



DEVELOPMENT STRATEGY FOR HYDROGEN CENTER

IN CROSS-BORDER REGION INTERREG SLOVENIA AND AUSTRIA

FROM INNOVATION ENVIRONMENT TO INNOVATION ECOSYSTEM

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PROJECT TITLE: Strengthening crossborder R&I capacities in advanced hydrogen technologies by developing synergies between enterprises, R&D centres and higher education.

Project partners

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Ministry of Education, Science and Sport, Slovenia

Chamber of Commerce and Industry of Štajerska, Slovenia

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ABBREVIATIONS

AT	Austria
B2B	Business to Business
CO NOT	Centre of Excellence Low carbon technologies, Slovenia
EU	European Union
FCH JU	Fuel Cells and Hydrogen Joint Undertaking
kWh	Kikowatt hour
MWh	Megawatt hour
GWh	Gigawatt hour
TWh	Terawatt hour
H ₂	Hydrogen
JSI	Jožef Stefan Institute
KET	Key enabling technology
MORS	Ministry of Defence, Republic Slovenia
NECP	National Energy and Climate Plans
NGO	Non-Governmental Organisation
NIC	National institute of Chemistry, Slovenia
RCVT	Development Centre for Hydrogen Technologies, Slovenia
R&D	Research and development
RES	Renewable energy sources
SI	Slovenia
SME	Small and medium-sized enterprises
SGZ	Chamber of Commerce and Industry of Štajerska
TU Graz	Technical University of Graz
UL FS	University of Ljubljana, Faculty of Mechanical Engineering
UM FKKT	University of Maribor, Faculty of Chemistry and Chemistry Engineering
UNG	University of Nova Gorica

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1 Introduction

In order to strengthen cooperation and networking and to achieve the critical mass of capacity in hydrogen and hydrogen technologies, a sustainable regional research and industry network in the form of the HYDROGEN CENTER has been set up in the framework of the H2GreenTECH Interreg SI-AT project. The partners involved in the project H2GreenTECH from Slovenia and Austria (Carinthia, Styria and Burgenland) have been collaborating with the aim to strengthen regional cooperation and research and innovation in the field of hydrogen technologies through cross-border cooperation between companies, research and development (R&D) centres and higher education institutions.

Hydrogen Center's aim, as a One- Stop Shop and B2B platform, is to improve access to and use of hydrogen research infrastructure in Slovenia and Austria by cooperation between companies, researchers and students and lecturers.

As global energy consumption continues to increase, there is an urgent need to develop and introduce new alternatives to fossil fuels. Expected growth in greenhouse gas emissions and strong dependence on fossil energy sources are strong reasons for switching to new alternatives and encouraging industrial players to invest in various new technologies. In this context, hydrogen is enjoying a renewed and rapidly growing attention in Europe and around the world. Hydrogen can be used as a feedstock, a fuel or an energy carrier and storage, and has many possible applications across industry, transport, power and buildings sectors [4], [5]. Most importantly, it does not emit CO₂ and almost no air pollution when used. It thus offers a solution to decarbonise industrial processes and economic sectors where reducing carbon emissions is both urgent and hard to achieve.

2 Regional hydrogen center and development strategy 2025

The Hydrogen Center Development Strategy up to 2025 and beyond is crucial for the functioning of the members of the regional Hydrogen Center network as a sustainable outcome of the H2GreenTECH project in the cross-border area Interreg Slovenia-Austria. The development strategy aims at strengthening regional innovation capacities, promoting networking and cooperation in R&D and transfer of green and clean technologies in the economy. In this way, the Hydrogen Center will contribute to increased cross-border competitiveness and the development of innovative services and products from dynamic companies in the field of green hydrogen and hydrogen technologies.

Hydrogen (H₂) and fuel cell technologies are Key Enabling Technologies (KETs) for a competitive low carbon society and at the same time for a low carbon region. These technologies directly address the societal challenges identified in the EU 2020 Strategy, EU Green Deal, and EU Hydrogen strategy.

According to the data available so far, the greatest potential for innovation is found in SMEs while a production of innovated products suits to large companies. It is therefore the priority task of the members of the Hydrogen Center to encourage more innovation from the small and medium-sized enterprises (SMEs) that dominate in the cross-border area.

These are the new challenges for the regional network of the Hydrogen Center and its members to jointly examine their development orientations, implementation, monitoring and evaluation of innovation policy and innovation in the region in the field of green hydrogen and hydrogen technologies.

The presented Hydrogen Center's development strategy takes into account hydrogen related documents (the starting points of the Roadmap for Hydrogen Technologies in Slovenia and Austria [1], as well as the NECP of Slovenia [2] and the NECP of Austria [3]). For Austria, we have also considered the new Hydrogen Strategy adopted in June 2022 (Slovenia does not yet have a strategy, as well as other additional documents relevant for the R&D, production and use of green hydrogen and hydrogen technologies).

2.1 Regional framework for hydrogen technologies

The Slovenian-Austrian cross-border region has established a strong R&D activity and economy, but the development of hydrogen and hydrogen technologies is more or less at an early stage.

The H2GreenTECH Roadmap for Hydrogen Technologies in Slovenia and Austria presents the views of a wide range of stakeholders from both governments and industry, as well as NGOs and academia, on cross-border cooperation in the development of hydrogen technology by 2025 and beyond.

The members of the Hydrogen Center are aware that research and development and the transfer of hydrogen technologies to the economic sector are a key importance in the cross-border region, especially in terms of innovation and increased competitiveness, and to contribute to a low-carbon society.

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2.2 Scaling up and approach to innovation

The Slovenian-Austrian cross-border region can become one of the leaders with innovative achievements in the development of hydrogen technologies and green hydrogen production. Therefore, the cross-border network of the Hydrogen Center as a 'One-Stop Shop' and B2B platform aims at intensive networking and fostering project cooperation and the search for common innovative solutions.

The Center's work will focus on technological innovation in the context of regional innovation policies, as well as on opportunities for social innovation. On the basis of membership, the Hydrogen Center will perform on a quadruple helix model.

3 Hydrogen role

Hydrogen is a promising energy vector/carrier, but today's production method (mostly steam reforming of natural gas) is not in line with long-term climate and energy goals. Hydrogen produced by water electrolysis driven by electricity from renewable sources (photovoltaics, wind farms, hydropower) has an added value, because its production is CO₂-emission free, and, consequently, it can be referred to as “green hydrogen” [6]. So, it could make a key contribution to reducing CO₂ emissions, reducing local pollution, ensuring energy independence and helping to achieve sustainable goals, as shown on Figure 1.

The role of hydrogen in the local energy transition

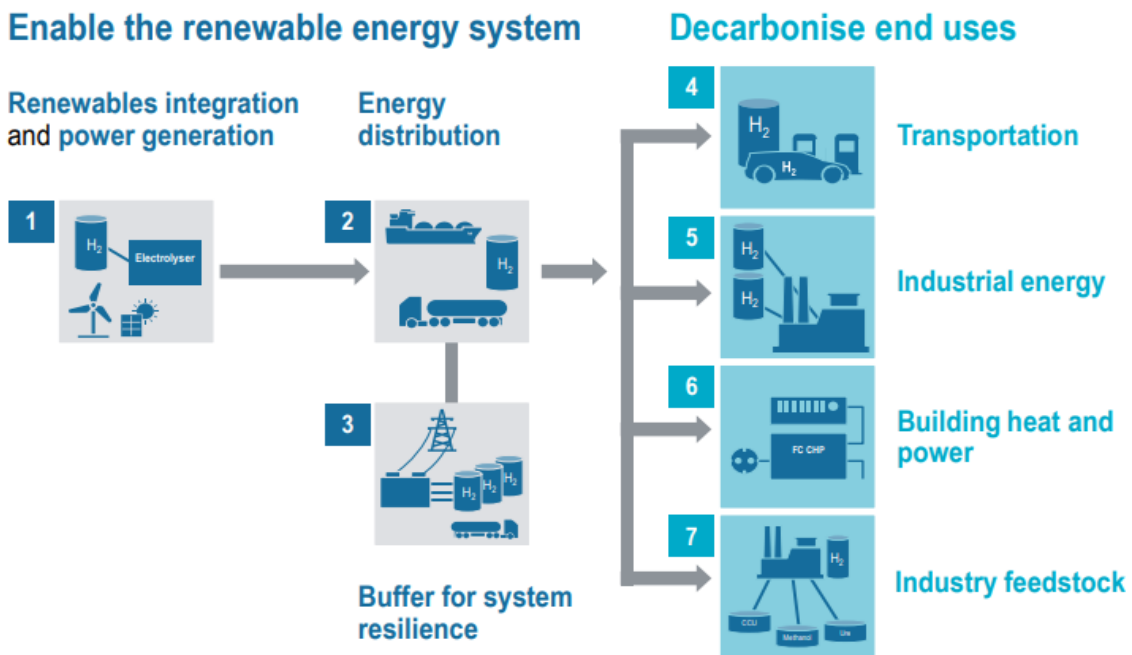


Figure 1: Potentials for the introduction of hydrogen technologies [4]

Over the past few years, several EU countries (Portugal, Spain, Germany, Netherlands, Norway, Hungary, France) and others (Japan, China, USA, GB, etc.) have adopted their hydrogen strategy and already implemented policies increasing the role of hydrogen in various applications. These and other drivers will increase worldwide demand for hydrogen from around 80 million tons per year in 2020 to over 183 million tons per year in 2050, as shown in Figure 2.

