By comparing different plant configurations and related LCOH values, it is possible to understand with respect to the entire lifetime of the plant operability, which is the equivalent overall cost of generating 1kg of H2 with one configuration in respect of another. When, instead, cash flow (*CF*), as in the case of the electricity sold for EV fast charging, is accounted for, the most adequate financial indicator for project feasibility is *NPV*. This metric considers annual cash flow, interest rate, inflation, and the system's lifespan. It is calculated by subtracting annual costs from annual revenues. A simplified form of NPV is given in Equation 3:

$$NPV = \sum_{k=1}^{N} \frac{CF_k}{(1+i)^k} - C_{APEX} \quad (3)$$

In the case study section, the authors will benefit from the proposed economic parameters for assessing the environment techno-economic viability of the different system configurations and operations.

4 Case Study

This case study investigates a smart decentralised energy system, a H2-based EV charging system designed around a 1.0 MW H2-fed ICE combustion engine. The system configuration is built upon a hybrid renewable generation and virtual pipeline model, leveraging solar energy for green H2 production at a remote site and transporting the H2 to an urban EV charging station located approximately 200 km away. The proposed architecture decouples energy production and utilisation to address the challenges of integrating large-scale solar PV generation with urban EV infrastructure, particularly in areas constrained by land availability or grid limitations. A dedicated solar 12 MWe PV plant is installed in a high-irradiance, remote location, operating in island mode within a microgrid framework. This plant powers a local alkaline or PEM electrolyzer, which converts electricity generated through solar energy into green H2, for a yearly production capacity up to 200,000 kgH2/year. The H2 is then compressed, stored on-site, and delivered via tube trucks to the utilization point using a virtual pipeline approach. At the point of use, a Jenbacher J420 H2-fed engine (from INNIO Group) - a 20-cylinder known for high efficiency and reliability - is deployed to convert the green H2 into electrical power and heat to supply high-demand EV chargers and the Smart Multi Energy District demands.

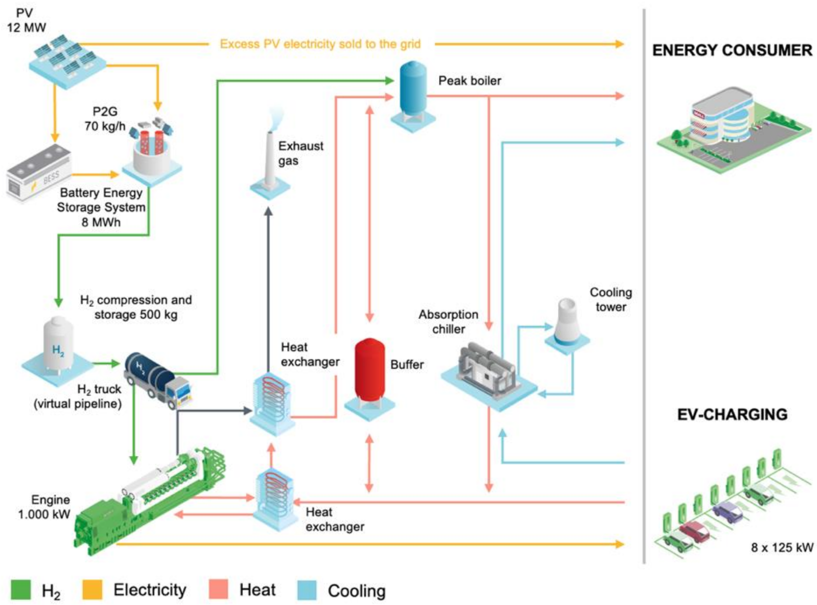

Figure 2: Case Study together with optimal component capacities [3]

