JET Journal of Energy Technology

JET Volume 13 (2020) p.p. 25-38
Issue 1, May 2020
Type of article 1.01
www.fe.um.si/en/jet.html

IMPACTS OF ZERO-EMISSION POWERTRAINS BASED ON HYDROGEN TECHNOLOGIES IN PUBLIC TRANSPORT

VPLIVI UPORABE NIZKO-EMISIJSKIH POGONSKIH SKLOPOV NA PODLAGI VODIKOVIH TEHNOLOGIJ V JAVNEM TRANSPORTU

Niko Natek[ℜ], Boštjan Krajnc[1]

Keywords: Hydrogen, Fuel Cell, Transport, Energy efficiency, Green-house gas emissions, EU, Energy transition, Environment, Public transport service, Internal combustion Engine, CO_2

Abstract

This article reviews the development potentials and environmental impact of introducing category M3 vehicles (for passenger transport/buses) with fuel cell electric powertrains to an urban and inter-urban public transport service (PTS) to be operated in the Savinjsko-Šaleška region. The main focus is the demonstration of the PTS modelling and preliminary environmental impact assessment of the operation compared to conventional (modern) diesel-powered internal combustion engines.

Povzetek

Ta članek preučuje razvojne potenciale in vplive na okolje na primeru uvedbe vozil s pogonom na gorivne celice kategorije M3 (vozila za prevoz potnikov/avtobusi) za obratovanje v mestnem in medmestnem javnem prometu v Savinjsko-Šaleški regiji. Glavni poudarek je prikaz modeliranja storitve javnega prevoza in izvedba predhodne ocene učinka na okolje v primerjavi s klasičnimi (sodobnimi) dizelskimi motorji z notranjim zgorevanjem.

[ℜ] Corresponding author: Niko Natek, Tel.: +386 3 896 1520, Fax: +386 3 896 1522, Mailing address: KSSENA - Energy Agency of Savinjska, Šaleška and Koroška Region, Titov trg 1, 3320 Velenje, Slovenija; E-mail address: niko.natek@kssena.velenje.eu

[1] KSSENA - Energy Agency of Savinjska, Šaleška and Koroška Region, Titov trg 1, 3320 Velenje, Slovenija

1 INTRODUCTION

Sustainable mobility is recognized as one of the key areas of intervention within Europe's ambitious endeavour to address issues related to climate change and its high dependence on fossil fuel imports. Transport currently accounts for approximately one quarter of the EU's greenhouse gas emissions (GHG) and represents the lifeblood of the connected economies within the block. GHG emissions are, of course, only one part of the wider negative externalities (environmental and health costs) associated with transport, which are currently not taken into account to a sufficient degree.

Developing more efficient and less environmentally detrimental means of mobility while maintaining high transportation flows and excellent connectivity essential to a robust economy will be critical for achieving the targets of the European Green Deal, which pursues a 90% reduction of said emissions by 2050. The transnational policy of the EU is, among rail and inland waterways (with the core principle of multimodality), highly focused on facilitating wide market uptake of cleaner road vehicles and alternative fuels. One of its objectives is to achieve not less than 13 million zero and low-emission vehicles on European roads, that will be serviced by approximately one million public recharging and refuelling stations by as early as 2025. Whether or not this very ambitious objective is attainable and, in the end, beneficial to our society overall, will very much depend on administrating a pragmatic approach that will curb expenses and provide wider benefit to the EU economy and social cohesion. In this respect, the debate on which technologies would be most well suited to achieve these goals is ongoing and full of opposing opinions from different interest groups, while the only legitimate claim is that the advantages and inadequacies of individual technologies are highly dependent on specific use cases and cannot be generically declared to be superior or inferior for a broad area of applications.

This article will examine the performance of fuel-cell electric (FCEV) powertrain technology with hydrogen as the main energy carrier compared to conventional (high-efficiency, diesel-powered) internal combustion engines (ICE) on the example of a planned zero-emission urban and inter-urban public transport service (PTS) in the Savinjsko-Šaleška region of Slovenia. The article is derived from the main results achieved by the efforts of the City municipality of Velenje to establish a zero-emission PTS that would help drive the energy transition and decarbonization of the region.

2 FRAMEWORK AND POLICY BACKGROUND

Slovenia has formally declared ambitious targets in the areas of decarbonization, low-carbon energy, and transport. The core legislative framework for the energy sector, in general, is outlined in the new Energy Act, *[1]*, from 2014, which in the context of supporting the energy transition defines some essential provisions, for example, in Chapter II on increasing energy efficiency (EE) and the use of renewable energy sources (RES). Articles 314 to 316 define how EE and RES shall be supported and also the types of financial incentives provided by the state for this purpose. Article 317 defines the "contribution for energy efficiency" (an important funding source for the national environmental fund – Eko sklad) paid by final users for energy from district heating, electricity, solid, fluid and gas energy carriers. Grants (non-refundable) and soft-loans provided through the Eko sklad are an essential driver of supporting initial investment into sustainable mobility, which is provided for various vehicle categories (motorcycles, passenger cars, light-duty vehicles, buses and coaches, heavy-duty transport) with electric or hybrid powertrains. Eko sklad also manages certain investment support schemes provided by the Fund for Climate Change (Sklad za podnebne razmere) financed in accordance to Article 129. of the Environmental Protection Act (ZVO), which stipulates that the provision from the sale of emission coupons obtained through auction are used for providing financial support to climate mitigation measures. The major contributor to the fund is the Šoštanj thermopower plant (TEŠ).