Today, EU's a total annual hydrogen production is around 8 million tonnes of H₂, where EU industry accounts for more than 90% of the market share of hydrogen. The main industrial consumers are:

- 63% chemical industry,
- 30% of the refinery,
- 6% metal processing,

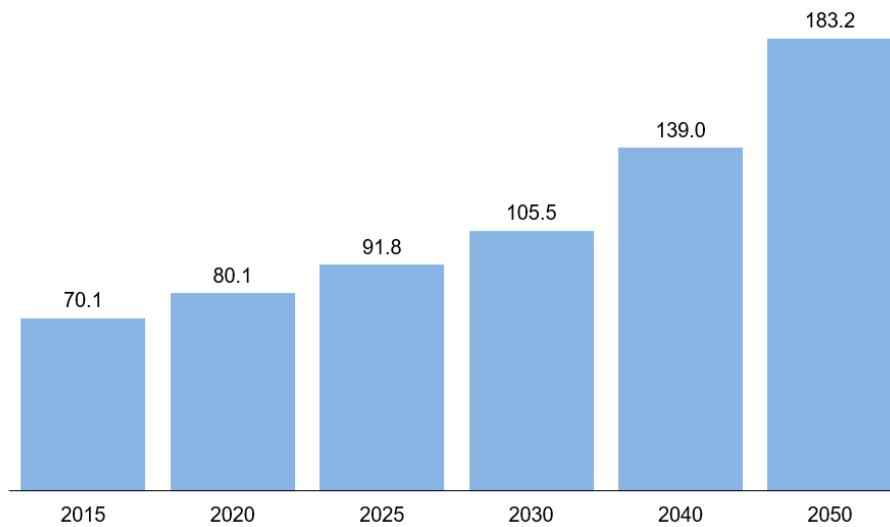


Figure 2: Outlook for world hydrogen demand in million tons per year [7]

However, the introduction of hydrogen as an energy vector is not only a technological challenge, but also requires the coordination and convergence of the goals of many political and socio-economic factors. Political will, improved regulation and appropriate financial support are the instruments that will be needed to promote the use of green hydrogen. Green hydrogen has many benefits, but policy initiatives are also needed to help reduce production costs and remove market barriers.

The systematic initiatives needed are mainly those that:

- reduce local emissions;
- reduce global greenhouse gas emissions;
- increase energy security through the use of local sources and alternative energy sources
- develop new technological areas and thus new jobs.

In addition to political decisions, the ability of the industry to reduce the cost of manufacturing and using the building blocks of hydrogen technologies will be extremely important for the future of the hydrogen economy, as is the condition for mass production of the necessary equipment.

Finally, a brief SWOT analysis of hydrogen technologies is given below:

STRENGTHS (S)

- Practically unlimited reserves of (bound) hydrogen in nature (see also weaknesses below)
- Great development potential of new technologies
- Great effects in preserving the environment, especially decarbonization
- Reducing dependence on traditional energy suppliers
- Hydrogen is a suitable fuel for all types of vehicles

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- Hydrogen storage options for different purposes
- The storage of energy obtained from renewable sources allows for greater flexibility of use
- Flexibility of the method of hydrogen distribution and storage
- Maintaining the existing way of refuelling and consumer habits

WEAKNESSES (W)

- To generate elementary hydrogen, energy input is demanded
- Relatively high investment costs
- Lack of maturity of key technologies
- Deficient or incomplete infrastructure for hydrogen storage, transport and distribution
- Low efficiency of the hydrogen supply chain
- Prior investment in infrastructure is needed
- Lack of experienced workforce

OPPORTUNITIES (O)

- Reducing dependence on fossil fuels
- Possibility of obtaining state subsidies
- Social acceptability for the transition to a low-carbon environment
- Possibility of in-depth cooperation between the energy, industry and transport sectors
- Leading energy storage technologies
- Establish uniform international standards for hydrogen technologies
- Reduction of emissions and other negative impacts on the environment
- Possibility of hydrogen production on a large scale
- Decentralization of hydrogen production, storage and transport

THREATS (T)

- Deficit in the volume of necessary investment funds
- Compete with other ways of obtaining and storing renewable energy
- Unconfirmed/unknown market potential
- Attachment to selected equipment supplier/manufacturer
- Lack of key equipment suppliers.

4 Overview of research and development activities and demonstration projects

Project title	Duration	Project partners	Project description	Financing
International R&I projects				
Monitoring the degradation of high-temperature electrolyzers in order to increase the service lifetime	2018-20	JSI	Estimation of SOFC electrolyzers service lifetime	Bilateral project SLO-CEA 2018-2020
Development of an Innovative Auxiliary Power UNIT for military purposes based on high temperature PEM fuel cell and reforming technology for military logistic fuels – IAPUNIT	2019-20	JSI NIC TU Graz	Development of an Innovative Auxiliary Power UNIT for military purposes	Project EDA- European Defence Agency
Advanced electrochemical characterization of the intrinsic properties and the improvement of the state-of-the-art Non-CRM oxygen reduction reaction electrocatalysts with SECM and floating electrode	2019-21	NIC	The project proposes the synthesis of new affordable, efficient and stable catalysts based on functionalized nano-carbon materials for use in low-temperature fuel cell cathodes.	ARRS: NC-0006

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Highly active cathode with ultra-low PGM content and MEA integration for synthesis into a single PEMFC cell	2019-21	NIC	Research on the implementation of new more active electrocatalysts into the membrane-electrode assembly (MEA) application for technology commercialization	ARRS-CEA NC-0007
Condition monitoring and life estimation of solid oxide fuel cells and electrolyzers	2018-19		Development of condition monitoring algorithms for SOFC fuel cells	Bilateral project BI-AT/18-19-010
Optimization of fuel cell catalysts in integration with reforming	2020 – 2024	NIC	Development of an integrated fuel cell prototype based on highly efficient platinum-based electrocatalysts and non-platinum electrocatalysts on graphene-based supports.	NATO SPS Programme
Towards nanostructured electrocatalysts with superior stability	2020-24	NIC	The project explores how the atomic structure of electrocatalyst nanoparticles changes when operation is performed in low-temperature fuel cells and electrolyzers.	ERC-STG - Starting Grant
Performance-recovery strategy & advanced control for efficient fuel cell operation	2018-21	TU Graz	The project is on the development of durable PEM fuel cells and has the following defined goals: to identify low-damage processes for start-up and shutdown and to develop new control procedures for high dynamic PEM fuel cell operation	BMK Mobilität der Zukunft

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FC-Core	2021-22	TU Graz	The FC-Core project has been designed to develop, patent and publish prototypes for the core of the fuel cell system.	Zukunftsfonds Steiermark
Graphene oxide based MEAs for the direct ethanol fuel cell	2019-21	TU Graz UL UM	Development of a new anode and cathode catalysts containing non-noble metals and new anion exchange membranes based on sustainable and economical materials for use in the direct alkaline ethanol fuel cell.	FWF
Precious metal free electrocatalysts for regenerative alkaline fuel cells	2019-20	TU Graz	The project's aim is to synthesize and characterize cost-effective materials that support hydrogen evolution (HER) and oxygen reduction (ORR) reactions in two devices: the fuel cell and the single electrolyzer.	#
FluMaBack - Fluid Management Improvement Component for Back Up Fuel Cell Systems	2012 - 15	JSI	Development and improvement of various BoP components for PEM fuel cells	FW7
DIAMOND - Diagnosis-aided Control for SOFC Power System	2014 – 17	JSI	Use of Electrochemical Impedance Spectroscopy for the assesment of remaining life of SOFC system	FW7

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MEAPower - Resource-saving composite materials for long-term stable stationary PEM fuel cells with increased power density	2015-18	TU Graz AVL UL FS	In the project, a low-cost membrane electrode assembly - MEA (<€ 0.60 / cm ²) was developed and manufactured on a laboratory scale, which enables an estimated service life of 80,000 hours under real operating conditions.	BMK Klima- und Energiefonds
SOH4PEM - State-of-health observers for PEM fuel cells	2016-19	TU Graz UL FS	Development of a device for assessing the current technical condition of automotive fuel cells	BMK Klima- und Energiefonds
INSIGHT - Implementation of monitoring diagnostic tools using signal analysis to increase their life Time in real SOFC systems	2017 – 19	JSI	Development of diagnostic tool for predicting life time of SOFC systems	FW7
MEMPHYS - Membrane based purification of Hydrogen system	2017 – 19	JSI	Development of electrochemical compression unit (up to 1000 Bars)	Horizon 2020
RUBY - Robust and reliable general management tool for performance and dUraBility improvement of fuel cell stationary units	2020 – 23	JSI	Estimation of durability of fuel cell stationary units	Horizon 2020

