

Design and prototyping of a rapid-charge electric bus for urban passenger transportation

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Summary

Collective transport means must obviously be designed and used to minimize their environmental impact. The way to reach this aim, however, is certainly not obvious, since it must consider a number of aspects connected both with the fulfilment of users' expectations in terms of number and frequency of vehicle stops, and with the energetic and economic balances of the service offered.

Taking the lead from these consideration, one of the authors previously developed a easy-to-use tool for the energetic assessment of alternative transport means to be used on a given route. Here, this tool is put in use by the authors for the design and prototyping of a rapid-charge electric bus for urban passenger transportation, within a close cooperation with an Italian Transportation Authority.

Keywords: Electric vehicle, Public transportation, Fast Charge, Lithium-ion battery

1 INTRODUCTION

Collective transport means must obviously be designed and used to minimize their environmental impact. The way to reach this aim, however, is certainly not obvious, since it must consider a number of aspects connected both with the fulfilment of users' expectations in terms of number and frequency of vehicle stops, and with the energetic and economic balances of the service offered.

Therefore, for a given service, there are a number of possible options to be compared, varying in terms of vehicle dimension and payload, powertrain design and management, fuel used, and so on [1].

Limiting the attention on road transport means, electric propulsion is one of the most promising alternatives, but may use a number of different technologies, also including hybrid configurations (using a combination of an ICE and an electric motor) [2-6], and/or alternative fuels, both based on renewable or fossil sources [7-9].

Author gained a huge experience modelling all these possible alternative solutions and still are convinced that electric mobility is certainly the most effective solution in a mid-term future within urban mobility applications.

A full and effective comparison among the given alternatives is only possible on a Well to Wheel (WTW) basis, to take into account potential benefits for the community connected with different energy vectors use.

Taking the lead from these consideration, one of the authors previously developed a easy-to-use tool for the energetic assessment of alternative transport means to be used on a given route [10].

The tool starts from the definition of vehicle cycle and mission on a GPS web-based interface. Then it automatically defines vehicle mission and compares possible solutions (among conventional vehicles, BEV, HEV, FCEV and PHEV) modelling their Tank to Wheel behaviour on the defined mission.

Finally, the comparison is extended on a Well to Wheel basis, making use of numerical and experimental results about Well to Tank emissions and energy consumption gained by the Joint Research Centre of the European Union [11], to take into account potential benefits for the community connected with different energy vectors use.

Here, this tool is put in use by the authors for the design and prototyping of a rapid-charge electric bus for urban passenger transportation, within a close cooperation with an Italian Transportation Authority.

2 Application frame

The procedure was applied to the design of an urban bus which will make its service within the historical center of L'Aquila, in Italy. The possible path of the vehicle was designed and georeferenced according to a simple GPS based procedure. Vehicle stops were positioned as well, according to Figure 1. The developed SW tool [10] permits the derivation of the altitude profile of the mission: results are reported in Figure 2.

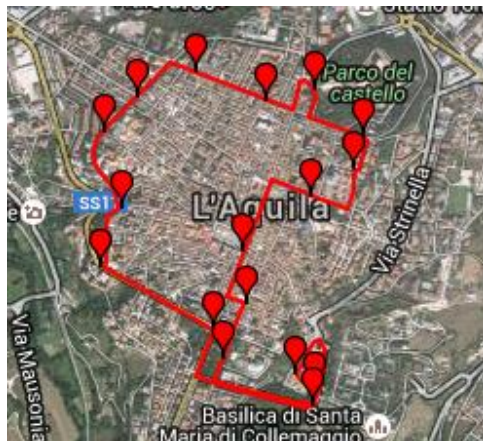


Figure 1 – Service Path

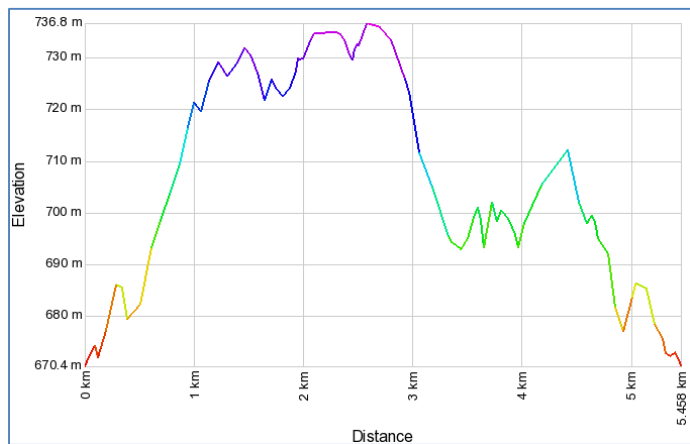


Figure 2 – Path altitude profile

Moreover, it was considered that Italian National Government (within a grant with ENEL, the main Italian electric services company), is setting up in the city of L'Aquila a smart city plan which includes the diffusion of electric mobility: the plan will lead in the next months to the installation of 50 electric charging points throughout the city. One of these will be a rapid charge charging station and will be installed at the bus terminal, just at the start of the path represented in Figure 1. The charging station will have a maximum charging power of 43 kW and could be used both for AC charging, and for DC Chademo compliant charging.

