Trolleybuses in Smart Grids as effective strategy to reduce greenhouse emissions

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Abstract—this paper analyses the need of reintroduce electric transportation systems in countries that abandoned these modes and brings a methodology to assess the effectiveness of the electrification in terms of global warming mitigation. The potential interaction of grid connected vehicles and Smart Grids is presented among some ideas related to features that could be developed for massive transportation systems based on electric traction. As will be presented, Smart Grids could help to accelerate the electrification of transportation systems and the electrification could be used to accelerate the introduction of Smart grids. As reference cases in Colombia and Ecuador will be taken.

Keywords-component: Air pollution, Electric Vehicle, Trolleybus, Smart Grids, Transport sector Electrification.

I. INTRODUCTION: WHY ELECTRIFY TRANSPORT SECTOR

Latin-American as United Stated had an extensive network of trams and trolleybuses until the decade of 1950’s when mostly of these system were dismantled. Is infamous the case of National City Lines constituted by General Motors Corporation (GMC), Firestone and Esso Oil Company, with a common goal: the elimination of the electrical transport systems in United States’ cities, especially the network of trams and commuter trains, to make way for buses and cars with Internal Combustion Engines (ICE), as many experts[1] pointed out. These electrical transport systems provided services of recognized quality and popular acceptance, but afterward they were marked as obsolete and inflexible, while the obvious drawbacks of the Internal Combustion Engines (ICE) buses were ignored. This wave of “anti-development” quickly spread to Latin America, where major cities had, by the decade of 1950, intricate networks of trams and trolleybuses, that were rapidly dismantled as a reflex of United States (USA). Colombia was not an exception, by 1960, all trams and trolleybus lines of Medellin ended into the history. In Bogotá also the streetcar lines were replaced by buses lines and only few trolleybus lines survived until 1991. Nowadays both cities present high pollution levels, over the concentration recommended by experts [2][3], greatly due to the effect of the public transportation buses, and respiratory diseases are the principal illness that affect the citizens.

Among the advantages of transportation based on electric traction could be cited:

- Reduction of total energy consumption for their major efficiency.
- Oil products substitution and the possibility of use of renewable energy trough the grid.
- Reduction of noise levels, because electric vehicles are by fare quieter than the other buses.
- Reduction of pollutant that affects the health, because of the unique feature of zero emissions on street.
- Increase of the comfort, because electric buses have less vibration and finest acceleration.
- In countries where generation systems are based in plants with low emission of greenhouse gases (prevalence of hydro, wind, nuclear, etc), the electrification is an effective way to mitigate the global warming.

II. BUSES RETURN TO GRID

Bus Rapid System –BRT-, is a bus-based system with many physical and operational elements that brings higher capacity, better performance and a stronger image than regular buses [1], has gained notability because of its much lower infrastructure cost involved, compared to systems like Subways or Metros. BRT systems could be the key to a massive return of the buses to the grid, representing an important step to the electrification of transportation sector; typical BRT features are exclusive or preferential bus lanes, defined stations and pre-boarding payment, programmed schedule and high frequency dispatch. These features facilitate the operation of electric trolleybuses because they solve or minimize the major disadvantage of this kind of electric vehicles: inflexibility due to the connection to the overhead line.
Bogotá’s BRT system is called Transmilenio and nowadays it transports around a million people daily through 84 km of dedicated bus lanes. Transmilenio has become a reference to follow in the whole country, and other Latin-American cities. Electric traction was not considered for the buses and instead, diesel technology was selected, despite the Colombian hydro power predominance. On the other hand, the trolleybus has been successfully introduced into BRT systems in the cities of Quito and Merida (Ecuador and Venezuela), but despite these good experiences, it seems that they are been ignored in new systems all around the world. Only in few cases as Castellón (Spain), Lyon (France) and Bologna (Italy), BRT approaches are using Trolleybuses.

![Trolleybus](image)

Fig. 1. On BRT operation visual impact of the overhead line is reduced. Up left Mérida (Ven), Upright Bologna (Ita), DownrightCastellón (Sp). Pictures from Tbus.org, Trolleymotion.org and Merida 360°.