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REACTT – RELIABLE Advanced Diagnostics and Control Tools for increased lifetime of solid oxide cell Technology	2021 -23	JSI AVL	REACTT is about the development of an HW platform for optimal control, condition monitoring and estimation of the remaining useful life for solid oxide electrolysis (SOE) and reverse solid oxide cell (rSOC) systems	Horizon 2020
SOFC5-60 -High efficiency 5-kWe1 SOFC CHP development to flexibly meet the electricity and heat demand in buildings and small industries	2017-21	Forschung Burgenland	The economic viability of a 5-kWe1 SOFC CHP (Solid Oxide Fuel Cell Combined Heat and Power) system for residential and non-residential applications is evaluated	#
Fully integrated reversible solid oxide cell system	2019-21	Forschung Burgenland	Development of a reversible solid oxide cell system (rSOC)	#
Chemical Looping for efficient biomass utilization	2020-24	TU Graz NIC	Investigation of chemical looping technologies with regard to bioenergy carbon capture and storage (BECCS). The aim is to derive promising technologies for the decentralized production of renewable heat, electricity and hydrogen from biomass with negative CO ₂ emissions	BMK COMET-Module
Best4Hy - SustainABIE SoluTions FOR recycling of end of life Hydrogen technologies	2021-23	UL FS	Development, upgrading and evaluation of recycling processes for critical materials, rare earth elements and cobalt and nickel as two important materials in the production of hydrogen technologies	Horizon 2020

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eGHOST - Establishing Eco-design Guidelines for Hydrogen Systems and Technologies	2021-23	UL FS	The project deals with the ecological (re)design of technologies for the production of hydrogen technology equipment. The main part of the project will focus on eco-design, including the remaining two pillars of sustainable development - social and economic.	Horizon 2020
MORELife - Material, Operating strategy and Reliability optimisation for LIFETIME improvements in heavy duty trucks	2021-24	AVL Mebius UL FS	Development of an innovative methodology for determining and identifying degradation mechanisms based on experimental data obtained from actual use, which will enable the improvement of old and development of new more specific accelerated stress tests (AST) for assessment and development of advanced degradation models	Horizon 2020
ELUVAT - Development of an innovative Electric Light Utility Vehicle All-Terrain for defence purposes based on in-wheel electro motors	2022-23	GDELS-Mowag AVL List AVL Schrick AVL SLO ELAPHE UL FS	The project will virtually explore various electrified vehicle propulsion systems (hybrid electric propulsion system, battery electric propulsion and hybrid fuel cell propulsion system)	#

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H2GreenTECH	2020-2022	NIC TU Graz Chamber of Commerce and Industry of Štajerska FH Kärnten Forschung Burgenland	Strengthen crossborder R&I capacities in ADVANCED HYDROGEN TECHNOLOGIES by developing synergies between enterprises, R&D centres and higher education.	Interreg V SI-AT
National R&I projects				
SOFC4City -Solid oxide fuel cell use of waste heat for buildings and industry	2015-16	Forschung Burgenland Austrian Energy Agency Vaillant	Testing of the application of a SOFC for energy supply (heat and power) in urban areas.	#
State-of-health prognostics of electrochemical energy systems	2016-19	JSI	Design of the method for condition monitoring of electrochemical energy systems	Slovenian Research Agency, Cofinancing: Domel d.o.o.
Bridging the gap between model and real electrocatalysts	2018-20	NIC JSI	The main goal of the proposed basic research project is to develop a transition metal-based catalyst that contains active centres appropriate for the direct conversion of CO ₂ and H ₂ to methanol	Slovenian Research Agency: Z1-9165
Optimization based control of P2G converter connected to hydro power plant	2019-22	JSI	Use of a P2G system for hydrogen generation in a hydropower plant	Slovenian Research Agency, Cofinancing: HESS d.o.o.

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Development and demonstration of key technologies for low-cost electric vehicle platforms	2017-20	TU Graz	In the KEYTECH4EV project, industrial several automotive polymer electrolyte fuel cells were investigated to identify the most feasible cell configuration and to forecast their lifetimes under realistic conditions	BMK Klima- und Energiefonds
RESHUB - Support for Sustainable energy and mobility in the Slovenian defence sector	2021-22	MORS UL FS	The project focuses on the support and supply of Slovenian military facilities with sustainable resources for mobility. The aim is to analyze the energy needs in military facilities and the possibility of self-sufficiency with electricity and hydrogen as a fuel.	Under preparation
Industrial contractual projects				
TESTLAB – Laboratory for hydrogen technologies	2014-16	JSI	The container laboratory for demonstration and validation of hydrogen technologies. It consists of 1kW PEM fuel cells stack, various types of H ₂ storages, electrolyzer, solar cells, electrical and thermal converters or storages.	Ministry of Defence, Slovenia
Feasibility study on P2G system installation in HE Brežice hydropower plant	2020	JSI	Cogeneration of electricity and hydrogen in a Hydropower plant and an estimation of financial effects	Contract: HESS d.o.o, U4-KE-E2-48/19

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Selection of energy storage devices providing flexibility in the operation of Drava river power plants	2019		Feasibility study on energy storage devices providing flexibility in the operation of Drava river power plants	Dravske elektrarne d.o.o., Maribor
Determining the required power and storage capacity to provide reserve for automatic frequency restoration within HSE d.o.o.	2019		Evaluation of required power and storage capacity to provide reserve for automatic frequency restoration	Dravske elektrarne Maribor d.o.o.
Unified methodology for evaluating solutions in an advanced distribution system	2020		Recommendations for evaluating solutions in an advanced distribution system;	National distribution system operator SODO
Introducing energy flexibility market in Slovenia: state of the art analysis and starting points	2020		State-of-the art analysis recommendations for introduction of energy flexibility market in Slovenia	Energy Agency of Republic of Slovenia
Demonstration projects				
HyMIV – Auxiliary PEM fuel cell based system for a special purpose military vehicle	2010	JSI	7 kW PEM fuel cell based electric generator was installed as an auxiliary power source for electronic equipment installed in a military vehicle	Ministry of Defence, Slovenia
30 KW PEM FC APU	2014	Genera	Installation of 30 KW Uninterrupted Power Supply based on PEM FC in a military facility	Ministry of Defence, Slovenia

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Installation of the 1st hydrogen filling station	2013	CONOT	The first hydrogen filling station was installed in Lesce, Bled, Slovenia	Petrol d.d., CONOT
GCCOGEN" - Demonstration prototype of a fuel cell based cogeneration system	2014-16	JSI	Installation of 8 KW PEM fuel cell system for electricity and hot water supply in a mobile military dwelling container	Ministry of Defence, Slovenia
SustainHuts - Sustainable Mountain Huts in Europe	2016-21	RCV UL FS	Energy modernization of nine mountain huts from four European countries (Spain, Italy, Romania and Slovenia) in order to reduce harmful emissions	LIFE Programme
Optimization of energy conversion to reduce the share of fossil fuels with hydrogen in industrial glass melting	2017-20	NIC	In this project, we developed, installed and demonstrated a new, innovative hydrogen-based technological solution for glass smelting, whereby we reduced carbon emissions per unit of glass produced using clean, low-carbon gas hydrogen.	#
Installation of the 2nd hydrogen filling station	2021	Ecubes technologies Salonit Anhovo	The second hydrogen filling station was installed in Anhovo, Slovenia	#
On-site use of biogas for decentralized hydrogen production	2020-21	TU Graz	The project demonstrates and techno-economic validate the potential of using fixed-bed chemical looping systems to produce hydrogen from biogas	#



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<p>SENERGY NETS - Increase the Synergy among different ENERGY NETWORKS</p>	<p>2022-26</p>	<p>Energetika Ljubljana UL FS</p>	<p>Demonstration of the technical and economic capacity of multi-energy systems for decarbonisation of the heating / cooling, energy and gas sectors using local renewable energy sources</p>	<p>#</p>
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5 Education activities related to Hydrogen Technologies

Slovenian higher education institutions are currently conducting a series of courses on all three cycles of study programme that are related to the development and use of hydrogen technologies.