This occurrence makes it possible to recharge the designed bus (for a limited time) at the end of each service cycle (whose length is about 5.5 km, according to Figure 2).

3 Mission Definition

According the procedure fully described in [10], the SW tool then proceeds to vehicle cycle and mission definition, according to some data given from municipal administration (max vehicle speed and acceleration stops durations and cycle frequency). The Results of these design phase are reported in Figures 3.

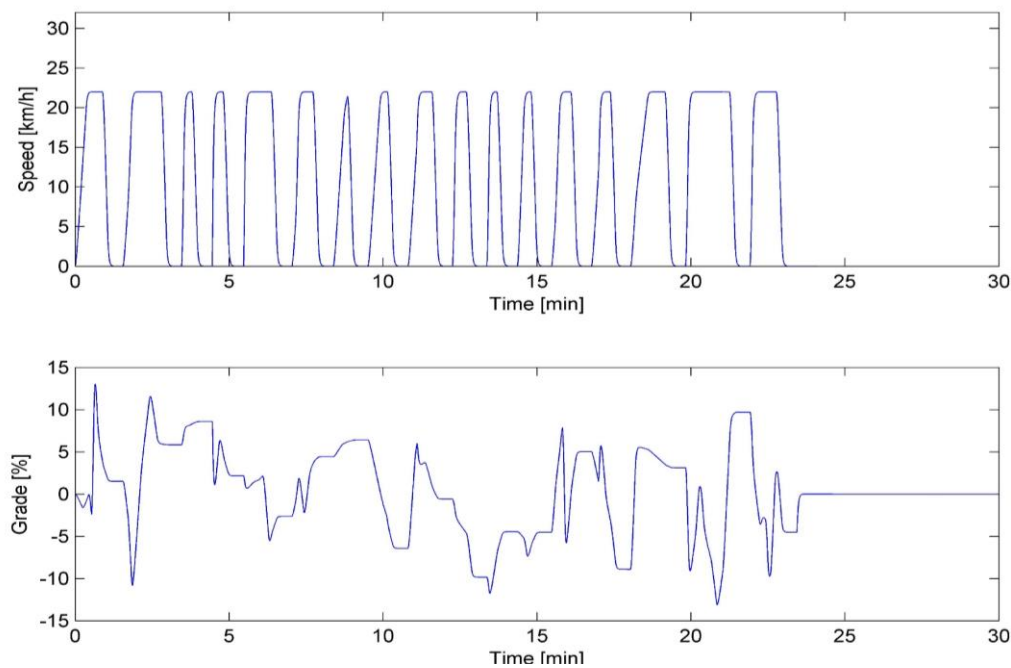


Figure 3 – Vehicle cycle

Each vehicle cycles lasts about 23 minutes and is repeated 24 times during the daylight vehicle mission. Between each 2 successive cycles, a period of about 7 minutes is therefore available for rapid charging operations. These charging phases, in the following simulations, will be realized at 1C max current, leading to a full charge duration of approximately one hour. Therefore, at each stop of the bus at the terminal stops, one can imagine to recharge approximately the 10% of max battery pack capacity: the charging power required, as well as the recharged energy obviously depends on battery size.

4 Vehicle revamping

The present design and prototyping activity has been taken ahead with the cooperation of L'Aquila Municipal Transportation Authority (called AMA). AMA currently holds 4 series hybrid buses named Horus by EPT. One of those buses (which were bought in 2008) is no longer making any service since its Diesel-fed turbo-gas APU needs maintenance and OEM is expired.

