Energy evaluation of urban railroad systems

Massimo Ceraolo
DESTEC
University of Pisa
Pisa, Italy
massimo.ceraolo@unipi.it

Aljon Kociu
Dept. of Industrial Engineering
University of Florence
Florence, Italy
aljon.kociu@unifi.it

Giovanni Lutzemberger
DESTEC
University of Pisa
Pisa, Italy
giovanni.lutzemberger@unipi.it

Luca Pugi
Dept. of Industrial Engineering
University of Florence
Florence, Italy
luca.pugi@unifi.it

Francesco Giuseppe Quilici
DESTEC
University of Pisa
Pisa, Italy
francesco.quilici@phd.unipi.it

Alessandro Ruvio
DIAEE
University of Rome, la Sapienza
Rome, Italy
alessandro.ruvio@uniroma1.it

Gaetano Zumbo
GEST S.p.A.
Responsabile Manutenzione Impianti fissi, Innovazione e Sviluppo
gaetano.zumbo@ratpdev.com

2024 IEEE International Conference on Electrical Systems for Aircraft, Railway, Ship Propulsion and Road Vehicles & International Transportation Electrification Conference (ESARS-ITEC) | 979-8-3503-7390-5/24/$31.00 ©2024 IEEE | DOI: 10.1109/ESARS-ITEC60450.2024.10819795

***Abstract*—The paper presents a techno-economic analysis regarding the simulation of conventional and battery-operated tramways in the urban contexts of cities having a very high historical value. In these sensitive sites the adoption of innovative storage technologies can contribute to further improve efficiency and sustainability also in terms of potential impact on the surrounding cultural and historical heritage. In this work, a benchmark case study for the city of Florence is reported. This study is a preliminary work of a larger joint study of the Italian universities of Pisa, Rome, and Florence devoted to the development standardized common simulation procedures and tools. Trainrunner Studio and Modelica software packages have been utilized to carried out simulations.**

Keywords—battery operated tramways, Digital Twins, multimodal systems

I. Introduction

Recent developments in storage technologies for the tram sector are driving the adoption of on-board storage solutions, enabling battery-operated tram services. These services benefit from rapid recharging, either at fixed points or on the move, using dedicated infrastructure or short electrified sections. The benefits of these technologies, particularly in terms of reducing environmental impact, are particularly evident in sensitive cultural areas where the installation of overhead lines is not only costly but also poses a risk to the surrounding heritage.

The socio-economic benefits for communities in historic cities such as Florence have been extensively studied in studies by Budiakivska [1] and Grossi [2], which evaluated the economic viability and wider community benefits, including increased vitality for both central and peripheral areas. As a result, Florence has become a focal point for substantial investment aimed at expanding public transport networks while experimenting with innovative and sustainable solutions [3]. As such, it serves as a recognised benchmark for the implementation of battery-powered trams and intelligent energy management systems.

In the academic literature, there is a growing focus on developing frameworks for simulating on-board and wayside storage systems that support regenerative braking. A notable contribution in this area is the comprehensive study by Tostado [4]. The increasing availability of advanced industrial products, such as battery trams [5] and advanced power plants [6], is further stimulating this research interest.

Authors from Pisa and Rome have collaborated on studies involving simulations of Rome's suburban trams [7][8], while researchers from the Universities of Pisa and Florence have worked together on simulations of trams [9], trains [10] and storage systems [11]. The aim of this work is to apply this shared competence to the study of a realistic benchmark represented by two existing lines of the Florence tramway, as illustrated in Fig. 1:

- T1 from the parking exchanger of Villa Costanza to Careggi Hospital.
- T2 from Florence Airport to the city center (Piazza dell'Unità).