Faculty	Course
Faculty of Electrical Engineering, University of Ljubljana	Energy and Environment
	Alternative Sources of Electricity and Energy Markets
	Sustainable Electricity Supply
	Energy
Faculty of Mechanical Engineering, University of Ljubljana	Energy and Environment
	Energy Machines and Devices
	Sustainable sources of electric energy
	Electromobility
	Energy in Circular Economy
Faculty of Chemistry and Chemical Technology, University of Ljubljana	Chemistry for Sustainable Development
	Electrochemistry
	Applied Electrochemistry
Jožef Stefan International Postgraduate School, Ljubljana	Fuel Cells
	Renewable Energy Sources
Faculty of Electrical Engineering and Computer Science, University of Maribor	Energy Conversion
	Energy Conversion and Electricity Networks
Faculty of Chemistry and Chemical Engineering, University of Maribor	Energy Management
Faculty of Mechanical Engineering, University of Maribor	Fuels for Sustainable Development
School of Environmental Sciences, University of Nova Gorica	Functional Materials
	Advanced Functional Materials
ECUBES TEHNOLOGIJE d.o.o. Faculty of Logistic, University of Maribor	H2STUDENT

Austria's partners/universities involved in the project also conduct various educational programmes and courses on all three cycles of study programme that are related to the development and use of hydrogen technologies

Faculty	Course
University of Applied Sciences Burgenland	Building Technology and Management
	Sustainable Energy Systems
	Energy and Environmental Management
	Fuel Cell Laboratory
Graz University of Technology	Advanced Studies of Polymer Electrolyte Fuel Cells
	Energy Storage and Conversion
	Hydrogen Production and Storage
	Fuel Cells and Energy Storage
	Project Laboratory Renewable Resources
	Laboratory Course Technical Chemistry
Carinthia University of Applied Sciences	Inspiring and preparing the next generation for green energy – an educational concept

More information on H2GreenTech partners' educational offers (Courses, Lectures, Laboratory Courses, Workshops, Summer Schools, other Events) can be found in the document [10].

6 Demands for green hydrogen

Even before the idea of using hydrogen for energy storage and transfer, hydrogen was used and is still used for various industrial purposes, as a raw material embedded in produced materials and products and as a means for various material processing methods. In majority of cases “grey” hydrogen is used, produced by steam reforming of natural gas, which generates CO₂ emissions. Fields of existing usage of hydrogen are shown in the table and can be found in both, Austria and Slovenia:

Table 1: Current hydrogen use

Industry field	Purpose
Chemical industry	Feedstock for the production of ammonia, hydrogen peroxide, fertilizers and more
Electronic industry	Anelng, tempering, lithography, epitaxy or thin film deposition, incorporation into materials of electronic elements
Petrochemical industry	Removal of sulfur compounds from hydrocarbons in the production of petroleum products
Steel industry	Refrigerant or agent with high thermal conductivity or protective atmosphere
Electric energy generation	Cooling of turbine generators

Green hydrogen can therefore replace grey hydrogen for the application areas of the table above. The use of hydrogen for energy purposes greatly expands the possibilities for the use of green hydrogen, as follows from the table below.

Table 2: Future hydrogen use

Energy storage and transfer	<p>Conversion and storage of electricity into hydrogen, whereby hydrogen is generated by electrolysis of water, driven by green electricity. Stored hydrogen can later be used in different ways:</p> <ul style="list-style-type: none"> • fuel for heat production (in the past it was rarely used for heating due to the high price per kWh compared to natural gas before the crisis situation) • fuel for transport or mobility (for vehicles and devices powered by fuel cells, such as forklifts, small vans, buses, the first examples of passenger cars) • conversion back into electricity • industrial use according to the table above
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Current hydrogen use

Austria and Slovenia currently produce 140.000 and 2400 tons of hydrogen per year, respectively. In both countries, almost the entire amounts are produced by the steam reforming of natural gas. As explained, this type of hydrogen production generates CO₂ emissions originating from natural gas, which is used as a feedstock in the reforming process and as an energy source for generation of heat required by the process. Due to CO₂ emissions, the hydrogen produced by the reforming process is called "grey hydrogen".

In Slovenia about 1200 tons (48 GWh) of hydrogen per year are used for the production of hydrogen peroxide. Uncertain natural gas supplies and rising prices are leading to a situation where green hydrogen produced by water electrolysis is becoming competitive and economically viable. The transition of hydrogen production from natural gas reforming to electrolysis therefore represents a great potential for the use of green hydrogen in Slovenia. The remaining 1200 t per year is used for various other purposes, such as steel industry, oxygen removal from various processes, and for heat production in particular production processes. Current hydrogen consumption in Austria is 140.000 t (5,6 TWh) per year and is used in the steel and chemical industry.

Future hydrogen use

The major potential is the use of hydrogen to generate high-temperature heat in steel, cement, brick and glass industry. For instance, glass furnaces are currently powered by natural gas and electricity, and it is desirable to replace part of the natural gas with hydrogen. Demonstration projects of hydrogen use have already been performed. The heat consumption in the glass furnace is in the range of 20 MW. Generating 10% (2 MW) of thermal energy with hydrogen means a hydrogen consumption of 1500 t / year (60 GWh / year).

Next promising potential for both Austria and Slovenia is the use of hydrogen in transport or mobility. In principle, hydrogen can be used in all modes of transport (cars, trucks, buses and also railways). Use for passenger cars and vans is still problematic because there is no diversified hydrogen charging infrastructure and because there is not yet a wide choice of passenger cars and vans powered by hydrogen fuel cells. The ideal mobility application are city buses:

- the entire fleet of city buses is charged at one dedicated location, so there is no need for a wide charging infrastructure,
- for economic reasons, buses must be operated most of the time in a day, longer stops e.g. for charging batteries are undesirable,
- the daily distance travelled by city buses exceeds the range of the batteries, so the battery propulsion is not ideal for city buses,
- Hydrogen fuel cell buses do not generate any emissions and generate much less noise than existing buses with internal combustion engines
- Diesel fuels are heavily burdened by environmental and energy taxes, resulting in a final price in the range of 150 EUR / MWh, which is the price at which hydrogen already becomes competitive (see Section 1) assuming not being burdened with the said taxes, but only with VAT.

The use of hydrogen in city buses could be technically and economically viable today and could represent a breakthrough in the use of hydrogen technologies. According to a rough estimate, one

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bus consumes 30 kg of hydrogen per day, assuming a typical driving cycle, which is 10 tons of hydrogen per year. A fleet of 100 city buses therefore consumes 1000 tonnes of hydrogen per year.

The next potential in mobility is railway transport, especially non-electrified lines (there are approx. 600 km in Slovenia or 50% of all lines). Non-electrified lines are operated by Diesel-powered locomotives that cause emissions and noise, which could be eliminated by using hydrogen-powered locomotives either via fuel cells or via gas turbine generators.

The table below shows a comparison of the current consumption of natural gas and hydrogen in Austria and Slovenia. Also, rough estimates of hydrogen consumption in 2040 are given.

Table 3: Current demands for hydrogen

	Austria	Slovenia
POPULATION	8,9 million	2,1 million
NATURAL GAS current yearly consumption	100 TWh	10,2 TWh
HYDROGEN current yearly consumption	140.000 t (5,6 TWh)	2.400 t (96 GWh)
HYDROGEN current yearly consumption per capita	15,7 kg	1,2 kg
HYDROGEN yearly consumption in 2040	67-75 TWh (1.775.000 t)	1,14 TWh (28.500 t)
HYDROGEN yearly consumption in 2040 per capita	199,4 kg	13,6 kg

Sources: [8], [13]

7 Production possibilities of green hydrogen

The main method of producing green hydrogen is electrolysis of water, where green electricity must be used to drive electrolysis. Green electricity comes from three main primary sources: solar power plants, wind power plants and hydroelectric power plants. If electrolysis is driven by mixed source electricity from the grid, which includes thermal power plants, the result is yellow hydrogen, since the production of electricity used for electrolysis generates CO₂. Without primary sources of green electricity, therefore, the production of green hydrogen is not possible. The possibilities of producing green hydrogen are therefore directly related to the possibilities of producing green electricity. Green hydrogen can be produced from surpluses of existing green electricity or from newly installed green electricity sources. If hydrogen were to be produced from existing (already assigned or already reserved) green electricity sources, then existing green energy users would have to switch to less environmentally friendly sources (thermal power plants), so at the country level this would not reduce CO₂ emissions and other negative environmental impacts.

The main question in this section is what are the potentials in Austria and Slovenia for building new sources of green electricity, i.e. new solar, wind and hydro power plants. The answer can be given by the following table:

Table 4: Existing and planned green electricity sources

Green electricity source		Austria	Slovenia
Hydro power plants	Existing	38,4 TWh/year	4,95 TWh/year
	Potential for new	11 TWh/year	1 TWh/year
Wind farms	Existing	6,6 TWh/year	Neglectable
	Potential for new	5,4 – 15,8 TWh/year	Not known
Solar power plants	Existing	1,27 TWh/year	0,29 TWh/year
	Potential for new	48 TWh/year	7,28 TWh/year

It can be seen that possibilities for new hydro power plants are limited in both countries. The reason is that hydro potential is already well exploited in both Austria and Slovenia. The plan is to provide additional yearly production of 11 TWh in Austria and 1 TWh in Slovenia. In Slovenia there is a plan to install ten new power plants on the Sava river with a total annual production of approx. 1 TWh, source: <https://www.gen-energija.si/investiramo-in-razvijamo/srednjesavske-elektrarne>.

The next possibility are wind power plants. Austria is quite ambitious at planning new wind farms, planned new production capacity is 5,4 – 15,8 TWh per year. In Slovenia the public is strongly opposed to the placement of wind farms in the environment, therefore the growth of wind farms is not expected in the near future.

