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ZEMoS

Zero Emission Mobility Salzburg

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Table of content

1 Kurzfassung

Ausgangssituation:

Im Bundesland Salzburg sind die Emissionsbelastungen durch den Verkehr sehr hoch, maßgeblich auch, da der Großteil der Busse und LKWs mit Diesel betrieben werden.

Problemstellung:

Zur Erreichung der Klimaziele sowohl auf EU-Ebene als auch im Rahmen der Klima- und Energiestrategie des Landes Salzburg, müssen dieselbetriebene Fahrzeuge durch Zero-Emission (ZE) Fahrzeuge ersetzt werden. Für diese notwendige Umstellung auf Zero Emission Mobility (ZEM) sind sowohl batterieelektrische (BE) als auch brennstoffzellenelektrische (FCE) Fahrzeuge geeignet. Die notwendige großflächige Umsetzung von ZEM-Lösungen im öffentlichen Verkehr und im Schwerlast-Verkehr im urbanen und alpinen Raum Salzburgs ist eine Herausforderung. Die erforderliche Infrastruktur und Logistik (insbesondere H2) stehen nicht zur Verfügung. Auch sind die Energie-Anforderungen an die Fahrzeuge aufgrund von Topografie (alpines Gelände) und harschen Witterungsbedingungen (heizen im Winter und kühlen im Sommer) hoch.

Motivation:

FCE- und BE-Antriebstechnologien sind reif für eine breitere Anwendung. Vor dem flächendeckenden Rollout und Einsatz inklusive entsprechender Infrastruktur ist jedoch ein echter "Dauerbetrieb" in Modellregionen notwendig.

Ziele:

Im Rahmen des Projektes "Zero Emission Mobility Salzburg" (ZEMoS) hat sich daher ein starkes Konsortium unter der Leitung der Salzburg AG (S-AG) zusammengefunden, das sich aus dem Salzburger Verkehrsverbund (SVG) und Forschungspartnern der industriellen und experimentellen Entwicklung zusammensetzt. Das Ziel dieses Konsortiums war die Entwicklung von zwei ZEM-Modellregionen, eine urbane und eine alpine/touristische, für den öffentlichen Busverkehr, und die Implementierung zweier Pilotprojekte für den Umstieg des Schwerlastverkehrs. ZEMoS sollte als „Living Lab“ eingerichtet und durch einen kontinuierlichen Verbesserungsprozess (KVP) ständig gemonitort und weiterentwickelt werden. Die Ziele innerhalb der beiden Modellregionen waren (i) die Entwicklung neuartiger ganzheitlicher, großflächiger ZEM-Buskonzepte, (ii) die Umsetzung dieser ZEM-Buskonzepte für 10 Buslinien (32 Busse), (iii) die Umsetzung des FCE-Schwerlastverkehrs (4 FCE-Müllfahrzeuge und 4 FCE-LKW), (iv) die Entwicklung und Implementierung einer grünen Wasserstoffinfrastruktur einschließlich innovativer Sektorkopplung und Regelenergieeinsatz im Stromnetz.

Innovation:

Ursprünglich war beim Start des ZEMoS Projektes die Entwicklung und Umsetzung eines nachhaltigen großflächigen ZEM-Konzeptes in dieser Dimension im Bundesland Salzburg geplant. Weiters war der Einsatz und der Betrieb einer PEM-Elektrolyseanlage in Kombination mit einer 1 MW Hochtemperatur-Wärmepumpe vorgesehen, um die Einspeisung der Elektrolyse-Abwärme in das regionale Fernwärme-Netz zu ermöglichen. Zur Optimierung hinsichtlich Effizienz und Betriebskosten der geplanten innovativen Anlagen waren zudem ein sorgfältiges wissenschaftliches Monitoring, sozioökonomische Analysen sowie ein digitaler Zwilling für die Optimierung der Elektrolyse-Betriebsstrategien geplant.

Ergebnisse:
Aufgrund unvorhergesehener Entwicklungen wie dem Ukraine-Krieg, mangelnder Verfügbarkeit und starken Preissteigerungen bei Wasserstofffahrzeugen konnte eine Wasserstoffinfrastruktur innerhalb der dreijährigen Projektlaufzeit nicht mehr wirtschaftlich umgesetzt werden. Zudem fehlte aufgrund dessen die ausreichende Finanzierung für Fahrzeuge und Infrastrukturen wie Elektrolyseure oder Tankstellen. In gegenseitigem Einvernehmen mit der Förderstelle wurde beschlossen, das Projekt mit den im zweiten Projektjahr erzielten Ergebnissen abzuschließen.

Das Projekt ZEMoS brachte innovative Lösungen für Wasserstoff- (FCE) und Batterie-Elektrobusse (BE) hervor. Dazu gehören Werkzeuge zur Berechnung des Energieverbrauchs, die auf den spezifischen Anforderungen der Topografie, Masse und Geschwindigkeit basieren und damit bestehende oder zukünftig geplante Buslinien optimiert werden können. Zudem wurden Modelle und Algorithmen entwickelt, die die Simulation mehrerer Depots und gemischter Flotten von FCE- und BE-Bussen ermöglichen.
Um eine fundierte Datenbasis für zukünftige Implementierungen zu schaffen.wurde zur Realdatenerfassung auch ein einmonatiger Testbetrieb eines H2-Busses inklusive einer mobilen Tankstelle durchgeführt. Diese Feldversuche halfen dabei, mögliche Herausforderungen und Optimierungspotenziale in der Praxis zu identifizieren und entsprechend anzupassen.
Für schwere FCE-Fahrzeuge wurden ebenfalls Bedarfsanalysen durchgeführt und Strategien zur Betankung sowie Wartung von Müllfahrzeugen und LKWs für städtische und alpine Gebiete entwickelt. Darüber hinaus wurden Konzepte für eine Elektrolyseanlage mit integrierter Abwärmenutzung mit Einspeisung in ein Fernwärmenetz und Wasserstofftankstellean Hauptverkehrsknotenpunkte gemäß der EU-AFIR-Verordnung ausgearbeitet.

Trotz der aktuellen Herausforderungen, was die Fahrzeugverfügbarkeit und die Implementierung einer Wasserstoffinfrastruktur für den Mobilitätssektor betrifft, hat das ZEMoS Projekt bedeutende Fortschritte in der Entwicklung und Implementierung emissionsfreier Technologien im Bundesland erzielt. Durch den Betrieb von insgesamt 21 neue Elektrobusse während der Projektlaufzeit bis zum 28. Februar 2025 konnten insgesamt 584.449,74 Kilometer (gewerbliche Fahrzeugkilometer) auf 10 Strecken im Bundesland Salzburg zurückgelegt werden. Dadurch konnten insgesamt 510 Tonnen CO2 eingespart werden und auch die öffentliche Akzeptanz für emmissionsfreie Busse im öffentlichen Verkehr erhöht werden.. Weiters bilden die im Projekt erarbeiteten Ergebnisse und Erfahrungen eine solide Grundlage für zukünftige Entwicklungen in diesem Bereich.

2 Executive Summary

Initial Situation:

In the federal state of Salzburg, traffic emissions are very high, mainly because most buses and trucks run on diesel.

Problem:

To achieve climate goals both at the EU level and within the climate and energy strategy of the state of Salzburg, diesel-powered vehicles must be replaced by zero-emission (ZE) vehicles. Both battery electric (BE) and fuel cell electric (FCE) vehicles are suitable for this necessary transition to Zero Emission Mobility (ZEM). The large-scale implementation of ZEM solutions in public transportn and heavy-duty transport in Salzburg's urban and alpine regions is challenging. The necessary infrastructure and logistics (especially H2) are not available. Furthermore, the energy demands on the vehicles due to topography (alpine terrain) and harsh weather conditions (heating in winter and cooling in summer) are high.

Motivation:

FCE and BE drive technologies are ready for wider application. Before widespread rollout and deployment, including the necessary infrastructure, a real "continuous operation" in model regions is necessary.

Goals:

As part of the "Zero Emission Mobility Salzburg" (ZEMoS) project, a strong consortium has been formed under the leadership of Salzburg AG (S-AG), consisting of the Salzburg Transport Association (SVG) and research partners from industrial and experimental development. The aim of the consortium was to develop two ZEM model regions, one urban and one alpine/touristic, for public bus transport, and to implement two pilot projects for the transition of heavy-duty transport. ZEMoS was set up as a "Living Lab" and is continuously monitored and further developed through a continuous improvement process (CIP). The goals within the two model regions were (i) the development of novel, holistic, large-scale ZEM bus concepts, (ii) the implementation of these ZEM bus concepts for 10 bus lines (32 buses), (iii) the implementation of FCE heavy-duty transport (4 FCE garbage trucks and 4 FCE trucks), (iv) the development and implementation of a green hydrogen infrastructure including innovative sector coupling and control energy use in the power grid.

Innovation:

Originally, the start of the ZEMoS project aimed at developing and implementing a sustainable large-scale ZEM concept in the Austrian federal state of Salzburg. Furthermore, the operation of a PEM electrolysis plant in combination with a 1 MW high-temperature heat pump was intended to enable the feed-in of electrolysis waste heat into the regional district heating network. To optimize efficiency and operating costs of the planned innovative plants, careful scientific monitoring, socio-economic analyses, and a digital twin for optimizing electrolysis operating strategies were also planned.

Results:

Due to unforeseen developments such as the war in Ukraine, the unavailability of hydrogen vehicles, and significant price increases, it was no longer economically feasible to implement a hydrogen infrastructure within the three-year project period. Consequently, the necessary funding for vehicles and infrastructure, such as electrolysers or filling stations, was also lacking. By mutual agreement with the funding agency, it was decided to conclude the project with the results achieved in the second year.

The ZEMoS project brought forth innovative solutions for hydrogen (FCE) and battery-electric buses (BE). These include tools for calculating energy consumption based on the specific requirements of topography, mass, and speed, which can optimize existing or future-planned bus routes. Models and algorithms were also developed to simulate multiple depots and mixed fleets of FCE and BE buses.
To create a solid data foundation for future implementations, a one-month test operation of an H2 bus, including a mobile refueling station, was conducted. These field tests helped to identify potential challenges and optimization opportunities in practice and adjust accordingly. Needs analyses for heavy FCE vehicles were also conducted, and strategies for refueling and maintaining garbage trucks and trucks for urban and alpine areas were developed. Furthermore, concepts for an electrolysis plant with integrated waste heat utilization feeding into a district heating network and hydrogen filling stations at key traffic points were developed.

Despite current challenges related to vehicle availability and the implementation of a hydrogen infrastructure for the mobility sector, the ZEMoS project has made significant progress in the development and implementation of zero-emission technologies in the state. Through the operation of a total of 21 new electric buses during the project period until February 28, 2025, a total of 584,449.74 kilometers (commercial vehicle kilometers) were covered on 10 routes in the state of Salzburg. As a result, a total of 510 tons of CO2 were saved, and public acceptance of zero-emission buses in public transport was increased. Furthermore, the results and experiences gained in the project provide a solid foundation for future developments in this area.