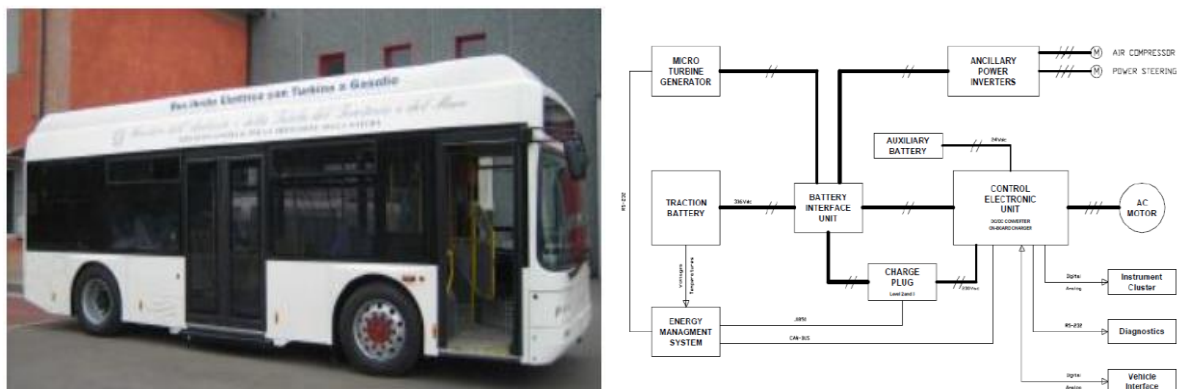


Figure 4 – EPT Horus Bus and its OEM power electronics schematic

Taking the lead from these considerations, a cooperation between AMA, University of L'Aquila and ENEA has started which will lead in the following months to the realizations of a fully electric rapid charge bus.

This prototype will make use of particular Li-ion cells specifically designed by ENEA for rapid charging applications and equipped by a Battery Management System originally designed by Pisa University in cooperation with ENEA [12] (see Figure 5).

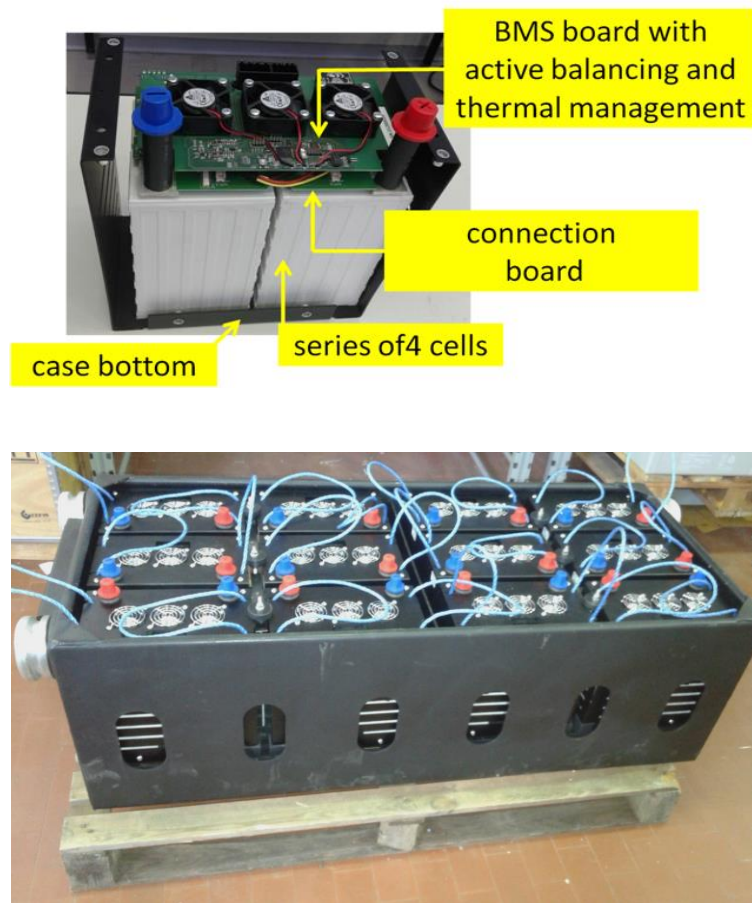


Figure 5: Design and final assembly of battery modules by ENEA

The battery system manufactured in ENEA is made by 12.8V modules 12.8 V – 60 Ah, obtained connecting in series 4 lithium-iron-phosphate cells. These modules may be connected in series and in parallel to have required drivetrain voltage and power.

The modules were successfully tested by ENEA for rapid charging applications. The results of these activities are reported in [13].

5 Modelling results

Here the results of modeling activities are reported. Model used was completely developed by one of the authors and is fully described in [10].

The model was firstly applied to the simulation of the original OEM Diesel-fed series hybrid bus (referred to as “HYB” Configuration). The results of this modeling activity are reported in Figures 6 to 8.