Very attractive possibility are solar power plants. In both countries they could be installed on building roofs, parking lots and degraded areas. Building roofs represents great potential. For example, in Slovenia total roof surface is estimated at 270 million m² [9]. With typical solar radiation AT-SI region, a photovoltaic panel with a peak power of 125 W/m² produces around 135 kWh/m² of electricity per

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year. Multiplying total roof surface and yearly energy produced by 1m² photovoltaic panel gives the total amount of electric energy produced in one year (36,4 TWh) in Slovenia. Covering all roofs with solar panels is highly unrealistic scenario. By using 20 % of available roof surface would generate 7,28 TWh of electric energy per year, which could be used for decarbonisation of different processes and sectors by either direct electrification or by hydrogen route.

When assessing the possibility of producing green hydrogen, it is also necessary to consider the hydrogen production cost, as we want to produce hydrogen at the lowest possible cost. As follows from Section 1, the cost of producing green hydrogen can be reduced in two main ways:

- by ensuring the lowest possible price of green electricity, which drives the electrolysis process,
- by ensuring high degree of utilization of the electrolyzer (by minimizing the intervals when the electrolyzer is not in operation).

The price of green electricity used to drive electrolysis has a direct impact on the final production price of hydrogen, see section 1. The price of electricity generally consists of the following components: energy price, transmission price, duties and taxes. Prices of transmission, duties and taxes can represent over 50 % of the total electricity bill, and the price of electricity itself is subject to daily fluctuations and stock market speculation. From this point of view, it seems convenient to connect the electrolysis directly to the solar power plant and thus avoid energy transmission costs and duties. However, in this case the utilization rate of the electrolyzer is low, the reason being that electricity from the solar power plant is only available for a limited time of the day. The optimal solution is a combined power supply directly from the solar power plant, when the solar radiation is sufficient (day time) and power supply from the grid, when the solar radiation is insufficient, and surplus cheap energy is available in the grid (night time), as follows from Figure 3. In this way, it is possible to achieve a high level of utilization of the electrolyzer and at the same time low average price of electricity, which minimizes the production costs of hydrogen.

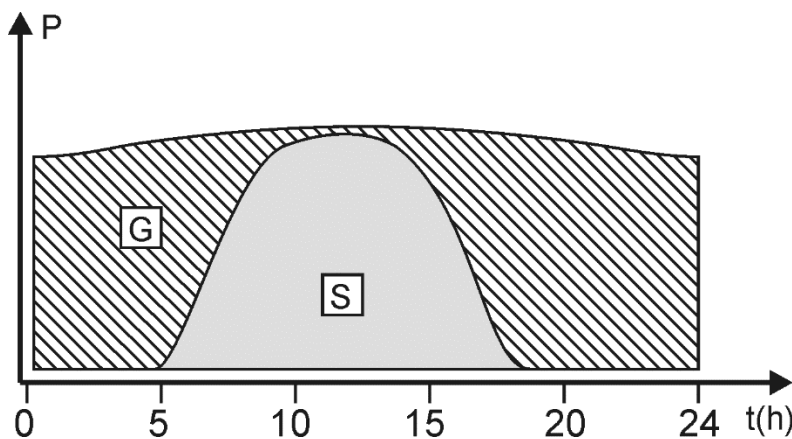


Figure 3: Example of green hydrogen production during the day (S-electric power from photovoltaics, G-electric power from the grid)

8 Production costs of green hydrogen

Production price of green hydrogen strongly affects its competitiveness in comparison to existing fuels and feedstocks. Production price is composed of three main components:

PC1	Price component, which originates from investment costs (CAPEX) of the equipment (electrolyzer, hydrogen storage tank and other equipment). Effect of this component to the final hydrogen price depends on the degree of utilization and life time of the equipment.
PC2	Price component, which originates from operation costs (OPEX), such as costs of personnel, equipment maintenance costs and costs of consumables.
PC3	Price component, which originates from price of green electric energy, used is for hydrogen production. The main part represents electrolyzer consumption (typically 50 kWh/kg), but other components also consume electricity (estimated 5 kWh/kg H ₂).

Let us assume that hydrogen is produced by the electrolyzer with 1 MW electric power:

CAPEX: Investments (project documentation, electrolyzer, high pressure hydrogen storage, auxiliary components, electric connection, construction and assembly works, control system)	2.500.000 EUR
OPEX: Estimated flat rate of 5 % of CAPEX each year	125.000 EUR/year
Actual utilization of available production capacity	80 %
Expected lifetime of the system	15 years
Production capacity of the electrolyzer at full load	20 kg H ₂ / h
Power consumption of the system at full load	55 kWh / kg H ₂

Price component PC1

Price component PC1 is calculated as a quotient of CAPEX costs and a total mass of produced hydrogen during system life time:

$$PC1(EUR/kg) = \frac{CAPEX}{m_{TOT}}$$

Mass of produced hydrogen during system life-time:

$$m_{TOT} = 20 \text{ kg/h} * 24 \text{ h/day} * 365 \text{ day/year} * 15 \text{ years} * 80 \% = 2.102.400 \text{ kg}$$

Based on this PC1 can be calculated:

$$PC1 = \frac{2.500.000 \text{ EUR}}{2.102.400 \text{ kg}} = 1,19 \frac{\text{EUR}}{\text{kg}}$$

Price component PC2 is calculated as quotient of OPEX costs and total mass of produced hydrogen during system life time:

$$PC2 \left(\frac{EUR}{kg} \right) = \frac{OPEX}{m_{TOT}} = \frac{15 * 125.000 EUR}{2.102.400 kg} = 0,89 \frac{EUR}{kg}$$

Price component PC3

Price component PC3 represents the cost of electric energy needed for green hydrogen production and directly depends electric energy price (EUR/MWh) and system consumption (55 kWh / kg H₂):

$$PC3 \left(\frac{EUR}{kg} \right) = Electricity\ price \left(\frac{EUR}{MWh} \right) * 0,001 * System\ power\ consumption \left(\frac{kWh}{kg} \right)$$

Total costs of green hydrogen

Total production cost is a sum of all three components (PC1+PC2+PC3) expressed in EUR / kg H₂.

Considering heating value of hydrogen (HHV = 39,39 kWh/kg), hydrogen price can be expressed in EUR / MWh, which is relevant for applications, where hydrogen is used as energy carrier.

$$PC3 \left(\frac{EUR}{MWh} \right) = PC3 \left(\frac{EUR}{kg} \right) * \left(HHV_{H_2} \left(\frac{kWh}{kg} \right) \right)^{-1} * 1000$$

Table 5: Hydrogen price a function of electricity price

Case	Electric energy price (EUR/MWh)	PC1 CAPEX (EUR/kg)	PC2 OPEX (EUR/kg)	PC3 Electricity (EUR/kg)	Hydrogen total price (EUR/kg)	Hydrogen total price (EUR/MWh)
1	30	1,19	0,89	1,65	3,73	94,69
2	60	1,19	0,89	3,30	5,38	136,58
3	120	1,19	0,89	6,60	8,68	220,36
4	180	1,19	0,89	9,90	11,98	304,14

Value-Added Tax (VAT) and other charges not included

Remarks

- By subsidies and co-financing of the equipment purchase and installation costs (CAPEX), hydrogen production price can be reduced, maximum reduction potential is 1,19 EUR/kg, which equals price component PC1.
- For further reductions of hydrogen production price, subsidies and co-financing of operation costs (OPEX) and electricity for hydrogen production would be needed.

9 Hydrogen technologies in electric power system balancing

The electric power system operator continuously ensures that the production of electric energy matches the consumption. Depending on the predicted future consumption, the system operator determines the power generation time profile of particular power plants. Despite the concerns about balancing, differences between production and consumption appear due to the following reasons:

- deviation of production of individual power plants from the plan due to technical failures,
- deviation of consumption of larger consumers from the plan due to outages for various reasons,
- Dependence of renewable electric energy sources (solar, wind and hydro power plants) on the time of year, time of day and weather and the consequent inability to follow demands for electric energy production.

The system operator resolves the imbalances, among other things, with system services that include primary, secondary and tertiary control:

- Primary control is the control of the frequency of the AC voltage. It is performed by power plants and it runs automatically and continuously during power plant operation.
- Secondary control is intended to compensate for larger deviations between production and consumption, it is triggered by the system operator, and it is performed by pre-selected contractors. At the request or signal of the system operator, contractors must increase their electricity generation or reduce consumption in the case of positive control. In the case of negative control, they must increase consumption or reduce generation. The required response time at the request of the system operator is in the range of seconds and the actions last up to 15 minutes. Payment of the contractors is composed of two components: payment for standby (readiness to react), and payment for actually supplied electric energy (stock exchange price, increased by a certain factor).
- Tertiary control serves to compensate for long-term power plant outages. Activation is not automatic but manual. The maximum positive power equals the power of the largest power plant. The maximum negative power equals the power of the largest consumer. Similar to secondary control, the contractors are paid for standby and for actually supplied electric energy.

