# Assessment of energy and emissions saving solutions in urban rail-based transport systems

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**Abstract**

Global warming and climate change are indisputable theories. Since the Industrial Revolution, the mean temperature of the planet has increased by 1°C. Now, temperatures are approaching a higher stage of +1.5°C and the attention is on both $CO_2$ emissions and energy consumption. Transportation is a major component of the environmental impact, accounting for approximately 30% of air pollution and energy consumption. Due to the rapid urbanization in the EU, with an estimated 74.3% of the population living in cities, forecasted to rise to 80% by 2050, urban mobility is dramatically increasing its relevance. Therefore, a reduction in energy consumption and pollutant emissions is a crucial factor to consider in developing urban transportation and particularly rail-based systems, able to provide energy saving transport services by improving urban environment. Several methods and techniques are under development to improve the energy performance of Light Rail Transport (LRT), which spread from different typologies of power supply to improving energy efficiency. The purpose of this paper is to start from the last developments and innovative energy sources for LRT systems. The focus is on two parts: a) trams running on Hydrogen in parallel with on board batteries with energy saving control techniques, b) potential renewable energy sources to meet power demand. The comparison is with traditional power sources and equipment (e.g. Catenary-based). The methods, based on selected indicators, are under development and test by calculations and simulations with reference to the case study of the new tramlines in the city of Brescia (Italy).

**Keywords**
Railways, Tram, Urban Transit, Renewable Energy, Fuel cell, Hydrogen

**Introduction**

Energy demand globally increased by 2.1% in 2017, according to IEA, more than twice the average growth rate over the previous five years, which was 0.9%. According to Global Energy and CO2 Status Report (OCED International Energy Agency, 2018) energy-related CO2 emissions grew by 1.4% in 2017, which was a record through the history, after three years of emissions remaining flat worldwide.

On the other hand, renewable energies had the highest growth rate of any energy source in 2017, meeting a quarter of global energy demand growth last year. China and the United States together accounted for half of the increase in renewables-based electricity generation, followed by the European Union (8%), Japan and India (with 6% of growth each).

The EU set an ambitious target of 40% greenhouse emission reduction by 2030, and 80% by 2050 (EC, 2016a). Based on the Paris agreement, adopted on 12 December 2015, at COP21 and signed by 195 states in 2016, the EU is promoting the following target (Council of the EU, 2016): *Holding the increase in the global average temperature to well below*

*2°C above pre-industrial levels and limiting the temperature increase to 1.5°C*. To foster low carbon transition, a framework strategy for a resilient Energy Union links the transport and energy systems (EC, 2016a, 2016b). Its key features are:

- Reduction of the dependency on particular fuels, energy suppliers and routes;
- Full integration of the internal energy market and more efficient energy consumption;
- Decarbonisation of the economy.

Mobility within cities and between suburban areas and towns is significantly important, since transport represents more than 30% of the final energy consumption in Europe (EC, 2016b) and the majority of EU population are urbanised. According to UITP (2016), in 2014 urban rail accounted for 44.3% of all local public transport journeys in Europe (13.6% suburban rail, 16.2% metro, 14.5% tram/LRT).
As the European economy and transport demand are continuing to grow, the mentioned aims are only achievable if attentions of policy makers, local and companies' authorities pulled them in. In this framework, the article promotes:

- Firstly, a comparative assessment of the traditional power supply (catenary based) in LRT systems with modern renewable energy sources;
- Secondly, new methods for a better climate adoptable, enhanced passenger comfort and finally improve urban environment by removing catenary-based infrastructure.

