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Original
Towards full electrification of local public transport: A tool to guide strategies for implementing the electric charging network / Caroleo, Brunella; Lazzeroni, Paolo; Arnone, Maurizio. - In: JOURNAL OF URBAN MOBILITY. - ISSN 2667-0917. - 6:(2024). [10.1016/j.urbmob.2024.100088]

Availability:
This version is available at: 11583/2993111 since: 2024-10-07T09:49:29Z

Publisher:
Elsevier

Published
DOI:10.1016/j.urbmob.2024.100088

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18 November 2024

Journal of Urban Mobility 6 (2024) 100088

Contents lists available at ScienceDirect

Journal of Urban Mobility

journal homepage: www.elsevier.com/locate/urbmob

Towards full electrification of local public transport: A tool to guide strategies for implementing the electric charging network

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ARTICLE INFO

Keywords:
Decision support tool
Sustainable mobility
Electric buses
Charging infrastructure
Charging strategies
Italy

ABSTRACT

This paper describes a methodology and a Decision Support Tool (DST) for the assessment of the impacts of future scenarios of public electric mobility on the electric Distribution Network (DN) of a city, aimed to support the implementation strategies of the electric charging network for the Local Public Transport (LPT).

The objective of the proposed tool is supporting the decision makers in estimating the effect of the future development of electromobility on the urban electric grid considering the evolution of both electric buses and their charging infrastructure.

Some scenarios for the development of electric charging infrastructure for LPT were identified together with the local public transport operator and the energy provider. The results, which are of interest to both the local Public Transport Operator (PTO) and the local Distribution System Operator (DSO), have been quantified for the city of Turin (Italy), but the methodology can be adopted in any urban context: DSOs and PTOs of each city can use the proposed tool as a support to define their public transport electrification strategies.

Some results from the case study examined in this paper (Turin, Italy) show that the energy demand related to the electrification of LPT on a typical weekday is about 45 MWh in 2030 (corresponding to 40 % e-bus), and about 90 MWh when the entire bus fleet is electric. It is also shown how more distributed recharging during the day (with intermediate recharging at the terminus) can dampen the energy/power peaks required at the depot compared to overnight recharging alone: a reduction of up to 27 % of energy demand at the depot is observed due to opportunity charging.

Introduction

The air pollution is still one of the main issues affecting the air quality and the public health in most of the urban and metropolitan areas of EU cities (European Environment Agency, 2019a). Even though road transport has significantly reduced its impact in the last decades, the emission of air pollutants from vehicles still counts about 30 % of the overall emission in some cases, contributing to the reduction in life expectancy (European Environment Agency, 2019b).

For this reason, the reduction of fossil fuels consumption in the transport sector is becoming a valuable opportunity to be considered for mitigating the environmental impact through the adoption of systems based on more clean fuels and the increasing availability of sustainable mobility solutions such as public transport, shared mobility and other micro/mini mobility solutions (Tsavachidis & Le Petit, 2022). Among the others, electrification is seen as the future challenge in road transport (Lazzeroni et al., 2021a), even if a wider diffusion of this solution is still contrasted by technological and infrastructural limitations or delays in some field of applications (Helgeson & Peter, 2020).

Nevertheless, positive perspectives are observed for the electrification of public transportation in urban areas, as pointed out in many EU projects and programs (Glotz-Richter & Koch, 2016; Kubanski, 2020; Gonzalez et al., 2021). For instance, Coppola et al. (2023) demonstrated how the transition from internal combustion engines to Battery Electric busses is the most promising way for a greener urban bus fleet. In this view, public transport companies have already revised their mobility plans by adopting a more "electric" point of view. Italy follows this European trend with some initiatives in the cities of Bergamo, Bolzano, Milan and Turin, where the use of the electric buses was introduced since the early 2000s (Borghetti et al., 2022).

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https://doi.org/10.1016/j.urbmob.2024.100088
Received 3 August 2023; Received in revised form 11 September 2024; Accepted 23 September 2024
Available online 5 October 2024
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However, the planning of an adequate charging infrastructure is fundamental to successfully deploy an electricity-based public transport network. As in fact highlighted by Perumal et al. (2022), electric buses (e-buses) need of a strategic planning of the charging infrastructure, since they are less flexible than conventional ones fuelled by natural gas (Transport & Environment, 2018). Specifically, a large deployment of electric busses has to consider the different mobility patterns, the locations of the charging points as well as the charging methods as discussed by Nazarenus et al. (2023).

