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Brief Report

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Establishment of Austria's First Regional Green Hydrogen Economy: WIVA P&G HyWest

Nikolaus Fleischhacker [1,*], Niusha Shakibi Nia [1,*], Markus Coll [2], Ewald Perwög [3], Helmut Schreiner [4], Andreas Burger [5], Emmanuel Stamatakis [1,6] and Ernst Fleischhacker [2]

1 FEN Research GmbH (FEN Research), Green Energy Center Europe, Technikerstraße 1-3, 6020 Innsbruck, Austria
2 FEN Sustain Systems GmbH (FEN Systems), Green Energy Center Europe, Technikerstraße 1-3, 6020 Innsbruck, Austria
3 MPREIS Warenvertriebs GmbH (MPREIS), 9900 Lienz, Austria
4 Zillertaler Verkehrsbetriebe AG, Austraße 1, 6200 Jenbach, Austria
5 TIWAG-Next Energy Solutions GmbH, Eduard-Wallnöfer-Platz 2, 6020 Innsbruck, Austria
6 Institute of Geoenergy/Foundation for Research and Technology—Hellas (IG/FORTH), 73100 Chania, Greece
* Correspondence: nikolaus.fleischhacker@fen-research.org (N.F.); niusha.shakibinia@fen-research.org (N.S.N.); Tel.: +43-512-209039-211 (N.F.); +43-512-209039-213 (N.S.N.)

Abstract: The regional parliament of Tyrol in Austria adopted the climate, energy, and resources strategy "Tyrol 2050 energy autonomous" in 2014 with the aim to become climate neutral and energy autonomous. "Use of own resources before others do, or have to do" is the main principle within this long-term strategic approach, in which the "*power on demand*" process is a main building block and the "*power-to-hydrogen*" process covers the intrinsic lack of a long-term, large-scale storage of electricity. Within this long-term strategy, the national research and development (R&D) flagship project WIVA P&G HyWest (ongoing since 2018) aims at the establishment of the first sustainable, business-case-driven, regional, green hydrogen economy in central Europe. This project is mainly based on the logistic principle and is a result of synergies between three ongoing complementary implementation projects. Among these three projects, to date, the industrial research within "MPREIS Hydrogen" resulted in the first green hydrogen economy. One hydrogen truck is operational as of January 2023 in the region of Tyrol for food distribution and related monitoring studies have been initiated. To fulfil the logistic principle as the main outcome, another two complementary projects are currently being further implemented.

Keywords: green hydrogen economy; green mobility; green industry; energy autonomy; circular economy; sustainability

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1. Introduction

Since the publication of the Club of Rome's report "The Limits to Growth" (LTG) in 1972 [1], human-induced irreversible damaging changes to the planet have been broadly reported through scientific and impact assessment studies over the last decades [2–4]. The LTG report was the starting point for novel developments in the region of Tyrol in Austria by E. Fleischhacker regarding the resource management using systems analysis and systems research [5]. As a result of developed strategies and projects by E. Fleischhacker in the late 1980s with a focus on Tyrolean hydropower and water management, the first Tyrolean energy concepts were published by the Tyrolean regional government in 1987 and 1993 [5,6]. In line with the required urgent measures to overcome the severe and continuous global warming issue (by 0.6 ± 0.2 °C over the 20th century and up to 1.09 °C from 2011 to 2020 [2,3]), the Tyrolean energy concepts presented the long-term framework for the development of a new energy system protecting the environment, conserving resources, and ensuring energy supply. The published concept in 1993 also first outlines a long-term strategical approach mentioning the year 2050 for achieving energetically/economically relevant contributions while taking into account the long-time constants for the reconstruction of the energy system as well as the market implementation of new energy technologies within at least several decades.

In this concept, technologies are considered that are capable of employing regional energy resources as electricity generation from hydropower [5,6]. According to the latest status report of the international hydropower association [7], Austria has an installed a hydropower capacity of 14.747 MW (including pumped storage) and is one of the top five countries in Europe by capacity added in 2021 (in 3rd place with 150 MW).

For a better understanding of the multidimensionality within the published concepts, a licensed problem-solving methodology was used to analyze the Tyrolean energy system in terms of energy demand, energy supply, and coverage of energy demand, quantitatively and qualitatively [5,8–11]. Since the main basis for the implementation strategy within this energy concept is the continuous analysis of the energy system, the periodic reporting of the Tyrolean energy monitoring was initiated by E. Fleischhacker and his team from "Wasser Tirol" in 2009 for the Tyrolean regional government [12]. These reports support the iterative procedure model for the stepwise and efficient processing of the Tyrolean energy strategy based on resource management, the energy system, and the understanding of circular economy and sustainability [9–11]. In the early 1990s, this procedure was developed independently and in parallel to the similar "balanced scorecard" process [13].

In 2014, the climate, energy, and resources strategy was presented by E. Fleischhacker—then, FEN Sustain Systems GmbH—to the Tyrolean parliament, focusing on the further development of strategic measures and priorities. This aimed to restrain the exponential increase in energy demand through the reconstruction of the Tyrolean energy system and thus to achieve the long-term goals towards energy autonomy and climate neutrality [5,10].

A study commissioned by the Federal Ministry of Agriculture, Forestry, Environment, and Water Management in 2010 calculated the feasibility of energy autarky for Austria until 2050, halving the energy demand [14]. However, according to E. Fleischhacker, such a reduction in energy demand alone is not sufficient. In order to achieve the strategic goal of autonomy alongside a reduction in nearly all CO_2 emissions, an extension of renewable energy sources (RES) by at least 30% [10] is needed due to significant growth of economics and population. It is, furthermore, noteworthy that according to the Tyrolean energy monitoring, the foreseen energy savings cannot be realized as anticipated at present. Consequently, an even higher use of RES is to be considered for achieving the long-term goals.

The "use of own resources before others do, or have to do", is the main principle within the "Tyrol 2050 energy autonomous" strategy of E. Fleischhacker [10]. Within the strategy development process, electrical power from RES was identified as the main energy for the reconstruction of the Tyrolean energy system due to its versatility regarding usage. With electricity, all processes from home to industry regarding heating with heat pumps and battery electric (BE) mobility can be powered with the highest efficiencies. Today, this novel strategical approach is in line with the latest published international scenarios and global measures for substantial reduction in greenhouse gas (GHG) emissions, focusing mainly on electricity from RES [15–19].

Since the main "*power on demand*" process of RES within the ongoing reconstruction of the energy system at a local, national, European, and even global level results in the production of local and/or grid-based green electricity that is non-storable, a complementary process needed to be introduced. This process is capable of supporting long-term (summer to winter) and high-quantity storage capabilities [10]. Therefore the "*power-to-gas*" process was identified and later was specified further to "*power-to-hydrogen*". This—back then—novel approach of complementing the "*power on demand*" process with the "*power-to-hydrogen*" process results in time-independent storability of otherwise useless power from RES by transforming green electricity to green hydrogen. This process further offers large-scale storability with the potential of current natural gas storage capacities due to the general compatibility, and therefore reusability, of this existing infrastructure [20].