To get an idea of the amount of energy and emission savings involved in this kind of systems, the case of Trole Quito will be analyzed to conclude that is far more convenient use the money to promote electrification of transport system in countries like Colombia or Ecuador (with low emission grids), that grant electric cars in countries like United Kingdom (emission factor 0.45 ton/MWh) where coal still have an important share in the energy mix.

### III. MEASUREMENT OF THE EFFECTIVENESS OF GRANTS

The effectiveness of the grants to reduce greenhouse emissions cases could be assessed by the ratio between the lifetime tons of CO2 saved and the cost of the additional investments to electrify a system. This methodology is used to compare the grand for an electric car in the UK, against the investments required for trolleybus operation (instead of diesel) in Ecuador. As TABLE I presents, is about 65% cheaper to save greenhouse emissions supporting projects as the Trolleybus of Quito.

<table>
<thead>
<tr>
<th>Lifetime Grid emission (CO2 Tons)</th>
<th>20</th>
<th>800</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lifetime saved emissions (CO2 Tons)</td>
<td>32</td>
<td>1680</td>
</tr>
<tr>
<td>Differential cost to be Electric (USD)</td>
<td>9000</td>
<td>308000</td>
</tr>
<tr>
<td>Emission Reduction Cost (USD/CO2 Ton)</td>
<td>281</td>
<td>183</td>
</tr>
</tbody>
</table>

A scenario of high penetration of electric transport based on BRT systems in Colombia is presented in TABLE II, considering the implementation of BRT in all cities with more than 300,000 inhabitants and the conversion of all current and planned system.

### IV. BATTERY OR GRID CONNECTED BUSES?

One of the greatest barriers to introduce grid connect vehicles in a city, (also infrastructure costs), is the use of overhead lines, so always is the temptation of the battery or hydrogen buses to avoid the presence of poles wires and all other accessories associated. However, there is not commercial offer of articulated buses (18 m) with battery nowadays, mainly because the huge capacity that those batteries should have and so their extra cost. For public service, vehicle operation range is especially critic; because of batteries, small personal vehicles range is limited to about 160 km. In average, a BRT vehicle has to be able to cover at least 250 km per day. Another important aspect appears when comparing the cost of the required batteries for vehicles with the cost of the required infrastructure to supply trolleybuses; for example, USD 2,340.450 is the estimated cost of the 6.4 km extension of the Electric BRT of Quito “Trole Quito” [4], this money just cover batteries for 90 small particular vehicles, if the reference cost of LiOn value given by U.S Department of Energy [6] of USD 33,000 is taken. Final version of the

| Reduction of diesel consumption | 15.1% |
| CO2 Reduction (national) | 4% |

![Table Image](image)
The paper will discuss the similarities and differences between charging infrastructure for electric buses and the required for trolleybuses, as another aspect related to battery cost and weight, using state of the art and projected data.

V. SMART GRID VEHICLE FEATURES

The implementation of trams and trolleybuses has a lot of advantages in addition with the integration of Smart Grid technologies in a local grid, improving the performance in comparison with the traditional (V2G) initiatives. Some of these features are:

A. Electrification of existing transportation system in established cities.

To current supply and demand concerns, with electricity demand increasing, and in many cases infrastructure under-investment, the reintroduction of electrical transportation modes in established cities represent an additional challenge. In this case demand management, efficient consumption and peak load shifting will be key, and so the Smart Grid as support. Mitigation of Power Quality disturbances occasioned by the connection of massive transportation systems on weak networks is also a challenge; considering their high nonlinear and fluctuating characteristics, these represents a potential source of harmonic distortion, voltage fluctuations and flicker respectively. Also a better use of the installed capacity of the new substations could be achieved, during nighttime for example, charging electrical vehicles or minibuses.

B. Management of regenerative Energy

Regenerative brake is one of the remarkable features of electric machines, impossible to be performed by an ICE. In fact, this is the key of the fuel economy of hybrid vehicles. When a grid connected vehicle is braking the electric energy generated could be stored either in batteries or ultracaps, or could be feedback to the grid where this energy could be used by other vehicle, or even more, trough reversible substations could be sent upstream, to other loads or users. This wide spectrum allows reduce the dissipative braking –usually in resistors- increasing the net efficiency of the system.