3 Introduction

In line with European Union (EU) measures and goals towards climate neutrality, in 2021 the "Master Plan climate+energy 2030" was launched in the federal state of Salzburg as a transfer program of the "*Climate and energy strategy Salzburg 2050*"[1]. This "Master Plan" focuses on sustainable solutions by promoting the use of renewable energy sources in all sectors within its climate and energy strategy and the goal to reduce the annual carbon dioxide (CO2) emissions by over 40 % until 2030. Numerous measures and partnerships with companies in Salzburg are included in this Master Plan. Salzburg AG (S-AG)[2], a Green Tech company with many years of experience in the fields of energy, mobility, and communication, has introduced a comprehensive package of topics as part of its partnership. This package includes coordinated strategies for district heating and gas supply as well as more electricity from hydro, wind and solar power. Since a reduction of about 50 % of CO2 by 2030 in Salzburg must be carried out in mobility and/or traffic sector, alternative drive solutions as BE and FCE concepts are further promoted within this package.
The R&D project ZEMoS (FFG Nr. FO999900979) initiated in April 2023 under the coordination of S-AG is in close alignment with the goals outlined in the strategical Master Plan of the federal state of Salzburg. With its focus on the mobility sector, ZEMoS was a pioneering project contributing to the necessary transition from conventional diesel vehicles to emission-free alternatives. The goals addressed in the ZEMoS project were not only limited to the identification of suitable technologies but also addressed the challenging task of developing the required infrastructure. Consortium partners of this project, in addition to S-AG, were Salzburger Verkehrsverbund GmbH (SVG), Energieinstitut and Johannes Kepler Universität Linz (EI), Institute of Production and Logistics Management, Johannes Kepler University Linz (JKU-PLM), Research Studios Austria Forschungs-GmbH / Research Studio iSpace (iSpace), FEN Research GmbH (FENR), FEN Sustain Systems GmbH (FEN Systems), Verein WIVA P&G (WIVA), HyCentA Research GmbH (HyCentA), Zentrale Müllklärschlammverwertungsanlagen GmbH (ZEMKA) and Magistrat der Stadt Salzburg (Stadt Salzburg).

The comprehensive scope of the ZEMoS project was encapsulated in its ambitious goals, which aimed to leverage innovative technologies and sustainable practices to transform the mobility landscape of Salzburg. Central to these efforts were the creation and implementation of model regions that served as testbeds for zero-emission mobility solutions. The goals of ZEMoS were outlined as follows:

Goals of ZEMoS:

The overall goal of the ZEMoS project was the development of two ZEM model regions for public bus-transport and two pilot-projects for transition of heavy-duty trucks:

- Model Region 1: Hydrogen Valley Central – urban;
- Model Region 2: Hydrogen Valley Pinzgau – alpine/touristic.

[1] *https://www.salzburg.gv.at/themen/umwelt/salzburg2050*

[2] *https://www.salzburg-ag.at/*

The ZEMoS project was intended to be a living lab which should be continuously examined and improved by a Continual Improvement Process (CIP). The results foreseen in the frame of this project will further facilitate to build-up future innovative green H2-infrastructure at the regional, national and international level. In order to reach the afore mentioned overall goal, following main objectives within both model regions were considered:

- **Goal 1** Development of novel holistic and spatial FCE- and BE-bus concepts for ZEM.
- **Goal 2** Vast area implementation of the novel ZEM public bus concepts for all bus lines (FCE- and BE-buses) in both model regions.
- **Goal 3** Implementation of the developed concepts within the two ZEM regions for hydrogen heavy-duty transport.
- **Goal 4** Development and implementation of a Green Hydrogen Infrastructure for ZEM in the two model regions in combination with innovative sector-coupling and balancing energy services.
- **Goal 5** Accompanying scientific research and innovative technology development for optimization and publication of a universal operation guideline to support further ZEM roll-outs.
- **Goal 6** Strengthening of public acceptance for H2-applications.

Goal 1: Development of novel holistic and spatial FCE- and BE-bus concepts for ZEM:

- Collection, analysis and extension of relevant data, results and methods from preliminary projects for its integration into a spatial database.
- Elaboration of a new innovative spatial planning tool including spatial characteristics of bus routes, refuelling/recharging infrastructure and operational strategies for H2- and BE-buses in order to create a database for holistic analyses of H2- and BE-bus structures.
- Holistic and spatial analysis (modelling) of specific bus routes based on the above-mentioned data basis for the prioritized determination of either a FCE- or BE-propulsion for each specific analysed bus route.
- Analysis of future mobility scenarios through the incorporation of potential future bus line developments into the holistic and spatial mobility models to identify and quantify future ZEM potentials.

<u>Expected results</u>: *Novel integrated area-wide coordinated and optimized mobility concepts for public FCE- and BE-buses.*

Goal 2: Vast area implementation of 32 E-buses for ZEM public bus live operation on 10 bus lines of both model regions:

- Employment of a requirement analysis for FCE and BE public buses in terms of seasonal H2 demand and route planning for year-round live operation.
- Detailed preparation of the tender documents for the respective public bus lines or public bus line bundles.
- Procurement of H2-buses, based on the identified main bus lines in accordance with the FCE- and BE-mobility concepts, for FEM transition in both model regions after completion of the tender process.

Expected results: *Use of valuable knowledge for further concept improvement within and beyond the project's time frame and vast area implementation of the ZEM public bus transport in live operation for the first time.*

Goal 3: Implementation of two ZEM projects for heavy-duty vehicles:

- Employment of a requirement analysis for FCE trucks and FCE garbage trucks in terms of seasonal H2 demand for year-round operation.
- Build-up of maintenance infrastructure for FCE trucks within the alpine model region and for FCE garbage trucks within the urban model region.
- Procurement of 4 garbage trucks to ZEM drives in the urban model region.
- Transition of 4 diesel trucks to FCE drive for the transportation of residues from Zell am See to an incinerator facility in central Austria.

Expected results: *Conclusion of the requirement analyses and initiation of the transition of heavy-duty transport as well as build-up of maintenance infrastructure within both model regions.*

Goal 4: Development and implementation of green hydrogen infrastructure in combination with innovative sector-coupling and balancing energy services:

- Establishment of a comprehensive green hydrogen infrastructure in year-round continuous operation (electrolyser, container filling station, refuelling stations, etc.) to supply the two model regions and as an infrastructure basis for the long-term complete transition to emission-free drives.
- Efficiency optimization via utilization of a large-scale heat pump with the electrolysis plant. A simulation study based on the digital twin of the facility, being provided with real case data from the large-scale heat pump, will allow the optimization of its performance.
- Development of an innovative complementary operational tool for balancing energy services.
- Development and implementation of a H2-container based logistic concept for the supply of decentralized H2-supply points such as the HRS in the alpine model region.
- Development of an interconnected predictive model for H2-supply & H2-distribution based on real-time information exchange of tank status data between the operating FCE-buses and the electrolyser facility.
- Monitoring of the temporal degradation of the electrolyser through the documentation of voltage-current curves, as well as the altering of compressors through different operational modes.

Expected results: *Establishment of an operationally optimized green H2-production facility for ZEM purposes. Utilization of the container logistic concept and a predictive model in the frame of the H2 supply & distribution process for an optimal operation of buses within both model regions.*

Goal 5: Accompanying scientific research and innovative technology development for publication of a universal operation guideline to support further ZEM roll-outs:

- Technological comparison of waste heat usage and compression-possibilities based on simulation studies that employ separate digital twins.
- Defining optimized configuration of hydrogen infrastructure and most promising related innovative technology combinations for it.

- Identification of barriers to the implementation and use of zero-emission mobility technologies at the level of the model regions, accounting for different attitudes between the local population and tourists.
- Information regarding short run and long run metrics on the collective outputs that governments, consumers, and firms make in an economy (micro- and macro-level) through the economic analyses of ZEMoS.
- Identification of the TCO of FCE- and BE-mobility concepts for public buses.

Expected results: *Effective development of digital twins and definition of suitable promising and innovative technology combinations for an optimized configuration of hydrogen infrastructure, successful assessment of ecological, economic and social impacts as well as the determination of TCO of the mobility concepts for public buses.*

Goal 6 Build-up of acceptance for ZEM and H2-applications:

- Strengthening social and public acceptance regarding the feasibility and reliability of H2-applications.
- Increasing the attractiveness of ZEM public transport and initiating complete transition of current heavy-duty means to zero emission transport.

Expected results: Heightening of public acceptance for H2-applications and initiation of complete transition of heavy-duty means to ZEM.

After explaining the initial objectives of the ZEMoS project, a presentation of the state of the art, the methodology used and a detailed presentation of the project results and conclusions follows. The following section will delve into the current technological advancements and the challenges faced in implementing zero-emission mobility solutions. Furthermore, it will assess the economic viability and social acceptance of various hydrogen and electric mobility concepts.

4 The ZEMoS Project

4.1 State of the Art

In order to reach the EU climate goals, it is necessary to replace the diesel operating heavy-duty vehicles by low- and zero-emission vehicles. In this regard, the employment of BE and/or fuel cell electric FCE buses are considered as complementary technologies. Despite being highly efficient, the BE-buses have limitations in terms of charging time, range (especially in winter because of low temperatures and corresponding heating demands) and the disadvantage of “power on demand”. On the contrary, the refuelling time of FCE-buses is short, and they can be used at low temperatures for heavy load transportations over long distances. It is noteworthy that both e-buses (FCE- and BE-buses) are currently still in the phase of first small series production and the prototyping process, resulting in higher prices for them in comparison to conventional buses.

In 2020, the share of newly registered BE and hydrogen FCE-buses in the EU (excluding Bulgaria, Malta and Lithuania) was at 6.1 % which showed an increase of 18.4 % compared to 2019. In the EU plus UK, Norway, and Switzerland over 1500 e-buses (includes hybrid electric, FCE, trolley, and BE technologies) have been sold in 2020. Austria lags behind in this respect with only 175 e-buses or a share of new registrations of E-buses (including FCE-buses) of only 1.6 %[3] in 2020[4]. Preparations for the roll-out of FCE buses in Austria have officially started in 2021 in the framework of the national cooperative R&D HyBus Implementation project[5] [6] with the aim to implement the European “Clean Vehicle Directive” 2009/33/EC[7]. The large-scale demonstration of first 700-bar FCE buses (Hyundai) initiated in Vienna (urban case) and Graz (regional case) to accelerate their implementation and to establish the required know-how. Furthermore, the suitability of a Hyundai ElecCity hydrogen bus in alpine terrain was investigated through test drives made available by Graz Linien.[8]

Regarding electric heavy-duty trucks, FCE-trucks have some major benefits in comparison to BE-trucks. Heavy duty vehicles have limitations regarding the maximum allowed gross vehicle weight (GVW). Since batteries add considerably to the weight of the vehicle, BE-trucks have less payload capacity in comparison to FCE-trucks. Besides higher ranges and fast refuelling compared to charging and in future lower TCO are further decisive advantages of FCE-trucks.

In Austria, the first heavy-duty FCET logistic fleet is being implemented in the framework of the “MPREIS Hydrogen”[9] project in Tyrol. In the first quarter of 2022 green hydrogen was produced for the first time in

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[3] *Deloitte. H2-Mobility Austria Studie 2022: 2.000 H2-LKW auf Österreichs Straßen bis 2030; 2022.*

[4] *AustriaTech GmbH. Mobilitätsdaten in Österreich / Zahlen, Daten und Fakten.*

[5] *https://www.hybus.eu/*

[6] *https://www.klimafonds.gv.at/themen/mobilitaetswende/serviceseiten/zem/hybus-implementation-implementierung-der-ersten-drei-wasserstoff-busse-oesterreichs-in-den-realbetrieb/*

[7] *https://www.eumonitor.eu/9353000/1/j4nvk6yhcbpeywk_j9vvik7m1c3gyxp/vl04czyb9kzs*

[8] *Fleischhacker, N., Shakibi Nia, N., Coll, M., Perwög, E., Schreiner, H., Burger, A., Stamatakis, E., & Fleischhacker, E. (2023). Establishment of Austria’s First Regional Green Hydrogen Economy: WIVA P&G HyWest. Energies, 16(9), 3619.*

[9] *https://www.mpreis.at/wasserstoff/projekt*

the region of Tyrol. In the second quarter of 2022, a first prototype from Hyzon Motors[10] (tractor model 4 x 2) was made available by JuVe Automotion[11], through a framework agreement with MPREIS.[8] At the same time, a hydrogen refuelling station (HRS) operating at 350 bar, including pre-cooling, for heavy-duty vehicles was commissioned at MPREIS premises in Völs, Tyrol. This HRS was further used to validate the safety functions and the refuelling protocol for the hydrogen storage system (HSS) of FCET.[8] This truck was further employed for the training of local service technicians and drivers of MPREIS, organized and carried out by FEN Sustain Systems GmbH[12]. In January 2023, Austria's first hydrogen semi-trailer truck (tractor plus trailer) was handed over to MPREIS for commissioning[13]. Regarding quality assurance and optimization processes, a close collaboration took place between MPREIS/JuVe and Hyzon for their follow-up implementation in the next production series of FCETs[8]. Other main elements of the developed green hydrogen economy within "MPREIS Hydrogen" are a 3 MW pressurized alkaline electrolyser (AEL) system with a capacity of 1.3 tons of hydrogen production per day (implemented in the framework of the European project "Demo4Grid"[14]), three hydrogen storage vessels at 30 bar with the capacity to store a half a day of full production and the possibility of regulation at different pressures, and two multi element gas containers (MEGCs, 20-foot hydrogen storage containers).

