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Enabling technologies assessment for reducing Italian LPT emissions on short and long-term time frames

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Abstract

The international policies on energy transition and sustainable development for mitigating global warming aim to limit the rise in global temperatures to 1.5 °C and consequently to outline a transition towards zero greenhouse gas emissions (GHG) by 2050. Vehicular traffic is responsible for about 30% of the total direct GHG, making it one of the most critical sectors. The achievement of net zero GHG emission goal in transportation sector relies in both improving the energy efficiency of the actual vehicles and promoting more efficient modes of transport. In this context, the development and enhancement of local public transport (LPT) systems represent a key point for future mobility, due to the reduced consumption and emissions per unit of transported passenger. As a result, public transport companies need to take rapid action to modernize their fleets, which currently consist mostly of diesel buses, by introducing vehicles and fuels with a lower environmental impact. With reference to the bus transit component of LPT, this article provides an assessment of vehicle and energy enabling technologies for emission mitigation in Italian LPT in a short (2030) and medium-long term (2050) application time frame, in accordance with the EU policy objectives contained in the "Fitfor55" proposal. The study shows that achieving GHG reduction targets requires the use of a mix of technological solutions, both vehicular and energy. Some of them, reduced environmental benefits, are immediately exploitable, in terms of maturity and cost-effectiveness, while others, more promising, are based on less mature technologies, now more expensive, and on the use of energy vectors produced from renewable sources, for which a significant research and development effort is required.

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- Phase I: short term (2020-2030): the objectives aim to reverse the historical trend of the previous years by reducing emissions by 2030 to approximately 72.7 MtCO_{2eq}. Achieving this goal requires a reduction rate of 3.39% each year compared to the previous year.
- Phase II: medium/long term (2031-2050): the objectives set by the European Green Deal (EC, 2019) aim to reduce GHG emissions to about 10.22 Mt CO_{2eq}, corresponding to a decrease of 90% compared to 1990. If emissions to 2030 were equal the target of the previous phase, the reduction rate required to achieve the further objective by 2050 would be 10.1% each year compared to the previous year.

A recent study of the International Energy Agency (IEA, 2021) shows the estimated effectiveness of some main actions on GHG reduction in relation to the two time scenarios mentioned above. For Phase I, due to its transitional characteristics in terms of vehicular and energy technologies, political-administrative actions aimed at conditioning user behavior would have a marginal impact (3%); the remaining part is instead attributable to the technological factor. With reference to the latter, the appropriate use of high Technology Readiness Levels (TRL) solutions already on the market would contribute 82% to GHG reduction, while the remaining part (15%) would be related to the use of technologies currently in the research and demonstration phase. In Phase II, the behavioral factor would remain almost unchanged while in the technological one, the use of innovative technologies, both currently known in the previous phase and not very experienced, would assume great importance (47%) in GHG reduction.

Therefore, an important focus of research activities to reduce emissions is currently focused on alternative energy carriers. In this regard, even conventional energy carriers (diesel and methane) can be, at least in part, interesting, if they are made using RES, with appropriate technological processes. Fig. 1(b) shows the expected trend of penetration of RES on final energy consumption in the national transport sector. The EU Directive on the promotion of the use of energy from RES (RED II) establishes, as a specific target for 2030, the introduction of a percentage of 14% of fuels deriving from RES (EP, 2018). In the same direction, the EU objectives foresee, for urban transport, to halve the use of vehicles powered by traditional fuels by 2030, and then eliminate it completely by 2050 (EC, 2020a). Nationally, the share of RES in the energy mix for land transport will be higher than that envisaged by the RED II in the EU, reaching 22% of final energy consumption by 2030, corresponding to approximately 6000 ktoe (MISE, 2019). Extrapolating this trend in the period 2030-2050, the final penetration of RES should reach 70%. To fully exploit the generation from RES, which by its nature is typically non-programmable, it is necessary to develop in parallel an adequate capacity for storing the surplus of energy produced when favorable environmental circumstances exist.