Within the described strategy "Tyrol 2050 energy autonomous", sustainability is a dynamic system of ecology, economy, and social aspects, in which the three components constantly work together to ensure that the connection between them is never interrupted and that a constant balance is always maintained. This dynamic definition of sustainability is based on the static three-pillar model of the Brundtland report published in 1987 [21], and was developed from the context of the resource management system by E. Fleischhacker [10]. This definition was first published within the "Five Stars for Regions" movement launched by the Zillertal planning association in 2008 [22]. According to E. Fleischhacker, strategic infrastructure plans in the frame of a regional development can be fulfilled when the quality and sustainability within the aspects of ecology, sustainable economic attractiveness, and social compatibility are managed simultaneously [10].

After receiving positive votes for the launch of the "Tyrol 2050 energy autonomous" strategy from the Tyrolean parliament in 2014, Energie Tirol [23] was commissioned by the Tyrolean government to implement an ongoing "Tirol 2050" awareness program [24]. The methodology employed to achieve the goals within this long-term strategy [9,10] is further described in Section 2.

In parallel to the developed long-term strategies and measures in Tyrol, climate strategies were initiated at the National and European level, among which the 2050 long-term strategy as well as the European Green Deal are noticeable [25]. In accord with previously initiated measures in Tyrol since 2014, the International Energy Agency (IEA) in 2019 reported that hydrogen has a key role in the global energy transition—especially through its production using renewable energies, recommending a role establishment and scale-up for green hydrogen in industry, transport, buildings, and power generation [26]. With regards to transport, the EU Directive 2019/1161 or "Clean Vehicle Directive" (CVD) of the European Parliament and Council was transposed in August 2021 to the national law, foreseeing mandatory minimum procurement targets for clean light-duty and heavy-duty vehicles (trucks and buses) for each Member State until 2025 and 2030 [27], respectively. This directive aims to promote clean mobility solutions in public procurement tenders as well as in the private sector and generate a significant market for zero emission (ZE) trucks and buses, both for BE and fuel cell electric (FCE). Additionally, a recent tracking report by the IEA emphasizes that low-emission hydrogen production has to be scaled up with the aim to achieve 95 Mt total hydrogen production by 2030, which calls for hydrogen dedicated infrastructure and renewable generation capacity [28]. In line with these measures, recently published reviews in the field of energy and sustainability emphasize that despite the remaining cost and performance challenges, hydrogen competitiveness in various sectors of energy demand does not seem an unrealistic expectation in the medium-term future [29,30]. These measures at the European level further support the initiated efforts towards energy autonomy and climate neutrality in Tyrol since 2014.

At the national level, the development and implementation of large-scale energy solutions and their testing under operating conditions was initiated recently [31,32]. One of the first national initiatives supporting the launch of related projects and their subsequent implementation is the "Energy Flagship Regions", organized by the Climate and Energy Fund [33]. Three regions are involved within this initiative, among which the "WIVA P&G" (Wasserstoff-Initiative Vorzeigeregion Austria Power & Gas) [34] association is coordinating the energy flagship region and focuses on three fields of innovation: green hydrogen and CO_2-neutral gases within green (renewable) energy, green (sustainable) industry, and green (zero-emission) mobility. WIVA P&G further connects partners in science and economy with respect to knowledge and innovation achieved in related projects. Using the example of Austria, the feasibility of transition to a new green age employing green hydrogen as the predominant energy vector of a sustainable energy infrastructure was analyzed recently by the Austrian hydrogen center (HyCentA GmbH [35], research member of WIVA P&G) [36]. In their most recent publication, authors also investigated the refurbishment of the existing natural gas infrastructure towards 100% hydrogen using a thermodynamic-based analysis, which showed that a comparable operation parameter can be achieved using 20 to 30% of hydrogen [37].

Feasibility studies and published directives aiming to extend the transition to renewable energies as well as the large-scale implementation of solutions alone are not sufficient without employing a logistics system supported by a sustainability concept to achieve a required circular economy. Therefore, as a result of the "Tyrol 2050 energy autonomous" strategy and its main long-term goals towards energy autonomy and climate neutrality, the national R&D flagship project WIVA P&G HyWest [38,39] has been initiated. The goal of this project is to establish Austria's first regional green hydrogen economy and bring the complementary "power-to-hydrogen" process for the reconstruction of the energy system to existence.

Fully in line with subsequently associated developed global measures, this project investigates the cross-sectoral production, storage, and use of green hydrogen under real conditions and interconnects three sectors of Green Energy, Green Mobility, and Green Industry. In the frame of this holistic project, monitoring results, technical optimizations, and developed business models are actively being evaluated, validated, and a European-wide standardization for the hydrogen logistics system is being created. The applied multidisciplinary approach has been recently reported to be the essential requirement for enabling further use of hydrogen as a major energy vector [19]. It is noteworthy that major risks jeopardizing such a holistic project, especially with the current energy crisis in Europe and increased electricity prices, are not deniable by the authors. An example of effects of such risks has been recently reported in case of a similar project in Bavaria, Germany [40,41].

Various project partners in this project such as FEN Sustain Systems GmbH (FEN Systems) [42], FEN Research GmbH (FEN Research, research member of the WIVA P&G) [43,44], and MPREIS (regional food retailer and producer) [45] represent the Green Energy Center Europe (GEC) [20] in Innsbruck, which is a private sector Codex Partnership of global/European companies and start-ups jointly contributing to the reconstruction of the energy system and building the bridge into the green future.

In this brief report, we describe the employed problem-solving methodology and strategical approach, supported by the concept of a dynamic sustainability, within the Tyrolean energy system in the framework of the WIVA P&G HyWest project.

The first obtained results regarding the industrial research and experimental development within Green Mobility are reported, notably the testing of hydrogen heavy-duty vehicles and the already established hydrogen refueling station (HRS). Furthermore, procedures for hydrogen refueling backup solutions are developed for a regulated operating logistic between three hydrogen production sites.

Additionally, the synergies between the three ongoing complementary projects based on a first hydrogen logistics system and related technical research and optimization topics are further discussed and conclusions to the achievements to date are provided.

2. Materials and Methods

The establishment of a green hydrogen economy in western Austria, as the main outcome of the "Tyrol 2050 energy autonomous" strategy, is carried out in the following sequence: (a) Strategy Development, (b) Project Development and Implementation, (c) Quality Assurance and Monitoring, (d) Dissemination, Exploitation of Results, and Training.

As described in the introduction, the reconstruction of the energy system within this strategy by means of electric power generated from RES aims to achieve the long-term goal towards energy autonomy and climate neutrality. The chronicle Figure 1 depicts the exponential growth of the energy demand in the last decades since the beginning of the energy age according to the Tyrolean energy monitoring reports published in 2014 and 2015 [12]. Direct use of time-dependent green electricity via the "*power on demand*" process and time-independent indirect use of it via the "*power-to-hydrogen*" process are identified as the building blocks for the reconstruction of the energy system. The expansion of energy production from locally available resources until 2050 is foreseen to further reduce current

GHG emissions by 80–95% through an almost 100% share of renewable energies and a final energy consumption of around 48,000 TJ per year in comparison to 2005 [12].