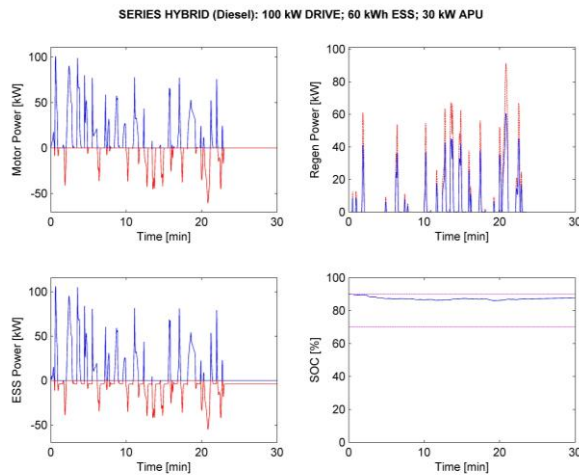


Figure 6: HYB: Cycle simulation

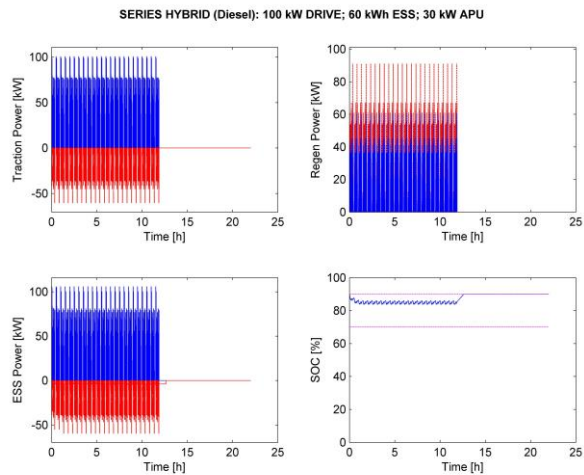


Figure 7: HYB: Mission simulation

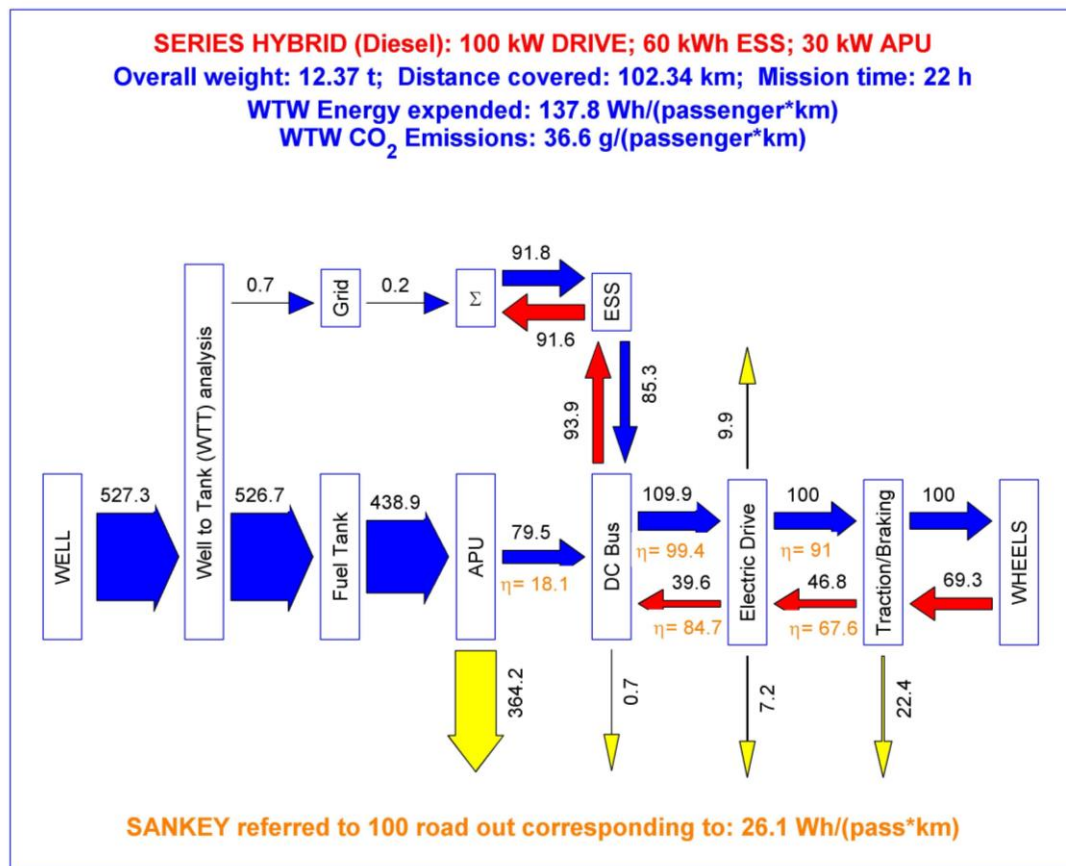


Figure 8: HYB: Overall energy performances

Then a first full electric version of the vehicle is obtained (referred to as “BEV” Configuration) removing its APU and its on-board Lead Acid Battery pack and substituting it with standard high capacity Li-ion cells available on the market. The overall size of the Li-ion battery pack was designed to fulfill the complete daily mission (24 cycles) of the vehicle: 102 kWh. Slow battery charging (1/8 C max current, with a normal 16 kW power charger) is simulated at the end of bus daily mission. The results are reported in Fig. 9 to 11.