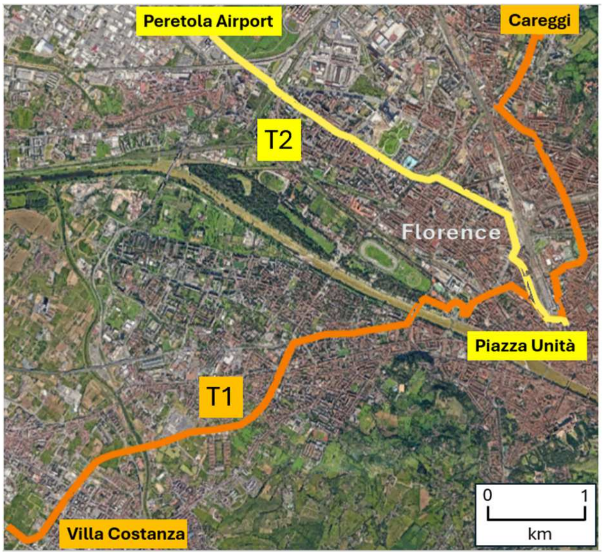

Fig. 1. Florence Tramway Lines T1 and T2

With respect to this benchmark, the authors have developed some models regarding the application of purely battery-powered systems. The aim of this activity is not to strictly evaluate the economic feasibility of the investigated solution, but to demonstrate the potential use of the proposed tools, their synergies resulting from the mutual validation of commercial tools with customised digital twins developed with bond graph-oriented tools such as OpenModelica or Simscape.

II. THE SIMULATION TOOLS

A. The simulation tool

Trainsrunner studio™ is a commercial tool currently adopted by University of Rome both for modelling and cross-validation of internal customize codes. This tool has been used to perform dynamic and cinematic simulation of trams on Line T1 and T2 [12]. It supports power supply network design through circuit diagrams and integrates tools for evaluating simulation results, system performance (including timetable and signaling), power supply operation, thermal component behavior, and safety in short-circuit scenarios.

The running resistance FR is calculated with the empirical formula (Davis formula) $FR = A + Bv + Cv^2$, where A, B and C (in our case $B = 0$) are constants, and v is the instantaneous speed.

The grade resistance FG is calculated with the formula $FG = m\ g\ i/100$ where m is the mass of the trains (tare plus payload) and i is the slope of the line in %.

The curve resistance FC is calculated with the empirical formula $FC = mCR/abs(radius)$, where m is the mass of the trains (tare plus payload), CR is an empirical coefficient and $radius$ is the curve radius. FC=0 for straight lines.

The vehicle chosen for the simulation of the tramway line is Sirio. The vehicle is equipped with four three-phase asynchronous electric motors. The drive is equipped with a rheostat for braking energy dissipation required in non-receptivity conditions of the electrical system.

The traction and braking characteristics of the tram are highlighted in Fig. 2 and its parameters, used for simulations, are reported in TABLE I.

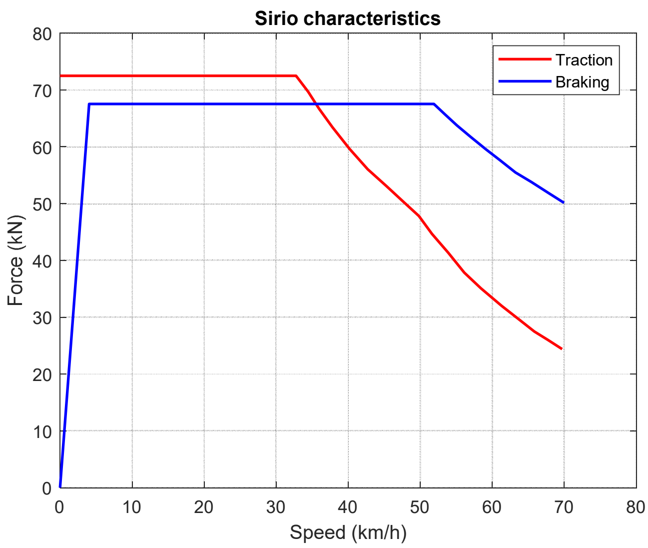

Fig. 2. Traction and braking features of Sirio tram

TABLE I. SIRIO TRAM PARAMETERS

Mass full load (kg)	58808
Resistance Coefficient A (N)	1442.3
Resistance Coefficient C (N*(s/m)2)	8.796
Coefficient curve (N*m/kg)	0.0834
Auxiliary loads (kW)	30
Max Speed (km/h)	50
Max Acceleration (m/s2)	1
Max Deceleration (m/s2)	1
Efficiency (traction and braking)	0.86

B. Storage system

The modelling of the storage system is essential, as it necessitates a detailed description. In this way, the commercial tool above presented simply shows the storage modelled as a simple energy reservoir, which is not sufficient to correctly achieve storage sizing. Furthermore, to see the evolution over time of electrical quantities such as voltage, current, power, energy and SOC, it is necessary to use a much more detailed dynamic model, developed in another simulation tool. For these reasons, the open-source software OpenModelica was used, having as input the results from the simulation tool above described.

So the two tools are proposed in sinergy, the commercial tool, offer the advantage of a validated dynamic model of the train, while the customized model can produce results with a higher level of detail for what concern behaviour as example of storage technologies. This is a very important feature since this sinergy make possible a detailed analysis of component that are currently the object of continuos research.