Reversible substations are used currently in the metro of Bilbao, Spain. This substations includes a DC-AC converter that allows send the regenerated energy to the AC network when the DC system cannot receive this energy. Usually the consumer consists in other vehicle starting. Smart Meter must be used when energy is feedback to the grid. In stationary energy storage case ultracapacitors had demonstrated to perform very well for regenerative energy. Fixed in certain points of the route, and connected to the overhead line through a converter, ultracapacitors allows energy storage when the network is not receptive; when another vehicle is demanding energy from the grid, the ultracapacitor energy is taken, reducing network peak demand; this feature has been used in metros and commuter trains as Dresden (2002), Madrid (2003) and Cologne (2003). Besides energy savings, a voltage control mode could be performed in a similar operation mode of static compensators.

Onboard storage devices allows both energy savings and off-wire operation for some kilometers, but will depend on particular cases whether stationary or onboard application will perform best, taking into account vehicle, network and operative characteristics. A smart control could coordinate and supervise the operation of the vehicles, to increase coincidences between brakes and starts and then reducing dissipation on heat.

C. Grid for buses, grid for users

As electrification implies the installation of overhead lines, it would be interesting to think that this new lines could be used both for feed the electric transportation system and as distribution network for users around the route. In this configuration the distribution of electricity would be based in a two wire DC bus, and residential users could be supplied trough DC-AC inverters and the voltage stabilization and filtering could be provided by Static Compensators based on ultracapacitors controlled by converters (see fig 3.), representing a convenient solution for electrification of small towns along routes of commuter trains.

![Fig3. Some features of grid vehicles on Smart Grids.](image)

As a matter of electrification, optimization of infrastructure demand management and Power Quality will become a need, and then Smart Grids will have an important role.

D. Mass transportation bus for a Smart Grid

Even though the effort to improve the capacity of energy storage devices such batteries, fuel cells and ultra-capacitors that eventually will make unnecessary the use of the overhead line, this expectation should not be argued to delay the electrification of transportation systems. It is most likely that systems in the future will still retain some of the overhead
line, for example in high slope gradients where the consumption of energy is important. In fact as other authors have pointed out [6], in the future mostly of land-based massive transportation systems will remain grid connected. The decision to withdraw a section of the overhead line has to consider the extra cost related to reduction of the lifespan of the batteries, the energy losses related to the process of charge and discharge, and the cost of the infrastructure required for fast charge. This also must be considered for hydrogen and plug-in hybrid technologies.

A Proposed bus for development could feature (Fig 3):

- **Short Term**: High Power energy storage, as an ultracapacitor to allow optimal regenerative performance and supplies quickly power for startups.
- **Long Term**: High Energy storage, as batteries or a fuel cell that can be charged gradually from the overhead line during operation or by a plug during the night.
- Energy management system, which decides whether and how the energy regenerated is stored or feedback to the overhead power line and control battery charge. In certain cases as black outs, battery stored energy to could be injected to distribution network.

This vehicle will be designed according to the needs in each case, depending on the independence desired for the overhead line, the driving cycles and the topography of the city.

This Smart Grid Trolleybus would be able to decide if takes the energy from the storage device or the net, depending on conditions as hourly prices of the energy, peak demand, system load among others.

A huge advantage of trolleybuses is its adaptability, if batteries reach an outstanding development with a noteworthy cost reduction in a near future, the trolleybuses can be easily modified to use it. Modern trolleybuses already feature storage devices such batteries in the case of Rome and Vancouver, and ultracapacitors in China, Italy and Germany.

VI. Conclusions

Massive plans for electrification of massive transportation system could be started now; development of batteries or other technologies to storage energy are not a condition to delay this important transformation with huge potential in US, Latin-America, and in general on developing countries. BRT systems are especially easy to electrify using modern trolleybuses that features small energy storage devices for an increased reliability and off-wire operation for few kilometers, a full range operation in batteries is neither technical nor financial feasible and will remain so for many years.

As for integration of renewable energies, distributed generation, demand management, Electric Vehicles among and many others features, Smart Grids could find a niche in mass transportation systems based on electric traction as trolleybuses, trans commuter trains metro and high speed trains.

Resources to promote electric vehicles as a way to deal greenhouse emission should be reoriented to promote the electrification of mass transportation systems in regions or countries where the electricity is produced with low emissions.

REFERENCES