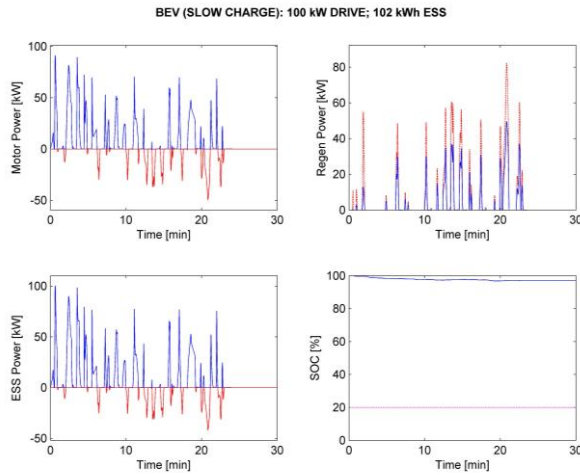


Figure 9: BEV: Cycle simulation

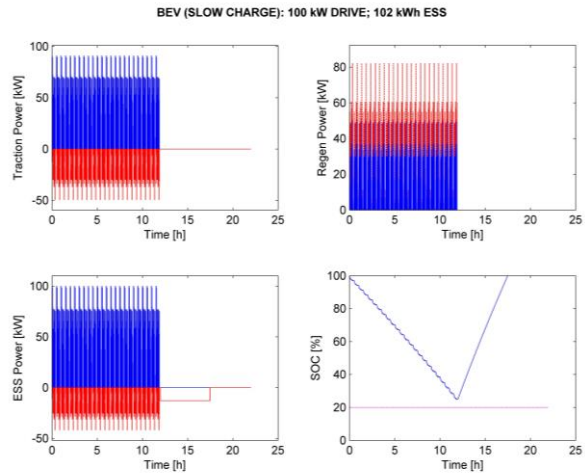


Figure 10: BEV: Mission simulation

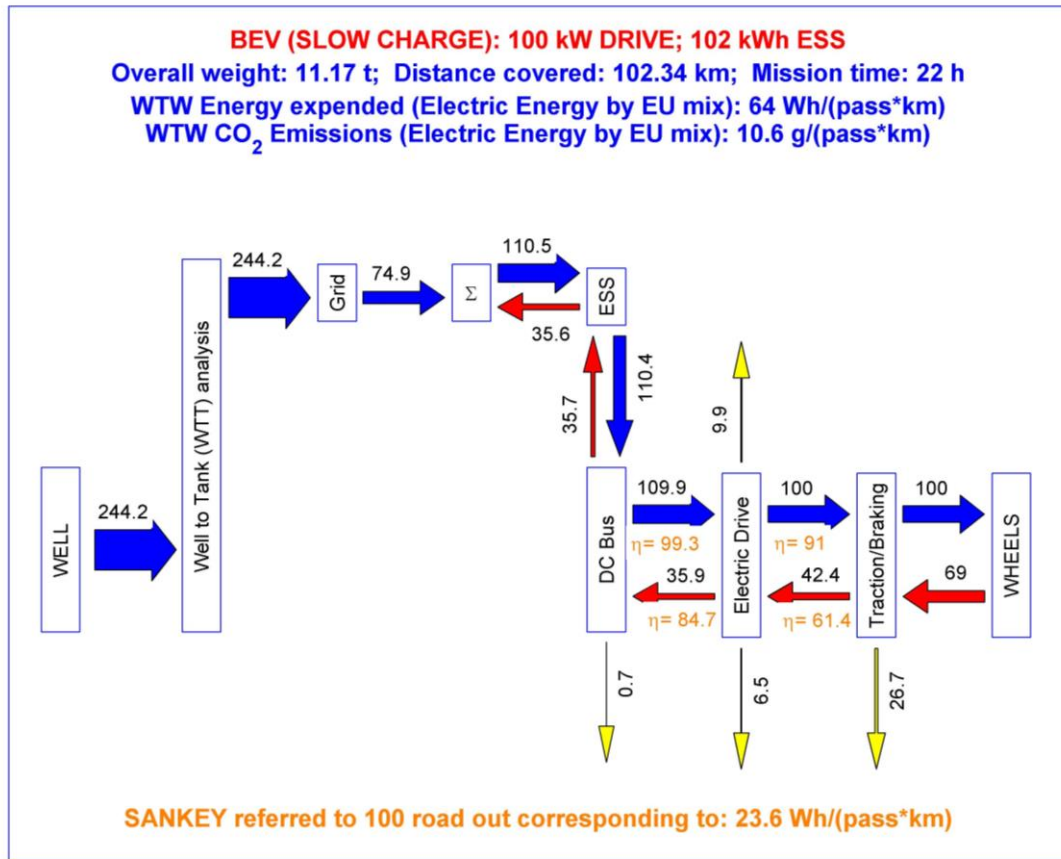


Figure 11: BEV: Overall energy performances

Lastly, the Battery pack was substituted by a number of the Li-ion modules designed by ENEA. Their dynamical characteristics were simulated in the model making use of the detailed testing results reported in [13]. The overall size of the Li-ion battery pack was customized for frequent rapid charging applications, so permitting to save costs, transported weight and therefore energy requirements: 15 kWh. 5 minutes lasting rapid charging operations (1C max current, largely available at bus terminal, where a 43 KW rapid charger

will be installed) are simulated at the terminal at the end of each bus cycle): during this charging phases, the pack approximately recovers 10% of its full capacitance, which almost corresponds to the energy spent during its 5.5 km elementary cycle. The results of this modeling activity are reported in Figures 12 to 14 (referred to as “BEVRC” Configuration).