Specific actions and sector-related targets are outlined in targeted action and operational plans, which are due for revisions for the post-2020 period. These include the National Renewable Energy Action Plan (NREAP) (Akcijski načrt za obnovljive vire energije za obdobje 2010-2020 - AN OVE), *[2]*, the Operational Programme for limiting greenhouse gas emissions until 2030 (Operativni program ukrepov zmanjšanja emisij toplogrednih plinov do leta 2030 (OP TGP)), *[3]*, and the National Energy Efficiency Action Plan (NEEAP) (Akcijski načrt za energetsko učinkovitost (AN URE 2020)), *[4]*.

Core national targets/milestones up to the year 2020 that have been defined within these operational and action plans include:

- **Milestone 1** – 25% share of RES in gross final energy supply (AN OVE, 2017)
- **Milestone 2** – Increasing energy efficiency by 20% up to 2020, defined as a threshold of total primary use not exceeding 7.125 Mtoe (≈82.86 TWh) or a maximum 2% annual increase cap (AN URE)
- **Milestone 3** – Meeting obligations on the reduction of GHG emissions, by capping maximum annual increases to no more than 4% from the base year 2005, i.e., total emissions will not exceed 12.117 kt of CO_2 equivalent in 2020 (OP TGP).

Milestone 1, which is specified for RES shares in specific sectors in accordance with the Renewable Energy Directive 2009/28/ES that targets a 25% share of RES in gross final energy supply and a 10% share of renewable energy in transport, likely will not be met by the end of 2020 even though the Ministry of Infrastructure has already outlined additional measures to be implemented to mitigate the shortfall. In the context of milestone 2, it was already achieved several years ago, mostly due to substantially reduced economic activity (the aftermath of the financial crisis of 2008) and has not surpassed the threshold (in 2017 it reached roughly 77.23 TWh). Concerning Milestone 3, the operational programme is limited to non-ETS sectors; thus, no direct measures for entities included in the scheme as well as for reducing indirect emission resulting in energy use are outlined. The emission cap is provided for non-ETS sectors, which account for about 59% of total CO_2 equivalent emission that reached 19,509 kt CO_2 in 2014 when the operational plan was published.

The main driver for decarbonization of the energy sector is, therefore, the implementation of the ETS, in which carbon allowances have increased more than 400% from May 2016 (from a low of €5,72 to over €25 per tonne of CO_2) to 2019 respectively. The implementation of the 4th stage of the ETS from 2021 onwards, which will increase the rate of annual reductions of available allowance to 2.2% will further exacerbate the already poor economics of energy production at TEŠ.

Strong expectations were placed on the development of the Energy Concept of Slovenia (Energetski Koncept Slovenije (EKS)) or the Resolution on the energy concept (ReEKS), *[5]*, planned to be adopted by the parliament in the first half of 2020. The EKS provides two core orientation milestones of reducing energy-related GHG emission by at least 40% by 2030 and at least 80% by 2050, compared to the baseline year of 1990. At present, the most up-to-date strategic development addressing the decarbonization in the comprehensive context of the energy transition is the National Energy and Climate Plan (Nacionalni energetski in podnebni načrt – NEPN), *[6]*, that is based on EU resolutions on establishing a reliable and transparent system for managing the energy union (2014), resolutions n. 14459/15 on the mandatory development of national plans for member states by the end of 2019 (205) and the Decree 2018/1999 instituted at the end of December 2018 on the management of the energy union and climate change mitigation measures. Core objectives and milestones from the existing legislative framework are reinstituted and collected within NEPN, which expands the development focus to 2030 and beyond to 2050. It comprehensively addresses several areas pertinent to carrying out the energy transition, from environmental aspects to socio-economic (research and innovation) implications. While the target on RES in gross final energy supply is increased to at least 27% until 2030 whereby the cap for final energy use is imposed at 54.9 TWh, transport plays an important role in the declared strategy. By 2030, at least 21% of the energy used in transport will be renewable (11% of bio-/alternative fuels) and transport will decrease its GHG emission by 12% overall. NEPN specifically indicates that Slovenia will support the development of infrastructure for alternative fuels in transport (including liquefied natural gas, compressed natural gas and hydrogen) and further electrification of transport also indicated in the Alternative Fuels Strategy (Strategija na področju razvoja trga za vzpostavitev ustrezne infrastrukture v zvezi z alternativnimi gorivi v prometnem sektorju v Republiki Sloveniji) adopted in 2017. The strategy also stipulates that special attention will be provided to supporting energy-efficient and clean public transport. Furthermore, NEPN specifies the support to pilot projects for producing synthetic methane and hydrogen with an indicative objective to achieve a share of synthetic methane and hydrogen in the transmission and distribution gas grid at 10% by 2030.