3. Phase I enabling technologies

The current Italian transit bus fleet has over 51000 vehicles serving LPT companies, of which more than 93% are powered by diesel engines. About 23500 buses (45.5% of the total) has motorization less than Euro IV, resulting in a strong impact on air quality (ACI, 2021). Buses with conventional diesel engine fulfilling Euro VI standards represent the most mature and widespread technical solution and for this they are used as baseline for this assessment. The achievement of the GHG emission reduction targets requires the use of a mix of technological solutions. On the one hand there are technologically mature solutions, with reduced environmental benefits, characterized by relatively competitive costs. On the other hand, there are emerging technologies that, while representing effective solutions, still present significant issues in terms of TRL and high costs. With the aim of pursuing a decarbonization path that implies the gradual replacement of buses powered by fossil fuels with a new generation of electrically driven vehicles with zero direct emissions, the technologies considered are:

- *Natural Gas buses*: the technology consists in a conventional spark ignition engine running on compressed natural gas (CNG). They are widely used mainly for urban mission profiles, and, when high autonomy range is required (extra-urban profiles) NG can be also used in liquified form (LNG), by storing it in cryogenic tanks. Both CNG and LNG buses can be fueled with biogas (biomethane and bio-CNG).
- *Biodiesel buses*: diesel derived from organic material could lead to a potential reduction in WTW GHG emissions and an improve of energy security. One of the most promising biodiesel is hydrotreated vegetable oil (HVO), obtained converting vegetable or animal triglycerides with hydrogen. Fossil diesel yet contains fractions of biodiesel and for each type and/or blend of biofuel, specific engine modifications can be required. In the case of HVO, fossil diesel can be blended up to 30% without engine modifications.

- *Hybrid buses*: in this technology the propulsion is ensured by multiple energy sources (typically a chemical and an electric one). The restoration of the electrical energy can take place on board, using the chemical source to produce electrical energy and/or recovering the inertial and potential energy of the vehicle itself, or by means of suitable charging stations (plug-in hybrid). There are many different types of hybrid vehicles, differing in degree of hybridization, type (series, parallel, mixed), and energy storage system.
- *Battery electric buses*: the technology relies in electric propulsion with electrochemical on-board storage (Battery Electric Vehicles – BEV). The battery can be charge slowly during the night (overnight charge) or at higher frequencies by the means of medium (50 kW) and high (>150 kW) power charging stations (opportunity charge).
- *Fuel cell electric buses*: in this technology, the propulsion system is still purely electric, but it is powered by energy produced on board by electrochemical devices (fuel cells, FC) that transform the chemical energy of the hydrogen vector into electricity. Hydrogen is stored on board the vehicle in pressurized tanks (from 350 to 700 bar), while an electric energy storage system (ESS) is always present on-board.

Assessment indicator comparison

The evaluation of the different bus technologies alternative to fossil fuel diesel, currently on the market, is carried out. The results from the assessment are presented in terms of several indicator (Dahlgren and Ammenberg, 2021; Tzeng et al., 2005), concerning environmental, technical & operational, and economic performance. For the sake of uniformity, evaluations are made with a regular single deck, 12m length bus (CIVITAS, 2017). A value between Poor, Acceptable, Good, and Excellent is provided for each indicator. The proposed comparative analysis also includes fossil-fueled diesel buses, emphasizing their necessary replacement over time.