In this view, this paper proposes a methodology and a tool for the assessment of the impacts of future scenarios of public electric mobility on the electric Distribution Network (DN) of a city, aimed to support the implementation strategies of the electric charging network for the Local Public Transport (LPT).

The objective of the proposed tool is supporting the decision makers in estimating the effect of the future development of electromobility on the urban electric grid considering the evolution of both electric buses and their charging infrastructure. Since a previous study already investigated the impact of private mobility (Lazzeroni et al., 2021b), this analysis mainly focuses on LPT, so that a comprehensive and integrated view can be obtained for the whole mobility system.

More in detail, this study presents a methodology for estimating the hourly energy demand and the corresponding peaks load occurring in different zones of the city of Turin. The proposed approach considers several aspects influencing the impact on the DN of an electricity based LPT, like the share of electric buses, the adoption of different charging strategies (e.g., only on depot, at bus terminals, etc.) and the charging infrastructure typology (i.e., the charging power). Results will be presented and discussed also in terms of impact indicators (e.g., number of charging e-buses) considering two development scenarios: a centralised charging infrastructure (i.e., all e-buses charging at depots during nighttime) or a partially distributed one (i.e., part of e-buses charging at terminals or hubs during daytime).

The rest of the paper is structured as follows: a literature review is presented in Section 2 to point out differences and common elements of the proposed approach with respect to existing studies; the methodology adopted to estimate the impacts of a charging infrastructure for LPT is instead discussed in Section 3; the results and indicators calculated for the city of Turin are finally presented and commented in Section 4. Section 5 provides conclusions and insights for further research.

Literature review

The identification of strategies for developing a charging infrastructure capable to support the electrification of LPT is a fundamental aspect that has been already studied in literature. In most cases, the economic and the environmental aspect are the focuses of the analysis, while minor interest appears in terms of DN impacts.

Wei et al. (2018) introduces a spatio-temporal optimization to identify the optimal deployment strategies for e-buses compliant with the existing bus operation routes and schedules. In particular, the analysis concerns the optimal plan for replacing conventional diesel or CNG buses with electric ones by minimizing the total cost of purchasing e-buses and building the required in-depot and/or on-route charging stations. However, authors do not include any limitations due to potential bottlenecks in the DN since energy demand is not evaluated.

Similarly, Krawiec et al. (2016) investigated, only from an economic and environmental point of view, the possibility to convert conventional buses operating in urban public transport system with e-buses. The costs for the deployment of a charging infrastructure and ones for purchasing e-buses are here integrated with the external costs to ensure an economic and environmental sustainability of the electrification of LPT, but without the evaluation of potential impacts in the existing DN. Also (May 2018) proposes a different approach for developing the electromobility in urban public transport systems based on ecological and environmental aspects instead of the economics and/or energy ones. The vulnerability of the environment is included in this study as well as its relief potential to identify the most suitable routes to be electrified adopting a GIS-based analysis.

Differently, Majumder et al. (2019) proposes a public transportation system based on electric buses where the integration of photovoltaic production is used to avoid additional burden to the DN in terms of peak demand. The authors introduce the use of supercapacitors to charge e-buses, while high-capacity batteries are placed at bus stops to be charged during off-peak hours and then flash charge e-buses during daytime operations. In this case, the coordinated operation of photovoltaic, batteries and supercapacitors can effectively reduce the grid impact by flattening the hourly energy demand of e-buses. However, the proposed study does not consider different lines and routes, but it adopts an average behaviour of the e-buses.

More recently, Purnell et al. (2022) present a tool for the estimation of the energy demand due to the charging of an electrified LPT by using available public data. This study considers two different potential charging regimes/options: the End-of-Service (EoS) charge at depot typically during night-time (also known as overnight charging), and the During Service (DS) charging (also known as opportunity charging) where e-bus can recharge both at depot and at bus stops (or bus terminals). In this case the trip timetable is generated for each bus line though the use of General Transit Feed Specification (GTFS) data. Results highlight how EoS charge have a significant demand, and an impact on the DN, during the night, while DS option introduces a supplementary peak demand during morning. Peaks demand, however, appear not to be particularly influenced by the charging strategies and the authors did not assume the possibility of introducing charge in intermediate hubs for all those e-buses with long trips (i.e. distance travelled higher than the driving range of the e-buses).

Likewise Valentini et al. (2022) developed a Decision Support System (DSS) to identify which lines are more suitable for the deployment of e-buses considering the available GTFS open data and three different charging solutions (slow charge at depot, opportunity charge at terminals and flash charge at intermediate stops along the routes). For each route, the tool identifies the technical feasibility, the number of e-buses needed and the size (power) of charging infrastructure for each charging option. Then an economic and environmental comparison is made to identify the best solution to be adopted, but potential energy bottlenecks in the DN are not considered.