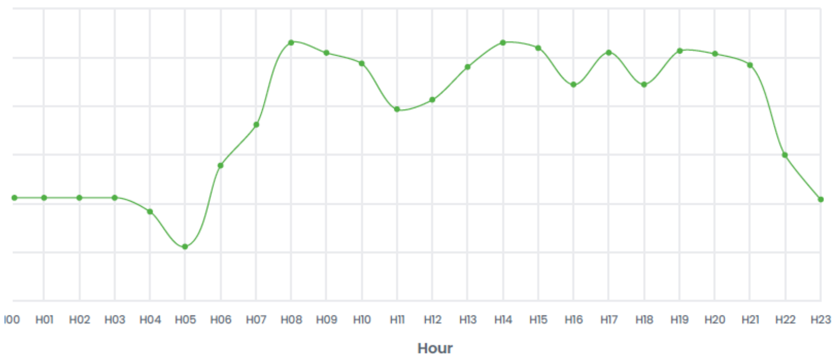

Figure 3: Case Study together with optimal component capacities [3]

Given the smart multi-energy system demands, the generation unit is also configured to enable combined cooling, heat, and power (CCHP) operations, thus meeting ancillary thermal and cooling demands of end-users where applicable. The generator's nominal capacity is constrained to be 1,000 kWe, according to the H2-fed ICE commercial details. Based on manufacturer data, the engine consumes 70–75 kg of H2 per hour, generating approximately 1,000 kWh of electrical output. This implies a daily H2 requirement of ~600 kg for an 8-hour operation window. Consequently, the electrolyser is sized at 70 kg/h to ensure a consistent fuel supply during full-load operation. To support this level of H2 production, 12 MW PV array is supported by 8 MWh capacity BESS, ensuring a sufficiently high-capacity factor for the electrolyzer, especially during peak solar hours. The complete system includes the following key components:

- A 12 MW PV field equipped with smart inverters and DC/AC conversion systems.
- A 70 kg/h electrolyzer for on-site green H2 production.
- A H2 compression and storage facility with a 500 kg buffer tank.
- A virtual pipeline logistics subsystem consisting of tube trailer trucks can transport 600 kg of H2 at 250 bar pressure per trip.
- An 8 MWh BESS to support short-term buffering and grid-forming capability at the production site.
- A 1,000 kWe H2-fed ICE for EV charging and cogeneration.

H2 transportation is managed via tube trailer trucks, equipped with high-pressure storage cylinders. While tube trailer capacities vary by design and storage pressure, typical configurations range from 300 kg to 1,000 kg. In this study, a capacity of 600 kg per trailer is evaluated to be the optimal one, limiting the Scope 1 emissions, related to H2 transportation, to value lower than 0.40 kgCO2/kgH2. To meet the daily demand at the charging site, the model estimates an average of two round trips per day. The system model also includes the optimization of local H2 storage to balance production variability (linked to solar generation) with the requirements of compression, delivery logistics, and EV load demand. Storage sizing is critical for enabling smooth H2 loading operations and reducing the frequency of transport trips. An additional revenue stream is considered by enabling the sale of surplus PV electricity to the local grid, should excess generation occur beyond the electrolyzer's capacity. This grid export option not only improves the overall economic viability of the system but also offers the potential for CO_2 credit recognition, depending on the regulatory framework and national policies surrounding green energy certification. In summary, this case study presents a replicable model for a distributed, H2-based EV charging architecture that maximizes RES utilization, decouples generation and consumption, and enhances energy resilience and sustainability. The system is particularly relevant for regions with high solar availability and limited grid expansion potential, offering a strategic path toward net-zero, off-grid EV infrastructure deployment. In order to understand the system capacity holistically, it is important to bind the computation to a certain EV profile. Accordingly, a representative daily averaged load profile was adopted to model the H2-powered EV charging system realistically, as shown in Figure 3. Given the lack of standardized usage data due to the evolving state of e-mobility infrastructure, the approach incorporates empirical assumptions validated against recent studies and simulation tools. The load curve exhibits significant variability throughout the day, with a pronounced increase in demand between 06:00 and 09:00, followed by a secondary peak between 13:00 and 20:00. Early morning (H00–H05) and late evening (post-H21) show the lowest demand levels reflecting typical EV charging behaviour aligned with commuting and fleet operation cycles. These fluctuations highlight the need for a flexible dispatch strategy. The H2 generator is sized to meet the base load, while a BESS oversees transient peaks and supports load balancing. Additionally, waste heat recovery from the H2 engine enables tri-generation, allowing thermal energy to serve adjacent end-uses (e.g., heating or cooling in nearby facilities), thereby increasing the overall system efficiency, and reducing the LCOH. This load-driven simulation framework ensures that energy supply aligns dynamically with demand while enhancing economic and environmental performance through integrated multi-energy utilisation.