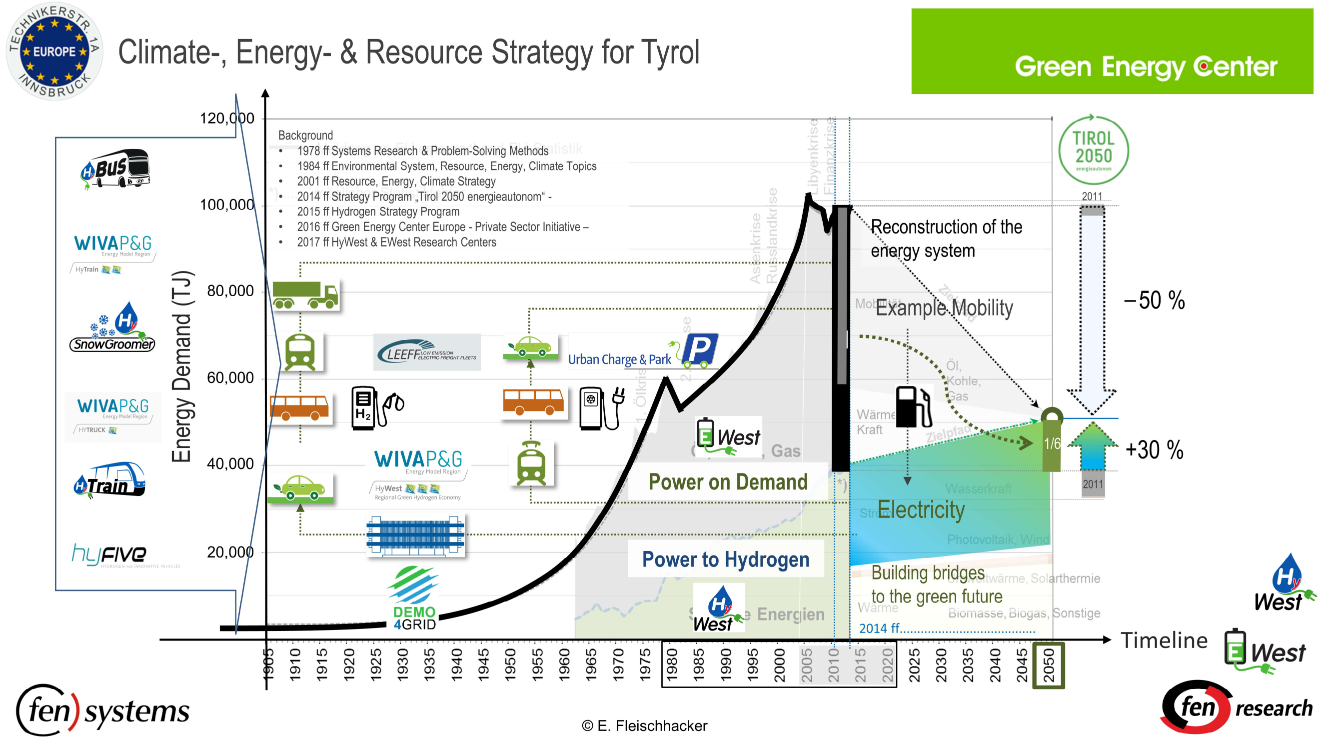


Figure 1. Chronicle figure of the Energy and Hydrogen Strategy “Tirol 2050 Energy Autonomous” [10,12].

In the framework of step (b) Project Development and Implementation, as well as for step (c) Quality Assurance and Monitoring, the licensed problem-solving methodology by E. Fleischhacker [8–10] is used, resulting in transparent depiction of interrelations and processes in the Tyrolean energy system. In this methodology which is based on the understanding of sustainability and a circular economy [5,10], an iterative process model in the sense of a “balanced scorecard process” [13] is employed for the “step-by-step processing” of the Tyrolean energy strategy.

Within this iterative approach, all involved processes are therefore managed within a “self-stabilizing circular model” in which concrete problems are gradually identified and solutions are found for further incorporation into concrete implementation projects. The obtained results are then used for a new system analysis. As iterations progress, the level of knowledge increases, accompanied by a decrease in the risk involved in achieving the goals. Energy monitoring is thus based on a dynamic conceptual approach, for which an overview of all existing data and quantifiable results in terms of energy savings and energy efficiency as well as the results of exchange between different agencies are gathered in periodic annual energy monitoring reports. The improved system knowledge and updated input from the periodic energy monitoring results is then used for improving the Tyrolean resource, energy, and climate system over time. Since the risk in the goal achievement decreases through this repetitive process, the system state starts to converge towards the given target (in this case, Tyrol 2050 energy autonomous) within a progressive decrease in uncertainties.

The energy system within this strategy is identified as a logistics system, which further overlays with the dynamic sustainability described previously in the introduction (see Figure 2) [5,9,10]. The result of this overlay is the central conception and analysis model for any comprehensive multidisciplinary strategy, project, and product development as well as process-oriented management including quality assurance, monitoring, and the final dissemination process. Within this logistics system—which can be applied to each and every resource management tasks—the right goods (service) in the adequate condition (e.g., qualitatively impeccable) and the proper quantity (neither shortage nor surplus) at the time of request (e.g., according to daily demand) to the place of demand (e.g., household) at the minimum cost is to be delivered. The system consists of the subsystems **resource** (procurement market), **demand** (entrepreneur market), and **coverage of demand** (sales market), which are functionally connected via the flow of materials, values, and information (see Figure 2) [5,9,10].