An electrolyzer that produces hydrogen for final consumers (e.g. to supply city buses) and is powered from the grid, could be included in the secondary control. Under normal conditions, when there is no requirement for activation, the electrolyzer operates at rated power. When the requirement arises to activate the positive control and thus to supply additional electric power to the grid, the production of hydrogen is reduced and consequently the electric consumption of the electrolyzer is reduced, which has the same effect as the supply of additional electric power to the grid. By participating in secondary control, the profitability of the electrolyzer can be increased:

- each MW of standby power brings an additional annual income
- the electricity actually supplied generates additional income if the following condition is met:

$$\text{Price of electric energy, supplied to the grid (EUR/kWh)} > \text{Hydrogen selling price (EUR/kg H}_2\text{) / Electrolyzer consumption (kWh/kg H}_2\text{)} - \text{Price of electric energy consumed from the grid (EUR/kWh)}$$

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As an example, the table below shows the profit from hydrogen production after fifteen years of operation. The left column represents the situation where the electrolyzer participates in the secondary control, with 90% of the electric energy being used to produce hydrogen and 10% representing the activation of the secondary control. The right column represents a situation where the electrolyzer does not participate in the secondary control scheme and operates independently, with all electricity being used to produce hydrogen.

Table 6: Effect of participation in secondary control

Parameters	90 % of energy for hydrogen production, 10 % for secondary control	100 % of energy for hydrogen production, no participation in secondary control	Unit
CAPEX investment	2.500.000,00	2.500.000,00	EUR
OPEX as % of CAPEX per year	5,00	5,00	%
OPEX per year	125.000,00	125.000,00	EUR
Electrolyser electric consumption	0,0550	0,0550	MWh/kg H2
Electricity price (electricity consumed for hydrogen generation)	100,00	100,00	EUR/MWh
Electricity price (electricity supplied during secondary control)	250,00	250,00	EUR/MWh
Hydrogen selling price	10,00	10,00	EUR/kg
Average electric power for hydrogen production	0,90	1,00	MW
Average electric power for secondary control	0,10	0,00	MW
Power reserved for secondary control	1,00	0,00	MW
Secondary control income (for standby)	183.000,00	0,00	EUR/(MW*year)
Observation period	15,00	15,00	years
Intermediate results			
Amount of produced hydrogen	2.150.181,82	2.389.090,91	kg
Energy for hydrogen production	118.260,00	131.400,00	MWh
Energy for secondary control	13.140,00	0,00	MWh
Costs			
Costs - CAPEX	2.500.000,00	2.500.000,00	EUR
Costs - OPEX	1.875.000,00	1.875.000,00	EUR
Costs of electric energy for hydrogen production	11.826.000,00	13.140.000,00	EUR
Total	16.201.000,00	17.515.000,00	EUR
Income			
Income from selling hydrogen	21.501.818,18	23.890.909,09	EUR
Income from electric energy supplied during secondary control	3.285.000,00	0,00	EUR
Income from secondary control standby	2.745.000,00	0,00	EUR
Total	27.531.818,18	23.890.909,09	EUR
Profit=Income-Costs	11.330.818,18	6.375.909,09	EUR

Another way to participate the electric power system balancing is through the storage of electricity. In periods when production from renewable sources is high (summer days in good weather), surpluses of cheap electricity arise, which can be stored and used in periods of increased consumption, reduced production and higher electricity prices. This is done with the help of pumped storage hydro power plants, which store energy in the form of potential energy of water, but the problem is that this type of storage is difficult to be placed in the environment, and storage capacity is limited. Batteries are an alternative, but they are only suitable for short-term storage of small amounts of electric energy. Hydrogen technologies are also potentially useful. Excess electricity can be converted into hydrogen

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by electrolysis of water and stored. In periods of lack of electric energy and high prices, stored hydrogen can be converted back into electricity by fuel cells or gas turbine generators, or, alternatively, hydrogen can be used for other purposes.

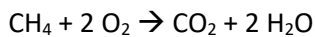
Hydrogen based energy storage is not an ideal energy storage technology, the total efficiency of the "charge-discharge cycle" is about 35%, which means that if 1 MWh of electricity is delivered to the storage, then the storage returns 0.35 MWh of electricity. The next challenge is hydrogen gas storage. Hydrogen contains high amount of energy per unit mass (39.39 kWh / kg), but due to its extremely low specific mass it takes up a lot of space in the storage tank, which can be reduced by compressing to high pressure (50...300 bar). However, high storage pressure requires high mechanical strength of the tank, and compression consumes energy, which negatively affects the final storage efficiency.

Storage capacity (amount of stored MWh) can be increased by increasing the volume of the tank or by increasing the number of tanks. Multiplication of storage capacity multiplies the cost of the tank, but the cost of converters (electrolyzer and fuel cell) remains the same. Therefore, the cost of storage increases more slowly depending on capacity than for batteries, where the connection between capacity and price is approximately linear.

Due to ability to store energy, hydrogen technologies are suitable for balancing the electric power system, which is also confirmed by scientific and professional literature. Due to the low efficiency of the charging-discharging cycle, storage in hydrogen is economically viable only with very large differences in the price of electricity.

10 The environmental benefits of using green hydrogen

Following EU Green Deal and Fit for 55, EU has defined a goal to achieve a climate neutrality by 2050. As an intermediate step towards climate neutrality, the EU has committed to reduce emissions by at least 55% by 2030. Following EU hydrogen policy, the hydrogen is defined as an energy carrier for a climate-neutral economy. Green hydrogen, which originates from renewable energy sources, can gradually and partially replace fossil fuels such as natural gas, heating oils and coal. The abandonment of fossil fuels directly brings environmental benefits, which are mainly reflected in the reduction of emissions of CO₂ and other harmful compounds, mainly from the use of coal and fuel oils, such as CO, sulfur compounds, NO_x, particles and many other pollutants. In this chapter, we will focus on the potential for reducing CO₂ emissions. To assess the possibility of reducing emissions, we first list the basic relationships and data. The mass balance of natural gas combustion approximated by methane (CH₄) is given by the following relation:



It follows from the relation that 1 mole of CH₄ generates 1 mol of CO₂. The molar masses for CH₄ and CO₂ are: M_{CH₄} = 16,04 g / mole and M_{CO₂} = 44,01 g / mol. The upper and lower energy values of natural gas or methane (CH₄) are:

HHV _{CH₄} : 15,4 kWh/kg	55,5 MJ/kg	39,8 MJ/m ³
LHV _{CH₄} : 13,9 kWh/kg	50,0 MJ/kg	35,8 MJ/m ³

Energy values for hydrogen are:

HHV _{H₂} : 39,39 kWh/kg	141,80 MJ/kg	12,7 MJ/m ³
LHV _{H₂} : 33,32 kWh/kg	119,96 MJ/kg	10,8 MJ/m ³

We calculate CO₂ emissions from the combustion of an amount of methane, which corresponds to 1 MWh of energy. First, calculate the mass of methane for 1 MWh, considering the energy value of LHV_{CH₄} = 13,9 kWh / kg:

$$m_{\text{CH}_4} = \text{Energy (kWh)} / \text{LHV}_{\text{CH}_4} (\text{kWh/kg}) = 1000 \text{ kWh} / 13,9 \text{ kWh/kg} = 71,94 \text{ kg}$$

Then we express the amount of methane in moles:

$$n_{\text{CH}_4} = m_{\text{CH}_4} (\text{kg}) \times (1000 \text{ g/kg}) / M_{\text{CH}_4} (\text{g/mol}) = 71,94 \times 10^3 \text{ g} / 16,4 \text{ g/mol} = 4386,73 \text{ mol}$$

As mentioned above, the number of moles of CO₂ produced by methane combustion is equal to the number of moles of methane (n_{CH₄} = n_{CO₂} = 4386,73 mol). Finally, calculate the mass of CO₂ emissions from the number of moles and the molar mass:

$$m_{\text{CO}_2} = n_{\text{CO}_2} \times M_{\text{CO}_2} = 4386,73 \text{ mol} \times 44,01 \text{ g/mol} \times 0,001 \text{ kg/g} = 193,06 \text{ kg}$$

The following are the main summaries:

- Combustion of methane with an energy value of 1 MWh generates 193 kg of CO₂.
- Combustion of 1 kg of methane generates 2,68 kg of CO₂.
- The energy values of methane and hydrogen show that 1 kg of methane can be replaced by 0,39 kg of hydrogen.

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In a similar way, also CO₂ emissions for oil and coal can be calculated.

Table below shows yearly fossil energy usage in Austria and Slovenia, which could in future be replaced by direct electrifications, renewable fuels and hydrogen.