The "MPREIS Hydrogen" project is one of the three ongoing complementary implementation projects within the WIVA P&G HyWest[15] [16] project, initiated since 2018. This project is the result of the developed "Tyrol 2050 energy autonomous" strategy, ongoing since 2014[17].

Other national projects focusing on the long-term green energy supply are namely "Renewable Gasfield"[18] and "H2Real"[19]. The green hydrogen production from wind power or photovoltaics (PV) in Renewable Gasfield is further used in a methanation process and mobility as well. In the H2Real project a hydrogen valley as the key for hydrogen technology and application in eastern Austria is under development. The overview of other national R&D projects within the scope of the energy model region is depicted in Figure 1.

In Salzburg, currently the necessary infrastructure in the case of hydrogen buses and trucks is still unavailable. It was recently reported that fossil-based production of 1 kg of hydrogen results in 10 kg of CO2 emissions[20]. Furthermore, given the advantage of green hydrogen production via electrolysis and its storage on site, as described above within current cases in Austria, this concept was considered in the ZEMoS project.

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10 *https://www.hyzonmotors.com/*

11 *https://juvemotion.at/*

12 *https://www.fen-systems.com/wasserstoffausbildung-und-fahrzeugtraining-fur-die-mechaniker-fur-ersten-wasserstoff-trucks-von-mpreis/*

13 *https://www.youtube.com/watch?v=m9-5WU2_4pA*

14 *https://www.demo4grid.eu/*

15 *https://www.hywest.at/*

16 *https://www.wiva.at/project/hywest/?lang=en*

17 *https://www.tirol2050.at/*

18 *https://www.wiva.at/project/renewable-gasfield/?lang=en*

19 *https://www.wiva.at/project/h2real/?lang=en*

20 *Chouhan K, Sinha S, Kumar S. International Journal of Hydrogen Energy 2021, 46(53), 26809–24.*

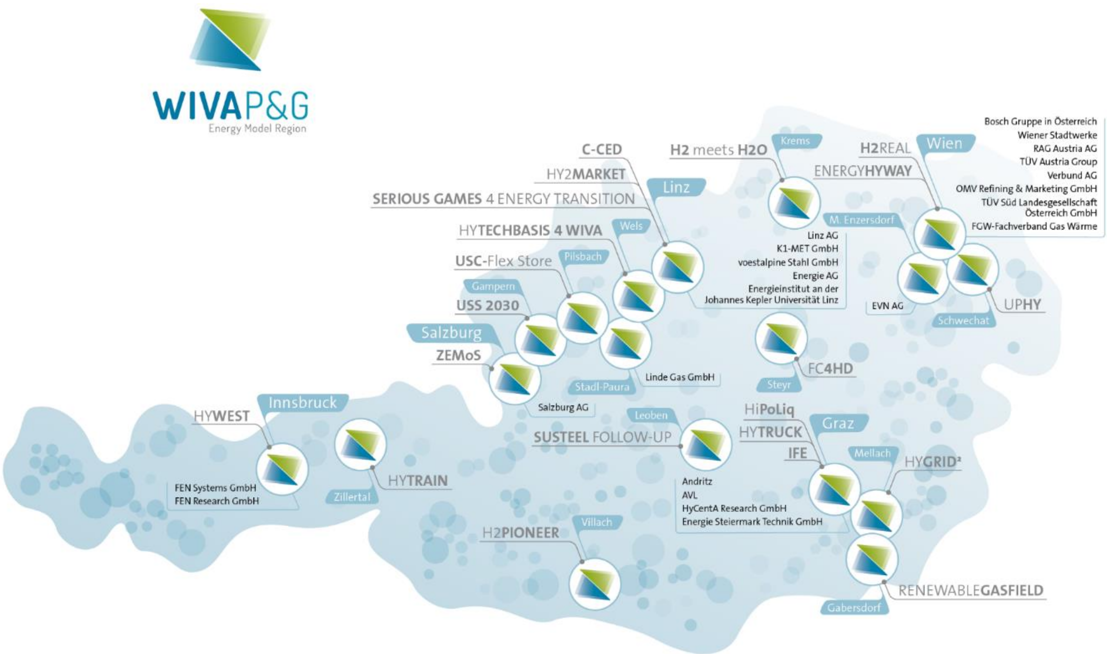

Figure 1: Geographical overview of national R&D projects within the WIVA P&G Energy Model Region[21]

The comparison of different electrolysis technologies is provided in Table 1. PEMEL is advantageous regarding dynamic operation, hydrogen quality, maintenance effort as well as required space but still comes with higher capital expenditures (CAPEX). This technology provides system efficiencies up to 65 % (based on the lower heating value), which means that a minimum of 35 % of the supplied energy is transformed into thermal energy. The overall system efficiency can therefore be improved by using the waste heat. This will additionally result in a reduced levelized cost of hydrogen (LCOH) production and will generate additional revenues.

Table 1: Overview of actual key parameters of different electrolyser technologies[22] [23] [24]

	AEL	AEMEL	PEMEL	SOEC
System Efficiency [%][a)]	Up to 65	Up to 68	Up to 65	Up to 82
Current Densities [A/cm^2]	0.2 – 0.6	0.5 – 2	1 – 3	0.3 – 1
Operating temperature [°C]	60 – 95	40 – 80	50 – 80	700 – 1000
Operating Pressure [bar]	Atm. – 32	30 – 35	Atm. – 40[b)]	1 – 3
Module size [kW]	5 – 6 000	Up to 5	5 – 2 500	-
System size [MW]	Up to 100	-	Up to 100	Up to 0.15
Lifetime [h]	60 000 – 90 000	> 2000	30 000 – 90 000	< 20 000
CAPEX costs [€/kW]	500 – 1200	-	800 – 1800	1200 – 2000

a) based on H_u = 3 kWh/Nm^3 H_2; b) demonstration up to 700 bar

21 *https://www.wiva.at/activities/?lang=en*

22 *The International Renewable Energy Agency. Green hydrogen cost reduction, 2020.*

23 *International Energy Agency. The Future of Hydrogen: Seizing today's opportunities, 2019.*

24 *Christensen A. Assessment of Hydrogen Production Costs from Electrolysis: United States and Europe; 2020.*

For an integration into a district heat system, technological pathways may be considered which would require further comprehensive techno economical assessments by means of plant simulations. Such studies regarding commercially available systems as well as their durability, operational behaviour and demonstration in large scale operation are still missing[25]. Economic and socio-technical analyses are important tools to identify market relevant influencing factors. In order to be able to identify various decision-relevant factors and corresponding correlations regarding the transition to FCE and BE-mobility, a targeted analysis and evaluation is required.

The industrial research and experimental development topics which were investigated in the ZEMoS project dealt with technology readiness levels (TRLs) above 5 and aimed to investigate the open questions described in this section based on the real-world data.

4.2 Methodology

The ZEMoS project outlined a strategic framework that aimed for the gradual substitution of diesel-powered public transport and heavy-duty vehicles in operation all year round. Based on the considered technology-open approach in this project, both BE and FCE vehicles were examined.

4.2.1 ZEMoS Model Regions

ZEMoS aimed to develop two ZEM model regions – one urban (Tennengau) and one alpine/tourist (Pinzgau) – for public bus transport and pilot projects for the transfer of heavy-duty transport (see Figure 2). ZEMoS was set up as a "living lab", meaning that the acquired real-case data was reevaluated periodically. This ensured that the developed models were continuously improved and therefore, the evaluated results were continuously plausibilised. ZEMoS was further developed as part of a continuous improvement process (CIP).

4.2.1.1 Urban Model Region – Tennengau

Tennengau, as the urban model region (Figure 2), was a key focus area for ZEMoS. The project envisioned the development and implementation of innovative, holistic, large-scale zero-emission bus concepts for public transport. An optimization model was created to determine the most suitable zero-emission drive technology for each specific bus line. Additionally, pilot projects for garbage trucks and heavy-duty trucks were initiated as well.

4.2.1.2 Alpine/Tourist Model Region – Pinzgau

Pinzgau, known for its alpine and tourist characteristics, posed unique challenges and opportunities. ZEMoS planned to extend its impact to heavy-duty transport by initiating FCE projects for heavy-duty trucks. The project also aimed at the partial decarbonization of public transport during the ski world championship in Saalbach in 2025 by providing ZEM buses for the event. Additionally, this region was set to serve as a testing ground for establishing a green hydrogen infrastructure.

The focus on public transport and heavy-duty traffic, predominantly diesel-operated, represented a crucial and challenging shift. ZEMoS addressed the diverse weather conditions, topography, and seasonal

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[25] *Moradi Nafchi F, Baniasadi E, Afshari E, Javani N. International Journal of Hydrogen Energy 2018, 43(11), 5820–31.*

variations, especially in alpine terrain, adding an innovative perspective to zero-emission mobility in challenging environments.

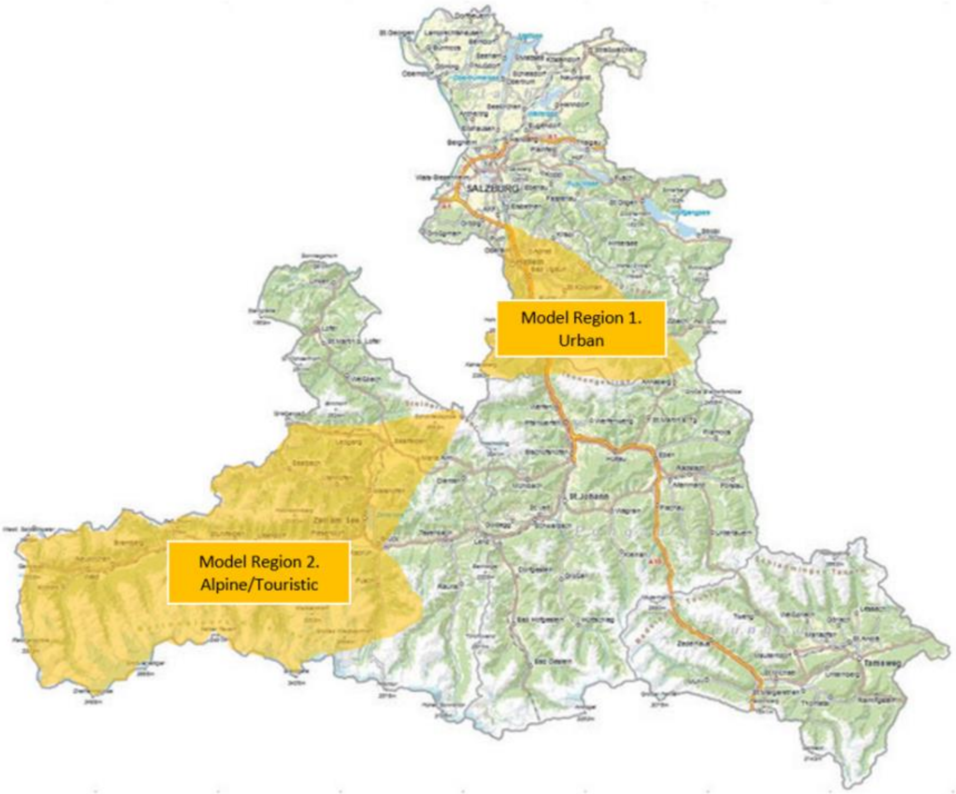

Figure 2: Map of ZEMoS model regions: Urban model region 1 (Tennengau), Alpin/Tourist model region 2 (Pinzgau).