In 2017, Slovenia's energy dependency rate was 48%. Generation of energy from non-renewable RES (PV, wind energy) is problematic for the stability of the electricity system, and a high proportion of such sources will require significant investments in upgrading existing infrastructure, in particular energy transmission, distribution and storage/regulation systems. Current trends in the field of electro-mobility (along with the trend of electrification of heating systems) indicate, among other things, a significant increase in the share of battery electric vehicles (BEV) in transport (and an overall increase in electricity use), which does not offer an appropriate long-term sustainable solution to Slovenia's energy situation and development targets. It creates a number of additional problems, the primary question of which is, among many others, that of providing additional electricity generation capacities (substantial public resistance to investment is already being made, even in RES, e.g., in the projects of Volovja Reber, HPP on the Mura River) and more importantly, significant investments in transmission/distribution networks, energy storage, etc. that could lead to high energy prices for households and make the economy uncompetitive. Energy investments should be designed in a comprehensive manner that will, to the greatest extent, allow the Slovenian economy to be involved in the development, production and maintenance of the installed infrastructure in the wider context of available natural resources (human resources, energy, critical raw materials (CRMs)). With many hydrogen applications still being a relatively underdeveloped market, domestic businesses have tremendous opportunities to develop and promote their high value-added products and services in European and global markets.

3 HYDROGEN TECHNOLOGIES IN THE SAŠA REGION

The ambition to implement hydrogen technologies as an important part of sustainable development efforts of the region is based on over 10 years of activities related to planning, technical analysis, stakeholder engagement, and consultation, as well as research and pilot testing. The requirement for hydrogen as a coolant for generators of the Šoštanj thermopower plant (TEŠ), which was originally fired by locally mined lignite, was first signified after the concluded construction of power unit 3 in 1960. With the following construction of units 4 and 5, these requirements increased to the point that the management of TEŠ decided to establish on-site hydrogen production. Due to high awareness that energy production from lignite is limited in time and accessible reserves as well as the outstanding commitment of the company and local communities to reduce negative environmental impacts caused by energy production, TEŠ joined the Centre of Excellence on Low-Carbon Technologies (CONOT), where they began a research project titled “Hydrogen technologies in advanced energy supply” alongside 22 partner organizations including renowned research institutions and high-profile companies. Within the scope of the project, CONOT established an experimental hydrogen production unit (alkaline electrolysis), which is still in operation today and has a maximum capacity of 15 Nm^3/h.

The hydrogen is produced by alkaline water electrolysis that utilizes potassium hydroxide (KOH) for enhancing the conductivity of the electrolyte solutions. The on-site hydrogen generator (type HYSTAT-A 1000/15/25 from Hydrogenics with a single cell stack) is powered through a transformer (3 × 400 V~/250 V=) with 250 V and 376 A direct current. Obtained gasses (H_2, O_2) are stored in pressurized containment vessels. The unit can deliver gaseous hydrogen at 2500 kPa (25 bar) without the use of an additional external compressor, which helps to reduce the overall energy consumption (highest energy-consuming stage of the compressor from 1 to 10 bars is excluded) of the unit, as well as to avoid electrolyte loses that are typical for atmospheric electrolysers. The low energy consumption of the cell stack is 4.2 kWh/Nm3 and 4.9 kWh/Nm^3 on the level of the unit is the result of a highly conductive membrane and catalysed electrodes constructed in a so-called “zero-gap” configuration (reduced drops in voltage). The unit offers highly flexible production in the range of 25% to 100% output by adjusting the current density on the cell stack. HYSTAT-A also offers flexibility in terms of compatibility with optional equipment (closed-loop cooling systems, reversed osmoses systems, deoxo-driers, compressors, etc.) that can provide a tailor-to- fit to specific user requirements. Additional features include integrated safety, fully automated operation, compact and flexible modular design (capacity determined by the number of cells incorporated in the unit), easy installation and the ability for direct coupling with a DC renewable energy source (input of fluctuating currents). The production unit is now primarily used to supply the technical tasks of power plant maintenance with oxygen while hydrogen is being used mainly for the cooling of electrical generators. The demand for oxygen exceeds the demand for hydrogen; therefore, a substantial amount is vented to local surroundings. On average, TEŠ generates about one third of electrical energy in Slovenia but can operate to supply more than half of the national demand. With an installed power of 1304 MW, it produces from 3500 to 3800 GWh of electrical energy on an annual basis but also supplies heat to the Šaleška Valley by a district heating system in the amount of 300 to 350 GWh. For annual operation, it requires from 3.5 to 3.8 million tons of lignite supplied by the local mine, Premogovnik Velenje, *[7]*.