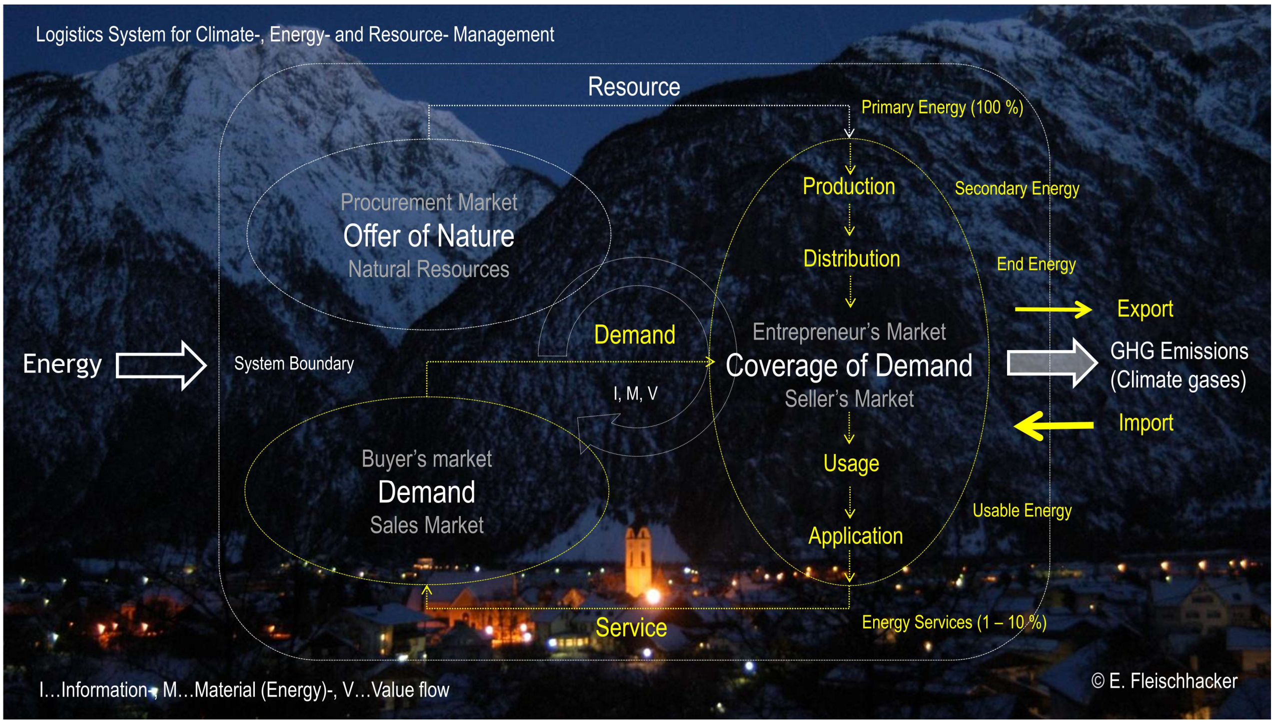


Figure 2. Schematic presentation of the logistics system according to the sustainability approach by E. Fleischhacker [5,9,10].

Accordingly, the circular economy is achieved once three subsystems operate sustainably within the system boundaries (community, region, country) without external dependencies. In case of the "Tyrol 2050 energy autonomous" strategy, the Tyrol region is defined as the boundary of the system, and the required sustainability for the establishment of a circular economy can be achieved within successful management between three subsystems of ecology (resource), social (demand), and economy (coverage of demand). This conceptual model has shown to be of crucial importance in the implementation of projects, since all involved and interested actors in this process are given a shared responsibility for maintaining the stability of the system under development [5,10].

The employed logistics system and sustainability concept within this strategy as well as the achieved results can thus further be applied at the national and international level to fulfil project development processes with the aim to achieve the goals within the reconstruction of the energy system. The use of one's own resources to achieve energy autonomy and sustainability at an individual and societal level by transition to renewable energies in the form of a regional circular economy is at present even more emphasized given the current global situation due to the ongoing war in Ukraine. Regarding sociological systems, the GABEK® (Holistic Coping with Complexity—Ganzheitliche Bewältigung von Komplex-ität) study is known to have determining effects within a successful regional development, since it compromises decision-making processes and relations between existing actors that can be stimulated in order to create mutual interest, respect, and trust, with the aim to enable common overarching goals to be pursued [46].

The green hydrogen economy under establishment within the project WIVA P&G HyWest is the result of synergies between three ongoing complementary implementation projects developed and/or supported by FEN Systems and FEN Research [42–44]. These projects are as follows (see Figure 3):

- "Green Hydrogen for MPREIS, Tyrol and Europe" (MPREIS Hydrogen), initiated in the frame of the European project "Demo4Grid" [47,48] and ongoing since 2016 with the aim to implement a 3 MW pressurized alkaline electrolyzer (PAE) at the production facility of MPREIS in Völs (Tyrol, Austria) to provide grid balancing services. For the first time in the region of Tyrol, high quantities of green hydrogen for industrial use in the production of aliments as well as for heavy-duty mobility applications will be supplied.
- "Hydrogen Valley Zillertal" starting with the "Zillertalbahn 2020+ energy autonomous" project [49] ongoing since 2017, in which a holistic approach including required hydrogen infrastructure and business cases for the implementation of hydrogen electric trains is employed. This project serves as a basis for the establishment of the hydrogen valley Zillertal.
- "Power2X Kufstein" [50] ongoing since 2019, in which the construction of an innovative sector coupling (P2X) plant with a hydrogen center in the southwest of Kufstein near the TIWAG (Tiroler Wasserkraft AG) hydro power plant in Langkampfen in Tyrol is planned.

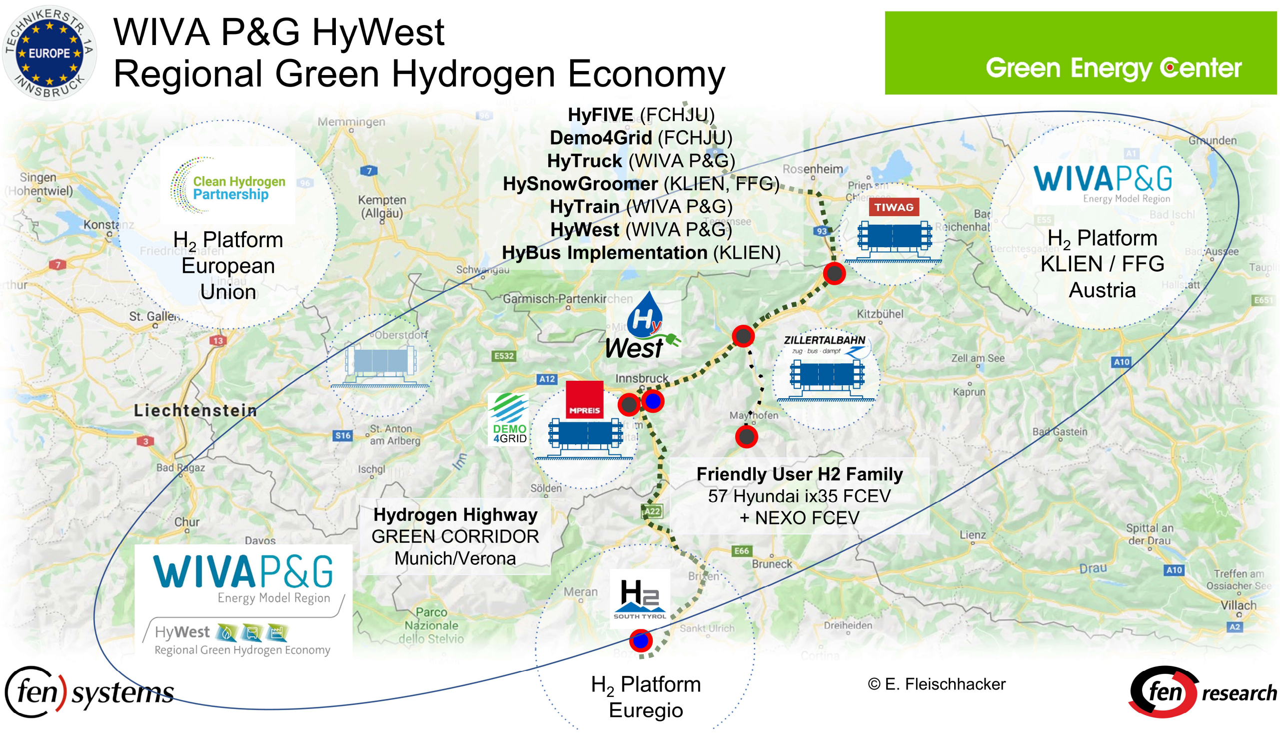


Figure 3. Overview of the three complementary projects; "MPREIS Hydrogen" in Völs, "Zillertalbahn 2020+ energy autonomous" in Jenbach, and Power2X in Kufstein, within WIVA P&G HyWest as well as chronicle overview of finalized and ongoing projects within the European Green Corridor from Munich to Verona in western Austria.