5 Results and Discussion

In this section, the authors present the results of the optimisation process by first presenting, through heat-map charts, the results of the yearly optimal dispatching strategy both on the RES island and the EV fast charging infrastructure. In the second part of the analysis, by carrying out a sensitivity analysis, the authors investigate the effect of LCOH, the potential incentivization mechanism, and the price of the electricity sold to perform a comparative net present value analysis. Summary of the assumptions, the required CAPEX, the OPEX and the overall energy consumption are presented in Table 1, where the various macro-island details are described.

Starting from the RES island optimal dispatch results analysis, Figure 4 illustrates the behavior of an integrated energy system comprising RES, BESS, and electrolysers operating under a strict no-import constraint. The optimal dispatch strategy evaluated by the software ensures that all electrical demand for H2 production is met exclusively through on-site RES, with no reliance on the grid, to ensure 100% Green H2. Excess RES generation is exported to the grid, contributing to overall carbon emission reductions due to its 100% renewable origin. The dispatch strategy dynamically balances intermittent RES output with the state-of-charge of the battery, which ranges between 20% and 95%, to ensure long life cycling and the operational flexibility of the electrolyser. During periods of surplus RES availability, BESS is charged, and the electrolyser operated at nominal capacity. In the low-RES availability period, the system relies on stored energy or reduces H2 production. The optimisation platform prioritizes maximising electrolyser utilization, meeting the required constraint capacity of up to 200,000 kgH2. Exported electricity, although not the primary target, represents an environmentally favorable by-product of the dispatching optimisation. Indeed, the exported capacity allows for integration of quasi-zero emissions green electrons in the power grid, allowing for potential CO2 credits recognition, and thus offsetting other potential HTA sectors.

The dispatch results capture the complexity and variability of a hybrid multi-energy system that balances dynamic electric loads from EV fast chargers and a smart energy district. Looking at Figure 5, where results are presented, the upper plot (blue) shows the structure of the total load demand (P_{EL}+P_{EV}), with strong daily cycles and a noticeable seasonal modulation. The system faces highly fluctuating demand, consistent with the behavior of EV fleets and flexible building loads responding to time-of-use or thermal dynamics. The green middle plot, showing the power output of the H_2-fed ICE, shows a highly responsive generation asset that ramps frequently in reaction to real-time load variations. Its dispatch is spread throughout the year, with no evident prolonged downtime, suggesting it plays a critical role in providing firm capacity, especially during peak demand. Its intermittent activation pattern also implies that the H2-fed ICE is not used continuously, possibly preserving H2 fuel for peak shaving or resilience purposes. The bottom plot (black), representing the battery power dispatch, displays an intense pattern of short-duration charge/discharge cycles, confirming its role in high-frequency load balancing and EV charging profile smoothing. The battery appears to absorb daily volatility from EV charging spikes and load ramps, supporting the fast response needed in urban electrification contexts. While the pattern is noisy (as expected), it suggests good utilisation of the battery asset, although efficiency losses and degradation implications may require further economic assessment.