The vision of CONOT at that time also included the establishment of a hydrogen refuelling station and mobile assets that would operate in the Savinjsko-Šaleška region, which unfortunately did not come to fruition due to external factors related to poor economic status and subsequent lack of political will. CONOT was, however, successful in establishing one of the two originally planned hydrogen refuelling stations in Lesce (first HRS in Slovenia) in 2013 but did not anticipate the slow development of commercial hydrogen vehicles; therefore, the actual operation of the station was negligible. The failure to plan for actual hydrogen demand was a significant flaw of the project approach, which has almost entirely halted additional capacity development in the field to this day. Nevertheless, the increasing political and economic (carbon allowances) pressure on coal-fired energy production mandates that the powerplant, as well as the local and national authorities, actively seek a feasible development strategy that would allow for the gradual substitution of energy production from lignite (on average provides over one third of electrical energy production on the national level) taking into account the significance of a wider range of technical (energy production and storage), environmental (reduction of GHG and pollutants) and socio-economic (employment, supporting knowledge-intensive industries and innovation, etc.) factors.

Under the leadership of the Municipality of Velenje, the deployment of hydrogen technologies was approached again in 2017 and confirmed with the adherence to the Fuel Cells and Hydrogen Joint Undertaking (FCH JU) Regions and Cities initiative to address the targets related to green mobility and emissions reduction of the municipality outlined in the local strategic documents.

4 MODEL PUBLIC TRANSPORT SERVICE

Since 2008, the municipality of Velenje has operated a public transport service under the name “Lokalc” that was developed with a purpose to increase the efficiency of urban transport within the area by offering citizens, employees and visitors an alternative to their private passenger vehicles. To support wide uptake of the service, it was designed and remained free of charge providing simple access for its entire time it operated. Today the PTS operates 5 lines with 43 stations, which are serviced by diesel-powered minibuses with EURO5 and EURO6 emission ratings. On average it accommodates approximately 35,000 passenger trips per month (2018) and has proven to be highly successful in reducing the number of vehicles used for transport along with all their negative externalities.

The model for the zero-emission PTS builds on the experience with Lokalc followed up by a comprehensive stakeholder dialogue with the local community as well as detailed planning process with internal experts, public transport operators and private companies to determine optimal routes for the renewed service. The zero-emission PTS is structured by seven routes that encompass over 500,000 km of travelled distance annually and target service over 410,000 passengers annually. The routes connect the key interest areas of the Municipality of Velenje and the Municipality of Šoštanj, as indicated in Figure 1.