The innovative concept includes the possibility to either transfer energy supply to street ground surface with such systems like third rail electrification and magnetic fields or moving the energy source on board to practically remove the catenary infrastructure.
The most common on-board source are nowadays batteries, but they are expensive, heavy, they required the extensive use of rare earth metals and the production of lithium-ion batteries itself is an energy-intensive process; Furthermore, charging them take a long time. Another way to carry clean energy source is using the most abundant element of universe, Hydrogen, that already used in automobile industry but rarely in railway, especially urban. Hydrogen has specific energy up to 40,000 Wh/kg, comparing to only 278 Wh/kg for batteries, which is 236 times more and makes using fuel cell vehicles a feasible choice.
Toyota Mirai (2014), Fuel cell-powered 113 kW with a total range of almost 500 km with only 5 kg of Hydrogen, was one of the first mass production Fuel Cell Vehicle (FCV) with a combination of power train, runs on both Hydrogen and Battery with variable energy consumption. The development of FCVs followed by other automotive companies (Honda, Hyundai) and Locomotive companies.
In September 2018, Alstom commercialised the world's first hydrogen powered train, the Coradia iLint that entered passenger service in Lower Saxony, Germany. The two pre-series trains, homologated by the German Federal Railway Association in July, are now running over the cities of Cuxhaven, Bremerhaven, Bremervörde and Buxtehude. The train is able to operate over a daily range of 1000 km. Alstom and the local transport authority of Lower Saxony (LNVG) signed a contract for the delivery of 14 hydrogen fuel cell trains by 2021. Moreover, the most relevant FCV in mass urban transit ran in October 2017 in China: CRRC Tangshan Railway Company unveiled a prototype low-floor LRV powered by Canadian

supplier Ballard Power Systems' hydrogen fuel cell technology, FCveloCity, which trialled on the new 14 km light rail line in Tangshan, China.
Ballard's fuel cell technology work in combination with batteries and super-capacitors over a range of 40 km, top speed of 70 km/h and capacity of 336 passengers to offer entirely catenary-free operation on the line. The LRVs have a range of 40 km on a single 12 kg hydrogen fill-up, which takes 15 minutes to complete. The four-station line includes a 100 kg capacity hydrogen refilling station.
Finally, for better understanding differences, potentials and drawbacks of traditional catenary based system and fuel cells, the comparison, calculation and simulations are under development for the new tramline project in Brescia (Italy) basing on infrastructural and operational data concerning both line and vehicles.
The new tramway network includes three main sections (Fig.1) of double track lines: T1, T2 and T3 for a total extension of about 23 km (46 km of single equivalent track), 65% shared with current urban road including approximately 41 signalized intersections. The project cost would be 450,000,000€, forecasted to be operated by 2026 with a total number of 14040 pax/h in rush hours with estimated yearly demanded power of 9,000,000 kW.

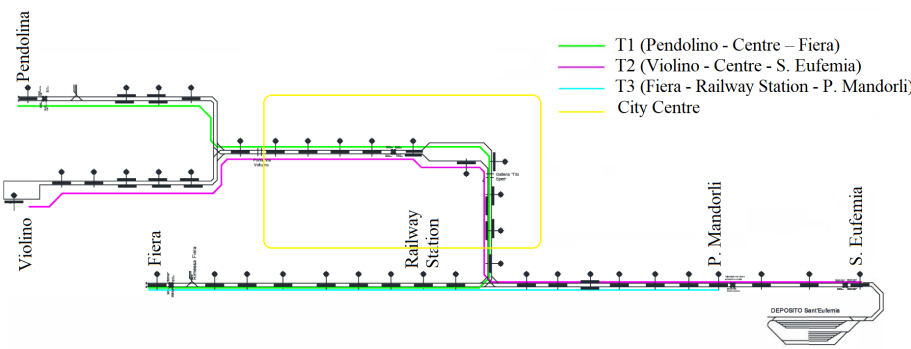


Figure 1: Track layout

The paper will forecast possible environmentally friendly clean local power sources to cover at least 20% of demanded power. Moreover, it promotes low-cost technology to make renewable hydrogen using sunlight and any source of water (Hyper Solar Inc.) directly at or near the depot area, to make a self-sustained renewable zero carbon Hydrogen powered urban transit combined with intelligent energy management (Fig.2).