4.2.2 ZEMoS Concept

The R&D national projects laid the groundwork for technical maturity regarding green hydrogen production and infrastructural know-how (see State of the Art). The knowledge obtained and optimizations achieved in the ZEMoS model regions, depicted in Figure 3 and Figure 4, were intended to provide the basis for nationwide deployment, establishing a pioneering role in this regard.

ZEMoS should introduce a paradigm shift in planning, moving from traditional demand-centric approaches to focusing on infrastructure considerations. This involved addressing issues such as charging station accessibility, HRS placement, and charging times. The project pioneered new GIS-based methods and spatial databases to effectively plan locations based on accessibility and demand. By integrating infrastructure location and fleet composition decisions into its planning process, ZEMoS aimed to develop a mixed-integer linear program to optimize these intertwined decisions simultaneously. The model was tested on real-world data from Tennengau and Pinzgau, showcasing a commitment to practical application. The complex technological challenges of hydrogen production by electrolysis were investigated. Furthermore, the supply strategy of green hydrogen, produced by the electrolyser situated in the urban model region, and the decentralized HRS situated in the alpine model region was considered through hydrogen logistics between both model regions (see Figure 3 and Figure 4).

In addition to the technical aspects, ZEMoS emphasized socio-technical analyses aiming to understand acceptance among the population, particularly in the model regions of Salzburg. Willingness-to-pay analyses referred to both the local population and tourists, taking into account possible differences in attitudes.

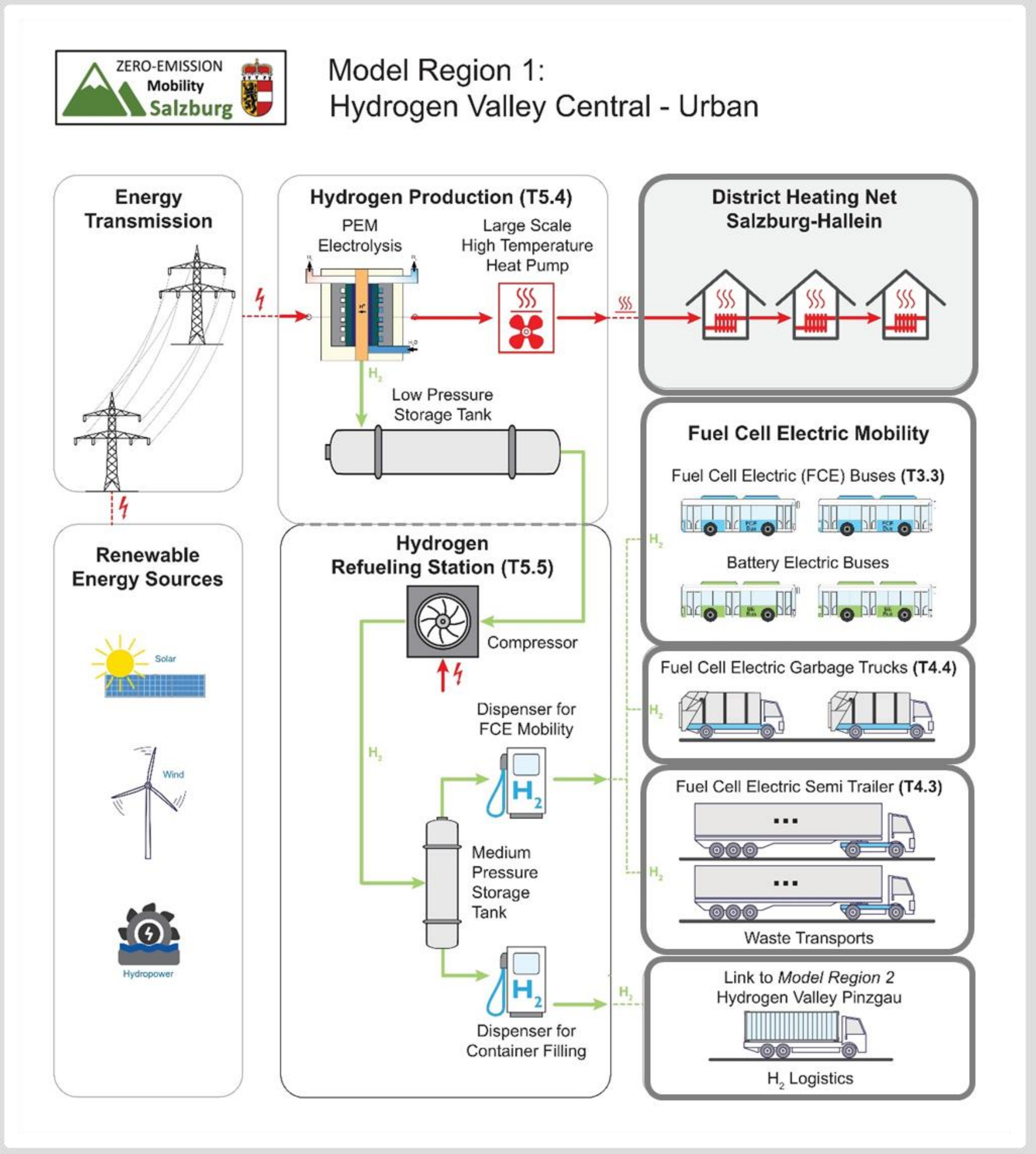

Figure 3: ZEMoS Concept Model Region 1

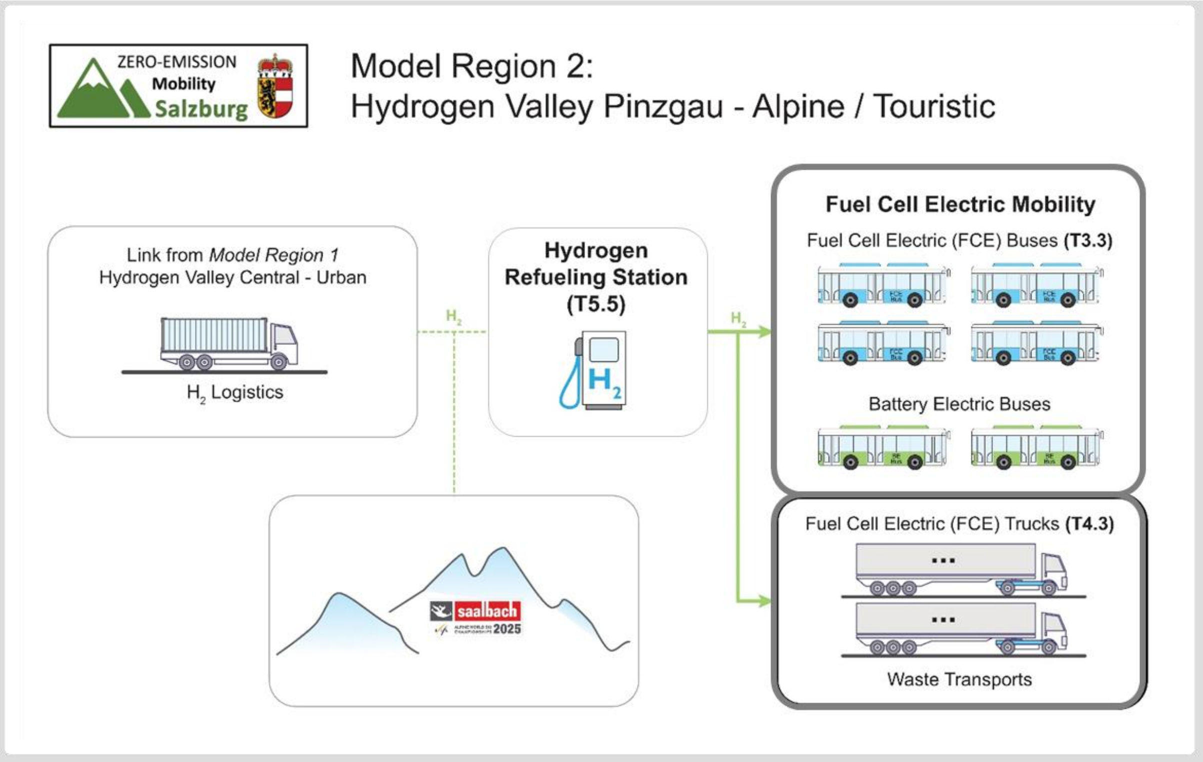

Figure 4: ZEMoS Concept Model Region 2

4.3 Feasibility Assessment

Addressing the critical aspect of feasibility, ZEMoS undertook a comprehensive approach to assess the viability of ZEM solutions. The project's primary objective was to formulate an inclusive roadmap for transitioning to ZEM, accounting for the diverse geographical and operational landscapes of Salzburg.
The foundation of this assessment was laid in detailed data collection, encompassing spatial typologies, demographic data, bus routes with timetables, and specifics concerning hydrogen and charging infrastructure in the Pinzgau and Tennengau regions. Collaborative efforts with SVG enhanced existing spatial planning tools, integrating spatial characteristics of bus routes and infrastructure for both hydrogen and battery-electric mobility.
ZEMoS began with the identification of potential bus routes that could enable an efficient transition to sustainable propulsion methods. The project used modelling techniques to assess the potential of FCE and BE buses for selected routes. Additionally, the analysis considered potential locations for new charging and HRSs as well as future developments, such as new charging infrastructure or increases in demand. This approach included a thorough comparison of FCE and BE buses for different routes and incorporated a prioritisation strategy via a bus planning tool, which was a computational mathematical optimization model. Using this model, the number of E-buses (BE or FCE) were optimized based on the total costs of substitution for each specific bus line from diesel propulsion to ZEM propulsion.

5 Results and conclusions

The research and development (R&D) project ZEMoS (FFG Nr. FO999900979) initiated in April 2023 under the coordination of Salzburg AG[26] (S-AG) in close alignment with the goals outlined in the strategical Master Plan of the federal state of Salzburg[27]. With its focus on the mobility sector, ZEMoS was a pioneering project contributing to the necessary transition from conventional diesel vehicles to emission-free alternatives. The goals outlined in this project within fostering sustainable mobility applications in the region were not only limited to the identification of suitable technologies but also addressed the challenging task of developing the required infrastructure. This project was part of the Austrian KLIEN-FFG Energie-Vorzeigeregion WIVA P&G program[28]. The goal of the "Energie-Vorzeigeregion WIVA P&G" was to demonstrate the transition of the Austrian economy and energy production to a largely CO_2 neutral system based strongly on renewable hydrogen in the fields of *Green Energy*, *Green Industry* and *Green Mobility*. Regarding the initial conceived concept, some changes were made due to unforeseen events. For instance, the current unavailability of a implemented refuelling infrastructure and uncertainty concerning the green hydrogen price were identified as the main factors inhibiting investment decisions in fuel cell electric vehicles (buses, garbage trucks and trucks). Furthermore, the expected capital expenditure costs for hydrogen vehicles were budgeted before the increase in prices due to the inflation period, resulting in a gap in the funding volume.

Due to the lack of implemented hydrogen vehicles in the first year of the research project and significant changes and delays in the hydrogen infrastructure , the consortium received a list of requirements from the expert panel after the hearing on the 1st of August 2024. These requirements included the following confirmations by the end of Q1 2025: acquisition of one hydrogen bus, acquisition of one hydrogen truck, acquisition of one hydrogen garbage truck, operational concept for the vehicles, and proof of scaling the hydrogen mobility according to the funding application.