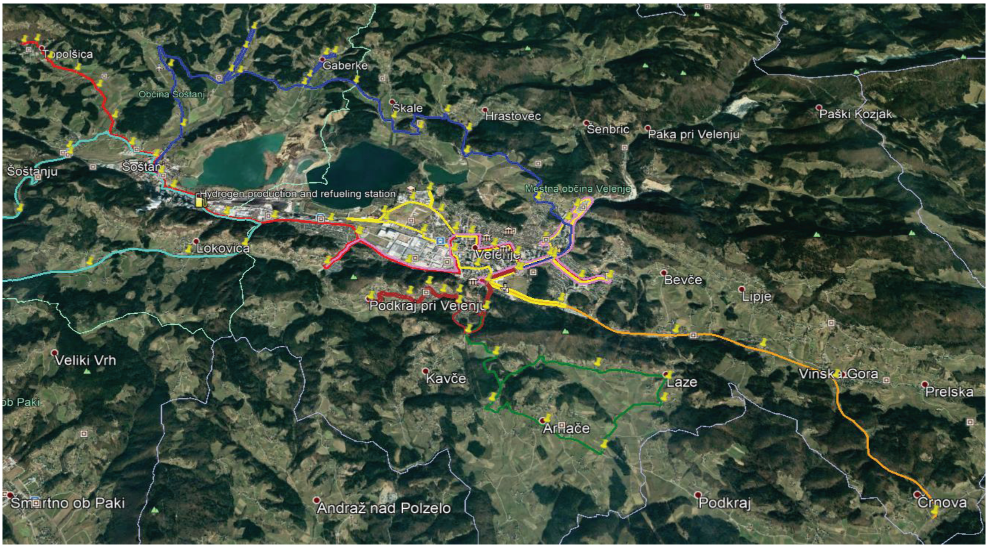

Figure 1: *Modelled routes for the zero-emission PTS*

4.1 Route analysis

The analysed routes are assumed to be operated by 6 (six) fuel-cell electric M3 category vehicles, model "Businova hydrogen Midibus", which is a 10.5 metre-long urban bus powered by a 32 kW PEM Michelin fuel-cell and a 132 kWh buffer and range extender battery. The vehicle is capable of storing 30kg of hydrogen at 350 bars, allowing for vehicle autonomy of over 350 km. The routes and respective distribution of vehicles to the public transport service is structured to require only one refuelling cycle per day. The modelling took into account different consumption scenarios in terms of the average number of people using the service, driving mode, air conditioning and thermal management requirements (six basic scenarios) for each route according to the predeveloped travel itineraries. The modelling scenarios were determined for two passenger loads (at 25 and 45 passengers) and three thermal management regimes (power consumption levels between heating and AC switched off and full power: 0, 3, and 5 kW of nominal power consumption respectively, *[9].* The modelling approach for the yellow line (Rumena proga) is represented in Figure 2 and Table 1 below:

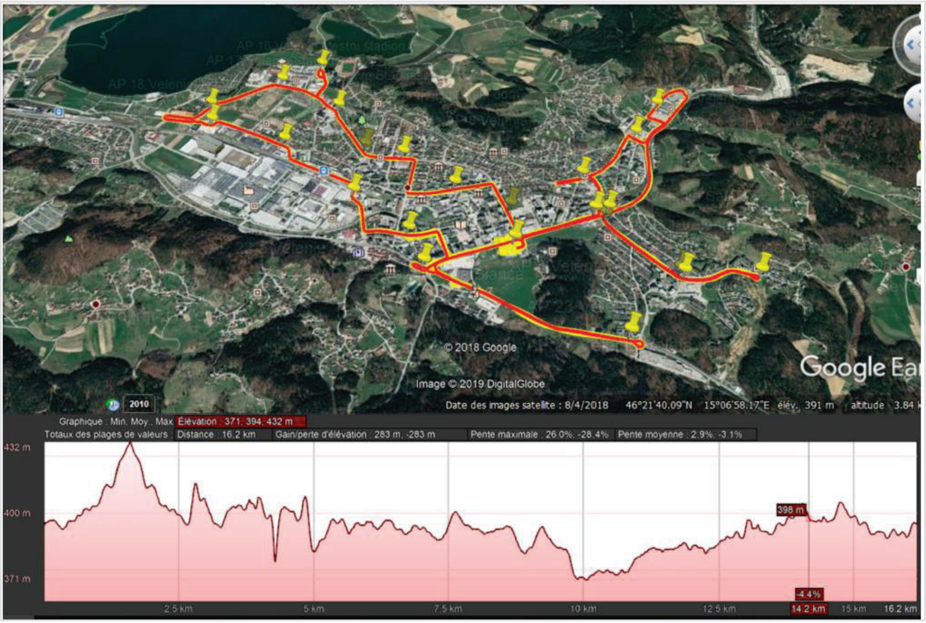

Figure 2: Yellow route overview (stops, route, incline) with Keyhole Markup Language

The modelling analysis is of the route is carried out on the assumption that the useful mass of hydrogen stored in the tanks that can be utilized by the fuel cell equals 29.1 kg. The case presented in Table 1 builds on the premise that all of the energy required to operate the vehicles is supplied from the hydrogen only whereby the energy from the battery is only used as a buffer (to provide continuous power supply to the electric engine) which represent the nominal mode of vehicle operation. It is also possible to apply the maximum energy stored in the energy to increase vehicle autonomy, which can increase easily above 400 km. In terms of nominal vehicle operation, it was found that an average consumption between 7.5 and 8 kg of hydrogen per 100 km can is easily achievable in eco-driving mode (utilizing regenerative braking) which would bring the autonomy range to a minimum 339 km in the highest load configuration (not realistic everyday operation but rather a highly conservative estimate of vehicle capability). The results are presented in Table 1 below:

P. *	Thermal management (kW)	Traction energy (kW/km) *	Auxiliaries energy (kW/km) **	Regene-ration (kW/km) ***	Total energy (kWh/km)	Daily H2 consumption (kg)	Battery SOC final (%)	Autonomy range (km)	Hydrogen consumption (kg/100km)
25	0	1.012	0.173	-0.243	**0.942**	29.1	90%	**448**	**6.50**
	3	1.012	0.302	-0.243	**1.071**	29.1	90%	**392**	**7.43**
	5	1.012	0.389	-0.243	**1.158**	29.1	90%	**363**	**8.02**
45	0	1.096	0.173	-0.244	**1.024**	29.1	90%	**410**	**7.09**
	3	1.096	0.302	-0.244	**1.154**	29.1	90%	**364**	**8.00**
	5	1.096	0.389	-0.244	**1.240**	29.1	90%	**339**	**8.59**

Table 1: Modelling results for the yellow route according to baseline scenarios

Table 1 demonstrates the modelling results for operating the yellow route under different passenger loads and thermal management requirements. The modelling is based on the assumption that no thermal management is required when the external temperature is between 15 and 22° C, moderate thermal management is required to power the AC unit when outside temperatures are in the range from 23 to 28° C or below -5° C to power the additional resistor heaters, and maximum thermal management is required for temperatures above 28 and below -5°C. The average assumed weight for the individual passenger is 70 kg, excluding the driver. The results of the modelling for all seven routes are presented in Table 2.