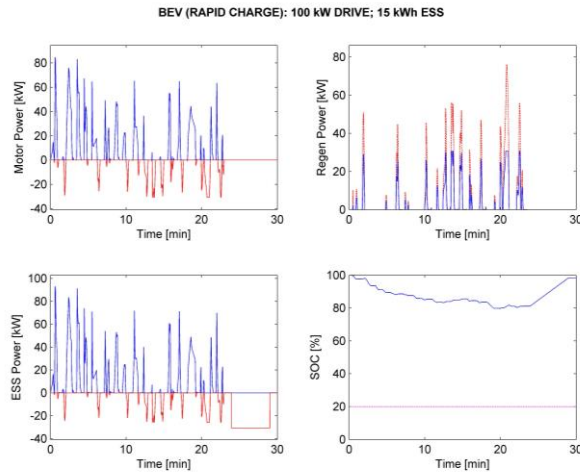


Figure 12: BEVRC: Cycle simulation

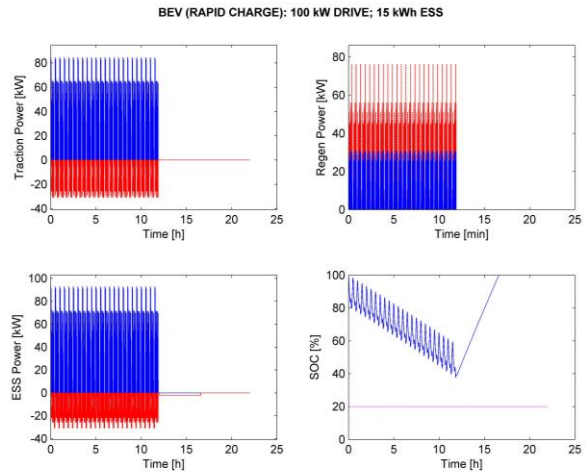


Figure 13: BEVRC: Mission simulation

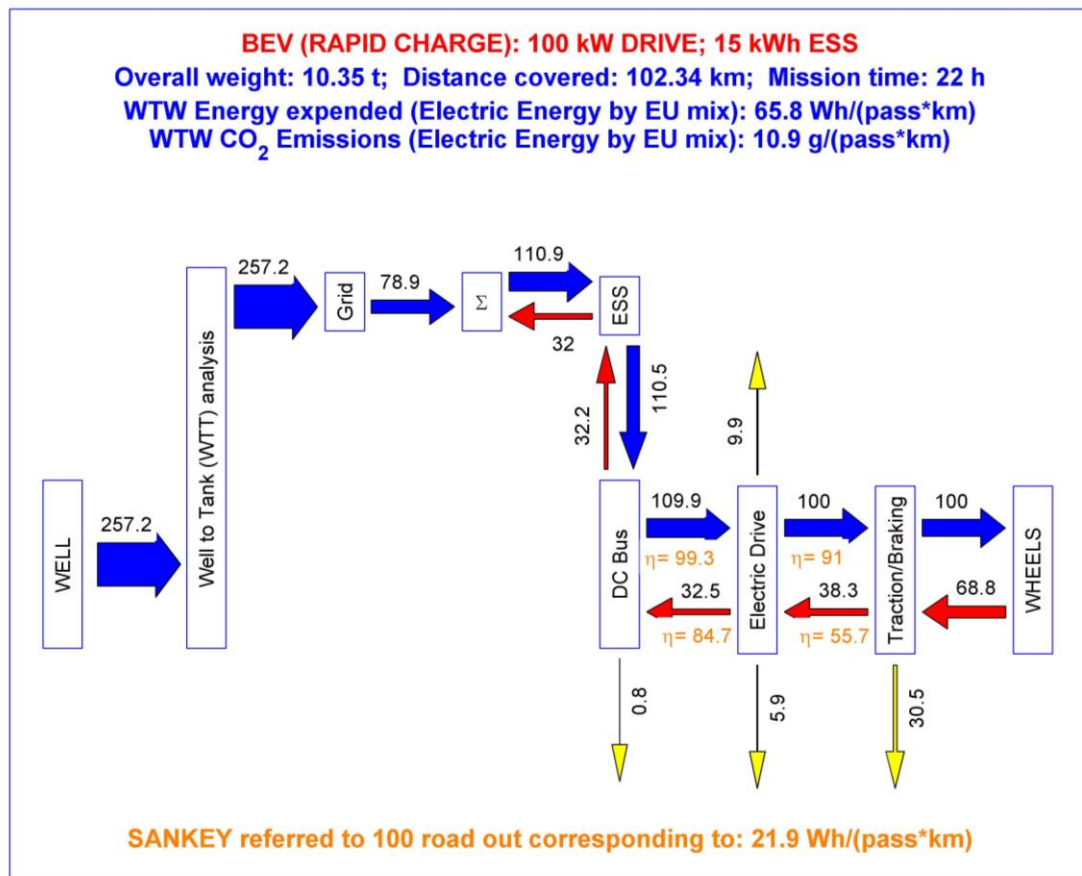


Figure 14: BEVRC: Overall energy performances

Looking at the represented results, one may think that a 15 kWh pack is certainly still a bit over-dimensioned for the specific application. Anyway, a further reduction in the installed capacity could lead to problems during a 1C charging, because the energy spent during the elementary cycle may not be recovered during the stops.

As already underlined, the SW permits the comparison of the performances of the three simulated vehicle configurations on a Well-To-Wheel (WTW), also making use of reliable and up-to-date data about Well-To-Tank (WTT) CO₂ emissions and energy consumption reported in [11]. Comparison results are reported in Figures 15 and 16.