The detailed model of the storage system adopted is the equivalent circuit model and consists of the electrical part only [13][14]. The thermal behaviour of the battery was not considered, since it was not necessary to go deep into this level of detail. In particular, the battery was modelled as one R-C block, with the parameters defined from the experimental tests carried out on a cell which was then used to size the battery pack. This type of modelling procedure also allows losses during battery operation to be considered [15].

Finally, the charging profile used for the simulations is shown in Fig. 3 and is taken from [16]. The charging power has the beginning portion with almost constant power at low SOC, which then gradually decreases as it moves towards higher SOC, where the voltage limits are reached.

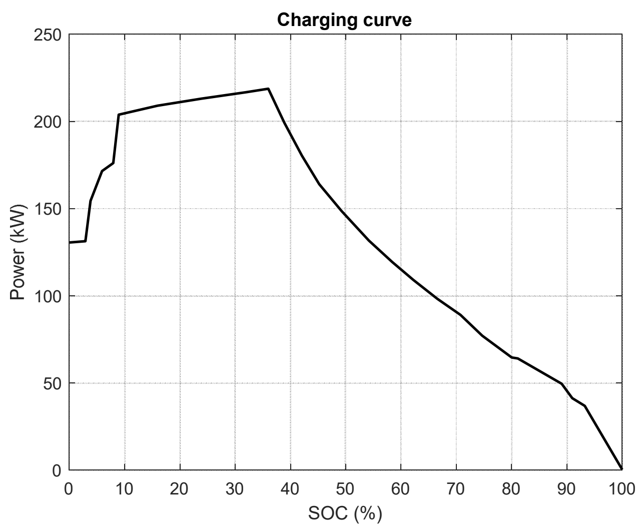

Fig. 3. Charge curve used to recharge the tram battery

Fig. 4 shows the system used in OpenModelica to analyse the evolution over time of the battery behaviour. The power profile to be served was obtained from simulations carried out with Trainsrunner studio and extended to the entire time span of the working day.

The current demand by the tram is provided as an input to the battery model as the ratio between the required power and the voltage at the battery terminals. In addition to the electrical circuit, there is also the part relating to the implementation of the electrical recharging, where the power-SOC recharging curve is introduced by means of a look-up table: the SOC measured over time is reported at its input and the corresponding electrical signal is at its output, enabled or not by an internal logic.

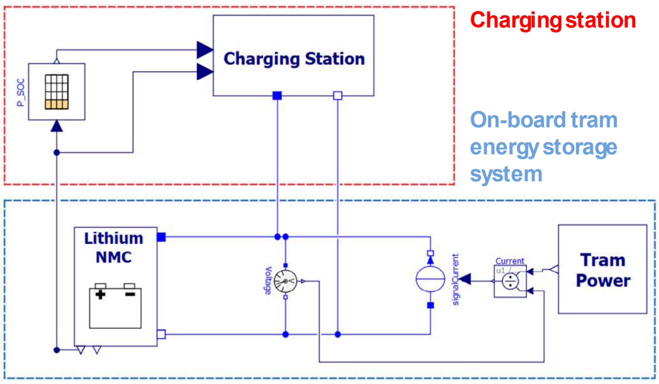

Fig. 4. OpenModelica model for the dynamic simulation of the energy storage system

III. THE CONSIDERED CASE STUDY

A. The considered lines

The models of the T1 and T2 lines were constructed based on the information obtained thanks to the available data from Institutional and Industrial Partner that has supported this work. After knowing the partial and final sections in metres with their respective heights, the presence of straight sections or curves, the longitudinal and altimetric profile of the two lines was obtained. The speed was limited to 50 km/h, while the maximum speed in bends was defined accordingly to their radius. The outward and return routes were perfectly identical. TABLE II. shows the characteristics of each line. The dwell time at the terminals is between 200 and 300 seconds, while the dwell time at the stops is set at 20 seconds.

TABLE II. LINES CHARACTERISTICS

Feature	Line T1	Line T2
Total length (km)	22.9	10.7
Maximum altitude difference (m)	26.7	21.9
Duration (min)	69.3	43.6
Stops number	24	13

B. Energy flows

Using TrainsRunner Studio software, the tram's kinematic parameters and power requirements were calculated. The software uses inputs such as drive efficiency, topography, stops, and electromechanical properties of the rolling stock to generate speed and power demand profiles during traction and braking. For example, Fig. 5 shows the outputs for the T1 line, while TABLE III. presents the main numerical output values for both lines.