Route/ Parameter	**Blue**	**Orange**	**Red**	**Brown**	**Yellow**	**Turquoise**	**Violet**	**Green**	**Total**
Travelled distance (km/day)	390.78	63.76	639.58	31.21	696.34	65.57	45.26	49.20	**1981.69**
Travelled distance (km/year)	101948.64	16634.03	166855.78	8141.70	181665.18	17104.93	2353.52	12835.54	**507539.32**
Operational hours (h/year)	1948.88	466.72	7769.94	313.06	8493.51	521.77	97.07	417.42	**20028.36**
Fuel economy (kg H2/100km)	8.01	6.23	6.94	7.98	6.93	6.20	6.75	8.22	**7.16**
Hydrogen consumption (kg/day)	31.30	3.97	44.39	2.49	48.26	4.07	3.06	4.04	**141.57**
Hydrogen consumption (kg/year)	8166.09	1036.30	16542.56	649.71	14638.83	1060.51	158.86	1055.08	**43307.94**
Average speed (km/h)	52	36	21	26	21	33	24	31	**30.58**
No. of refuelling (no./IND)	1.043	0.132	1.480	0.083	1.609	0.136	0.102	0.135	**4.72**
No. of stops (no.)	24	11	24	8	21	13	16	8	/

***Table 2**: Main results of route modelling*

5 ENVIRONMENTAL IMPACTS

The baseline assumption of the preliminary environmental impact assessment presented in this article is that the hydrogen used to operate the PTS is sourced from highly efficient production methods that require little to no additional energy input (specifically in the case of the analysed project; this could be achieved within the requirements/capacity of grid balancing, i.e., powering down the operation of the thermopower plant or by means of waste gasification). This remains feasible while the amount of required hydrogen is at a relatively low scale, compared to the overall production capacity of either the thermal power plant or in terms of gasification, when the input raw material includes various types of carbonaceous waste (biomass, municipal waste, wastewater treatment sludge, etc.). In this respect, the approach of quantification is similar as to consider these available sources as energy that would otherwise need to be curtailed or simply not applied, meaning that the life-cycle impact assessment from primary energy (lignite) to hydrogen can be avoided. In reality, a certain amount of energy would need to be considered to account for the impact of required equipment and infrastructure; therefore, baseline assumptions used in the calculations are highly conservative in order to compensate for this effect, while primary impacts are focused on triggering energy savings and renewable energy production (in the form of alternative fuel). The secondary impacts are mostly attributed to other direct benefits derived from the deployment of the zero-emission PTS, including GHG and pollutant emissions (NOx, HC, CO and PMs) reduction directly due to the PTS operation and indirectly as a result of reduced use of personal vehicles in urban trips and improved access to public transport.

5.1 Energy savings triggered

The energy savings triggered by the project are determined based on preliminary design and analysis of the new zero-emission PTS, compared to the current energy use of the ongoing service Lokalc which deploys standard ICE vehicles with EURO5 and EURO6 diesel engines. The current operation of the Lokalc PTS has a scope of 320,000 kilometres of annual travelled distance to operate the existing routes. As mentioned before, the preliminary design of the renewed PTS indicates that to meet the needs of the various local and regional beneficiaries, the new routes should encompass a total distance of 517,000 km of annual travel.

In the technical report of the Lokalc operation, despite using much smaller and less accommodating vehicles, an average fuel economy of 25l of diesel per 100 km was recorded in 2017 and 2018. A volume of 1l od diesel fuel equals about 10kWh of energy, meaning that the total energy consumption based on the use of propellant fuel alone was about 800 MWh in 2017 to service the existing line, while the travelled distance of the new PTS would indicate a value of 1292.5 MWh of direct primary energy savings of the project which would decrease the use of diesel fuel 129,250 l of unused diesel fuel in relation the required travelled distance of the new zero-emission PTS.

The FCEVs comparatively use much less energy per travelled distance, due to the higher efficiency of the FCE drivetrain and regeneration braking (estimated at 1.5 kWh/km for fuel vehicle occupancy compared to the 2.5 kWh/km on average of the ICE vehicles currently in operation) so even a pessimistic scenario in which there is little available excess energy on peaks (which is not the case), the comparable operation would still entail an energy saving of 517 MWh less than the existing baseline. In addition, the preliminary design of the routes is planned to accommodate improved access to public transport with new stops, new routes, higher frequency on rush hours and overall optimized operation, meant to increase the individual trips with the PTS by at least 7% from 2017 when it was 421,198, which would entail an additional 30,000 additional trips with the PTS per annum. Based on the experience of the deployment of the existing Lokalc PTS, surveys with users and technical analysis indicated that at least one third of travellers opted out of using their own means of transportation when the service was made available. In the case of the renewed zero-emission PTS, this would encompass at least 10,000 individual trips with public transport instead of their car on a yearly basis. Considering an average 8,7 l/100 km fuel economy for urban driving and that each trip was calculated to be 6km, this signifies 60,000 km of mitigated passenger car travel distance. A 45% to 55% share of gasoline versus diesel-powered vehicles outlines a reduction of 2871 l and 2349 l of spent diesel and gasoline fuel respectively, amounting to a reduction of a total of 49.851 MWh (28,710 kWh of energy in diesel and 21,141 kWh in gasoline) of additional energy savings even by these very conservative assumptions. A total primary energy savings of at least 1.424 GWh would be achieved.