The established logistics system shall assure that the produced green hydrogen is highly available with the required purity and the necessary quantity (neither shortage nor surplus), at the time of request (in both peak and crisis times) and the place of demand (locations Innsbruck, Jenbach and Kufstein) at the minimum cost.

It is noteworthy that WIVA P&G HyWest also benefits from the results of other related finalized or ongoing projects focusing on Green Energy and Green Mobility. As an example, in the framework of the EU project HyFIVE [51], Europe's first fuel cell electric vehicles (FCEVs) were ordered from Hyundai for the Euregio Tyrol. In 2015, the establishment of the hydrogen highway from Munich to Verona in the "Green Corridor" of the European region Tyrol/South Tyrol/Trentino as well as the required filling stations were pioneered for the first time at the international level. Experiences from the inception of the new technology resulted in the development of the "Friendly User FCEV Roll-Out" strategy by FEN Systems for Hyundai Austria (see Figure 3). Other examples include national projects such as HyTruck [52], in which FEN Systems instrumented fleet vehicles and recorded real-life driving data of 2 trucks from MPREIS and 43 DB Schenker trucks over 2 months, accompanied by a corresponding simulation of power demands. In the HySnowGroomer project [53], developed since 2019 as part of the regional green hydrogen economy and led by FEN Systems, a mobile hydrogen refueling system (mobileHRS) equipped with both 350- and 700-bar refueling hoses were developed by Schmidberber/EDC/Wolftank and commercialized to further supply snow groomers from project partner Kässbohrer with green hydrogen from the region.

3. Results

As of now, the developed "Tyrol 2050 energy autonomous" strategy mainly led to the initiation of the WIVA P&G HyWest project since 2018, which is at present under further implementation. Out of the three implementation projects that are part of the WIVA P&G HyWest project, "MPREIS Hydrogen" has progressed the furthest to date. Quality assurance and monitoring as well as the dissemination and exploitation of results and training are currently being carried out in parallel to the implementation.

To date, "MPREIS Hydrogen" is the leading project at the international level since it contains all elements of a regional green hydrogen economy with a first green hydrogen logistic including a PAE and hydrogen storage as part of the Demo4Grid European project (demonstration of power grid balancing services under real operating and market conditions) [47,48]. A HRS for heavy-duty applications as part of the funding agreement for the infrastructure subsidy granted by KPC (Kommunalkredit Public Consulting GmbH) [54] as well as a hydrogen logistics system based on multi element gas containers (MEGCs) and heavy-duty FCE Trucks as part of WIVA P&G HyWest funding are notable. With the production of the first green hydrogen in the region as of March 2022, the current publication reports the main outcomes of "MPREIS Hydrogen" regarding "Green Mobility" and "Standard Operating Logistics Procedures for Hydrogen Refueling Backup Solutions". These results mainly focus on industrial research topics and experimental development and thus deal with technology readiness levels (TRLs) above 5 [55–57].

3.1. Green Mobility

Austria's first heavy-duty FCE logistic fleet is being implemented by MPREIS according to a framework agreement between JuVe Automotion GmbH [58] and Hyzon Motors [59]. Functional specifications of the FCE trucks ordered by JuVe Automotion are presented in Table 1. A first prototype (tractor model 4×2) was available in the second quarter of 2022 for test operations. The MPREIS drivers were trained on the received vehicle by FENS including basic knowledge regarding hydrogen technology and related mandatory safety instructions and were therefore able to obtain the necessary information regarding the new technology. Preparational work related to the adaptation of current workshops for the hydrogen FCE trucks has additionally been initiated.

Table 1. Functional specifications of Hyzon FCE trucks ordered by JuVe Automotion.

Hyzon Motors FCE Trucks	Model 4 × 2, Tractor	Model 6 × 2, Rigid Truck
Wheelbase dimensions (mm)	3800	5600 + 1350
Length/Width/Height (mm), (incl. trailer/body)	16,500/2584/3962	11,045 /2584 /3962
Max. Permissible total weight (kg)	18,000	26,000
Max. Gross combination weight (kg)	40,000	40,000
Maximum speed (km/h)	85	85
Fuel cell stack	120 kW	120 kW
Battery	700 V/140 kWh	700 V/140 kWh
Motor	350 kW/3000 Nm	350 kW/3000 Nm
Transmission	DAF * transmission	DAF transmission
Hydrogen tank capacity	38 kgH_2	40 kgH_2
Max. Driving Range (km)	410	490

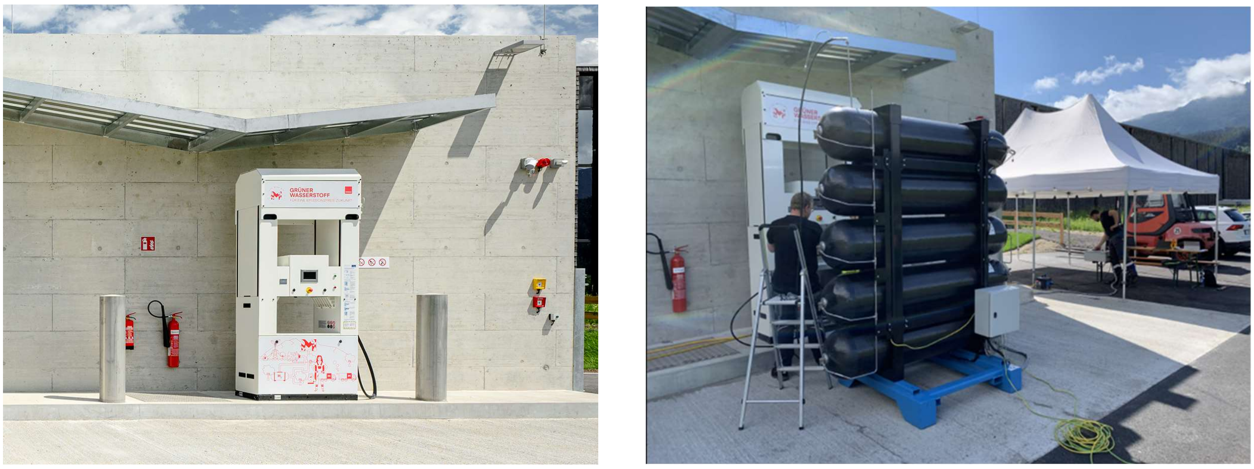
* DAF trucks—Dutch truck manufacturing company.

The first operational tractor model 4 × 2 truck (see Figure 4) was delivered in January 2023 and is currently being operated in the region of Innsbruck.