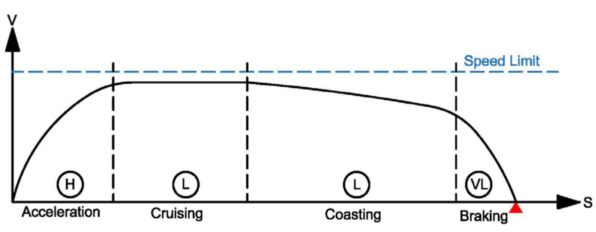


Figure 2: Energy-saving driving strategies
(Energy demand level H: High, L: Low, VL: Very Low)

Comparisons are following by discussing the most important issues concerning using

Hydrogen, such as safety, infrastructure and cost. Simulations are carried out by OPEUS simulator which is part of the Shift2Rail and stands for "Modelling and strategies for the assessment and OPtimisation of Energy Usage aspects of rail innovation", and is aiming to develop a simulation methodology and accompanying modelling tool to evaluate, improve and optimise the energy consumption of rail systems with a particular focus on in-vehicle innovation. The OPEUS concept is based on the need to understand and measure the energy being used by each of the relevant components of the rail system and in particular the vehicle. This includes the energy losses in the traction chain, the use of technologies to reduce these and to optimise energy consumption (e.g. ESSs). Specifically, the OPEUS approach has three components at its core: The energy simulation model, the energy use requirements (e.g. duty cycles) and the energy usage outlook and optimisation strategies recommendation.

**Why Hydrogen?**

Electricity production is carbon intensive, releases massive heat and noise at local power plants, gives rise to negative impacts on the environment and human health throughout all stages of its lifecycle, from resource extraction to electricity use. Impacts on climate change, air and water quality, direct and indirect impacts on land resources, etc. Impacts stemming from electricity production depend on the (fossil) fuel employed, how it was extracted and processed, the actual technology (and its efficiency) used to produce electricity, as well as the use of abatement technologies. An almost full decarbonisation of the electricity sector will be needed in order to meet the EU's objective of reducing greenhouse gas emissions by 90% by 2050. Increasing electricity generation and use throughout Europe without reforming the current energy system will lead to higher overall health and environmental impacts. Nevertheless, an increase in electricity consumption in the transport sector might signal a positive modal shift towards rail transport or a higher penetration of electric vehicles. The carbon intensity of total electricity generation in EU in 2016 was 296 g CO2/kWh. 1207 million tonnes of CO2 emitted from electricity generation in EU in 2013, leading by Germany 332 Mt, UK 163 Mt and Italy with 111Mt. An increase in electricity consumption in transport sector (mainly railways) arose in countries such as France and Italy.

Instead, Hydrogen and Fuel cell technology can contribute significantly towards reducing emissions and facilitating the necessary green energy transition in EU regions and cities. Fuel-cell technology usage can improve air quality and create positive health impacts for local population, hence enhancing life quality. Regarding recent study, about 90 cities in EU planned to invest about 1.8 billion euros in coming five years to deploy different $H_2$ transport modes and electrolysers for $H_2$ production and power generation. This conversion is expected to have not only environmental but also local economic effects.
For example, according to Unione Petrolifera, in 2017 Italy imported 15.9 million tonnes of refined petroleum products. However, the petroleum industry employs relatively few people; historical data shows that 1 million euro of value added in the petroleum sector in Italy created only 3.5 jobs in 2017, while hydrogen sectors are almost 5 times more labour intensive. Overall, the transition towards low and zero carbon economy has a net positive impact on employment (19,225 additional jobs in 2030), and will create opportunities for the adaptation and transformation of workers. As another example, German state of Baden-Württemberg *FCV and $H_2$ for green energy in EU cities and regions* estimate a value added of around 680 million euros by the year 2030. The Hydrogen council's vision is to create

around 30 million additional jobs globally as well as sales of approximately 2000 billion $ by 2050 should Hydrogen become a global energy carrier. Which could then serve up to 18% of global energy demand.