Follow-up the hearing, extensive work has been done by the project management team in close cooperation with FFG and project consortium to fulfil the requirements. However, since the necessary demand in mobility was lacking on one hand, and the necessary funding on the other hand, it was decided to conclude the project with the results achieved in the second year of the project. The main achievements and results of the project are summarised below:

- Development of novel holistic and spatial FCE- and BE-bus concepts:
    - *Energy consumption calculation tool implemented using topography, mass, and speed data to optimise electric bus routes.*
    - *Models/algorithms developed for multi-depot operations and mixed fleets of hydrogen/battery buses.*
- Deployment of 32 BE-buses across 10 routes:
    - *21 BE buses already operational in model regions.*
    - *Tender issued for remaining 6 BE buses.*
    - *Demand and analysis for five FCE H2 buses are available.*

[26] *https://www.salzburg-ag.at*

[27] *https://www.salzburg.gv.at/themen/umwelt/salzburg2050*

[28] *https://www.wiva.at/vorzeigeregion/*

- Implementation of two ZEM projects for heavy-duty vehicles:
  - *Demand analysis for the vehicles as well as the need for maintenance infrastructure was updated.*
  - *Finalised H2 refuelling concepts for garbage trucks.*
  - *H2 refuelling concepts and vehicle specifications for the implementation of two H2 trucks in the urban and alpine regions were updated.*
- Green hydrogen infrastructure development in combination with innovative sector-coupling and balancing energy services:
  - *Electrolysis plant design completed with waste-heat recovery integration.*
  - *H2 station concepts adapted to EU AFIR regulations (Alternative Fuels Infrastructure Regulation) at key transport hubs.*
- Accompanying scientific research and innovative technology development:
  - *TCO analysis shows battery-electric buses as most cost-effective solution.*
  - *Digital twin simulations implemented for H2 infrastructure testing.*
- Public acceptance initiatives:
  - *In public bus transport, the implementation of BE buses by SVG significantly increased the attractiveness and acceptance of zero-emission vehicles.*
  - *Operation of the FCE H2 demo bus in combination with a mobile H2 refuelling station demonstrated the technical practicality in real-world operations*.
- Knowledge dissemination, communication and exploitation:
  - *ZEMoS Information Event showcased Hyundai's H2 vehicles and Albus' operational experience.*
  - *Mobile HRS demonstrated real-world practicality.*
  - *Several dissemination, communication and networking activities including publications.*
  - *Identification of exploitable project results and their presentation at final project event.*

In the following section, the detailed results of the various work packages will be presented, showcasing the significant advancements and practical implementations achieved throughout the ZEMoS project.

5.1 WP1: Project Management

The project management team, primarily consisting of S-AG and supported by FEN Systems, frequently monitored activities and the project budget. They organized hearing meetings, prepared project results, coordinated internally with the S-AG team, and externally with project partners and the FFG team. Following the expert panel's requirements, the management team continually controlled activities and the project budget, making the results available to the project consortium and updating the e-Call accordingly. Numerous consultations between scientific and industrial partners were conducted online or on-site, with results shared in monthly work package meetings. These tasks were documented in a RASIC matrix. SharePoint, managed by S-AG, served as the central platform for document exchange, ensuring smooth access for all partners.
A critical evaluation of the various tasks in the work packages was carried out on the basis of the first interim report. As the project was terminated prematurely after 2 years, the benefits of the individual tasks that could still reasonably be achieved were analysed. This survey made it possible to control the workload for the different tasks in order to achieve meaningful project results that could also be used after the ZEMoS project.

5.2 WP2: Integrated FCE- and BE-mobility concept for public bus transport

In this work package, optimized integrated FCE- and BE-mobility concepts for the two model regions were planned. All tasks of this WP started at the beginning of the project and had been ongoing since then.

5.2.1 Task 2.1 Data collection and innovative processing from relevant preliminary projects

To generate the most accurate result, preliminary studies have been considered either to extend existing methods and data or to adapt them. Due to the specific task for the methods and data within ZEMoS, most parts of the models and data have been developed or collected specifically for the aim of the project. Nevertheless, the knowhow of Ultimob concerning the planning process using indicators, was used and built upon as well as spatial concepts from the project GEL S/E/P II. Furthermore, findings on FCE-busses have been transferred from the project HyBus. In exchange with the partner of SVG and JKU-PLM as well as iteratively with first results of the holistic model (Task 2.2) new tools were created which take factors like topography, temperature, velocity, load, and more into account. This data is stored in a geodatabase. Furthermore, the test operating FCE-bus in July 2024 offered the opportunity to collect measured data. In a first step, a concept was developed to integrate these data to the existing models. As a result, we decided to use the mountainous drive of the bus route and use the data to validate the models, due to a low reliability of the data to do precise modelling on themselves.

5.2.2 Task 2.2 Spatial data basis and tools for holistic analysis of regional bus lines and routes (Lead: iSPACE)

In cooperation with SVG, spatial and non-spatial data relating to the bus lines have been collected and stored within a spatial data base. Concretely the routes as well as the stops of the buses, the timetable and circulation plans and the load approximated by the number of entries, have been integrated in the data base. Furthermore, potential positions for charging and refilling stations have been deciphered, located, and added to this database.
Based on this data, a tool was created to calculate the “worst case scenario”, which means that the data was processed in a way, that the highest energy consumption would be described and ensures that in practice the bus can complete the necessary distance in any condition. In terms of the model, this means that the highest load, the highest possible velocity, the maximum amount of frost and heat days have been taken into account. This data is combined with the values for the slope for each relation between two bus stops. The slope values for each segment are based on the 1-meter DEM (digital elevation model) and in a first approach, they have been stored as maximum and mean slope. Missing or incorrect information within the GIP (Graphenintegrations-Plattform) was added or corrected. This includes tunnels and bridges. This is implemented for all relations between each bus stops of all aimed bus lines, as well as the routes from and to the refilling and charging stations as well as the bus garages. Within the project and driven by the access to measured data a second approach was implemented, which calculates the drivetrain power based on a physical model including parameters speed, slope, mass etc.
To extract slope parameters, a new model was implemented which enhances the quality of the elevation data at bridges and tunnels. The output was compared to measured data, which was gathered by an FCE test operating bus in July 2024 on a mountainous drive and showed coherent results. In contrast, using linear regression model with least mean square error did not yield reliable results. So, focus stayed on the physical model, whereon constants for air condition and auxiliary systems were added. As it turned out

that heating has a higher energy consumption than cooling, the model was adjusted for low air temperatures only. As an output, the energy consumption each segment between two bus stops has been stored in an csv-file and transmitted to JKU-PLM for further analyses.

5.2.3 Task 2.3 Holistic analysis of optimized FCE- and BE-mobility structures based on bus tour planning

To optimize bus fleet and route scheduling, differently structured mathematical models, more specifically mixed integer linear programming (MIP) formulations, have been developed during the project. The main ingredient to these formulations is a graph representation which relies on the input data provided by iSpace and allows formulations that do not require time variables since any schedule in the graph is automatically time feasible. A tailored exact method, relying on branch-and-cut has been developed for the multi-depot but homogeneous fleet electric bus scheduling problem, which allows to compute the minimum fleet size for a homogeneous fleet of buses, e.g. for a single bus line. It has also been tested on benchmark-type instances as it can solve any multi-depot electric bus scheduling problem.[29] The advantage of the proposed two-index model, relying on an exponential number of constraints that are generated dynamically, over a more straightforward three-index model could be shown. For the heterogeneous fleet, multi-depot case, which arises when bus schedules and fleet composition across multiple lines are optimized, the three-index model has been extended. Since it does not rely on an exponential number of constraints, it can be solved by any off-the-shelf MIP-solver. Using, CPLEX, single line data sets from the model regions could be solved in less than a second of computation time. For complete regions, the optimality gaps remained quite high. Therefore, for this problem version, also a metaheuristic algorithm has been designed which produces good results in short amounts of time. It relies on large neighbourhood search ideas and when applied to single line data with homogeneous bus fleets from the model region, even the construction step, in some cases, achieves solutions requiring just one additional bus than the minimum number of buses possible to serve the line. Interestingly, how difficult it is to obtain good results on a certain data set quickly is not always linked to the number of service trips that must be scheduled. The most complicating aspect seems to be the consideration of different charging technologies and partial charging, which requires clever ideas on how to efficiently evaluate changes in the route plan. The model as well as the heuristic approach are publicly available as a Julia code bundle under an MIT Open Source license, using a jupyter notebook as user interface: http://www.jku.at/zemos[30]

5.3 WP3: H2 Mobility: Public transport

5.3.1 Task 3.1 Requirement analysis for urban & rural public transport

As mentioned in Task 2.1, public transport-related data was also used within the spatial database. Therefore, requirements of the data have been defined in exchange with SVG and iSPACE, to generate a standardized database as an input for the developed tool. The defined and collected data which was used

[29] *Haslinger, X., Gaar, E., and Parragh, S. N. (2025). An exact approach for the multi-depot electric vehicle scheduling problem. Technical report, https://arxiv.org/abs/2504.13063.*

[30] *Ertl, T., Forget, N., Gaar, E., Haslinger, X., Hiermann, G., Kainz, C., Krisch, P., Parragh, S.N. (2025) Operations Research Supports the Transition to Zero-Emission Bus Fleets in Salzburg. Working Paper, Johannes Kepler University Linz.*

in the project is mentioned in task 2.2. During the work progress the slope parameter was adjusted, leading to changes in the internal exchange format. While the first version transmitted only parameters such as mean and maximum slope, the latest version introduces a more precise model. This model takes energy consumption into account based on small-scale gradients.

5.3.2 Task 3.2 Concept design and planning of novel H2 powered local public transports

All planned scheduled services were successfully tendered and commissioned throughout the entire project period.
As of now, there is no standardised or agreed procedure for setting up the necessary charging infrastructure for the BE buses in the province of Salzburg. The operator of the Hallein city bus routes (41, 42, 43, 44) independently set up the e-charging infrastructure at its new operating site in Kaltenhausen. For the Saalfelden city bus routes (60, 61, 62), the municipality of Saalfelden has made land available at Postplatz (bus station), where the charging infrastructure was installed on behalf of the Salzburg Transport Association. The operator of the Wals-Siezenheim (151) and City of Salzburg (11) routes has set up the necessary charging infrastructure independently at its depot in the city of Salzburg. For Bad Hofgastein (558 + ski buses), there is the possibility that the future operator will set up the charging infrastructure itself or that the charging facility will be provided by the Gasteiner Bergbahnen AG - final negotiations are currently underway.

5.3.3 Task 3.3 Implementation FCE-Buses

Due to adaptations to the initial project proposal the planned number and drive technology of the buses has changed during the project. According to the current status, 27 BE buses are to be procured in Salzburg via external projects (EBIN funding track).

Ordered and in regular service in the first reporting period:

- Line 181 (Salzburg main station - Wals - Grünau - Walserberg state border)
    - **4 BE Solobus 12 m – in operation since 12/2022**
- Line 36 (Wals fire station - Salzburg Europark)
    - **2 BE Solobus 12 m – in operation since 12/2022**

Ordered in the first reporting period and in regular service during this reporting period:

- Hallein city transport
- Line 41 (Hallein railroad station - Bad Dürnberg)
- Line 42 (Hallein railroad station - Bad Vigaun)
- Line 43 (Hallein railroad station - Neualm)
- Line 44 (Hallein Hospital - Rehhofsiedlung - Rif)
    - **5 BE Solobus 12 m - in operation since 12/2023**
- Saalfelden city bus
- Line 60 (Saalfelden train station - post office - Bsuch - Hof)
- Line 61 (Saalfelden Post Office - Farmach - Dorfheim - Bachwinkl - Post Office)
- Line 62 (Saalfelden post office - train station - Haid - Bürgerau - post office)
    - **3 BE Midibus 10 m - in operation since 12/2023**
    - **3 BE Solobus 12 m – Delay in delivery - operation planed from 06/2025**
- City of Salzburg
- Line 11 (Josefiau - Leopoldskron - Aiglhof - Messe/Salzburgarena)
- Line 151 (Salzburg - Gaisberg)
    - **7 BE Solobus 12 m - in operation since 12/2024**

Tendered and ordered during this reporting period:

- Gastein Valley
- Line 558 (Bad Hofgastein [bus terminal - Wieden - train station - center - south])
- Ski buses
    - **3 BE Midibus 10 m – operation planned for the first quarter of 2026**

A total of 21 new BE-buses were put into operation during the project period. By 28.02.2025, a total of 584,449.74 km (commercial vehicle kilometres) had been covered on 10 routes in the province of Salzburg. This has saved a total of 510.14 tons of CO2 to date.