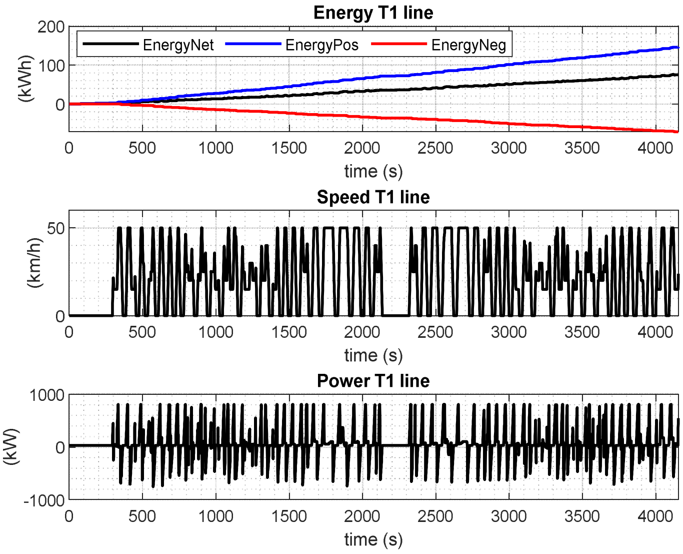

Fig. 5. Energy (divided in net, positive and negative quantities, at top), speed (at the middle) and power (at the bottom) of T1 line

TABLE III. ENERGETIC EVALUATION OF T1 AND T2 LINES

Quantity	Line T1	Line T2
Net energy (kWh)	75.8	42
Delivered energy (kWh)	146.8	79.5
Recoverable energy (kWh)	71	37.5
Max power (kW)	808.7	809.1
Mean power (kW)	65.7	57.9

IV. STORAGE SIZING

For the purpose of this study, it was assumed that the tram serving line T1 would make 8 full trips per day, evenly divided between the morning and the afternoon workshifts, with one stop to recharge the battery. The same approach was used for the T2 line, but the number of full trips per day was assumed equal to 14. The final case study defines what needs to be done to convert electric trams to battery trams.

Four case studies were analysed, depending by the type of recharging adopted. The aim was therefore to observe the variation in the sizing of the storage system, considering the influence of the charging power:

- Case study 1: first half of trips, 2-hour of fast recharging at 220 kW at the depot, second half of trips, full recharging at night.
- Case study 2: first half of trips with fast recharging at the Villa Costanza (T1) and Peretola (T2) terminals at 220 kW, 2-hour of fast recharging at 220 kW at the depot, second half of trips with fast recharging at 220 kW at the Villa Costanza (T1) and Peretola (T2) terminals, full recharging at night.
- Case study 3: first half of trips with fast recharging at 220 kW at the terminals of Villa Costanza and Careggi (T1), Peretola and Pizza Unità (T2), 2-hour of fast recharging at 220 kW at the depot, second half of trips with fast recharging at 220 kW at the terminals of Villa Costanza and Careggi (T1), Peretola and Piazza Unità (T2), full recharging at night.
- Case study 4: 17 trips on the T1 line and 27 trips on the T2 line (current daily average), without recharging the battery at the depot and assuming only ultra-fast

recharging at 660 kW for standard time duration of stops (4÷7 minutes) at the terminals, always according to the charging curve depicted in Figure 3.

A. General criteria

For all the hypothesized case studies, it was immediately clear that this type of application requires cells that are more energy-oriented than power-oriented, since the tram is a BEV having to ensure adequate autonomy. Once the battery size had been selected, the required peak power coverage was assessed, as was the expected number of cycles as a function of the observed Depth of Discharge (DOD). The 78 Ah NMC LG CHEM E78 cell with a pouch geometry was therefore chosen. The cell parameters are given in TABLE IV.