Environmental performance

The assessment of bus technologies and fuel pathways environmental performance has been carried out by two indicators: GHG emission savings and air quality. The evaluation of GHG emission saving must consider well-to-wheel (WTW) emissions. Since tank-to-wheel (TTW) specific emissions depend, among the other, by bus characteristics (length, mass, engine power, ...) and cinematic profile of the mission, a range of values founded in bibliography has been adopted in this work (Table 1). GHG emissions for diesel buses are on average equal to 1250 $\text{gCO}_2\text{eq/km}$ and it has been used as a reference for evaluating the GHG savings. Score: Poor. Replacing diesel with HVO could lead to a reduction in GHG emissions up to 80%, depending on the production pathway of the biodiesel and the blending rate (Dahlgren and Ammenberg, 2021). Score: from Acceptable to Excellent. WTW emissions of NG buses are comparable to the diesel ones, despite the lower WTT emissions for all production and distribution pathway (EEA, 2021). Fugitive emissions of methane during extraction and distribution phases, and methane slip after the on-board combustion process significantly affect the WTW GHG emissions. The use of biogas can significantly reduce GHG emissions, up to 80% (Prussi et al., 2020). Score: from Poor (NG) to Excellent (biogas). GHG emissions of hybrid buses are lower than buses with only diesel ICE, because of higher efficiency of the overall powertrain (up to 20%). The ability to reduce emissions in plug-in solutions increases as the portion of propulsion carried out in electric mode increases. Score: from Poor to Good. BEV and FC buses have zero tailpipe emissions, so for these technologies only the WTT emissions have been considered. In both cases, GHG emissions are directly related to the percentage of RES used, as highlighting by the wide range of values reported in Table 1. The current mix of electricity production in Italy is responsible for 213.4 $\text{gCO}_2\text{eq/kWh}$, below the EU average (230.7 $\text{gCO}_2\text{eq/kWh}$), proving its recent shifting towards RES (about 50% in the last year). Score: from Acceptable to Excellent. Regarding the hydrogen, about 95% of worldwide production of molecular hydrogen (H_2) is obtained from reforming of fossil sources (so called “grey H_2 ”), responsible for considerable CO_2 emissions (from 9 kg up to 13.2 $\text{kgCO}_2\text{eq/kgH}_2$) (H2IT, 2019). The production of H_2 from electrolysis of water by using RES (“green H_2 ”), could lead to a drastic reduction of GHG emissions, below 0.7 $\text{kgCO}_2\text{eq/kgH}_2$. Score: from Poor to Excellent. The air quality indicator refers to pollutants causing human diseases and environmental problems. Despite the presence of diesel particulate filter and selective catalytic reactor systems for actual diesel Euro VI buses, PM_{10} and NO_x emissions are still higher compared to the other technologies. The values remain unchanged by using HVO in diesel engines. Score: Poor. NO_x and PM_{10} emissions are both lower for NG buses (Hagos and Ahlgren, 2018), mainly due to the stoichiometric combustion and the presence of a three-way catalyst. The presence of nanoparticles (dimensions below 25 nm) at the exhaust, mainly attributable to the engine lubricating oil, can result in high particle number emissions (Thiruvengadam et al., 2018). Score: Good. NO_x and PM_{10} emissions of hybrid buses depend on the degree of hybridization. Score: form Acceptable to Good. BEV and FC buses have no tailpipe emissions. Score: Excellent.

Table 1. GHG specific emission for different technologies and fuel pathways (Dahlgren and Ammenberg, 2021; EEA, 2021; Lozanovski et al., 2018; Villante et al., 2018) and NOx and PM10 local emissions for different technologies (CIVITAS, 2017).

Bus Type	GHG WTW emission [g _{CO2eq} /km]	NO _x [g/km]	PM10 [g/km]
Diesel	1100 – 1400	0.5 – 1.1	0.015
Diesel - HVO	170 - 720	0.5 – 1.1	0.015
Natural Gas	800 – 1300	<1	<0.01
Natural Gas - Biogas	240 - 500		
Hybrid	950 - 1150	0 in pure electric; same as	0 in pure electric; same as
Plug-in Hybrid	550 - 750	diesel when ICE is on	diesel when ICE is on
BEV	5 - 580	0	0
FCEV	50 - 1200	0	0