**Why Fuel cell Tram?**

Fuel cells have achieved enough maturity to support railway sector as they are already on tracks in Germany and is being considered for operation in France and UK as inter-city trains. A fuel cell approach in urban area has the following characteristics and benefits, compared to overhead caternary systems:

- Less expensive due to much less infrastructure;
- Less impacting on urban area surroundings and operations;
- Visually more attractive, specially in old city centres and tourist attractions;
- Extendable to additional locations without additional infrastructure;
- Operable in power outage, independently powered;
- Enabling other independently powered alternatives in future;
- Operating with zero emissions and less pollution at electricity production plants.

This approach comparing to traditional Overhead Caternary System (OCS) eliminates the need for the overhead catenary wires, support poles, notching the existing tunnels and electrical substations. Costs related to removing or trimming trees and relocating existing electrical and telecommunication infrastructure, etc. would be reduced or eliminated. In the case study, the elimination of 13 electrical substations, with pitch of about 2 km each, provide power in two electrical zones through 750 Volt power supply, one dedicated transformer in each substation for auxiliaries. Estimated saving is 30 million euros (cost of OCS infrastructure). Additionally, caternary-free approach could make use of abandoned existing tram tracks with reduced or no additional infrastructure upgrades or costs.

A Fuel-cell tram could continue to operate as long as stored hydrogen fuel is available during a power outage. On site hydrogen production during periods of low electricity demand or such new methods like solar hydrogen generation with pumped in waste water and other equipment powered by solar panels this system could be *off-grid*. In contract, the heaviest electrical usage in an OCS system is during peak daytime hours. Considering geographical coordinates of Brescia, there is solar power production potential of 50.17 kwh/m² a year. With today's solar technology in market and available area of almost 30,000m² in depot, approximate 1.5 GWh production of electricity is feasible, which could run on site green hydrogen production with $CO_2$ emissions of zero kg for each kg of $H_2$.

**Powertrain Technology**

By early 2018, the Alstom Coradia iLint fuel cell entered service on a 100 km route in Germany. This train has a maximum velocity of 140 km/h, range of between 800 and 1000 km, a capacity of 150 sitting or 300 standing passengers.

In Brescia situation, an urban light fuel-cell tram would meet these requirements. On line T1 (Pendolina- Tangenziale Fiera) with length of 11.4 km, 23 stops, 143 trips per day on both directions in the most critical scenario, 5 units are running with expected range of 350 km a day each and max speed of 50 km/h.

The consumed energy for a single run is 71 kWh (Fig.3) considering total trips and number of operating units, each tram should be capable to store at least 2350 kWh per day.