5.2 Renewable energy production triggered

The preliminary operation of the renewed PTS consists of 517,000 km of annual travel distance. Based on baseline route modelling, it would require about 140 kg of hydrogen dispensed at 350 bar or about 44 tons of annual production to service the required distance. In line with the assumed hydrogen production scenario, whereby only excess electrical energy within the HSE groups of producers is used in the electrolyser, the system will produce at least 1318.38 MWh of green hydrogen from energy that would be otherwise be curtailed/unused.

5.3 Reduction of GHG emissions by the operation of the PTS

Reduction of greenhouse gas emissions expressed as CO_2 equivalent is determined based on the existing Lokalc PTS compared to the planned zero-emission PTS. Considering the 517,000 km of travel distance yearly, if it were to be operated by EURO5 end EURO6 as is the case today, the ICE vehicles would require a total of 129,250 l of diesel fuel. 1 litre of diesel weighs 835 g (gram). Diesel consists of 86.2% carbon, or 720 g of carbon per litre diesel. To combust this carbon to CO_2, 1920 g of oxygen is needed, hence 2640 g of CO_2 is produced for every litre of burned diesel. Taking into account the current distribution of EURO5 and EURO6 vehicles in operation (approximately a 1:2 ratio), the total GHG emissions from fuel combustion amount to 341.22 t per annum.

5.4 Reduction of GHG emission by increased use of PTS (reduced use of personal vehicles)

Similarly, as presented for the previous example of the direct PTS GHG reduction and considering the calculations applied to determine primary impacts with relation to impacts of increased use of public transport (lowering inefficient transport with personal ICE vehicles), this will further decrease emissions by a minimum of 13.78 tonnes of CO_2 equivalent per annum.

5.5 Reduction of pollutant emissions by the operation of the PTS

The zero-emission PTS will also substantially reduce pollutant emissions relative to those ICE vehicles would emit during their operation (baseline). Considering the declared ratio of EURO5 and EURO6 operation (1:2), the former would operate cca. 172,330) and the latter 344,670 kilometres yearly, which indicates an average annual operation time of 22,188 hours (at 23.3 km/h average speed and 20 s delays at preliminary bus stops). EURO standards for heavy-duty diesel engines (steady-state testing for the conservative estimate) are declared in g/kWh (pollutant emission in gram as for a unit of produced energy). The emission ratings applicable to the EU declared with the World Harmonized Stationary Cycle (WHSC) are presented in Table 3 for the steady-state testing (notable difference between CO and PM emission compared to transient testing, [8].

Stage	Date	Test	CO	HC	NOx	PM	PN	Smoke
			g/kWh				*1/kWh*	*1/m*
Euro III	*1999.10 EEV only*	ESC & ELR	*1.5*	*0.25*	*2*	*0.02*		*0.15*
	2000.10		2.1	0.66	5	0.1		0.8
Euro IV	2005.10		1.5	0.46	3.5	0.02		0.5
Euro V	2008.10		1.5	0.46	2	0.02		0.5
Euro VI	2013.01	WHSC	1.5	0.13	0.4	0.01	8.0×1011	

[a] PM = 0.13 g/kWh for engines < 0.75 dm^3 swept volume per cylinder and a rated power speed > 3000 min^{-1}

***Table 3**: Heavy-duty EU emission standards at steady-state testing (Source: Dieselnet.com)*

The existing vehicles are rated at 132 kW power output of the ICE, which determines the following parameters in accordance with an operational time of 7396.28 and 14792.56 for hours per annum EURO5 and EURO6:

Vehicle/pollutant	CO	HC	NO_X	PM
Emissions of EURO V	1464.46	449.10	1952.62	19.53
Emissions of EURO VI	2928.93	253.84	781.05	19.53
Total	4393.39	702.94	2733.67	39.05

***Table 4**: Pollutant emission reductions of FCEV compared to ICEs.*

5.6 Reduction of pollutant emissions by increased use of the PTS

Emission ratings for light-vehicles are provided per travelled distance (mass in g per travelled km). The impact estimation implies a conservative scenario where all personal vehicles removed from their operation are EURO6.