TABLE IV. CELL CHARACTERISTICS

Chemistry	Lithium NMC
Nominal capacity (Ah)	78
Nominal energy (Wh)	286
Cell voltage (V)	Nom.: 3.6; Ch.:4.2; Disch.:2.5
Continuos charge current (A)	78 (1C)
Continuos discharge current (A)	234 (3C)
Pulse current (10 s)	Disch.:496 (6.4C) Ch.:184 (2.4C)
Temperature window (°C)	-30÷55
Energy density (Wh/kg)	235
Typical resistance (mΩ)	1.48 (50% SOC)
Dimensions (mm)	548*100*8.65
Weight (kg)	1.083

The following main criteria were assumed when sizing the storage system:

- Autonomy: the energy that can be stored in the on-board storage system depends directly on this value. It was decided to ensure that at least half of the daily trips could be completed (92 and 75 km for T1 and T2 lines respectively), utilizing the intraday pause for recharging. This allows the size of the battery to be drastically reduced, with benefits in terms of mass and volume, as well as the cost of the storage system itself.
- C-rate: this value defines the maximum current that the battery can withstand, both continuous and peak, and it is a constraint that must be respected.
- Expected life: this value defines the number of cycles the battery must undergo before reaching a State of Health value of 80%, conventionally defined as the end of the first life of the storage system. The value of the expected life was fixed to at least 10 years.
- DOD during use less than or equal to 80%.
- Maximum battery voltage equal to 750 V (like the current pantograph line).
- Minimum SOC in use equal to 15% to maintain a safety margin for emergencies and/or to return to the depot at the end of the workshift. Also, a cautiously reduced depth of discharge usually assures a higher reliability of the cell with respect of cycle aging, and sensitivity to other operational parameters such as temperature.

In addition, it was necessary to consider the standardisation of the battery trams, given that some trams may run on both the T1 and T2 lines at different times of the day or year. This meant that the design of the battery system was consequently based on the heaviest profile, which turned out to be that of the T1 line.

In order to assess the life cycle, the cycle number-DOD curve shown in Fig. 6 was observed. This curve was obtained experimentally from ageing tests carried out on a cell like the one chosen for the storage system sizing [17].

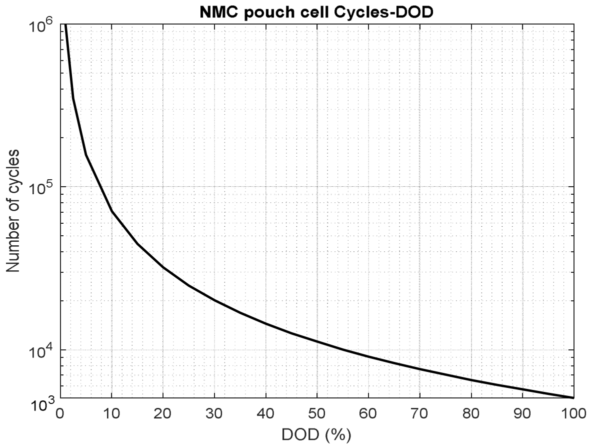

Fig. 6. Expected number of cycles depending on the depth of discharge for the selected cell

Based on the previous specifications, the following can be established for battery sizing (case study 1 example):

- Number of elements in series. $n_s = \frac{V_{maxbatt}}{V_{maxcell}} = 179.$ With these assumptions the storage has a nominal voltage of $V_n = 662.3\ V$.
- Number of elements in parallel. The estimated energy consumption using the simulator resulted in a total energy requirement of $E = 461\ kWh$. This means that the equivalent nominal capacity of the battery is $C_n = \frac{E}{V_n} = 695.6\ Ah$. The number of parallels is obtained as $n_p = \frac{C_n}{C_{cell}} = 9$.

TABLE V. shows the complete picture of the battery sizing in all case studies for the T1 and T2 lines.

TABLE V. STORAGE SYSTEM CHARACTERISTICS

Parameter	**Case study 1**		**Case study 2**		**Case study 3**		**Case study 4**	
	T1	T2	T1	T2	T1	T2	T1	T2
n_s	179		179		179		179	
n_p	9		8		7		7	
Cells number	1611		1432		1253		1253	
Nominal energy (kWh)	461		410		358		358	
Storage mass (kg)[a]	1920		1700		1500		1500	
Storage volume (l)[b]	2290		2040		1780		1780	
Expected life (years)	10.4	11.4	10.4	13.8	10.4	15.4	10.4	15.4

[a] The total mass of the storage is made up of the mass of the cells, to which is added a mass equal to 10% of the previous one, to consider that of the case and the electrical connections.

[b] The total volume of the storage system is the sum of all the volume cells multiplied by a factor of 3, due to the presence of the cooling system, on-board electronics and all the space required for safe connection.

B. Results

Using the OpenModelica software, simulations were carried out for all cases, i.e. four for the T1 line and four for the T2 line, over the entire tram operating day. Figure 8 shows the results obtained for case study 1 on line T1.