In line with the recent studies of Purnell et al. (2022) and Valentini et al. (2022) the tool presented in this paper considers GTFS open data for the City of Turin. Differently from this existing research, the possibility of an intermediate charging for all those lines/routes with terminals close to an identified charging hub has been introduced. Additionally, different shares of e-buses are considered to better understand how the charging infrastructure and the corresponding impacts on the local DN evolve in different time horizons so that bottlenecks in the deployment of the electrified LPT can be mitigated or avoided. In this way, the proposed DST can be useful from both sides of the planning process for developing an urban charging infrastructure, where local DSO (Distribution System Operator) and PTO (Public Transport Operator) interact to ensure better results removing barriers and limitations.

Methodology

The Decision Support Tool (DST) presented in this paper allows to orient the implementation strategies of the LPT electric charging network by means of a what-if simulation. In more detail, the DST has been developed for identifying the energy demands / power peaks in a city as the electrification rate of the fleet changes, and to measure the impact of different charging strategies (i.e., overnight charging only, or opportunity charging combined with overnight). Additionally, the DST can support to identify what should be the power and the type of charging infrastructure to be deployed. The methodology is based on GTFS data to ensure replicability in each city; the resulting tool,

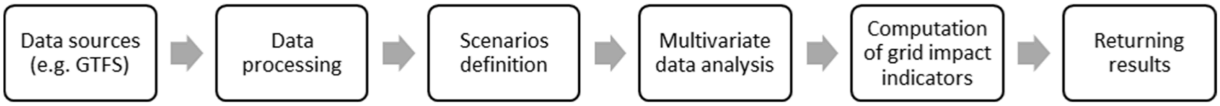


Fig. 1. Logical steps of the methodology.

developed in Python, is user-friendly, providing results in both graphical and tabular formats.

Fig. 1 shows the logical steps of the proposed methodology: first of all, the different data sources (i.e. GTFS, depot locations, bus line-depot association, vehicle-trip association, e-bus characteristics -e.g. range, consumption -, charging infrastructure characteristics -e.g. power of each charging station at the depot / terminal-, zoning to compute aggregate results) are collected and processed to proceed for further analysis.

The next step is the definition of electrification scenarios in the target area. Two dimensions are identified for the definition of these scenarios: (1) the time horizon, which corresponds to the percentage of electric bus penetration in the target area (and, consequently, to the percentage of electric bus-km/day travelled by LPT buses); (ii) the charging mode, e.g. overnight only at the depot, overnight combined to opportunity charging at the terminus/at the stop. The combination of the different levels of these two dimensions constitutes the list of electrification scenarios to be pursued in the next steps of the analysis.

Once in the scenario definition a certain percentage penetration of the electric fleet has been identified within a time horizon (e.g. 50 % of the electric bus fleet in 2030), it is necessary to identify which lines to electrify in order to achieve the stated percentage penetration. To this end, the proposed approach continues with a multivariate statistical analysis applied to the bus line fleet.

A Principal Component Analysis (PCA) is carried out on all the bus lines of the targeted area (e.g. urban area of the city). In the proposed methodology, the PCA is carried out considering the following six variables (extracted from the GTFS), using supply data from a typical weekday: number of trips (*num_trips*), total daily travelled distance (*service_distance*), average trip distance (*mean_trip_distance*), average number of trip stops (*n_stop_mean*), average headway (*mean_headway*) and maximum number of vehicles engaged on the line (*peak_num_trips*).

The result of the PCA is twofold: (i) the one hand, it provides a clustering of the bus lines, that could help the transport operator to have a clearer view of the supply of the LPT; (ii) on the other hand, in the event that some bus lines in the target area are already electrically powered, the PCA makes it possible to identify which other lines are 'similar' to the current power lines in terms of supply, and thus with a