Figure 4. Operational Hyzon FCE truck tractor model 4 × 2 received by MPREIS in January 2023.

In order to validate the full functionality of the HRS at MPREIS site in Völs, operating at 350 bar for heavy-duty vehicles, a hydrogen storage system (HSS) dummy of a FCE truck was provided by Hyzon in May 2022. The carried-out tests with the dummy validated the refueling protocol and the safety functions as well as the first successful refueling of the Hyzon prototype truck with approx. 15 kg of green hydrogen (see Figure 5).

The Zillertal mobility plan consists of three pillars: (a) the new Zillertal railway ("Zillertalbahn 2020+ energy autonomous" project), (b) a holistic mobility concept consisting of bus, train, and road, and (c) the guest card as a travel pass. This overall package is intended to make the Zillertal valley a pioneer for innovative and sustainable mobility, for which it would be important to combine the new Zillertal railway with an adapted bus service, resulting in the coordination of journey times, extension of connections, and shortening of frequencies.



(**a**) (**b**)

Figure 5. (**a**) HRS at MPREIS site in Völs with a dispenser operating at 350 bar; (**b**) Testing of the HRS using the Hyzon HSS dummy, with permission from MPREIS.

In parallel to the current WIVA P&G HyWest project, preparations for the roll-out of FCE buses in Austria are in progress and have officially started in 2021 in the framework of the national cooperative R&D HyBus Implementation project [60,61]. This project aims to significantly take part in the implementation of the European CVD in Austria through the large-scale demonstration of first 700-bar FCE buses to accelerate the implementation and to establish the required know-how. Hydrogen FCE buses are evaluated as complementary technology for BE buses. While BE buses have highly efficient drivetrains, they however have limitations in terms of range—especially in winter because of low temperatures and corresponding heating demands, charging time, and the disadvantage of *"power on demand"* in this case [60].

The FCE buses used in this project are provided by industry partner Hyundai and a recent test drive was carried out with a Hyundai ElecCity hydrogen bus (made available by Graz Linien, Graz, Austria) to verify its suitability in alpine terrain (see Figure 6). These test drives spanned several days in the alpine surroundings of Tyrol and Vorarlberg and focused on the following topics:

- Mastering the most demanding driving profile: Innsbruck → Kühtai → Ötz with an altitude of approximately 1500 m and downhill stretches.
- Examining the braking behavior on longer descents, as no classic braking system is built in.
- Proofing of snow chain suitability by using snow chains for the first time.

(**a**) (**b**) (**c**)

Figure 6. (**a**,**b**) Recent test drives with Hyundai ElecCity hydrogen bus in Tyrol; (**c**) Refueling the Hyundai ElecCity with green hydrogen at the MPREIS HRS, with permission from Hyundai Import GmbH & Thomas Kantor KG.

During these test drives, the hydrogen bus was successfully refueled up to 350 bar with green hydrogen at the MPREIS heavy-duty HRS in Völs (see Figure 6c).

3.2. Standard Operating Logistics Procedures for Hydrogen Refueling Backup Solutions

The main goal of the industrial project partners is to primarily use their own produced green hydrogen from their own facilities. However, to guarantee an uninterrupted hydrogen availability, backup solutions need to be foreseen in case production facilities become unavailable for a longer period. Moreover, excess quantities of green hydrogen that are not being used on-site can be offered on the market.

The three hydrogen production sites involved in the WIVA P&G HyWest project with an overall green hydrogen production capacity of 3690 to 5490 kgH_2 per day are as follows:

- MPREIS facility in Völs (built within the scope of "Demo4Grid" project), see Table 2 and Figure 7. A second electrolyzer is planned to be built in order to fulfill the required hydrogen demand in the region.
- Zillertaler Verkehrsbetriebe AG (ZVB)/Verbund facility in Mayrhofen (to be built as a separate project by Verbund AG [62]), see Table 3.
- TIWAG Power2X facility in Kufstein (to be built within the scope of "Power2X Kufstein"), see Table 4.

Table 2. Characteristics of the "MPREIS hydrogen" production site in Völs.

Parameter	Value	Comments
Type	PAE	Single stack
Status	Up and running	On trial runs
Electrolyzer power	3 MW	Overall system
Production rate	1300 kg per day	-
Hydrogen quality	4.7 according to ISO 14687-2:2012	-
Hydrogen output pressure	30 bar	Without additional compression

Table 3. Characteristics of the ZVB/Verbund hydrogen production site in Mayrhofen.

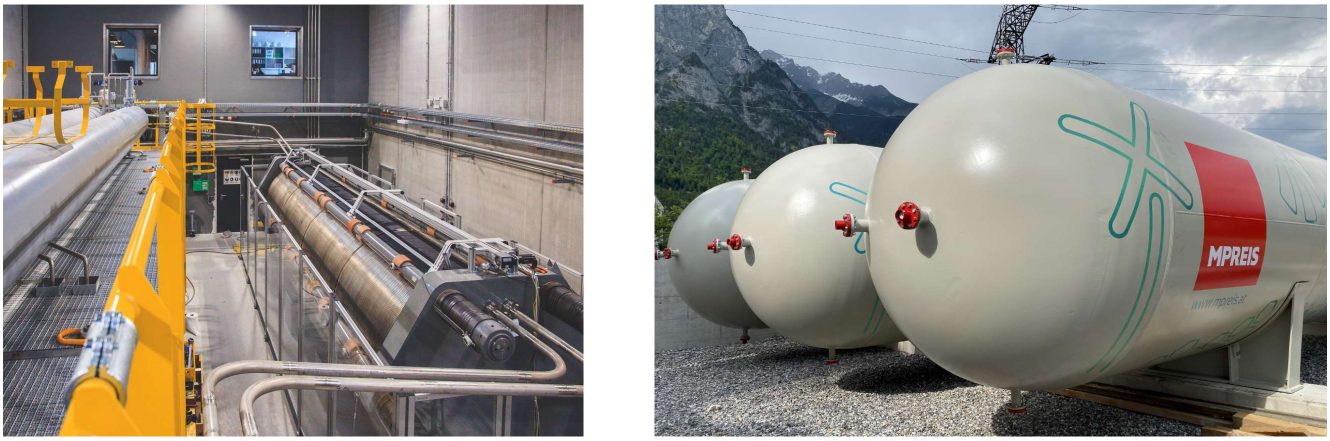
Parameter	Value	Comments
Type	Not yet decided	Technology-open Procurement
Status	Planned	-
Electrolyzer power	6.0 MW	3 + 1 containerized systems
Production rate	1980 kgH_2 per day	-
Hydrogen quality target	4.7 according to ISO 14687-2:2012	-
Hydrogen output pressure	30 bar	-

Table 4. Characteristics of the TIWAG hydrogen production site in Kufstein.

Parameter	Value	Comments
Type	Polymer electrolyte membrane (PEM) Electrolyzer	-
Status	planned	-
Electrolyzer power	1.0 to 5.0 MW	Expected starting with 1 MW
Production rate	Up to 2250 kgH_2 per day	Starting with 450 kgH_2 per day
Hydrogen storage	H2 5.0, 35 bar; H2 5.0, 100 bar;H2 5.0, 500 bar; H2 5.0, 1000 bar	-
Hydrogen output gas grid injection	H2 5.0, MOP * 70 bar	-

* Maximum Operating Pressure.