Looking at the results evaluated by the authors in environmental techno-economic assessment, in figure 6 Net Present Value (NPV) analysis is presented, assessing the economic viability of the proposed H2-powered EV charging system over a 15-year investment horizon, under four distinct scenarios combining variations in the LCOH and the electricity selling price (EL). The scenarios evaluated are as follows: Scenario 1 (LCOH = €7.5/kg, EL = €1.1/kWh); Scenario 2 (LCOH = €10.5/kg, EL = €1.2/kWh); Scenario 3 (LCOH = €9.5/kg, EL = €1.2/kWh) and Scenario 4 (LCOH = €7.0/kg, EL = €0.9/kWh)

The results highlight the strong influence of H2 production costs and electricity sales revenue on the system's financial performance. Scenario 1 emerges as the most favorable configuration, achieving a positive NPV in less than five years and reaching a cumulative value of approximately €600,000 by year 15. This scenario balances moderately low H2 costs and a robust electricity price point. Scenario 4, while benefiting from the lowest assumed H2 production cost (€7.0/kg), reflects a more conservative electricity revenue scenario. It still ensures steady financial growth, albeit with a slower payback trajectory.

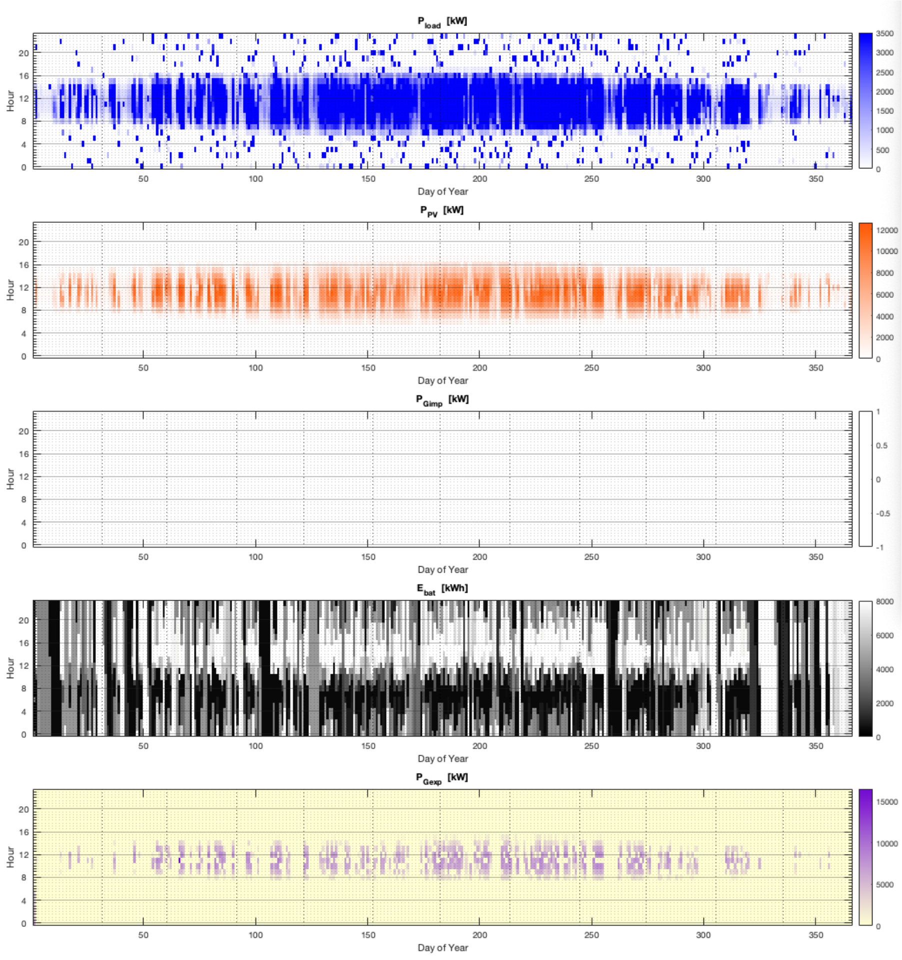

Figure 4: RES Island – Optimal Dispatch Profile over one year of operations