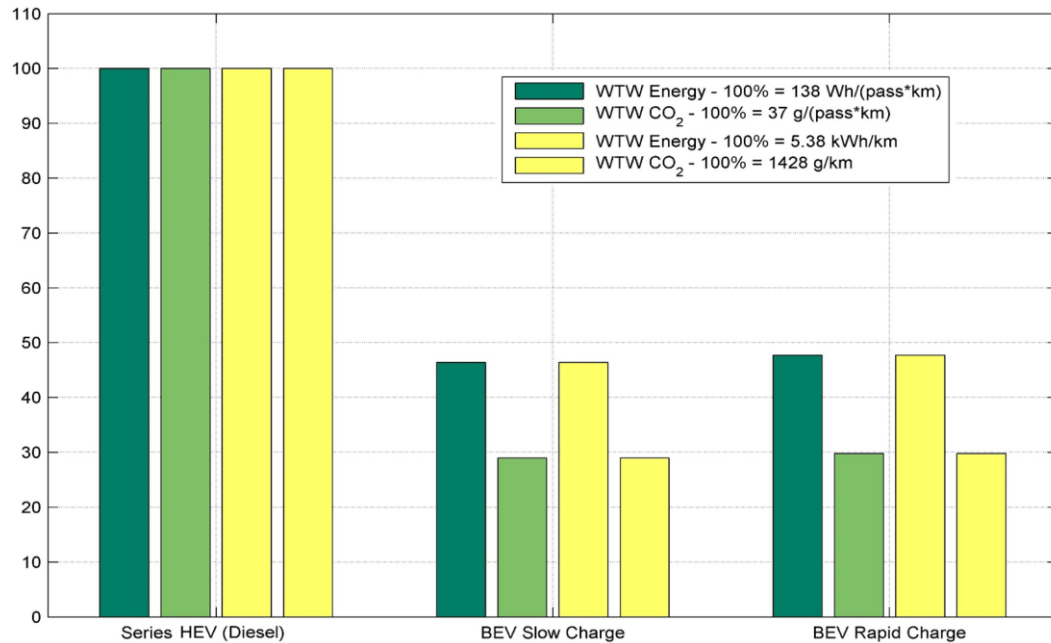


Figure 15: Results comparison

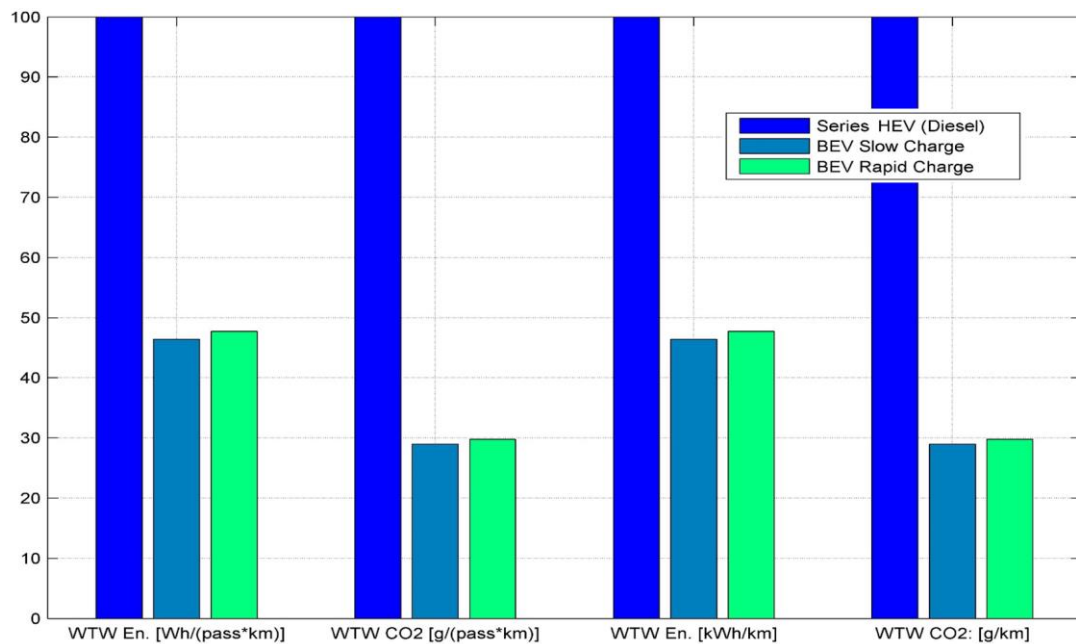


Figure 16: Results comparison

A clear convenience in using a fully electric vehicle instead of a hybrid one for this urban application was demonstrated.

Rapid charging Battery electric vehicle are fully successful in limiting the installed capacity of the battery pack to approximately 1/6 of the energy needed for its overall daily mission. Energy losses due to rapid charging are balanced by the energy saving connected to the lower vehicle weight.

Advantages are clear, on the other end, with respect to the limited costs of the rapid charging solution. Cost saved for the battery pack are not balanced by the additional costs of the rapid charging infrastructure, which is certainly compatible with those built for cars' application, not requiring significant power output (like those needed for high capacity Electric buses). Moreover, the costs of the infrastructure may be divided by the number of buses using it and may be depreciated in a much longer period (20 years) with respect to battery packs (2-3 years for heavy duty transportation applications).

6 Conclusions

A tool for the energetic assessment of alternative transport means to be used on a certain route, developed by one of the authors was here applied within the frame of a cooperation with L'Aquila Municipal transportation authority aimed to the design of revamping of a hybrid bus. The tool starts from the definition of vehicle cycle and mission on a GPS web-based interface and automatically defines vehicle mission and compares possible solutions (among conventional vehicles, BEV, HEV, FCEV and PHEV) modelling their Tank to Wheel behaviour on the defined mission.

The comparison is extended on a Well to Wheel basis, to take into account potential benefits for the community connected with different energy vectors use. Model also makes it possible to obtain detailed Sankey diagrams individuating energy fluxes on board. Results clearly show the capability of the proposed tool in vehicle comparison on a WTW basis, as well as the preference for proposed Rapid chargeable bus configuration with respect to higher mileage solutions, especially in historical city centre applications.

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