Since no FCE H2 bus could be implemented the measure from the risk mitigation strategy was implemented, and a demo operation of an FCE H2 bus was conducted in July for real data collection. In this context, Albus acted as the bus operator, and S-AG provided the refuelling infrastructure (mobile H2 filling station by Linde).

5.4 WP4: H2 Mobility: Heavy-duty transport

5.4.1 Task 4.1 Requirement analysis for urban FCE garbage trucks & alpine heavy-duty transport

The requirement analysis for H2 garbage trucks was conducted with the city of Salzburg. The availability of vehicles with the necessary technical specifications in the urban area was discussed on the one hand, and on the other hand, the potential infrastructure positioning of an H2 filling station was discussed with the operations manager. In contrast to the first project year, where the focus was on determining the required H2 quantity, the focus in the second project year was on reviewing the market availability of H2 garbage trucks. The H2 demand in the alpine operational area was also updated with ZEMKA.

5.4.2 Task 4.2 Concept design and planning of novel H2 powered local heavy-duty transports and garbage trucks

Key findings from Task 4.1 and the ZEMoS information events were integrated into the design of the H2 filling stations (pressure level for garbage trucks and trucks, space requirements, refuelling time, etc.). In addition to vehicle availability and infrastructure topics, the implementation of a maintenance infrastructure for H2 heavy-duty transport was also discussed.

5.4.3 Task 4.3 Implementation FCE-Trucks (Long haul)

Due to the inflation-driven increase in both investment costs and operating costs (calculated H2 price), it was not possible to deploy 4 FCE H2 trucks. Additionally, ZEMKA does not operate the trucks itself but outsources the waste transport to contracting freight forwarders, which are mostly small family businesses. For these small family businesses, the costs and risks of operating a FCE H2 truck are too high, despite the availability of national ENIN funding.

The lack of vehicle maturity was identified as particularly problematic. It would have been necessary to keep a conventional vehicle in reserve. Manufacturers provided very limited guarantees regarding operational reliability, meaning the vehicle user would have had to bear significant risks (of a technology not yet proven).

To highlight the challenges in the implementation of heavy-duty vehicles in Austria, framework conditions in other countries were also examined. Switzerland was particularly focused on, as H2 infrastructure and vehicles have already been implemented there.
While the ZEMoS project struggled with financial incentives, Daimler Trucks in Switzerland has received funding approval for the development and small-series production of 100 FCE H2 trucks (using liquid H2, providing an extended range of over 1 000 kilometres), with deployment expected from the end of 2026. The funding, totalling € 226 million, is being provided by the Federal Ministry of Digital and Transport (BMDV) alongside the German states of Baden-Württemberg and Rhineland-Palatinate. The funding falls under the Hydrogen Programme of the Important Project of Common European Interest (IPCEI), which aims to promote hydrogen technology across the European Union.[31] [32] In another example, Hyundai's XCIENT Fuel Cell trucks have collectively surpassed 10 million kilometres in Switzerland since October 2020. The XCIENT Fuel Cell truck is the world's first mass-produced heavy-duty hydrogen-electric truck and has proven its exceptional performance in key markets such as Switzerland, Germany, and the United States.[33]

Unique showcase for FCE H2 trucks in Switzerland[34] results from a strong privately organized cooperation and great willingness to invest in hydrogen technology in order to create increasing demand for the implemented hydrogen production and refuelling infrastructure, built in parallel. Furthermore, high number of participating end-users supports the development of a regional hydrogen economy, together with a common understanding that cooperation is the only way to enable a roll-out of FCE H2 trucks to a bigger extend.[35]
In general, Switzerland's national hydrogen strategy (published on 13 December 2024)[36] demonstrates several advantages over Austria's, regarding legal framework conditions, particularly in infrastructure integration, legislative support, and market development timelines. However, both strategies share common goals in decarbonizing hard-to-abate sectors and leveraging European partnerships. A summary of these differences is listed below:

<u>Infrastructure Integration with Europe</u>

- Switzerland explicitly prioritises connecting to European hydrogen transport networks through financial protections for transit pipelines and international partnerships. The strategy mandates an evaluation of financial security mechanisms for cross-border infrastructure by the end of 2025.[37] [38]

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[31] *https://theevreport.com/daimler-truck-secures-major-funding-for-hydrogen-trucks*

[32] *https://drivinghydrogen.com/2025/03/24/daimler-puts-next-gen-mercedes-benz-hydrogen-trucks-through-their-paces-in-the-alps/*

[33] *https://www.hyundaimotorgroup.com/story/CONT0000000000161400*

[34] *https://h2mobilitaet.ch/de/*

[35] *https://ecomento.de/2025/02/10/daimler-truck-es-braucht-batterie-und-wasserstoffbetriebene-lkw-und-busse/*

[36] *https://www.admin.ch/gov/de/start/dokumentation/medienmitteilungen.msg-id-103544.html*

[37] *https://research.csiro.au/hyresource/policy/international/switzerland/*

[38] *https://www.enerdata.net/publications/daily-energy-news/switzerland-adopts-its-national-hydrogen-strategy.html*

- Austria focuses on repurposing existing gas pipelines (such as WAG and TAG) for hydrogen transport but faces regulatory uncertainties about overlapping gas/electricity markets and permitting regimes. While Austria plans a dedicated hydrogen network by 2050, its current framework lacks Switzerland's specificity on cross-border collaboration.[39] [40]

Legislative and Financial Support

- Switzerland's Climate and Innovation Act (KIG) provides a six-year legislative pathway to subsidise domestic hydrogen production and storage. This creates immediate investment certainty.**Fehler! Textmarke nicht definiert.**
- Austria relies on evolving regulations such as the Hydrogen Promotion Act and proposed "green gas quotas", which remain under parliamentary review.[41]

Regulatory Clarity

- Switzerland designates specific infrastructure zones (e.g., HRS along national roads) under the supervision of DETEC, thus reducing bureaucratic hurdles.**Fehler! Textmarke nicht definiert.**
- Austria's strategy lacks equivalent land use provisions, and there are ongoing debates about increasing hydrogen blending limits in gas networks beyond 10 %.**Fehler! Textmarke nicht definiert.**

5.4.4 Task 4.4 Implementation FCE Garbage Trucks (Long haul)

Due to the lack of infrastructure and the high acquisition and operating costs, the use of H2 collection vehicles in the city of Salzburg is currently not planned. The fundamental requirement for the use of H2 collection vehicles is the availability of the necessary infrastructure. E-collection vehicles are already in use. These are significantly cheaper to purchase and operate. Additionally, the necessary infrastructure (connection capacity) is largely already in place. HVO100 is currently being tested in the city of Salzburg as part of a pilot project in the general fleet. If this test is successful, the use of HVO100 is also planned for the waste service. In the long term, it is planned to increase the share of alternatively powered collection vehicles in the waste service to around 30-40 %. The project has led the waste service to intensively consider the use of BE and FCE H2 garbage trucks and to make a medium-term decision for one of the two alternatives.

5.5 WP5: H2 Infrastructure: Hubs and Logistics

5.5.1 Task 5.1 Concept development for H2 supply, distribution and storage

The changes made in the first project year regarding the project location for the electrolysis plant and the fuelling station were subjected to a technical feasibility review in the second project year. In addition to the trailer supply of the fuelling station by the H2 production facility, a pipeline supply was also included in the concept.

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[39] *https://www.aggm.at/en/energy-transition/h2-roadmap/*

[40] *https://www.alpine-space.eu/project-news/territorial-perspectives-and-development-potentials-austria/*

[41] *https://www.schoenherr.eu/media/3r5d2nyl/ren25_chapter-3_austria.pdf*

Additionally, the pipeline supply for the fuelling station was conceptualized. The expert reports developed in the first project year for the project locations were considered and incorporated at the new project location (Noise assessment; Traffic assessment; Planting assessment; Installation assessment; Soil assessment; Explosion protection concepts; HAZID (Hazard Identification) and prevention measures; Water assessment; Fire protection assessment; Etc…)

5.5.2 Task 5.2 Conceptual design and detailed planning of H2 Hub

The H2 infrastructure concept includes a PEM electrolyser, low-pressure and high-pressure storage, compressors, a trailer filling station, a large heat pump, gaseous hydrogen (GH2) buffers, and a trailer filling station. GH2 is produced using a containerised solution with three electrolyser trains. An H2 buffer tank is installed between the electrolysers and H2 compressors. Nitrogen is utilised for purging as an inert gas after the electrolysers have been shut down.
A dynamic operation within the balancing energy market was also technically assessed. The option to inject hydrogen into the natural gas grid at the site further enhances the plant's flexibility.
<u>H2 Hub:</u>
In the initial phase, the refuelling concept involved supplying hydrogen via trailers from the H2 production site. Should the demand for the H2 Hub increase (ramping up heavy transport), the concept includes connecting the HRS with the production site via a pipeline. Possible routes for an H2 pipeline and the legal framework conditions were examined. Connecting the station with a pipeline would also save on H2 transport logistics and generally reduce traffic volume.
During the H2 demo bus operation (Figure 5), an initial mobile H2 refuelling station (pressure transfer system) was installed at the planning site. This facilitated the collection of practical experiences and led to adjustments in the traffic concept of the H2 Hub.

Figure 5: FCE H2 Demo bus

5.5.3 Task 5.3 Optimising production & distribution processes

The technical review of the electrolysis plant for the balancing energy market was conducted based on information from an electrolyser manufacturer. Initially, the requirements for participation in the balancing energy market were assessed. The analysis revealed that the PEM electrolyser is generally suitable for the balancing energy market within a certain partial load range, provided that sufficient hydrogen storage is available. Participation in the balancing energy market poses a challenge when combined with delivery commitments in mobility, affecting the economic optimization of the plant. The development of a predictive model for hydrogen supply and production could not be addressed in the project as it depends on the H2 infrastructure and bus implementation.

5.5.4 Task 5.4 Implementation Green H2 Production Infrastructure

The H2 production infrastructure could not be implemented for several reasons. Firstly, the availability of vehicles was not given, as the technical specifications were not met. Secondly, the economic conditions have further deteriorated due to the geopolitical situation and rising costs for energy and vehicles. Additionally, there are currently no sufficient funding sources for vehicles and infrastructure (e.g., electrolysers, refuelling stations). The restrictive requirements for producing green hydrogen (RFNBO, RED III) have mainly complicated its implementation.Lastly, planning uncertainty persists due to unresolved legal framework conditions.

5.6 WP6: Demonstration within the Living Lab

5.6.1 Task 6.1 FCE and BE buses for public transport in Saalbach Alpine World Ski Championships 2025

The organizers of the World Ski Championships have presented a concept for guest travel. This was refined with the support of SVG's planning department. The existing rail and bus connections were increased in frequency during the World Championships. In addition, there was a shuttle bus concept linking the Maishofen World Championships railway station, the World Championships car park (Maishofen Stablberg) and the Hinterglemm bus terminal. A total of 35 buses were used. The organisers decided that the shuttle bus operation should be carried out using buses with conventional drive systems and not battery electric, as only buses in the categories of multi-axle solo buses (up to 15m long) and articulated buses (up to 18.75m long) were used. However, there are currently no buses in these categories as BE buses in the province of Salzburg. But only with these vehicle sizes was it possible to cope with the flow of visitors. The organizer also decided not to use H2 buses due to the project changes in the ZEMoS project.

5.7 WP7: Technical innovations, ecologic, economic and social impact assessment and scientific monitoring

5.7.1 Task 7.1 Digital twin for plant optimisations & validation

As reported previously, an evaluation of two potentially suitable simulation software packages for the implementation of a digital twin has been conducted (Ebsilon and MATLAB-Simulink). After thorough consideration it was decided to choose the MATLAB-Simulink package since HyCentA has long lasting experience with the in-house HYDRA package.