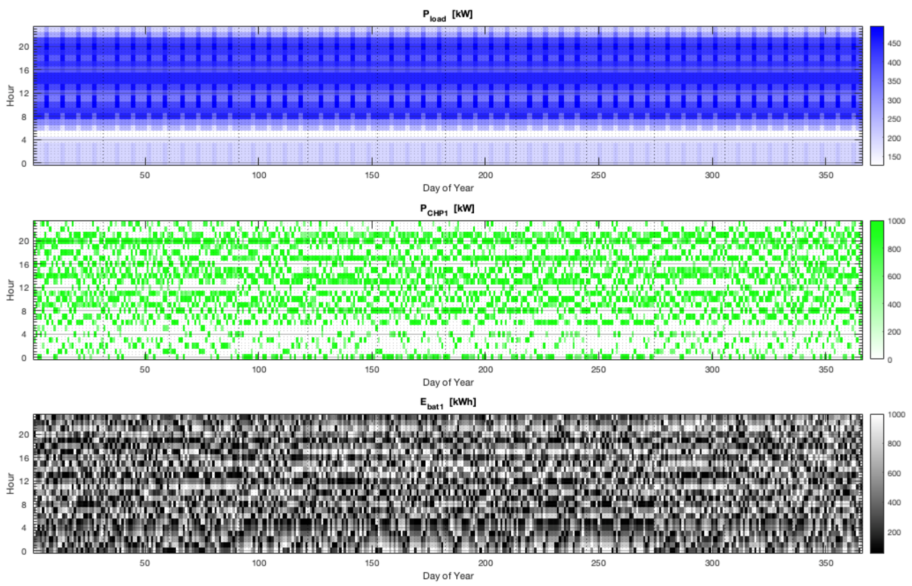

Figure 5: Smart Multi Energy District Island – EV & H2-fed ICE couple with Battery Optimal Dispatch Profile over one year of operations

Table 1: Integrated System Overview and Optimisation Summary

RES Island: Renewable H_2 Production and Storage	
Solar PV	12,000 kW DC, €9.6 MM
Electrolyzer	70 kg/h, €3.8 MM
Hydrogen buffer + compressor	500 kg @ 250 bar, €1.05 MM
BESS (RES side)	8,000 kWh, €5.5 MM
Buffer + compressor + trailers (60 m^3 @ 40 bar)	€3.0 MM
H_2 transported per trip	600 kg
Tube trailers (strategic reserve)	2 + 1 units
H_2 transport cost	€1.4/kg
CO_2 emissions (transport)	0.36 kg-CO_2/kg-H_2
Smart Multi-Energy District: CHP and EV Charging	
Jenbacher J420 H_2-Engine (CHP, chiller, boiler)	€1.83 MM
BESS (district, 8 min)	€0.68 MM
H_2 depressurization + mixing control system	€0.36 MM
EV charging (1 MW + infrastructure)	€1.62 MM
Optimization Summary	
Annual EV station energy demand	2,481,800 kWh
EVs charged/year (avg 60 kWh)	41,635
Recovered heat (Jenbacher)	1,743,000 kWh
Avoided heating cost (15 yrs @ €0.04/kWh)	€1.045 MM
Excess PV electricity sold to grid	3,000,000 kWh/yr
Cost of green hydrogen	€10–10.5/kg
Virtual pipeline system cost (15 yrs)	€25.5 MM
EV charging price (green H_2)	€1.0–1.2/kWh