Fig. 7a shows that the number of complete cycles per day is two, and the average depth of discharge is approximately 70%. This trend shows that with this evidence the number of cycles that can be performed is 7600, which corresponds to a life expectancy of 10.4 years. Fig. 7b shows the recharging phases which, in the case study considered, only occur during the extended intra-day and night stops. Finally, Fig. 7c and Fig.7d show the C-rate and the battery voltage respectively, both of which are always within the defined specifications and characteristics of the battery, as indicated in TABLE VI. , which shows the values of the quantities obtained for all four case studies of the T1 line.

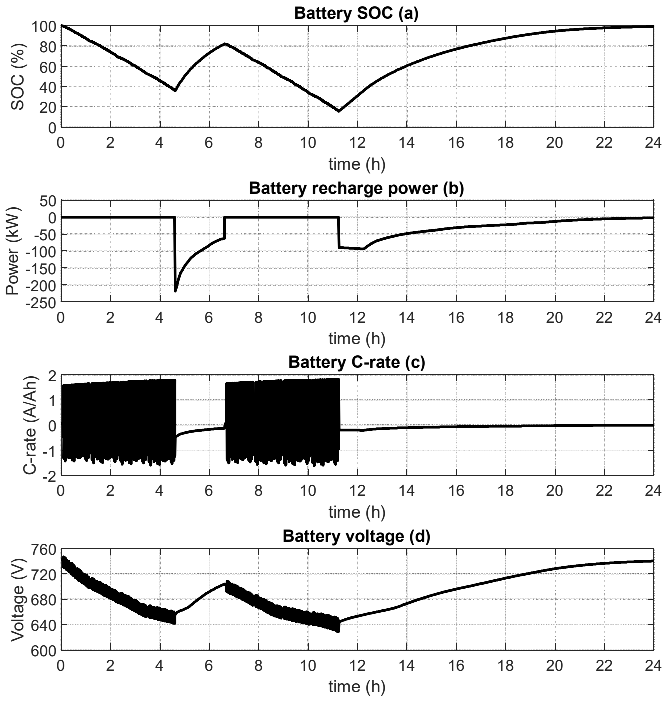

Fig. 7. Simulation results case study 1 line T1. From top to bottom: battery SoC, charging power, C-rate and battery voltage

TABLE VI. SIMULATION VALUES OF BATTERY ELECTRICAL QUANTITIES FOR LINE T1

Variable	Case study 1	Case study 2	Case study 3	Case study 4
Pulse current during discharge (A)	142.4 (1.83C)	160.8 (2.06C)	183.4 (2.35C)	182.2 (2.34C)
Pulse current during charge (A)	126.9 (1.63C)	142.6 (1.83C)	162.0 (2.08C)	161.5 (2.07C)
Maximum battery voltage (V)	742.6	742.6	742.6	742.6
Minimum battery voltage (V)	629.0	626.8	628.1	633.9
Maximum SOC (%)	100	100	100	100
Minimum SOC (%)	15.5	15	18.8	25
DOD (%)	70	70	70	70

The assumption that the vehicle battery should be sized to operate on both the T1 and T2 lines is practically reflected in the expected lifetime. In fact, on the T2 line, where the energy requirements are lower, the battery operates in a narrower SOC window than in the case of the T1 line, which increases the life expectancy of the storage system. At this point, intelligent management could be to divide the operation of the individual vehicle as evenly as possible between the two lines, e.g. by reversing the working section at a fixed frequency, to maximise the life expectancy together.

C. Economic evaluation

To assess the economic impact, just one simplified analysis was here presented, focused on the 10.4 years already considered as reference. The main difference between catenary and battery trams lies in the infrastructure, which in the former case requires the installation of the overhead line and the power substations, which will not be present in the latter case. On the other hand, battery trams will have a higher cost due to the presence of the storage system. In addition, from a power flow point of view, both solutions receive power from the distributor via the MV (medium voltage) connection, but in the first case the power dissipations relate to the MV/LV transformer, the diode rectifier and the contact line, whereas in the second case only the MV/LV transformer and the converter are present in the charging structure. Considering a transformer efficiency of 99%, a converter efficiency of 98% [18] and a catenary efficiency of 90% [19], the battery solution allows a saving of more than 10% in energy transit before final use.

The costs are divided into a fixed part, linked to the infrastructure, the means of transport [20][21] and the charging stations [22], and a variable part, linked to the purchase of energy for the overhead tram and for recharging the battery tram, with both unit prices set at 0.16 €/kWh [23], since the cost of increasing the average quarter-hourly peak power during recharge is negligible. The unit cost of the storage system was set at 130 €/kWh [24].