Technical & Operational performance

The technical and operational performances of a bus refer to how well a technology provides the public transport function. The first indicator concerns the TRL. The number of buses currently in use and the registration trend can be considered as an evaluation parameter. In 2020, diesel buses account for about 93.7% of the overall Italian fleet, followed by NG buses (4.1%), electric vehicles (0.51%, including BEV and FCEV) and hybrid electric (0.15%), values in line with the EU average percentages (ACEA, 2022). Diesel buses are also used for HVO, without engine modifications. Score: Excellent. In 2020, 253 CNG and 37 LNG new buses were sold in Italy, with only France and Spain exceeded these numbers in the EU. Score: Excellent. The number of new hybrid buses reached 384 units in 2020. Score: Good. The sales of new electrical buses in Italy increased by 49.2% (from 65 units in 2019 to 97 buses sold in 2020), more than twice the average EU percentage, reflecting how the increasing maturity of these technologies is stimulating its widespread in the Italian territory (ACEA, 2020). Score: Acceptable. At the end of 2020, there were only 13 FC buses in operation in Italy (FCHO, 2022), but many pilot programs have been starting in the last years throughout Europe whose objective is financing the purchase of hydrogen buses. Thus, experience with this technology is expected to grow rapidly. Score: Poor. Another key indicator is the route flexibility of the bus, related to the refilling time and to the autonomy range. For a medium sized urban bus a daily range of about 300 km can be considered (CIVITAS, 2017). Due to the high energy density of the fuel, diesel buses require very short refilling time (5-10 min) and present a very high autonomy range (up to 900 km), allowing for the best operational flexibility among other technologies. CNG buses given shorter range than for diesel buses (up to 450 km), depending on the number of on-board tanks. However, when refueling at a fast-filling station, the filling time required for a CNG bus is almost the same as for a diesel bus. The autonomy range of NG buses increases in the case of LNG buses. Score: from Good to Excellent. The route flexibility of electric buses mainly depends on the dimension of the ESS and the adopted charging strategy: buses with small batteries (20-60 kWh) require fast charging at selected stops, allowing for very short autonomy (less than 100 km). Buses with large batteries (250-300 kWh) allows for extended autonomy without recharging (about 250 km). Score: from Poor to Good. The driving range of hybrid buses depends on the hybridization level, namely on how the power is balanced between the on-board propulsion systems. Score: from Good to Excellent. Even for FC buses, the fuel economy is strongly related to the dimension of both electrical and hydrogen storage systems and to the FC power and efficiency. On average, the autonomy ranges of FC buses do not exceed 500 km (Albrecht et al., 2021) with hydrogen tank refueling time from 10 to 15 min, for 350 bar maximum storage pressure. Score: Good. The last indicator concerns the primary energy security, i.e., the origin of the sources to produce fuel and electricity and their national availability. In 2020, the Italian final energy consumption in the transport sector amounted to 30223 ktoe, of which about the 93% relied in fossil fuels. RES accounted for the 4.1% of total transport energy consumption, with the 3.2% of biofuels and the 0.9% of electricity. The remain 2.9% is electricity produced by fossil fuels (MITE, 2021). The Italian production of oil is able to satisfy only the 12% of total oil consumption and the remain percentage is imported (UNEM, 2022). Diesel Score: Poor. In 2020 the overall energy content of biofuels released for consumption in Italy was equal to 1350 ktoe, but only the 12% of biofuels for transport sector were produced by primary sources originated from Italy. HVO Score: Acceptable. The national production of NG (including biomethane) was 4100 million standard cubic meters in 2020 and the consumption in transport sector was 943 million standard cubic meters. The national production was not able to meet the overall energy requirement, so the 93% of NG was imported, mainly outside of Europe (88%). However, there was an increase in the national production of biomethane. Score: from Poor (NG) to Acceptable (bio-CNG). The electricity consumption in Italian transport sector

in 2019 was 992 ktoe, of which only 347 ktoe of electricity produced by RES. The actual production of renewable electricity is 20.3 Mtoe, accounting for the 41.5% of the total gross electricity production. Score: Acceptable. Finally, the assessment for hydrogen is Poor, due to the low production volumes, according to the low actual demand of this vector (560 kt per year) (H2IT, 2019). However, Italy has planned to install 5 GW of electrolysis capacity by 2030 (MISE, 2020).