Overview of emission reductions:

Indicator	**Quantification**		**Unit**
Reduction of GHG emissions by the operation of the PTS	Per annum	10 years	
	≈ 341.22	≈ 3400	t CO_2 eqv
Reduction of GHG emission by increased use of PTS	≈ 7.58 (diesel vehicles) ≈ 6.20 (gasoline vehicles)	≈ 137,8	t CO_2 eqv
Reduction of pollutant emissions by the operation of the PTS	≈ 4393.39 ≈ 702.94 ≈ 2733.67 ≈ 39.05	≈ 44000 ≈ 7000 ≈ 27300 ≈ 390	(kg/year) CO (kg/year) HC (kg/year) NOx (kg/year) PM
Reduction of pollutant emissions by increased use of the PTS	≈ 43.5 ≈ 2.97 ≈ 4.26 ≈ 0.36	≈ 435 ≈ 29,7 ≈ 42,6 ≈ 3,6	(kg/year) CO (kg/year) HC (kg/year) NOx (kg/year) PM

***Table 5**: Pollutant emission reductions by reduction of personal vehicles in transport*

6 CONCLUSION

The benefits of introducing hydrogen technologies as demonstrated on the specific use case of applying FCEVs in public transport would be able to produce valuable environmental benefits and an effective step towards achieving several formal objectives related to sustainable development as formally adhered to by the Republic of Slovenia. However, positive wider benefits of such development far exceed the mere environmental benefits compared to conventional ICEs, but addresses cross-sectoral challenges based on the following core guidelines on which the energy transition would be programmatically built upon:

- highest possible use of local (domestically available) energy sources
- maximum integration of renewable energy sources in the national energy mix
- reduction of energy dependence (foreign energy imports)
- lowest achievable environmental impact of energy production and use
- maintain the stability of the transmission grid and distribution system
- implement investments with the potential to support research, innovation and development and the development of valuable skills for employees required by enterprises in knowledge-intensive industries
- support of international promotion
- contribute to the development of sustainable (green) tourism in the region.

Such deployment projects could be structured to support further technology and market development of both the Slovenian and the EU's automotive industry. The potential to establish synergies with other innovative technology applications (such as gasification of waste) could represent a major step towards achieving an economically sustainable circular economy on the transnational level. The potential to support the gradual transition of coal-intensive regions with this approach is immense, and the overall concept is relevant to and directly applicable in several countries/regions within and outside the EU, which are pressured to actualize the energy transition within a relatively short time basis but have no clear, comprehensive plan on how this could be achieved, especially in consideration of the resulting negative impacts on employment

References

[1] Energy act EZ-1, Official Gazette of the Republic of Slovenia, 2014
Available: http://www.pisrs.si/Pis.web/pregledPredpisa?id=ZAKO6665 (accessed 5.5.2020)

[2] **Ministry of Infrastructure of the Republic of Slovenia**, National Renewable Energy Action Plan (AN OVE), 2017
Available: https://www.energetika-portal.si/fileadmin/dokumenti/publikacije/an_ove/posodobitev_2017/an_ove_2010-2020_posod-2017.pdf (accessed 5.5.2020)

[3] **Government of the Republic of Slovenia**, Operational programme for limiting greenhouse gas emissions until 2020, 2014
Available: https://www.energetika-portal.si/fileadmin/dokumenti/publikacije/op_tgp/op_tgp_2020.pdf (accessed 5.5.2020)

[4] **Jožef Stefan Institute** *et al.*, National Energy Efficiency Action Plan - AN URE, 2017
Available: https://www.energetika-portal.si/fileadmin/dokumenti/publikacije/an_ure/an_ure_2017-2020-jo.pdf (accessed 5.5.2020)

[5] **Ministry of Infrastructure of the Republic of Slovenia** *et al.*, Resolution on the Energy concept of Slovenia, 2018
Available: https://www.energetika-portal.si/fileadmin/dokumenti/publikacije/eks/resolucija_eks/re-eks_jo_avg_2018.pdf (accessed 5.5.2020)

[6] **Jožef Stefan Institute** *et al.,* National Energy and Climate Plan, 2018
Available: https://www.energetika-portal.si/fileadmin/dokumenti/publikacije/nepn/dokumenti/nepn_5.0_final_feb-2020.pdf) (accessed 5.5.2020)

[7] **B. Krajnc** *et al.*, Investment programme: Hydrogen technologies in zero-emission transport. City municipality of Velenje, 2019

[8] **European Commission**, Heavy duty EU emission standards at steady-state testing (website publication based on Regulation (EC) No 595/2009 of the European Parliament and of the Council and amendments
Available: https://dieselnet.com/standards/eu/hd.php (accessed 5.5.2020)

[9] **Société Albigeoise de Fabrication et de Réparation Automobile**, Businova H2 preliminary technical information - Supply of Fuel Cell buses: Businova H2 Midibus L (10,5 meters), 2019