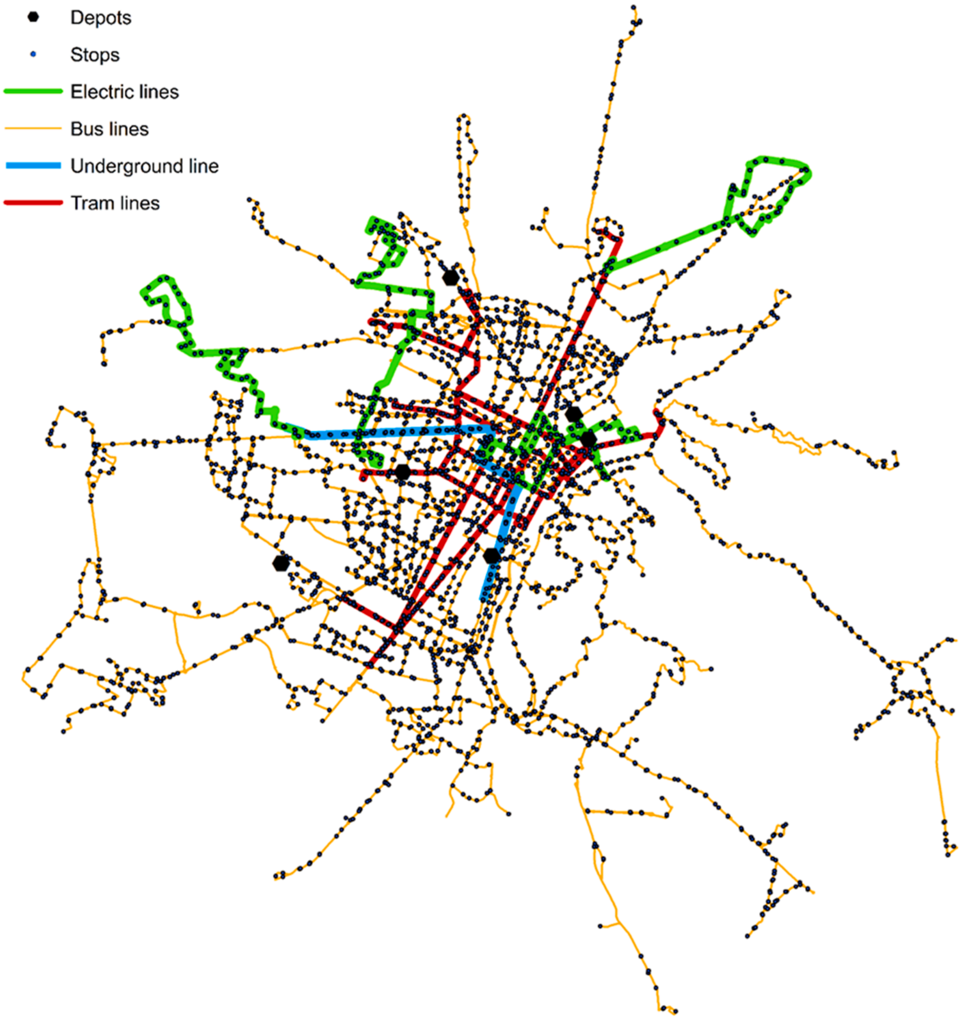


Fig. 2. Map of the LPT supply for the city of Turin (GTFS of a typical weekday of January 2021).