Figure 8 was obtained by comparing the costs (in the total lifespan of 10.4 years) in relation to the number of daily passengers to be served.

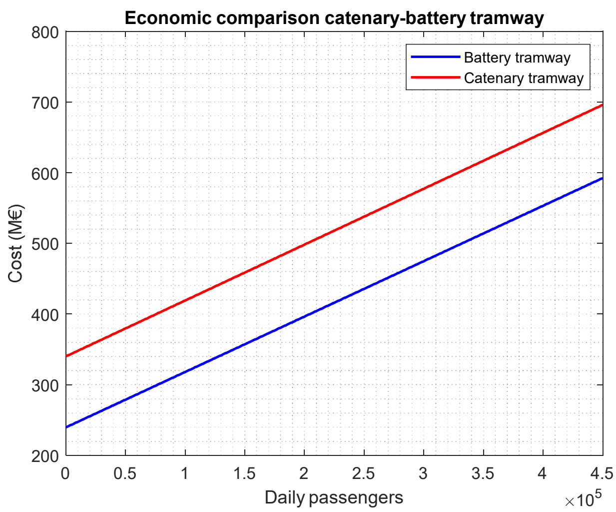

Fig. 8. Costs for daily passengers for the case study analysized

The graph shows that the main difference between battery and catenary tramway is in the initial cost, where the main advantage of battery trams, even if they are initially more expensive, is the absence of overhead contact line, which results in significant savings. The slopes of the two lines are very similar: the greater efficiency of the charging process for battery trams is almost entirely compensated by the cost of buying more battery trams and their charging infrastructure as passenger demand grows, such that the variable costs of the two solutions analysed are approximately equivalent.

CONCLUSIONS AND FUTURE DEVELOPMENTS

Development of innovative solutions which are strongly dependent on continuously evolving technologies involve the usage of strongly customized tools that can be easily adapted to different technologies and system layouts, also accelerating the transfer of know-how between different laboratories and research group. On the other and for the simulation of general common aspects simulation or cross validation with commercial tools offer the possibility of a well based and validated results for what concern tram or railway subsystems that are not the specific object of the proposed innovation.

This approach is convenient also from a computational point of view since different energy storage and management solutions can be tested without repeating dynamic or kinematic simulation of the mechanical vector.

So most important conclusion from this benchmark test case is strongly methodological confirming the validity of the proposed hybrid and synergic usage of different tools.

Starting from these shared methodological achievements, authors are going to further investigate economic aspects of proposed solution (which are currently preliminary drafted) and to extend proposed approach to a larger population of different layouts including different and more innovative kinds of accumulators and algorithms for opt. energy management with a particular attention to interaction arising with brake blending strategies.

ACKOWLEDGEMENTS

Authors wish to thank GEST SRL, and the structure coordinated by Eng. Gaetano Zumbo that has supported this work and more generally has contributed to increase technical and cultural interest for innovative tramway solutions hosting various technical visits and initiatives for engineering students and researchers.

This study was carried out within the MOST – Sustainable Mobility National Research Center and received funding from the European Union Next-Generation EU (PIANO NAZIONALE DI RIPRESA E RESILIENZA (PNRR) – MISSIONE 4 COMPONENTE 2, INVESTIMENTO 1.4 – D.D. 1033 17/06/2022, CN00000023). This manuscript reflects only the authors' views and opinions, neither the European Union nor the European Commission can be considered responsible for them.

REFERENCES

[1] Budiakivska, V., & Casolaro, L. (2018). Please in my back yard: the private and public benefits of a new tram line in Florence. Bank of Italy Temi di Discussione (Working Paper) No, 116

[2] Grossi, G., Mariani, M., Mattei, A., Lattarulo, P., & Öner, Ö. (2024). Direct and spillover effects of a new tramway line on the commercial vitality of peripheral streets: a synthetic-control approach. Journal of the Royal Statistical Society Series A: Statistics in Society, qnae032.

[3] Planned new lines and investments for Florence Tramway Network, information available on line (last access on July 2024)https://www.sustainable-bus.com/trolleybus-tramway/new-tram-lines-in-florence-by-2026/

[4] Tostado-Veliz, M., Arevalo, P., & Jurado, F. (2021). An optimization framework for planning wayside and on-board hybrid storage systems for tramway applications. Journal of Energy Storage, 43, 103207.