The valves of each of the hydrogen storage vessels can be switched on separately to ensure regulation at low, medium, and high levels for storing hydrogen at different pressures.



(**a**) (**b**)

Figure 7. (**a**) PAE supplied by Sunfire GmbH at the right and the gas separators at the left; (**b**) three hydrogen storage vessels supplied by APL GmbH (Tyrolean company), with permission from MPREIS.

4. Discussion

The developed living lab within "MPREIS Hydrogen" provides conditions in which the employed technologies can be further validated and optimized. Further technical research and optimization measures include measures for the operational enhancement of FCE trucks. These measures will be carried out during the operational phases of the received trucks and the obtained results will be implemented in the next production series of Hyzon Motors.

It is noteworthy that in the case of hydrogen buses, the necessary infrastructure for heavy-duty applications in Austria is still not available. For heavy load transportation over long distances, FCE buses can be used at low temperatures and can be refueled within short times. However, BE and especially FCE buses are both still in the phase of the first small series production and prototyping process with quite high prices. Accordingly, no FCE bus has ever been in use in Austria, apart from short-term demonstration. Thus, Austrian bus operators lack any experience in the procurement of FCE buses and their bus fleet renewal that will occur in the near future. For the fast implementation of the first hydrogen buses in Austria and to establish the required know-how, the HyBus implementation project [60,61] mitigates the following critical problems: (1) high acquisition costs of the FEC buses; (2) not yet existing hydrogen infrastructure; (3) unavailability of green hydrogen, within which the created green hydrogen demand will significantly accelerate the build-up of a green hydrogen economy project.

Following the first performed test drives with Hyundai ElecCity hydrogen buses in Austria, the monitoring and collection of required parameters (e.g., FCE system power, H2 tank pressure, buffer battery power, traction motor power, temperature, voltage and current, etc.) for the operation optimization of the hydrogen buses under various conditions (especially in alpine region) is currently ongoing.

Another important technical topic is considered within the green hydrogen logistics procedures. As a consequence of the short distances between involved hydrogen production sites and the need of being able to transport the hydrogen in both directions between all project partners, the economically viable solution for a first WIVA P&G HyWest hydrogen logistic system is road transport, as shown in Figure 8. According to the current plan, a hydrogen distribution system based on MEGCs was identified as the favorable solution. In this regard, MPREIS has already ordered and received a 20-foot hydrogen storage container from UMOE Advanced Composites for the setup of the exchange platform. Each container will provide a storage capability of approximately 300 kg of hydrogen (see Figure 9).

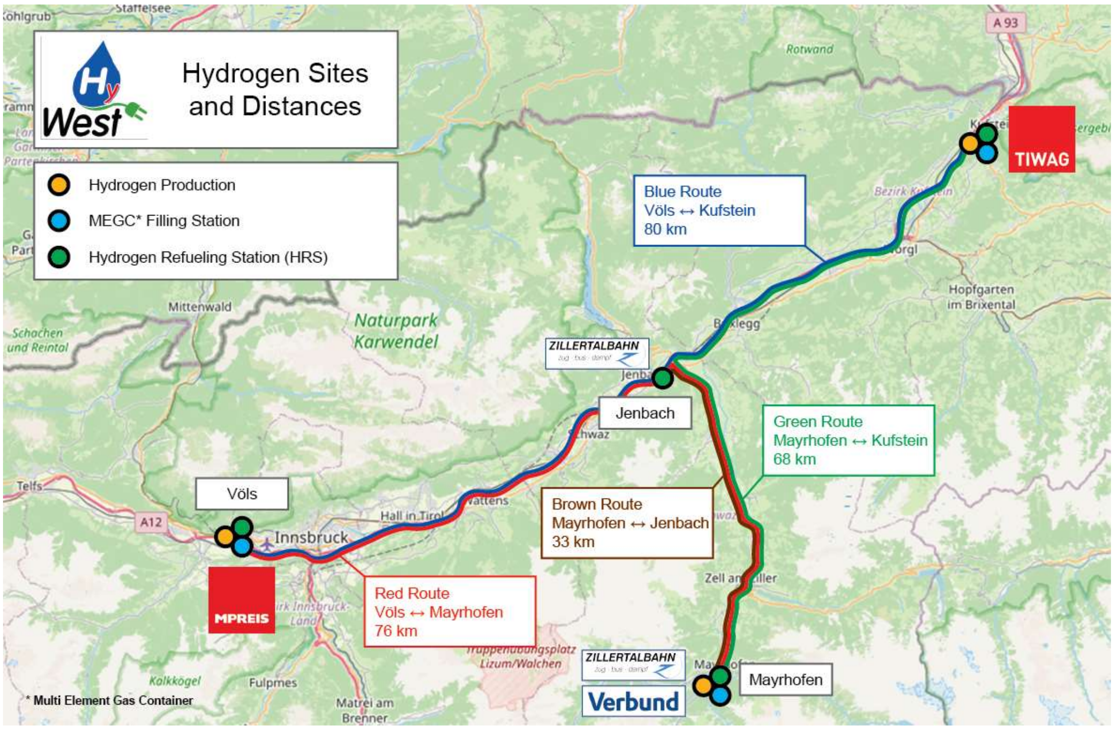


Figure 8. WIVA P&G HyWest hydrogen production sites and their distances from each other.

Figure 9. 20-foot hydrogen MEGC from MPREIS, with permission from MPREIS.

The characteristics of these containers are listed below:

- UMOE, 20 ft, glass fiber
- 11 type 4 pressure vessels with 4 pressure compartments
- Total mass: 17 tons
- Working pressure: nom. 300 bar at 15 °C, min. 20 bar
- Filling pressure: max. 355 bar at 65 °C
- Operating temperature: − 40 °C to + 65 °C
- Filling rate: nom. 55 kgH_2 per hour
- Filling connection: M36 × 2 LH (metric, left-handed)
- Drain connection: M40 × 2 LH (metric, left-handed)
- H_2 connector: Loading/Unloading

The containers will be exchanged between project partners using freight forwarders with the required ADR (Accord Dangereux Routier, European agreement concerning the international transport of dangerous goods by road) permissions and certified trucks (see Figure 8).

The hydrogen MEGC from MPREIS is planned to be further employed in the national R&D WIVA P&G HyTrain project [63,64], in a rail-based hydrogen logistic. This project aims on building up Austrian know-how for the development, procurement, acceptance, and operation of the world's first hydrogen-powered narrow-gauge train, with focus on risk minimization and quality assurance, based on the Zillertalbahn use case. Regarding the railway transport, investigations, and evaluations of the general conditions at the Zillertal railway, these showed that catenary line operation and hydrogen-electric operation result in similar costs. The corresponding business case developed by FEN Systems, based on their knowledge of the strategy and commissioned by the ZVB, provided calculations for a hydrogen drive train including its infrastructure versus the catenary line costs. This business case has since been confirmed by several independent international experts.