It was further decided that the focus for the second and final year was to be laid on the development of a simulation model of the hydrogen infrastructure (H2 production plant and HRS) to simulate the suitability of the planned infrastructure developed in Tasks 5.1 and 5.2 for the expected H2 demand. It was decided

not to focus on the utilisation of the waste heat via heat-pump or on a detailed economic analysis and optimisation of the H2 Hub.
The maximum expected H2 demand of up to 3.211 kgH2 per day included refuelling of 60 buses and 21 heavy-duty vehicles as well as filling a trailer with 871 kgH2. The simulation model included three 2.5 MW electrolysers, a buffer tank and storage management system at the production site as well as a buffer storage, storage management system, two compressors, medium- and high-pressure storage, chillers, 350 and 700 bar dispensers, and trailer filling stations at the HRS site. The scheme of the employed model is depicted in Figure 6.

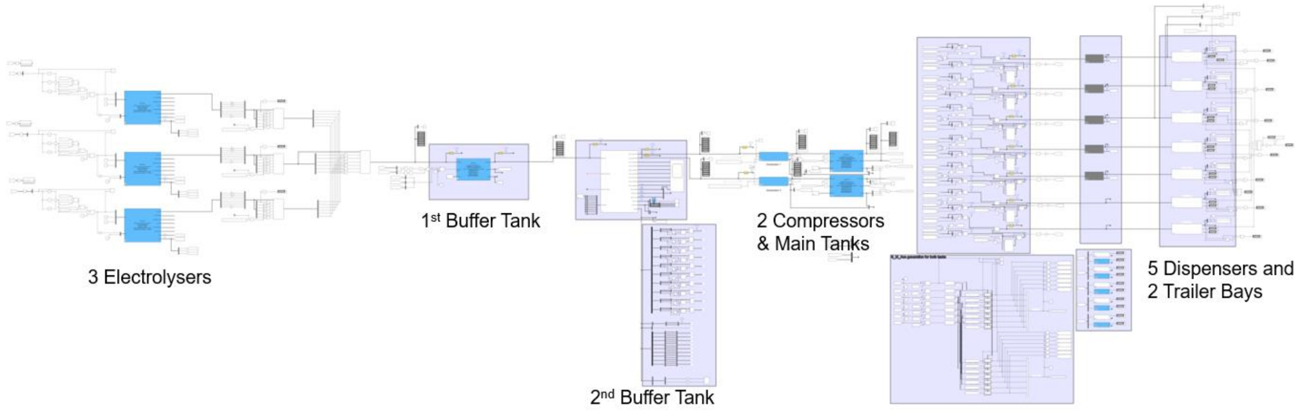

Figure 6: Simulation model overview used for plant optimisations and validation.

Simulation results showed that the initially proposed layout of the HRS was not suitable to meet the maximum demand of 3.211 kgH2 per day. This was on the one hand due to too little compressor throughput (ca. 80 kg/h) and too small hydrogen storage capacities (ca. 1046 kgH2). Initial simulation runs showed that over 50% (8.291 of 16.021 kgH2) of the demand could not be met. Therefore, both compressor mass flow and pressure end levels of compressors 1 and 2 as well as the storage capacity of the medium-pressure (MP) storage and the high-pressure (HP) storage have been adapted to find a (crude) estimate for the minimum mass flow and storage capacities. Table 2 gives an overview of the parameters studied for the simulation model.

One can see that even for mass flow capacities well above the maximum production capacity of the electrolysers (135 kg/h) and more than twice the storage capacity (option 9) the full demand cannot be met. After thorough analysis of the results, HyCentA concluded that this was not due to a lack of hardware but to the simple operating strategy implemented. These shortfalls could be met with an advanced operating strategy, though. The model based on the proposed infrastructure did not include a cascaded storage system, where the MP and HP storage system are split into sections with different minimum storage pressures. By doing so at least one section of the storage should have enough pressure to be able to meet the demanded pressure. Unfortunately, such an adaptation of the model could not be implemented before the premature end of the project. Also, a further optimization of the infrastructure components to find the minimum costs of the HRS could not be conducted anymore.

Table 2: Overview of parameter runs for the HRS simulations in HYDRA

Case#	p_{C1} [Bar]	Massflow$_{C1}$ [kg/h]	p_{C2} [Bar]	Massflow$_{C2}$ [kg/h]	HP-storage [kg]	MP-storage [kg]	Refuelled [kg]	Total demand [kg]	Shortfall quantity [kg]
Initial	900	27.5	450	52	380	666.5	7.730	16.021	8.291
Opt 1	940	27.5	550	52	380	666.5	7.730	16.021	8.291
Opt 2	940	37	550	100	380	666.5	12.030	16.021	3.991
Opt 3	940	50	550	100	380	666.5	13.320	16.021	2.701
Opt 4	940	37	550	125	380	666.5	14.000	16.021	2.021
Opt 5	940	50	550	125	380	666.5	14.160	16.021	1.861
Opt 6	940	37	550	100	600	1.000	13.305	16.021	2.716
Opt 7	940	50	550	125	600	1.000	14.800	16.021	1.221
Opt 8	940	37	550	100	1.000	1.500	13.678	16.021	2.343
Opt 9	940	50	550	125	1.000	1.500	15.622	16.021	399

5.7.2 Task 7.2 Key Technologies for innovative hydrogen infrastructures

The simulation of key technologies for innovative hydrogen infrastructures is based on the model under development in Task 7.1. Due to the controlled termination of the project, the simulation of new technologies such as electrochemical hydrogen compressors or PEM electrolysers with operating temperatures > 100 °C could not be implemented.

5.7.3 Task 7.3 TCO analysis

In the project, the comparison of zero-emission concepts for buses on the bases of the total cost of ownership should support decision-makers. Overall, in total 13 scenarios, separated with and without the Austrian EBIN subsidy were simulated based on data from consortium experts, bus-concept tests, optimized routes, literature and key parameters of the compared Diesel-buses (ICE), Battery-electric buses (BE) and fuel cell buses (FC).

The different TCO scenarios show that, without taking into account the Austrian EBIN subsidy, ICE- buses are the most cost-effective solution if diesel, electricity and hydrogen prices remain constant. However, this is mainly a competition between ICE- and BE-buses, as hydrogen is always more expensive. Only if diesel prices increase with annual inflation in a further scenario, the BE-bus become more cost-effective over the 10-year lifetime considered in 2040. In addition, FC-buses face individual cost challenges compared to BE-buses.

Looking at the different TCO scenarios including the Austrian EBIN subsidy, BE-buses are the most cost-effective solution in all years considered from 2025 to 2050, if diesel, electricity and hydrogen prices remain constant. Only if electricity costs are at a very high level in 2025, there will be a small cost advantage for ICE-buses. In the other scenarios considered, if the cost of hydrogen falls by 2050 and the consumption of the FC-bus is also significantly reduced, ICE-buses can be cheaper than BE-buses as early as 2030, but BE-buses are still the most cost-effective solution. In addition, the use of HVOs instead of diesel in ICE buses means that BE-buses are the most cost-effective solution from 2030 onwards, especially in the scenario without EBIN subsidy. However, an alternative scenario, which assumes that the investment costs of BE- and FC-buses are at the level of ICE-buses in 2040 and 2050 due to economies of scale, shows an advantage over ICE buses from 2040 onwards.
In summary, from today's perspective, BE-buses are the most cost-effective solution. However, it should be noted that this is a purely cost perspective and technical characteristics and infrastructure requirements are outside the system boundary of this analysis.

5.7.4 Task 7.4 Evaluation of business cases

An extensive literature review was carried out, covering the recent technoeconomic analysis and studies of FCE H2 heavy-duty vehicles. Business cases from similar ongoing or finalised projects at the European level were researched and used for the comparative studies. Due to the lack of available data from Task 7.1 regarding the TCO assessment of H2 infrastructure, the representative evaluation of business cases was based on the results of Task 7.3 and accepted proposals from previous FFG calls, EBIN and ENIN, which funded the conversion of bus and heavy-duty vehicle fleets to zero emission transports. In addition to the economic analysis of the HRS infrastructure costs, public transport and industrial freight forwarders, framework conditions and regulatory landscape was researched with the aim to propose guidelines and recommendations for a successful implementation of the FCE heavy-duty mobility business cases in Austria.
Main legal barriers and missing framework conditions for the implementation of FCE H2 trucks and buses were identified within the infrastructure, safety & storage and financial incentives:

- **H2 Infrastructure Regulations**
    - Lack of explicit national legislation for HRS, relying instead on general rules for conventional refuelling stations.[42]
    - Lack of binding HRS targets for heavy-duty vehicles, despite EU directives requiring hydrogen stations every 200 km along core transport corridors by 2030[43] . As of 2021, Austria had only seven HRS, with five publicly accessible[43]. Current Austrian H2 regulations focus on stationary HRS but lack heavy-duty vehicle specific mandates.[44]

[42] *https://multhyfuel.eu/images/event-documents/deliverables/MHYF_WP1_D12_Permitting_requirements_and_risk_assessment_methodologies_20210930_03.pdf*
[43] *https://iea-amf.org/app/webroot/files/file/Country_Task_Reports_2021_pdf/3b_Austria_2021_final.pdf?utm_source=chatgpt.com*
[44] *https://www.gasconnect.at/en/recent/news/energy-future-the-hydrogen-regulatory-framework-is-growing*

  - Permits for HRS involve multiple authorities, including local municipalities and safety regulators, but these authorities often lack experience with hydrogen-specific safety issues. This leads to subjective decision-making and inconsistent requirements across projects.[42]
  - Technical norms, such as ÖNORM EN 17127:2020 for outdoor hydrogen refuelling points, exist but are not legally binding, leaving operators without clear guidance.[42]
  - No standardised framework for mobile HRS needed at construction sites or industrial zones. While guidelines for mobile HRS were planned for early 2025, implementation status remains unclear to date.[44]
- **Technical Standardisation**
  - No binding specifications for onboard hydrogen storage systems in heavy-duty vehicles, despite identified needs for standardised solutions to accelerate commercialisation.[45]
- **Safety and Storage Challenges**[42]
  - Austria lacks standardized safety measures for hydrogen storage at refuelling stations, especially for large quantities exceeding 5 tonnes, which are subject to EU SEVESO Directive requirements but lack detailed national implementation guidelines.
  - Risk assessment methodologies are inconsistent, further complicating compliance during station construction and operation.
- **Financial Incentives**
  - EU frameworks allow up to 100 % CAPEX coverage for HRS via bidding processes[46], but Austrian implementation details are pending.
  - Missing fiscal incentives for renewable hydrogen in transport beyond 2035, as required by revised EU Energy Taxation Directive provisions.[43]
  - Administrative hurdles include lengthy approval timelines due to the absence of streamlined procedures for hydrogen-related projects.[45]

5.7.5 Task 7.5 Macroeconomic dimensions of ZEMoS

The task explored and quantified the macroeconomic implications of transitioning public transport diesel bus fleets to battery-electric (BE) and hydrogen fuel cell (FC) buses in the short- and mid-term. A key tool for this assessment was the macro-econometric simulation model MOVE2. It enabled a multi-sectoral analysis of the economic impacts. The results of the simulations undertaken for ZEMoS indicate positive effects on the overall economy, attributed to several factors: investment impulses, a reduction in diesel imports, and multiplier effects (leading to higher GDP, increased investment activities, and rising employment rates).

An economic benefit is attributed to investment impulses generated by the fleet conversion. These investments have been shown to stimulate economic activity, particularly in vehicle manufacturing,

[45] *https://www.rolandberger.com/publications/publication_pdf/roland_berger_fuel_cells_hydrogen_trucks.pdf*

[46] *https://hydrogeneurope.eu/wp-content/uploads/2024/11/2024.11_H2_Paper_FundingforH2mobility.pdf*

charging and hydrogen infrastructure, and energy production. Moreover, public transport operators stand to benefit financially from the transition due to lower CO_2 pricing and reduced fuel-related taxation, leading to cost savings. A further key impact is the improvement of the trade balance through the substitution of diesel imports with locally produced electricity and hydrogen. This substitution reduces capital outflows to fossil fuel exporters. In addition to the direct economic advantages, the transition process gives rise to a number of employment-related consequences. These effects can be categorised as either indirect or induced. The indirect effects are characterised by the strengthening of regional value chains, giving rise to infrastructure development and energy production, for instance. In contrast, the induced effects are driven by an increased demand for skilled labour within the domains of electric mobility and hydrogen technology.