[5] Battery Tram Technical Specification, data and informations available at manufacturer site (last visit on July 2024) https://www.hitachirail.com/products-and-solutions/battery-powered-trains/battery-powered-trams/battery-tram-technical-specification/

[6] Enviline™ ESS – Energy Storage System, data and information available at manufacturer site (last visit on July 2024) https://new.abb.com/medium-voltage/switchgear/railway-switchgear/dc-traction-power-supply/energy-management/enviline-ess

[7] Capasso, A., Lamedica, R., Ruvio, A., Ceraolo, M., & Lutzemberger, G. (2016, June). Modelling and simulation of electric urban transportation systems with energy storage. In 2016 IEEE 16th International Conference on Environment and Electrical Engineering (EEEIC) (pp. 1-5). IEEE.

[8] Lamedica, R., Gatta, F. M., Geri, A., Sangiovanni, S., & Ruvio, A. (2018, June). A software validation for dc electrified transportation system: A tram line of Rome. In 2018 IEEE International Conference on Environment and Electrical Engineering and 2018 IEEE Industrial and Commercial Power Systems Europe (EEEIC/I&CPS Europe) (pp. 1-6). IEEE.

[9] Pugi, L., Grasso, F., & Rossi, G. (2018, June). Energy simulation of tramway systems, simplified and efficient models. In 2018 IEEE International Conference on Environment and Electrical Engineering and 2018 IEEE Industrial and Commercial Power Systems Europe (EEEIC/I&CPS Europe) (pp. 1-6). IEEE.

[10] Ceraolo, M., Lutzemberger, G., Frilli, A., Pugi, L. Regenerative braking in high speed railway applications: Analysis by different simulation tools(2016) EEEIC 2016 - International Conference on Environment and Electrical Engineering, art. no. 7555474,

[11] Locorotondo, Edoardo; Lutzemberger, Giovanni; Pugi, Luca. State-of-charge estimation based on model-adaptive Kalman filters. Proceedings of the Institution of Mechanical Engineers, Part I: Journal of Systems and Control Engineering, 2021, 235.7: 1272-1286.

[12] TrainsRunner Studio, data and informance available at site (lasr visit August 2024) https://www.trainsrunner.com/TrainsRunnerStudio/TrainsRunnerStudioView

[13] M. Ceraolo, D. Fioriti, G. Lutzemberger, F. G. Quilici, C. Scarpelli and F. Bianchi, "Electro-Thermal Modeling and aging evaluation of Lithium Battery Packs for Electric Vehicles," in *IEEE Access.*

[14] M. Barbieri, M. Ceraolo, G. Lutzemberger, C. Scarpelli, T. Pesso and M. Giovannucci, "Simplified Electro-Thermal Model For Lithium Cells Based On Experimental Tests," *2020 AEIT International Conference of Electrical and Electronic Technologies for Automotive (AEIT AUTOMOTIVE)*, Turin, Italy, 2020, pp. 1-6.

[15] Barbieri M, Ceraolo M, Lutzemberger G, Scarpelli C. An Electro-Thermal Model for LFP Cells: Calibration Procedure and Validation. *Energies*. 2022; 15(7):2653.

[16] Fastned, data and informations available at site (last visit on August 2024) https://www.fastnedcharging.com/en

[17] Wikner, Evelina. Lithium ion battery aging: Battery lifetime testing and physics-based modeling for electric vehicle applications. Chalmers Tekniska Hogskola (Sweden), 2017.

[18] Rajendran, G., Vaithilingam, C.A., Naidu, K. *et al.* Energy-efficient converters for electric vehicle charging stations. *SN Appl. Sci.* **2**, 583 (2020).

[19] G. M. Scheepmaker and R. M. P. Goverde, "Energy-efficient train control including regenerative braking with catenary efficiency," *2016 IEEE International Conference on Intelligent Rail Transportation (ICIRT)*, Birmingham, UK, 2016, pp. 116-122.

[20] Florence tramway cost, data and information availble at site (last visit Septtember 2024) https://it.wikipedia.org/wiki/Rete_tranviaria_di_Firenze

[21] Mounir Bensalah, Abdelmajid Elouadi, Hassan Mharzi. Optimization of Cost of a Tram Through the Integration of BIM: A Theoretical Analysis. International Journal of Mechanical And Production Engineering, 2017, 5 (11), pp.138 - 142.

[22] Recharge infrastructure price, data and information available at site (last visit September 2024) https://www.cobat.it/

[23] Energy unit price, data and information available at site (last visit August 2024) https://www.lfi.it/

[24] Battery unit cost, data and information available at site (last visit August 2024) https://about.bnef.com/