Table 7: Structure and quantities of current fossil energy use in Austria and Slovenia

Energy supply	Austria	Slovenia	
Coal	27,59	12,22	TWh
Natural gas	84,89	8,55	TWh
Oil	124,28	21,98	TWh

Next, we analyze the potential for reducing CO₂ emissions in individual concrete cases:

Example 1: Replacement of natural gas with green hydrogen (addition of hydrogen to the gas grid)
 The annual consumption of natural gas (in 2020) in Slovenia is approximately 10,2 TWh, or 675.000 tons/year, which contributes 1,85 million tons of CO₂ emissions/year, or about 11% of all CO₂ emissions in Slovenia. Natural gas consumers are mostly non-household users (industry, energy, heating, ...). By direct addition of green hydrogen to the gas grid to supplement 5 % of natural gas mass flow and maintain energy flow unchanged, CO₂ emissions from CH₄ combustion are reduced by 5 %. To keep energy flow unchanged at 5 % lower natural gas mass flow, a daily production of green hydrogen of around 40 tons/day is needed. To add hydrogen, gas grid should be equipped with hydrogen mixing and control station. In case of larger fractions of hydrogen in natural gas grid there may be a need to modify metering and control systems of final gas users.

It is possible to reorganize industrial energy needs from the use of natural gas to the use of green hydrogen. In this case, it is necessary to purchase an electrolyzer of adequate power (or several electrolyzers) with associated equipment for the conditioning, compression, storage, and distribution of green hydrogen.

By supplying hydrogen to the gas grid up to 5 %, we can reduce CO₂ emissions by up to 93.000 tons / year.

Example 2: Replacement of the use of fossil fuels (coal, oil, gas) in the process industry with green hydrogen

Energy consumption in Slovenian industry is high. In 2020, the industry consumed 14,6 TWh of energy. If electricity and fossil fuels are the main energy sources in the industry and they share their volume in half, then fossil fuels account for about 7 TWh of energy consumed - about 500.000 tons of fossil fuels. By replacing 10% of fossil fuel use with green hydrogen, Slovenian industry could reduce CO₂ emissions by around 150,000 tons/year.

Example 3: Use of green hydrogen in transport

Transport is the largest consumer of fossil fuels in Slovenia and represents about 18,5 TWh of energy consumed annually - about 1,5 million tons. Replacing 10 % of the vehicle fleet (city and suburban buses, trucks and cars) with hydrogen vehicles would reduce CO₂ emissions from transport by around 480,000 tonnes/year.

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Example 4: The use of green hydrogen in industry in Austria

CO₂ emissions from industry in Austria is estimated to 28.4 Mio tons in the year 2020 [15]. The main contributors are the iron and steel industry with 11,3 Mio tons CO₂, other industries (energy related emissions) 9,2 Mio tons CO₂, mineral industry (e.g., cement) 2,9 Mio tons CO₂, and refinery with 2,8 Mio tons CO₂. Substitution of natural gas or grey hydrogen with green hydrogen in the range of 10 % can thus contribute to 2,8 Mio tons reduction of CO₂ emissions per year.

Example 5: Use of green hydrogen for transport in Austria

In the transport sector, heavy road transport is forecasted to be satisfied by a mixture of technologies; out of those, up to 55 % are expected to be hydrogen related [16]. Today, the share of the energy consumption of transport from fossil fuels in Austria is about 36,1 %. The emissions from light-duty vehicles were 14,9 Mio tons CO₂ and from heavy duty around 8,7 Mio tons CO₂. The substitution of 10% of transport facilities to hydrogen-based vehicles will contribute to 2.360.000 tons reduction of CO₂ emissions per year.

11 Potential for reducing of the dependence on fossil fuel imports

European countries, including Austria and Slovenia, are heavily dependent on foreign energy sources, which are mainly fossil sources (coal, oil derivatives and natural gas). By replacing these sources with green hydrogen, the dependence on imports from foreign suppliers is reduced, while at the same time reducing the CO₂ load on the environment, as follows from Section 1.

Table 8: Structure and quantities of energy resources for Austria and Slovenia

Energy supply	Austria	Slovenia	
Coal	27,59	12,22	TWh
Natural gas	84,89	8,55	TWh
Nuclear energy	0,00	19,25	TWh
Hydro energy	42,00	4,93	TWh
Wind, Solar energy	11,14	0,67	TWh
Biofuels and waste	73,36	8,83	TWh
Oil	124,28	21,98	TWh
TOTAL	363,26	76,44	TWh

source <https://www.iea.org/countries>

Substitution by hydrogen	Austria	Slovenia	
Coal	10%	10%	
Natural gas	10%	10%	
Oil	10%	10%	

Hydrogen demand	Austria	Slovenia	
Hydrogen (energy)	23,68	4,28	TWh
Hydrogen (mass)	430.477,27	77.734,85	t
Electrolysis utilization	0,80	0,80	
Electrolysis installed power	3378,46	610,08	MW

The table shows a situation where a share (10%) of fossil energy sources is replaced by green hydrogen obtained from green renewable electricity. From the table it follows that to replace 10% of energy from fossil fuels, it is necessary to produce 430,000 tons of hydrogen in Austria and 78,000 tons of hydrogen in Slovenia. This requires the installation of 3.4 GW electrolyzers in Austria and 0.61 GW in Slovenia, assuming their utilization rate is 80%.

The necessary electricity for the operation of the electrolyzers must be provided from newly built renewable sources (solar, wind and hydro power plants). It follows from the table in Section 7 that the planned new renewable sources (solar, hydro and wind) in both countries are sufficient to replace 10% of energy from fossil sources.

12 Legislation

For the efficient and rapid implementation of various types of hydrogen systems, transparency and efficiency in the field of legislation and safety regulations are necessary. Procedures for obtaining permits must be clear and feasible in a reasonably short time and preferably in one place. At the same time, the operational safety of hydrogen systems must be ensured.

For this purpose, it is necessary to prepare in advance sample procedures for different categories of hydrogen systems, such as:

- Electrolyzers
- Fuel cells
- Pressurized hydrogen storage tanks of different volumes and different pressures
- Systems for adding hydrogen to existing natural gas grid
- Pipelines for transporting hydrogen at different pressures
- Hydrogen fuelling stations for vehicles (independent or located in existing gas stations)
- Hydrogen systems upgraded to solar power plants
- Hydrogen systems for the supply of industrial facilities
- Hydrogen systems for local energy communities to supply the settlement of residential buildings
- Hydrogen systems for individual residential buildings and placement in or next to buildings
- Hydrogen systems for balancing the electrical energy system

It is necessary to determine the safety conditions that must be met by the basic elements of hydrogen technologies (electrolyzers, fuel cells, pressure accumulators). These include regulations that manufacturers of elements must follow during design and tests that manufacturers must perform after production (final quality and safety inspection).

It is necessary to determine the regime of periodic technical and safety inspections of individual categories of hydrogen systems.

From a safety point of view, hydrogen system elements that contain large amounts of stored hydrogen and thus can represent a potential danger, should be treated in particular, primarily hydrogen storage tanks and pipelines. It is necessary to define:

- safety regulations that must be met (materials, design, safety tests),
- permitted installation methods and locations,
- necessary safety equipment such as hydrogen leakage detectors and ventilation systems.

There are currently no specific regulations for hydrogen systems in Slovenia. The legislation for chemical industrial facilities and the legislation for technical gases is used. This leads to relatively complex and time-consuming procedures for placing hydrogen systems in space and in buildings.

According to the revised TEN-E Regulation [14], Austria and Slovenia will strive to prepare regulations and guidelines for the introduction of services and infrastructure of hydrogen technologies with the aim of decarbonization and reduction of dependence on fossil fuel imports. The revised guidelines for trans-European energy networks (TEN-E regulation) contribute to the decarbonization of Europe's electricity and gas infrastructure, while ensuring the integration of sectors and markets, security of



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supply and competition. In this way, it will be possible to launch new projects in the field of production, storage, transportation and use of hydrogen. In the scope of this, the introduction of hydrogen production by electrolysis and the upgrading of the existing gas infrastructure for the use of hydrogen and other renewable gases and the introduction of gas and energy storage systems are foreseen.



Project is co-financed by European Regional Development Fund under the Program Interreg V-A SI-AT.

13 Collaboration between sectors

The introduction of hydrogen technologies on a larger scale represents a significant financial burden, as investments in hydrogen systems of the MW rank are in the range of several million euros. Due to large investments, it is necessary to ensure the financial sustainability of projects at the planning stage, depending on the circumstances in the entire chain in which the hydrogen system is located, starting with the green electricity generation sector and ending in the hydrogen end-user sector. When introducing hydrogen systems, the whole chain needs to be considered and optimized.

The situation is explained with the example of green hydrogen production and addition to the existing natural gas grid.