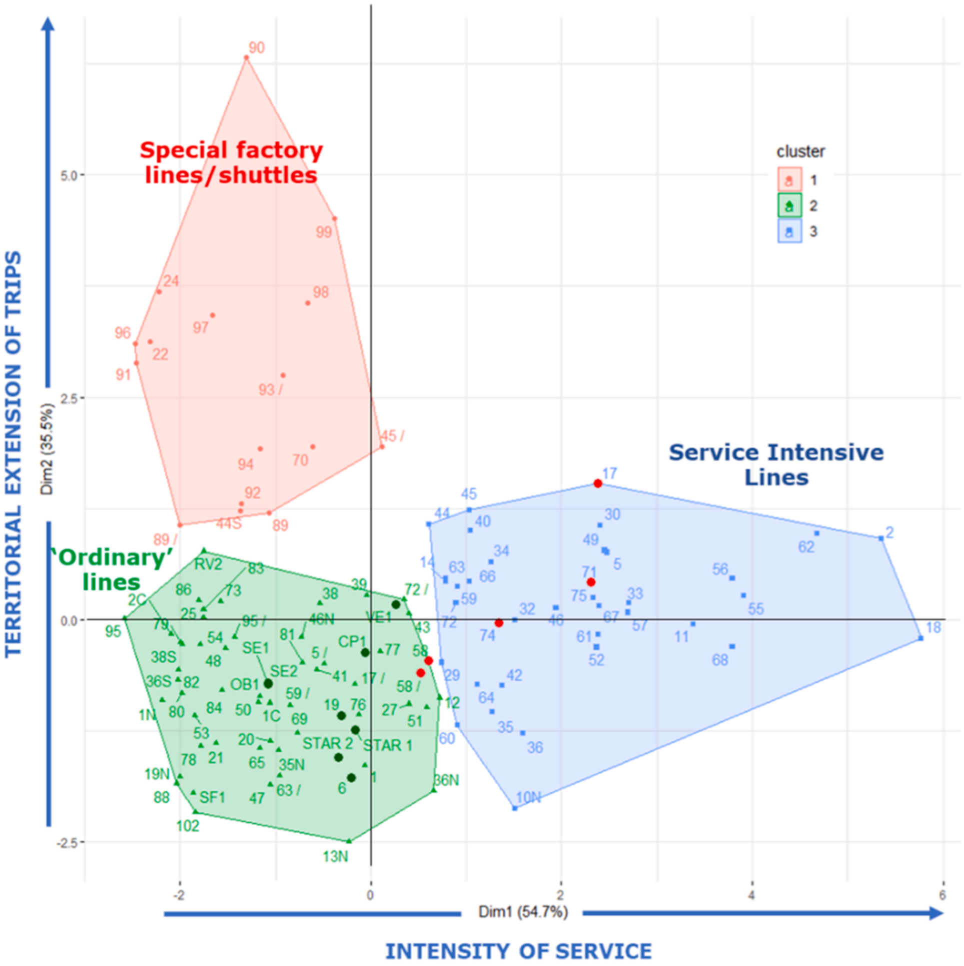


Fig. 3. PCA biplot: Turin bus lines in relation to the first two main components (currently electric lines in dark green dots; bus lines soon to be electrified in red dots).

good probability may also be close to electrification: this similarity is related to the proximity of two bus lines in the PCA biplot. It is, thus, possible to rank the not-electric bus lines according to their distance to current electric lines in the resulting PCA biplot, and return an "electrification priority", assigned by considering the bus lines closest to the current electric lines.

It is important to emphasise that the proposed tool constitutes a decision support but does not presume to be an automatic tool: the decision on which lines to electrify cannot be delegated to multivariate statistical analysis. The electrification priority resulting from PCA should be discussed together with the transport operator, who is best acquainted with the strategic plan for the evolution of LPT in the context of interest.

Finally, for each scenario, the following grid impact indicators (DST outputs) are computed for each typical weekday/holiday in the area of study (aggregating the results by zone, the zoning being an input data): (i) energy (kWh) / average power (kW) required for e-buses charging (per hour, per zone); (ii) peak power (kW) due to e-buses charging (per hour, per zone); (iii) number of e-buses being charged (per hour, per zone); (iv) total hours of charging (per zone). In addition to the above, all the outputs are also available in a disaggregated format, e.g. level of detail of each charging session of each vehicle during a typical weekday / holiday. All resulting scenarios are to be compared with the baseline (i.e. current state in the target area).

Application to the case study

The methodology proposed and described in the previous section has been implemented in the case study of the city of Turin located in the Northwest of Italy. Specifically, the scenarios identified for the urban area in Turin as well as the assumptions introduced in the analysis are presented in the following sections.

Data and scenarios

The municipality of Turin (Italy) was chosen as the area of study. Turin is a city in Northern Italy. It is the capital city of Piedmont region and of the Metropolitan City of Turin. The city is mainly on the western bank of the Po River, and it is surrounded by the western Alpine arch. The population of the city is about 843.000 (2023), while the population of the urban area is estimated to be 1.7 million inhabitants. The road system in Turin is well-developed, connecting the city with major national and European routes. Transportation is well-organized, offering various options for getting around the city. Modal split in Turin (2023) is: private cars: 53 %, motorbikes: 1 %, public transport: 16 %, bike: 4 %, walking: 26 %.

Since some bus lines cover part of the route in the urban area and part in the suburban area (beyond the boundaries of the municipality), the entire GTFS of the Turin metropolitan area of the LPT was considered, and then the energy demands were 'filtered' at the end of the analysis on the Turin municipality only.

Fig. 2 shows the map of the LPT supply for the city of Turin stated in 2021, highlighting the availability of public road transportation (i.e. the orange lines managed by not-electric buses with internal combustion engines and the green lines organized by e-buses), the urban railway transportation (i.e. the red lines managed by trams) and the

Table 1
The scenarios identified for the development of electric charging infrastructure for LPT in Turin municipality (all the percentages have to be considered as % of total bus fleet).