Sensitivity analyses underscored the pivotal role of the CO_2 price in this transition: (i) Higher CO_2 pricing increases the cost of diesel, making zero-emission technologies more competitive. (ii) Conversely, a reduction in CO_2 costs has the potential to negate the economic advantage previously held by BE and FC buses.

Hence, the transition to a zero-emission bus fleets has been shown to significantly contribute to economic value creation by stimulating investment, reducing import dependencies, and strengthening regional economic cycles. Furthermore, it generates both economic and ecological benefits ("double dividend"), making it a sustainable strategy for economic growth and climate policy goals.

5.7.6 Task 7.6 Socio-economic and – technical dimensions of ZEMoS

The originally planned survey of the population, tourists and users had to be cancelled due to time constraints, as it was planned for 2025, but the project is now being ended prematurely. Part of the survey was started early and deals with a targeted survey for bus drivers, some of whom already have experience with hydrogen and electric buses. This survey was carefully tailored to the research objectives of the project and disseminated via the respective bus operator, who organised the distribution to the drivers.

To ensure that the socio-economic analysis is consistent with the evolving project context, the methodology has been optimized accordingly. The six PESTLE dimensions (political, economic, social, technical, legal and environmental factors) were included in a newly structured questionnaire that was distributed to the project consortium. This approach aims to systematically identify the main barriers faced during the project and derive recommendations for action for future zero-emission mobility initiatives. An important aspect here is to reach the stakeholders of the project by distributing the survey among the consortium and to involve their expertise.

The surveys of bus drivers and the project consortium revealed the main obstacles to the introduction of hydrogen and electric buses. From the bus drivers' perspective, comfort and noise levels were seen as advantages of electric buses, while hydrogen buses were rated lower in terms of user-friendliness and reliability. Concerns were raised about range, refuelling times and operational efficiency, with diesel and HVO buses still seen as the most reliable options.

The consortium's survey, which was guided by the PESTLE dimensions, identified technological immaturity, high costs, regulatory uncertainties and lack of infrastructure as the main barriers. Hydrogen vehicles were still considered prototypes, making investment decisions risky, while financial constraints, inflation and lack of subsidies further hampered the feasibility of the project. Political support and regulatory clarity were considered insufficient, and the lack of a solid business model limited the willingness to invest.

The lack of hydrogen refuelling infrastructure was a key barrier that directly impacted fleet procurement decisions.
Both surveys emphasize that while there is general support for zero-emission technologies, economic feasibility, willingness to use the infrastructure and operational reliability must be considered for successful implementation.

5.7.7 Task 7.7 Comprehensive scientific monitoring of Key Performance Indicators of ZEMoS

The project progress and its contribution to the energy model region WIVA P&G was annually monitored by the Cluster Coordinator. The first regular scientific monitoring (RSM) of the Key Performance Indicators (KPIs) took place in June 2024 and the second and last one with the end of the project in March 2025.

The project has achieved some of the targeted values. It should be emphasised that great importance was attached to networking, cooperation training and dissemination of information. Despite the short duration of the programme, the target values were exceeded in these areas. Nevertheless, it must be taken into account that based on the short runtime of the project, several KPIs could not be achieved.

5.8 WP8: Dissemination, Publication and Exploitation

5.8.1 Task 8.1 Preparation and implementation of a Dissemination, Communication and Awareness Plan

The dissemination, communication and awareness plan (DCAP) prepared by FENR and WIVA in the first reporting period was used as a guideline for the dissemination activities carried out in the second year of the project by all project partners. These activities were regularly documented, and their results were further communicated to the WIVA P&G network. The LinkedIn of WIVA P&G and Green Energy Center Europe further promoted the joint activities results at the social media level.

5.8.2 Task 8.2 Use of dissemination tools

As part of the FCE H2 demo bus operation, a project video was created and published on the WIVA P&G website, introducing the ZEMoS project. Additionally, a second video was produced for Salzburg AG TV and made available online to reach a broader audience in the province of Salzburg. This video can also be seen on the Salzburg AG YouTube Channel[47]. During an internal S-AG operation trip with the H2 bus to Gaisberg, interested individuals were introduced to the H2 drive technology and had their questions were answered directly by the project team.
At the end of the FCE H2 demo bus operation, an information event was organised. The aim of the ZEMoS event was to assess the market availability of FCE H2 and BE vehicles and to present the technological maturity of both drive types.

5.8.3 Task 8.3 Workshops, Trainings and Stakeholders Alignment

Several workshops and stakeholder alignment events took place, among which a bilateral workshop between FENR and SAG on hydrogen safety is noteworthy where the need for maintenance infrastructure

[47] *https://www.youtube.com/watch?v=3IxA7hKswBk*

for vehicles was updated. In the ZEMoS Information Event key stakeholders had the opportunity to exchange information and learnings regarding the current status of BE and FCE heavy-duty implementation in Austria. Furthermore, project status and outcome were communicated and discussed within the Green Energy Center Europe CODEX partnership annual event 2024 and WIVA P&G annual event 2024.

5.8.4 Task 8.4 Coordination and Dissemination of ZEMoS for the Energy Flagship Region

With its full integration into WIVA P&G's dissemination activities, the information sheet regarding ZEMoS was actively made available to the partners of the flagship regions WIVA P&G and associated projects. The project general concept was presented by the WIVA P&G team in several events within the context of green mobility and hydrogen technology. Project highlights and results were constantly disseminated via the WIVA P&G social media channel LinkedIn as well as the flagship region website and during national and international conferences/stakeholder events, site visits and publications.
Examples of relevant dissemination events by WIVA P6G during the reporting period are:

- WIVA P&G annual event, 1st of October 2024
- Linzer Wasserstoff Convention 26 to 28 Nov 2024

Moreover, project results and experiences were shared and further processed within the reporting period in the WIVA P&G working groups on “Industry cooperation and utilization of results”

5.8.5 Task 8.5 Publication and presentation strategy for national and international dissemination activities

The strategical plan for publication and presentation previously developed and proposed in the DCAP was used as guideline for project publications. Furthermore, research for journals and platforms for open access publication of project results continued in this reporting period.
The percentage-based Author Contribution Index (ACI) was previously employed for the preparation of the conference paper submitted to the 18th energy innovation symposium and will be considered as a basis for future project publications.

5.8.6 Task 8.6 Exploitation of results

The bus model developed in WP2 served as a decision-making aid for implementing zero-emission buses for SVG. The economic evaluations carried out in WP7 support SVG in transitioning to emission-free drives even after the project end.
The value of the bus driver survey for SVG lies in identifying problems, obstacles, and areas for improvement that can be considered in future tenders. The project results provide SVG with well-founded decision bases for future tenders, especially regarding the procurement of emission-free buses following the clean vehicles directive. The insights gained allow for forecasts that include market changes and help estimate potential cost developments over a ten-year contract period. Additionally, problem areas, obstacles, and potential improvements were identified, which can be considered in future tenders to make the use of emission-free drive technologies efficient.
During the concept development of a HRS infrastructure and the implementation of H2 heavy-duty and waste collection trucks, technological challenges and economic risks were identified. These valuable project findings were also communicated to the supporting FFG funding agencies (ENIN, EBIN).

Due to the hearing requirements which demanded the operation of one FCE H2 garbage truck, one FCE H2 truck, and one FCE H2 bus, an intensive market study on vehicle availability was conducted and economic calculations were performed. Consequently, technological challenges and economic risks were identified. These valuable project results were also communicated to the supporting FFG funding agencies (ENIN, EBIN).

6 Summary

The ZEMoS project has achieved significant milestones by uniting a consortium of energy and transport companies with scientific partners, which include prominent research organizations, geoinformatics expertise hubs, and institutes specializing in energy system conversion and hydrogen technologies. These collaborators utilized the project to advance research capabilities in alternative propulsion technologies for public transportation, conducting economic and socio-technical analyses of Fuel Cell Electric (FCE) and Battery Electric (BE) mobility.

Within the scope of the ZEMoS project, innovative concepts for hydrogen (FCE) and battery (BE) buses were developed, including tools to calculate energy consumption based on topography, mass, and speed data to optimize bus routes. Additionally, models and algorithms were created for managing multiple depots and mixed fleets of FCE and BE buses. In Salzburg, 21 BE buses are operational across 10 routes, and the tender for the remaining 6 BE buses has been published. Through the operation of 21 new electric buses during the project period up to February 28, 2025, a total of 584,449.74 commercial vehicle kilometers were traveled. This resulted in a total savings of 510 tons of CO2. Consumption and infrastructure analyses for heavy FCE vehicles were conducted alongside the development of refuelling and maintenance concepts for FCE garbage trucks and FCE trucks in both urban and alpine areas. A comprehensive plan for an electrolysis plant featuring integrated waste heat utilization and hydrogen filling stations at key traffic hubs in alignment with EU AFIR regulations was completed.

Scientific research and technological development indicated that BE buses currently represent the more cost-effective solution. Due to unforeseen challenges such as the Ukraine war, limited availability, and substantial price increases in hydrogen vehicles, the implementation of hydrogen infrastructure became economically unfeasible within the 3-year project period. Furthermore, sufficient funding for vehicles and infrastructure, such as electrolysers or refuelling stations, was not available

Although there are current challenges with vehicle availability and implementing a hydrogen infrastructure for the mobility sector, the ZEMoS project has made significant progress in developing and implementing zero-emission technologies in the region. The accomplishments and insights gained through the project provide a strong foundation for future advancements in this domain.

Despite the availability of funds from the two FFG calls, EBIN and ENIN, no FCE H2 buses or trucks have been purchased so far, as the end users (ZEMKA and SVG) are not able to cover the risks associated with the implementation of FCE H2 heavy-duty vehicles. The main challenges identified at the current stage of the project are in summary:

- TCO analysis showed that the high costs related to purchase, operation and required infrastructure of BE and FCE H2 vehicles is a main barrier in the competition with conventional fleets powered by internal combustion engine (ICE).
- Contribution margins are not covered by the funding programmes available. Existing incentives are not sufficient for neither building infrastructure nor operating zero emission vehicles.
- Neither the public transport sector, with its bus operators, nor the free market economy, with its industrial hauliers, has been sufficiently supported by adequate regulation and funding to reduce the financial risks for the parties involved.
- Poor product availability, market maturity and high costs due to the lack of alternatives were identified as the main drawbacks.

To conclude, business cases for buses and trucks currently favour established lead technologies such as diesel vehicles, which have well-defined CAPEX and OPEX, serving as reliable benchmarks. For alternative technologies such as FCE H2 buses to be viable, they must be cost-competitive with these standards. However, as reported above, FCE buses currently involve significantly higher CAPEX and OPEX, posing substantial financial risks for buyers (risks most companies cannot afford to take). Only entities with larger budgets or sufficient external support can absorb such uncertainties, often relying on third parties to mitigate technological and financial risks. A marginal premium (e.g. 10 % over the cost of diesel) might be achievable if the product is marketed effectively, but the failure of companies such as Quantron or Hyzon to secure large-scale truck purchases underlines the danger of premature adoption. In this context, ZEMKA's decision to avoid such high-risk investments seems prudent and ensures its financial stability in a market where unproven technologies can threaten a company's survival.
The main legal barriers and framework conditions, such as restrictive requirements for producing green hydrogen (RFNBO, RED III), have complicated the planned demonstration in the ZEMoS project. Furthermore, uncertainties regarding H2 infrastructure regulations and technical standardisation still persist. A national hydrogen strategy providing stronger legal certainty and a clearer roadmap for integration into the pan-European hydrogen economy, considering cross-border collaboration, is required to support initiatives such as ZEMoS in the near future.

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7.2 Figures

7.3 Tables

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