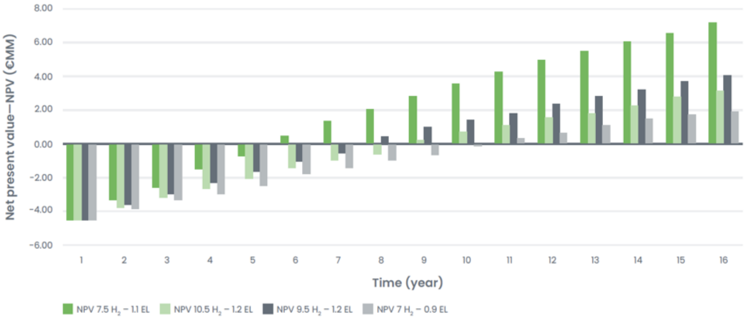

Figure 6: NPV Sensitivity Analysis by varying LCOH and EV Electricity price

Notably, the €7.0/kg assumption in Scenario 4 reflects conditions under which maximum H2 production incentives are captured, such as those provided under the U.S. Inflation Reduction Act (IRA), where the associated carbon intensity of H2 is well below the admissible threshold. Thus, this scenario assumes a full realization of available financial support mechanisms for low-carbon H2. In contrast, Scenarios 2 and 3, while maintaining high electricity sale prices (€1.2/kWh), are impacted by higher LCOH values, which slow the rate of NPV accumulation. Nevertheless, these cases remain economically viable in the medium to long term, especially under stable H2 pricing conditions. Overall, the analysis confirms that H2 production cost is the most critical determinant of project feasibility. The findings suggest that targeted policy incentives should prioritize generation, as cost reductions at the production level offer the most leverage for improving investment returns. With appropriate market conditions and regulatory support, the proposed H2-based EV charging infrastructure can deliver competitive returns within 5–7 years. It is also important to highlight that in all the proposed scenarios, the emission factor of the sold EV Fast Charging kWh is slightly higher than 10 kgCo2/MWh, a value about 90% less than average European national grid emissions factors.

6 Conclusion

The author presented a comprehensive analysis of an integrated, H2-powered EV charging infrastructure designed for smart multi-energy districts. The proposed system combines RES, green-H2 production, virtual pipeline logistics, and a H2-fed ICE, looking at the commercially available INNIO Jenbacher J420 - operating as a CCHP unit capable of supporting both EV mobility and auxiliary heating and cooling loads. A dedicated simulation framework has been developed to optimise the overall system design and the related operational dispatching strategy. The proposed layout comprises a 12.0 MW solar PV plant, a 8.0 MWh BESS, a 70.0 kgH2/h electrolyser, and a 1.0 MWe H2-fed ICE. The system has been designed to produce approximately 200,000 kg of H2 per year, enabling the EV fast charging of up to 128 EVs per 8-hour operational day via eight 125 kW charging points or equivalent configurations for other power levels.

Thanks to the proposed methodological approach, the results of the environment techno-economic analysis carried out by the optimisation framework developed by the authors indicate that LCOH for this system capacity, including shipping and transportation through virtual pipelines, ranges between €10.0 and € 10.5/kgH2, without incentives and CO2 credits mechanism. Nevertheless, assuming an electricity selling price of €0.9-1.2/kWh, the study finds the system to be cost-competitive with current EV charging tariffs in Europe. Notably, the solution enables quasi-zero (>90%) decarbonization of the EV charging process, achieving zero Scope 2 emissions. Integrating waste heat recovery for combined cooling, heat, and power (CCHP) significantly enhances overall system efficiency, balancing the LCOH values and making the EV framework more attractive. Thanks to the proposed sensitivity analysis, the results show that when propositive policy conditions and financial incentives are accounted for, the return on investment could be achieved in less than six years, reinforcing the system's viability for commercial deployment. Furthermore, looking at the technicalities of the proposed solutions, especially when compared to Fuel Cell systems, the exploitation of H2-fed ICE as a primary energy conversion unit allows for flexible and reliable operations, with reduced CAPEX and OPEX. In addition, thanks to the H2-fed ICE specification, both tension and current can be balanced to meet grid requirements, allowing smart multi-energy districts to participate actively in demand response and auxiliary services support. In conclusion, this work highlights a scalable, sustainable, and technically mature pathway toward zero-emission EV infrastructure, leveraging the synergies of renewable technologies for future smart energy ecosystems.

Acknowledgments

The authors would like to thank the R&D department of INNIO company for the funding and support. The Department of Industrial Engineering of the University of Roma Tor Vergata is also acknowledged.

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Presenter Biography

Abdessamad Saidi is an experienced professional in the field of hydrogen utilization within the energy sector. Presently, he is holding the position of Senior Business Development Manager for INNIO Group´s Jenbacher brand, where he spearheads initiatives to further their market presence and innovations. Having dedicated years to research and development in the field of renewable fuels, his most recent professional role involved advising energy providers in Germany on optimizing their business strategies within the emerging hydrogen market.
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