Scenario	Time horizon	% e-buses	Only overnight charging at depots	Overnight + opportunity charging at bus terminals	Overnight + opportunity charging at recharging hubs	Recharging hubs location	Charging power at terminal / hubs (at each charging column)
Baseline	2021	4 %	4 %	–	–	–	–
S1	2030	40 %	26 %	14 %	–	–	200 kW
S2	2030	40 %	26 %	10 %	4 %	Bengasi	200 kW
S3	2040	100 %	86 %	14 %	–	–	400 kW
S4	2040	100 %	70 %	4 %	26 %	Bengasi, Caio Mario, Porta Susa	400 kW

underground line (i.e. the light blue lines). Although the public transport service is mainly concentrated in the most populated urban area of the city, it is well distributed throughout the territory of Turin, while the electrification of road transportation is still growing and ongoing.

On a typical weekday, 98 bus lines run in the city of Turin (data of January 2021, baseline), covering >12,000 trips per day, corresponding to approximately 155,000 bus-km per day. Of these 98 lines, in 2021 (baseline) six are electric, corresponding to 4.3 % of the entire fleet, and recharge in a depot (by adopting overnight charging) which is already equipped for electric charging. Further five bus lines have been electrified after this study.

Some scenarios for the development of electric charging infrastructure for LPT were identified together with the local public transport operator and the energy provider:

- "centralised" infrastructure at vehicle depots, with overnight charging, in two time-horizons;
- "partially distributed" infrastructure allowing the 'bottle-feeding' of e-buses in support of depot recharging, with opportunity charging mode at the terminal / charging hub.

Each scenario is simulated in two time-horizons: 2030 (corresponding to 40 % of the electric bus fleet) and 2040 (100 % of the bus fleet is electric). The 40 % target in 2030 was defined in agreement with LPT according to its bus fleet electrification strategies.

In order to identify which bus lines will be electrified in the 2030 scenarios so as to reach 40 % of the electric bus fleet in this time horizon, a two-step process was carried out: (1) discussion with LPT, to understand which lines were, according to its strategies, in the process of being electrified; (2) a multivariate statistical analysis (PCA, Principal Component Analysis) was carried out to identify which lines were the most similar to the currently electric lines and, thus, which were potentially the most candidate for electrification.

The Principal Component Analysis (PCA) was carried out according to the methodology described in Section 3. Specifically, the dataset for the case study of Turin was considered as an input. This dataset consists of data for all 98 bus lines in the city and the six variables (extracted from the GTFS) needed for the PCA evaluation, using data from a typical weekday. The PCA results (Fig. 3) shows that the first two dimensions (latent variables) express 90.19 % of the total inertia of the dataset. The electrification priority of the bus lines was assigned by considering the bus lines closest to the currently electric lines in the resulting PCA biplot.

The result of this analysis was a prioritization of the bus lines to be electrified (ranked according to their distance to current electric lines), and the first bus lines in this ranking were considered to be electric - for the scenarios to 2030 - up to the 40 % electric fleet. In the scenarios to 2040, instead, the entire bus fleet is considered electric.

Apart from the rate of electrification of the bus fleet, the scenarios were determined by varying the recharging mode of the electric fleet. Following some discussions involving both the local PTO and the local DSO, it was decided - in addition to depot charging (overnight charging) - to consider two types of distributed charging (opportunity charging):

- recharging at a few infrastructured bus terminals: 5 bus lines were chosen together with the local PTO to have opportunity charging at their terminals;
- recharging at recharging hubs, i.e. areas with high density of bus terminals: in this way, it is possible -with a single infrastructure- to recharge many vehicles. The recharging hubs, identified after an appropriate analysis of the GTFS, are: Bengasi, Caio Mario e Porta Susa (see green labels in the map of Fig. 6). In discussions with local operators, it was decided to assume only the Bengasi hub for the 2030 scenarios, and to add Caio Mario and Porta Susa for the 2040 scenarios.

The resulting scenarios, summarized in Table 1, were compared with the baseline (i.e. current situation). The table refers to a total fleet of 603 buses, on 98 routes.

For each scenario, the following impact indicators on the electric network (DST outputs) were computed in the area of study (using the 166-zone zoning of 5T, the company that manages the Mobility and Infomobility Centre for the metropolitan area of Turin): (i) energy (kWh) / average power (kW) required for e-buses charging (per hour, per zone); (ii) peak power (kW) due to e-buses charging (per hour, per zone); (iii) number of e-buses being charged (per hour, per zone); (iv) total hours of charging (per zone). In addition to the above, all the outputs are also available in a disaggregated format, e.g. level of detail of each charging session of each vehicle during a typical weekday / holiday.