The second backup solution within the described logistics procedure is the purchase of industrial gases from Linde, Air Liquide, Messer, or Evonik, for which the economic and trading frameworks will be evaluated. Hydrogen delivery from the industrial gas producers could be achieved by either using their standard delivery service using tube trailers, or by employing project-defined hydrogen containers and the service of a freight forwarder.

Currently, the main technical research topic is the connectivitiy of the MEGC from MPREIS to other hydrogen filling stations (HFS), as depicted in Figure 10.

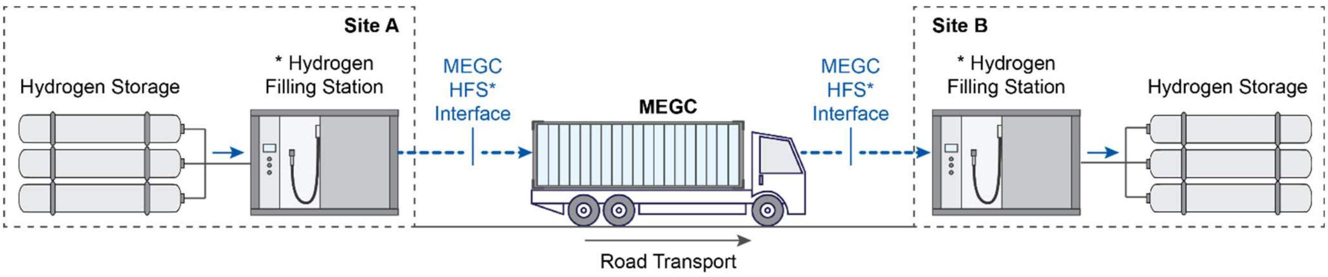


Figure 10. WIVA P&G HyWest hydrogen backup logistics based on MEGCs.

In order to ensure the exchange of hydrogen among the project partners without any problems, standardized interfaces between the filling/discharging stations and the MEGCs are an important prerequisite. As of now, MEGCs are custom-built according to the customer's demands. Since it can be assumed that not all project partners will use the same type of MEGC, a uniform assignment of the interface connectors between the filling/discharging stations and the MEGCs was selected. This further supports immediate connectivity of all MEGCs in three hydrogen sites.

Three identified connections between the MEGC and the filling/discharging stations are as follows:

- MEGC loading connection
- MEGC unloading connection
- MEGC control connection
- A ground connection

Besides the two hydrogen connections, a control connection needs to be established between the MEGC and the filling/discharging station. Taking the different capabilities of the MEGCs into account, a modular approach appears to be convenient. To provide the highest possible flexibility, a universal connection cable using modular plugs (e.g., HAN plugs from Harting Electronics GmbH) is planned to be employed. More details regarding the assignment of plugs is currently under further investigation with the Austrian association for the gas and water industry (ÖVGW). The results of these investigations are planned to be finalized and published in the current year.

Other technical research and optimization topics such as low grade waste heat from the electrolysis process at the MPREIS site are currently under investigation with the research partner HyCentA. In this regard, first reviews and definition of key performance indicators

(KPIs) have been performed so far and a first concept for the life cycle management was made available.

It is noteworthy that all employed technologies in the living lab developed within "MPREIS Hydrogen" are not yet at a commercial level (beyond TRL 9) but subject to industrial research and experimental development themselves. Furthermore, all implemented technologies (PAE, HRS, FCE trucks, MEGCs, etc.) can be considered merely "laboratory equipment" necessary for further interdisciplinary systems and process research.

The "P2X Kufstein" project is currently undergoing individual approval procedures by the authorities. The notifications are expected in mid-February 2023. At the same time, detailed planning has already been carried out. Offers have already been received from suppliers after the tendering process was already started in the year 2022. A resolution on the construction decision is to be taken in the second quarter of 2023. In this project, the planning of the plant was also supported by HyCentA with the related KPIs and modelling of the refueling infrastructure. This research partner will further support all project partners with technical assessment of optimized systems and related sector couplings.

Regarding the "Hydrogen Valley Zillertal" and "Zillertalbahn 2020+ energy autonomous" project, final technical topics are currently discussed internally, finalized, and negotiated with the supplier of the trains (Stadler Rail). It is foreseen to place the order for all the trains in 2023 and a delivery date could be expected in 2027.

Regarding future risks and challenges, it is noteworthy that the project builds upon components and systems that are still in the phase of prototyping and first small-scale production. Therefore, prices of all components are factors higher compared to state of the art options, leading to huge investment costs (CAPEX). This in return allows only for long-term "business cases" that are supported by contributions and makes the investment decisions difficult for the project owners. Hence, there is a non-negligable risk of the project not being fully implemented or even of parts being shut down.

5. Conclusions

This paper reports on the first obtained results regarding the industrial research and experimental development in the framework of "MPREIS Hydrogen", which is the furthest progressed to date among the three complementary "*power-to-gas*" implementation projects that are part of WIVA P&G HyWest.

The main elements of the developed green hydrogen logistic within "MPREIS Hydrogen" are a 3 MW pressurized alkaline water electrolysis system complemented by three hydrogen storage vessels, Europe's most powerful heavy-duty HRS operating at 350 bar including pre-cooling and a trailer filling station (10 trucks can be refueled back-to-back with a refueling time of 15 min per truck), MEGCs (20-foot hydrogen storage containers), and Austria's first hydrogen semi-trailer truck (tractor plus trailer) from Hyzon Motors, operational as of January 2023 for food distribution in the region of Tyrol. The optimization measures are planned to be carried out during the operational phases based on the collected monitoring results and to be further implemented in the next production series of Hyzon Motors. The full functionality of the HRS was validated with the FCE truck tractor model 4×2 prototype, from Hyzon Motors, which was also employed for the training of the MPREIS drivers and regional mechanicians.

In the framework of the "Hydrogen Valley Zillertal" project, test drives with a Hyundai ElecCity hydrogen bus (made available by Graz Linien, Graz, Austria) were performed in alpine terrain. The refueling of the hydrogen bus in use with the MPREIS heavy-duty HRS further validated the functionality of this refueling station. The monitoring and collection of required parameters for the operation optimization of the hydrogen buses under various conditions (especially in alpine regions), such as FCE system power, H2 tank pressure, buffer battery power, traction motor power, temperature, voltage, and current, is currently ongoing.

Further investigations also revealed that a hydrogen distribution system based on MEGCs via road transport would be the most promising solution with the aim to guarantee a high green hydrogen availability in the region. Additional technical research topics in this regard are under development regarding the connectivity between hydrogen containers and hydrogen filling stations in the three hydrogen production sites.

To fulfill the logistic principle foreseen as the main outcome of WIVA P&G HyWest, the other two complementary projects are being further implemented. Accompanying industrial research and monitoring results as well as related investigations aiming to improve the current processes within all three projects in order to guarantee that green hydrogen—with the required purity and the necessary quantity, at the time of request and the place of demand, at the minimum cost—is highly available.

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