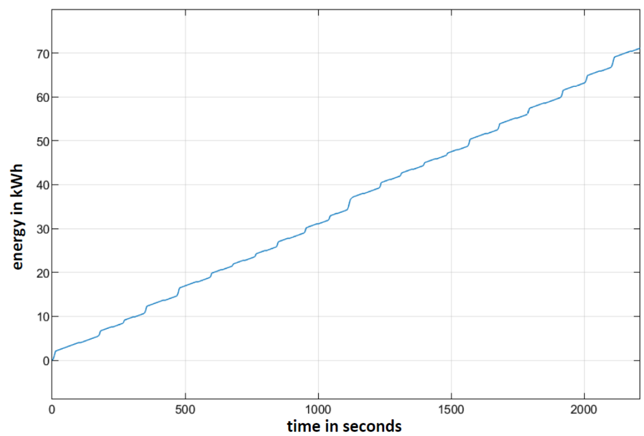


Figure 3: Energy consumption of a single run on studied line

The energy consumption on rail transport mainly depends on the rolling stock features, stop spacing and track profile. The local trains are heavier but they stop less frequently than the trams. The higher stop density includes more accelerations and braking than longer stop spacing (Fig.4). HyPM HD30 (33 kW) with efficiency map and technical data (Table 1) is the considered fuel cell component on the catenary-free tram. Battery and super-capacitors together are providing enough energy and power for traction and auxiliaries. On the other side, fuel cells and recovered braking energy (about 6.8 kWh) (Fig.5) are charging the battery with no sudden variation in output or a steady trend. By providing a balanced state of charge on our single branch battery, we need 11 fuel cells onboard. Hydrogen consumption of simulated tram is 0.3 kg/km and approximately 3.3 kg for one run.

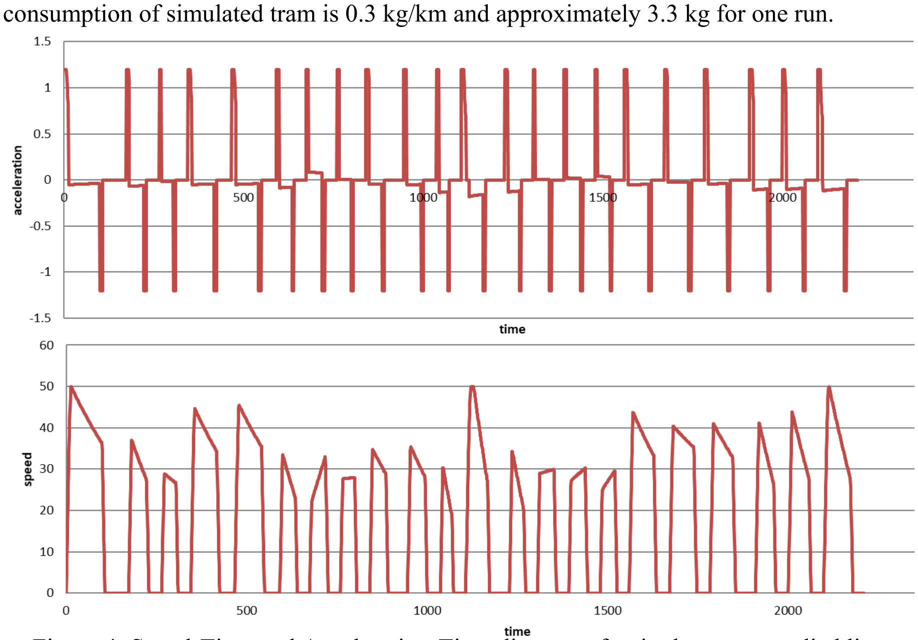


Figure 4: Speed-Time and Acceleration-Time diagram of a single run on studied line

Table 1: Parameters of HyPM HD30 (33 kW) Fuel Cell

| **Performances parameters** | **Unit** | **Value** |
|---|---|---|
| Rated (Max continuous) Power | kW | 30 (33) |
| Dimensions (L x W x H) | mm | 950 x 1630 x 265 |
| Mass | kg | ≤ 70 |
| Gravimetric Power Density | kW/kg | 0.5 |
| Operating Current | $A_{dc}$ | 0 to 500 |
| Operating Voltage | $V_{dc}$ | 60 to 120 |
| Peak Efficiency | $\%_{LHV}$ | 55 |
| Stack Operating Pressure | kPa | < 120 |

Carrying Hydrogen enough for a day would require massive hydrogen tanks, which would make the tram too heavy and will affect the autonomy, hence a refuel approach of less than 15 minutes at terminus after each cycle is a promising solution. Therefore, 10 kg of hydrogen compressed to 350 bar can be stored preferably in dual tanks for longer charging life cycle and reliability with total weight of 80 kg and a volume of 120 l each. Tanks are on the top and providing mechanical safety valves, which let the tram to release $H_2$ into atmosphere in case of high temperatures, furthermore they are able to indicate any leaking in the system.