In this scenario, there are entities from many areas or sectors of the economy that form the supply and transmission chain, which runs from the generation of energy for the production of green hydrogen to the end user of green hydrogen. They appear in a subsequent order: 1. producers of (green) electricity for the production of hydrogen, 2. companies for the transmission and distribution of electricity, 3. producers of green hydrogen, 4. gas grid operators that allow the addition of hydrogen to their gas grid and transmission to end-users, 5. natural gas trading companies, and 6. end-users of natural gas (industry, household consumption, etc.). From the above example, we can see that the complete chain is very extensive. For a project to be successful, all links in the chain must recognize their economic benefits and all must meet their share of the technical conditions for integration into the common system. To these six entities we can add the 7th entity, i.e. the state, which has a role in drafting legislation and administrative procedures leading to the issuance of permits for the installation of hydrogen systems. The state also needs to adopt a strategy for the introduction of hydrogen technologies and prepare financial instruments to accelerate investment in hydrogen technologies, as well as to cover the financial gap that may arise as a result of high market prices of green electricity needed to produce green hydrogen. In the following, we briefly analyze the position of individual subjects in the chain of production and use of green hydrogen.

During the preparation of this document (2nd quarter 2022), green electricity producers can sell their electricity on the market at extremely high prices. If these prices were included in the production price of green hydrogen, it would be uncompetitive with other energy sources, despite the fact that the price of other energy sources is also higher during this period. In a given period of high electricity prices, a green electricity subsidy would be needed to keep green hydrogen production costs at an acceptable level.

Electricity transmission and distribution companies or transmission and distribution system operators have the role of transporting green electricity from sources (typically solar power plants) to the hydrogen production location where the electrolysis equipment is installed. Transmission system operators add transmission costs (grid charge) to the total price of electricity, which is also included in the production price of green hydrogen. In order to partially compensate for the high costs of electricity and transmission costs, system operators have the option of including hydrogen systems in the balancing mechanisms of the electricity system, which can generate additional revenue that positively affects the profitability of hydrogen systems, as described in Section 1.

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Green hydrogen producers are central to the entire chain. They primarily manage the hydrogen production process, but at the same time they must be technically and economically coordinated with all other links in the chain. Technical coordination with the gas grid means ensuring the required purity of hydrogen and ensuring an adequate amount so that the prescribed ratio of hydrogen to natural gas can be maintained. Technical coordination with electricity producers refers to the quantities and prices of supplied energy and the time profile of supply. Coordination with transmission system operators includes details regarding integration into ancillary services of electric power system.

Gas grid operators enable the addition of green hydrogen to the gas grid. In doing so, they must maintain stable conditions in the gas grid, prevent fluctuations in calorific value (kWh / Sm³) of the mixture of natural gas and hydrogen, which is achieved by ensuring a constant mixing ratio between hydrogen and natural gas, e.g. 5%. Fluctuating calorific value can cause problems for final gas consumers, especially in combustion metering and control. It follows from the above that it is necessary to ensure coordination between the green hydrogen producer and the gas grid operator.

Gas trading companies can take on the role of marketing and selling green hydrogen mixed with natural gas. In marketing, they may to some extent consider the reduction in the cost of CO₂ allowances and possible subsidies for the use of green hydrogen.

Natural gas end-users use the gas in most cases as an energy source for heat production (production of heat and steam in industrial processes, heating of buildings) and also as a raw material (e.g. hydrogen production followed by hydrogen peroxide production). End-users must determine whether their technological process technically allows the replacement of part of the natural gas with hydrogen and the extent to which their technological processes are sensitive to possible fluctuations in the calorific value of the gas mixture. End-users need to determine whether they can incorporate the potentially higher energy price of natural gas / hydrogen mixture into their final products and services compared to natural gas, and whether the market is willing to pay a slightly higher price for ecologically produced products and services. Using a mixture of natural gas and green hydrogen helps end-users reduce the cost of CO₂ emission allowances, as green hydrogen and its production do not cause CO₂ emissions.

In addition to the above scenario, there are a number of other ways to use hydrogen technologies, such as:

- production of hydrogen for mobility and transportation (city buses),
- upgrading solar power plants with hydrogen technologies to reduce dependence on weather conditions,
- hydrogen systems to balance the power system and to provide flexibility,
- local hydrogen systems to help supply energy to local communities and individual facilities.

In each of the listed scenarios, in addition to the hydrogen producer or hydrogen system operator, there are other entities that must be included in the technical and economic analysis of the scenario. A link between companies from different sectors and state is therefore essential. Without this coordination, the successful introduction of hydrogen technologies cannot be expected.

14 Service and equipment production value chain

With the accelerated penetration of hydrogen technologies, the supply of technological equipment (electrolyzers, fuel cells, storage tanks, balance of plant components, etc.) will be a bottleneck, as demand will exceed supply by several times. So, there is already room today for new component manufacturers and service providers. The current production of components is still low-automated and mainly performed by SME companies, so there are still opportunities for new companies to be started and grown. Intellectual property rights of many technologies, solutions and components from the field of hydrogen technologies are protected by patents. This may represent an obstacle, which can be solved by buying the patents, paying royalty fees or generate alternative designs of components. Next opportunity is to design and set up production and assembly lines of hydrogen components, i.e. automated assembly plants with automated end-of-line quality inspection. Therefore, Austria and Slovenia can successfully participate in both, services and component production:

Services

- Feasibility studies for the implementation of various hydrogen systems (faculties, institutions)
- Techno-economic studies of the introduction of hydrogen technologies in industry and electric power system and market (faculties, institutions, particular companies);
- System engineering starting at commercially available basic modules of hydrogen technologies (fuel cell and electrolyzer stacks) resulting in different systems like energy conversion systems, fuel cell based electricity and heat generators, energy storage devices, fuel-cell based auxiliary power units, fuel-cell based cogeneration systems;
- Design and implementation of automated technological lines for the production components of hydrogen technologies.

Hardware components

- Balance of plant components like blowers, pumps;
- DC converters;
- Control modules;
- Catalysts, membranes;
- Complete fuel cell and electrolyzer modules;
- Photovoltaic panels.

Software components

- Automatic control algorithms,
- Algorithms for electric grid balancing via ancillary services and via automated trading on an electricity stock exchange market;
- Algorithms for condition monitoring, state-of-health prognostics and remaining useful life estimation of hydrogen systems.

15 Building up the economic and development cooperation of the members of the regional Hydrogen Center

Based on the results and analyzes in this document, we estimate that the consortium of participants in the regional Hydrogen Center in framework of the project H2GreenTECH has the appropriate capacities and competencies for efficient work in the areas of research and development of hydrogen technologies and their transfer into industry sector, and for production, storage and use of green hydrogen.

The above data and analyzes show that there is a great potential for regional cooperation in the cross-border region Slovenia-Austria. The Hydrogen Center Regional Network is an inclusive facilitator and motivator to seek common solutions with its existing and future additional members to contribute to the improvement of the regional ecosystem.

The development strategy of the Hydrogen Center cross-border network highlights the innovation potential of the cross-border region Slovenia-Austria in research, development and social aspects. In this way, a broad approach to innovation in the region in the field of green hydrogen and hydrogen technologies is facilitated and included:

- Promoting technological and non-technological innovation,
- Strengthening the innovation competences of SMEs and other enterprises,
- Setting up regional value chains.

For the sustainable and successful operation of the regional Hydrogen Center, it is important to:

- implementation of the Center's development strategy
- implementation of the Roadmap for hydrogen technologies in Slovenia and Austria, and
- marketing strategy [17].

The focus here is on the sustainable cooperation of all partners of the project H2GreenTECH and all members of the Hydrogen Center until 2025 and beyond.

Therefore, one of the important developments and marketing-promotion activities of the Hydrogen Center until 2025 and beyond is to network and connect regional innovation organisations and actors and to promote project cooperation.

The regional cooperation of the Hydrogen Center members will contribute to the creation of a stronger regional innovation ecosystem in the field of green hydrogen and hydrogen technologies.

At the same time, it also means supporting innovative entrepreneurship to generate new innovative developments and increase competitiveness and economic and industrial diversification in the field of hydrogen technologies. This will contribute to the growth of innovation potential.

It is important to recognise that an effective regional Hydrogen Center strategy and a resilient innovation ecosystem are key for the Interreg SI-AT region in the process of a green transition and a carbon-free society.

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At the same time, it is sensible and necessary to upgrade the activities performed in the H2GreenTech project, especially in the areas of:

- Awareness of the professional and lay public about the importance of the introduction of hydrogen technologies for a successful transition to a low-carbon society (conferences, seminars, web presentations, etc.)
- Cross-border education in undergraduate and postgraduate studies (exchange of lecturers and students in educational programs for the development and use of hydrogen technologies, design of a unified educational program in the field of hydrogen technologies)
- Formation of consortia for the preparation of the new proposals for relevant international R&I projects (Horizon Europe, Interreg, Innovation Fund, Eurostars, bilateral AT-SLO)
- Review and evaluation of implemented demonstration projects on the use of hydrogen technologies in both regions
- Preparation of proposals for new joint demonstration projects on the use of hydrogen technologies (assessment of the possibility of implementing a joint H2 Valley, similar to the cooperation between Slovenia, Italy and Croatia, energy storage in the field of hydropower plants on the Drava river, hydrogen urban and suburban transport)
- Assessment of the possibility of joint ventures in the field of services and production of equipment for hydrogen technologies
- Establishment of cooperation with governmental (and non-governmental) organizations working in the fields of hydrogen technologies and transition to a low-carbon society.

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