Economic performance

One of the major issues associated to the penetration of alternative solutions to diesel buses are their higher purchase costs (Ajanovic et al., 2021; CIVITAS, 2017; Dahlgren and Ammenberg, 2021). The purchase cost of diesel and NG buses are almost similar (among 210000 and 290000 €) with the latter slightly more expensive, due to the presence of multiple tanks. Score: Excellent. The current high investment cost for an electric bus (up to 500000 €) is mainly related to the cost of battery packs (up to 50% of the cost of bus). However, over the last few years there has been a rapid decline in battery costs, and it is estimated that they will continue to decrease, making the costs of electric buses comparable to those of diesel buses (Ziegler and Trancik, 2021). Score: Poor. Due to the low diffusion of FC buses, the purchase cost of a H₂ bus is still very high (over 700000 €), but it is expected to halve by 2030 (Ammerman et al., 2015), by increasing the maturity of the technology and promoting the integration of FC buses in LPT services. Score: Poor. Another economic indicator concerns the primary energy source price and its stability over time. The price of fuels and electricity produced from fossil sources varies following the trend of the global market. In addition, due to the European policies aimed at encouraging the use of the RES and reducing dependence on fossil fuels, the costs of diesel and NG are expected to increase over time (EIA, 2022; IEA, 2021). For NG, the possibility of fixed prices for primary sources required to produce biogas could lead to less fluctuation in the final fuel price. Score: from Poor to Acceptable. The European production cost of HVO is higher than fossil diesel (50 - 90 €/MWh), depending on the cost of the feedstock and the upstream purification requirements and its price is not expected to decrease in the next years (Brown et al., 2020). Score: Poor. Electricity in Italy is mainly produced by non-renewable thermoelectric. Despite the introduction of RES in the electricity mix can potentially lead to a decrease in price (Imani et al., 2021), electricity prices will continue to fluctuate, due to the inherent uncertainty of RES. Score: from Acceptable to Good. The actual cost of green H₂ is estimated between 2.5 and 5.5 €/kg, extremely higher compared to other alternatives. However, it is expected that the cost of green H₂ will drop below 2 €/kg by 2030, thus approaching the current cost of gray H₂ (1-1.5 €/kg) (EC, 2020b). Score: Poor. Table 2 provides an overview of the assessment results.

Table 2. Overview of the assessment results. P=Poor; A=Acceptable; G=Good; E=Excellent.

	Environmental					Technical & Operational					Economic				
	GHG Saving			Air Quality		TRL	Route			Energy	Purchase Cost	Source Cost			
Diesel	P			P		E	E			P	E	P			
Diesel – HVO	A	→	P	P		E	E			A	E	P			
NG	P			G		E	G	→	E	P	E	P			
NG – Biogas	A	→	E	G		E	G	→	E	A	E	A			
Hybrid	P	→	G	A	→	G	G	→	E	P	→	A	P	→	A
BEV	A	→	E	E		A	P	→	G	A	P	A	→	G	
FCEV	P	→	→	E	E		P	G			P	P	P		

4. Phase II enabling technologies

Considering the above analysis, the most significant possibilities for achieving the Phase II objectives involve:

- Transition of road transport to BEV with intelligent and distributed charging systems.
- Diffusion of the hydrogen vector. For this, it will be essential the diversification of production processes that will have to be oriented mainly towards green H₂, through the development of increasingly efficient and cheaper electrolyzers. By 2050, renewable hydrogen technologies are expected to reach a high TRL so that they can be deployed on a large scale. At a European level, total investments are estimated between 180 and 470 billion €, with the aim of producing about 500 GW of green hydrogen (EC, 2020b).