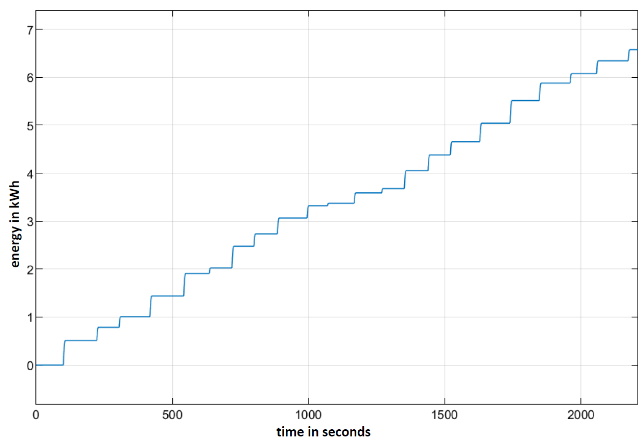


Figure 5: Energy recuperation in braking of a single run on studied line

In figure 6, you can see the suggested hybrid propulsion system, with a combination of super-capacitors, batteries (B) and fuel cell (Fc). The energy management system in hybrid powertrain enables the amount of needed power from each energy source to achieve high efficiencies, high performance and low consumption and take advantage of the components features. Batteries have high specific energy, and super capacitors (Sc) high specific power. Moreover, Sc provides energy for more charge/discharge cycles. In high demand of energy (Fig.2) Sc and B provide enough power and energy to supply traction motors. In low and very low energy demand phases recovered energy and surplus provided by the Fc with steady trend and no sudden output variation, charge B and Sc in cycles.

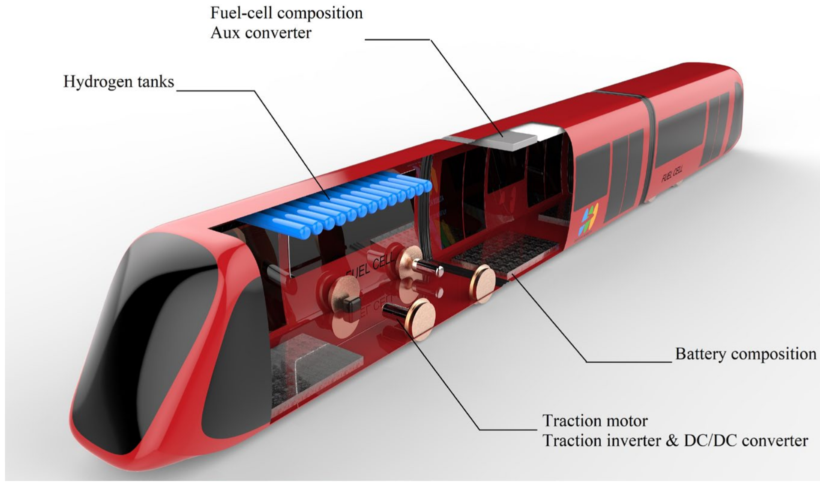

Figure 6: Schematic demonstration of conceptual simulated hybrid fuel-cell tram

**Conclusions**

The paper discusses new idea in a real-life hydrogen approach by taking into account Brescia tram project as a joint model for comparison, in light rail transport sector by highlighting benefits of using Fuel-cell tram instead of traditional catenary-based system. Generally, transition from pollutant electricity generation towards Hydrogen and Fuel-cell technologies would have direct and indirect benefits. Direct such as, zero local pollutant, reduced noise level, zero $CO_2$ emissions and increased used of renewables. Followed by indirect benefits, boosting research and innovation, attracting new businesses, creating new jobs, attracting skilled workforce, boosting local tourism, improving image as *green city* and increasing the quality of life. Hydrogen approach is perfectly in line with EU energy road map for 2050, reduction of emissions by at least 80% from their 1990s level, improving the security of energy supply and the flexibility of energy systems and infrastructures.

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