- Further efforts will have to be directed towards the development of high-efficiency on-board FC (powers up to 125 kW) to increase their duration and efficiency and reduce costs. A long-term goal concerns the development of a FC system with 65% efficiency and duration of over 8000 hours, mass-produced at a cost of approximately 25 €/kW (DOE, 2020). It will also be required the development of on-board vehicle storage systems capable of increasing the energy density of the H₂, also including gaseous storage at high pressures or in liquefied form and other alternative storage solutions (“Slush H₂”, metal hydrides, organic liquids with high absorption capacity and surface adsorption using organic/metal materials). Finally, it will be necessary the development of territorial infrastructures for the distribution and supply of H₂ in large volumes and over long distances and the resolution of legislative and regulatory issues and implementation of internationally recognized safety standards.
- Development of innovative electricity storage systems, both in terms of stationary systems for the accumulation of large quantities of electricity from RES (compressed air equipment (CAES) and inertial electromechanical equipment (FESS - Flywheel Energy Storage System)), and in terms of on-board ESS. The latter will ensure greater performance, while respecting the environment in terms of pollution over the entire life cycle. These include the development of electrochemical batteries (solid state lithium, electrolyte flow, organic batteries) with high capacity and reduced environmental impact, supercapacitors, and FESS (Ciancetta et al., 2016; D’Ovidio et al., 2020).
- Development of artificial intelligence (AI) technologies to support autonomous driving systems, increasing the current level of automation of the vehicle, high frequency mass transport platforms (Mobility-as-a-Service - MaaS), Intelligent Transport Systems (ITS), such as V2V (vehicle-to-vehicle), V2G (vehicle-to-grid) and V2X (vehicle-to-everything) communication protocols.
- Development of advanced materials for the conversion of solar energy into electrical and/or thermal, the distribution and storage of energy in the absence of joule losses (superconducting materials) and the reduction of the masses on board and the improvement of the active and passive safety of the vehicle.

5. Conclusion

An assessment of Italian LPT transit buses and enabling energy technologies was proposed according to the latest EU emission reduction strategies. The study shows the clear need to suddenly replace diesel-fuelled buses toward fully electrified technologies. However, due to several economic, technological and environmental barriers, the transition toward NZE mobility will go through the two phases investigated in the present work:

- **Phase I: short/medium term:** decreasing direct GHG emissions in transportation of 43.7% will require the use of a mix of technological solutions already and partially available on the market. Indeed, as highlighting from the assessment results, the most mature solutions (NG, hybrid and HVO buses) are also the less environmentally sustainable, due to the higher pollutant and GHG emissions. Furthermore, they present issues related to the energy security due to the strong import of fossil fuels in the national territory. For this, these technologies may represent a plausible solution in medium term only if NG and diesel fuels will be increasingly produced from national renewable sources. On the other hand, emerging technologies (BEV and FCEV) represent more effective solutions to environmental issues, but currently they present significant problems in terms of TRL and high costs.
- **Phase II: medium/long term:** the decrease of 90% of GHG emissions in transportation will require several technical efforts for developing the most resolute technologies, involving: i) transition of road transport to battery-powered vehicles with intelligent and distributed charging systems, ii) increase in the production and use of energy carriers from RES and construction of the related support infrastructures iii) diffusion of H₂ vector and related infrastructure network, iv) development of innovative ESS, v) development of AI technologies to support autonomous driving systems, increasing the current level of automation on board the vehicle, high frequency mass transport platforms, and ITS and vi) development of advanced materials. From this point of view, a lot will depend on future both national and European policies and fundings for replacing fossil fuel-powered internal combustion buses with a new generation of electric-powered vehicles with zero direct emissions.

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