Assumptions

The Decision Support Tool, developed in Python, was based on some assumptions agreed with the local PTO and DSO, detailed in the following:

- reference is made to GTT (local PTO) GTFS of January 2021. Changes to the routes and to the PT service of the subsequent months have not been considered, but the results can easily be updated with an updated GTFS dataset;
- no impact on the current organization of the LPT services, i.e. no modifications of bus routes, trips, stops and terminals;
- no change to the current number of vehicles in the operating fleet, no change to the current association trip/vehicle;
- in the absence of the vehicle id/trip association and in the absence of GTFS-RT (real time) data where such information was contained, the bus fleet was simulated and the vehicle id/trip association estimated. The resulting bus fleet includes 603 vehicles, on 98 routes;
- each bus is always associated with only one line;
- it is assumed that the 'typical' electric bus replacing a conventional one is a BYD K9 (theoretical driving range: 310 km):
  - e-bus range: a safety margin has been considered to take into account air conditioning/heating. The final assumed range of each bus is 250 km.
  - it is assumed that the e-bus range in 2030 and 2040 is equivalent;
  - in the computation of kilometres travelled, empty kilometres (i.e. from/to the depot without being in service) are separated from

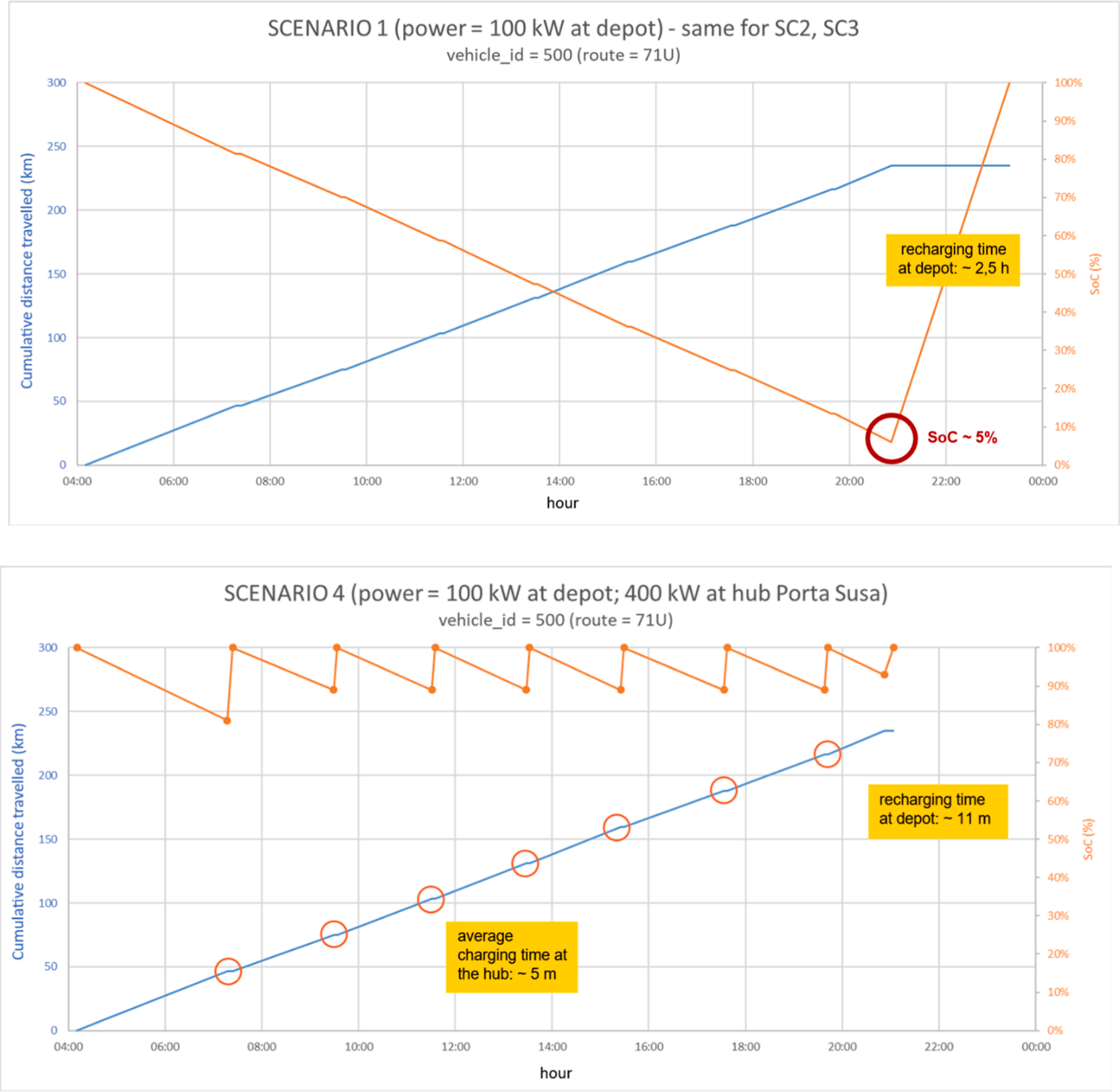
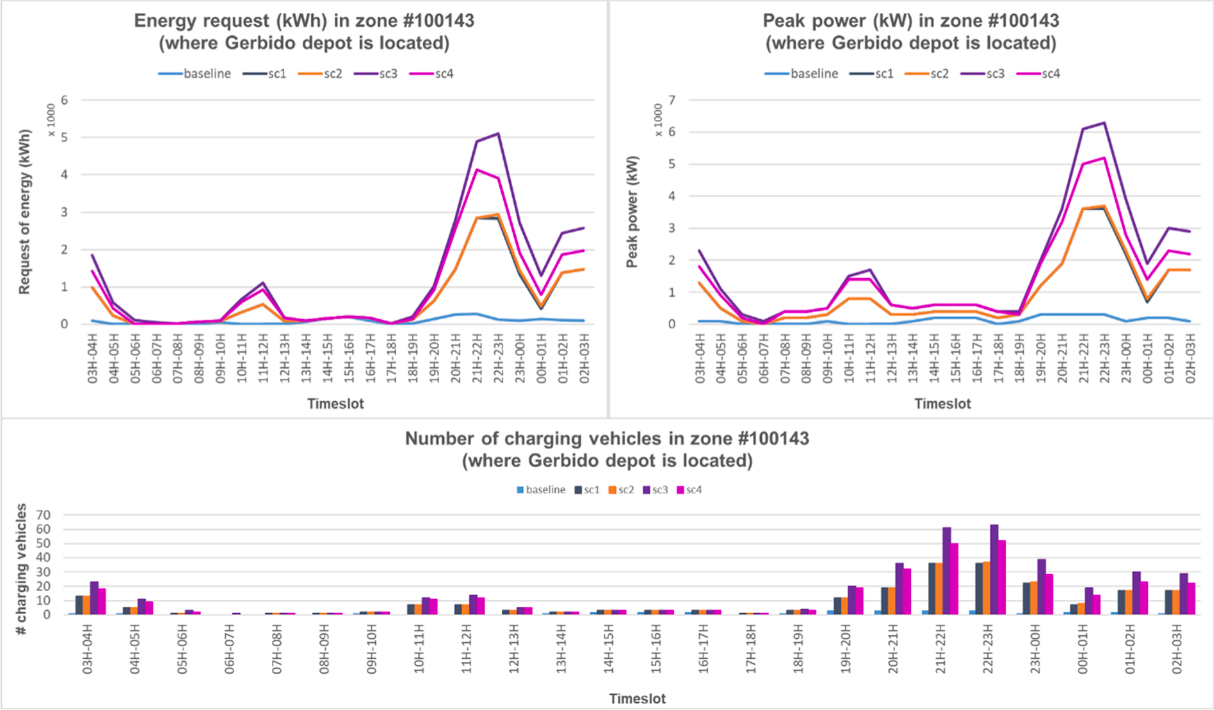


Fig. 4. Daily trend of the SoC (orange) of an e-bus of line 71 as a function of the distance travelled during the service (blue): in the upper part, trend in scenario 1 (only overnight charging at the depot); in the lower part, trend in scenario 4 (overnight + opportunity charging at the Porta Susa hub).

  operating kilometres (i.e. actual kilometres travelled during the service hours of the vehicles);
  - energy consumption: 1.04 kWh/km for 12 m buses; 2 kWh/km for 18 m buses;
  - % battery degradation of the BYD K9 (BYD data): in 8 years the battery loses 20 %, then the battery pack is replaced. The results show that, in the case of distributed charging, this assumption is not relevant.
- Recharging hubs / terminals:
  - Charging power: 200 kW (per recharging column) in 2030; 400 kW (per recharging column) in 2040;
  - recharging duration is equal to the dwell time at the terminus (according to GTFS timetables), or until the battery SoC (State of Charge) reaches 100 %;
  - the bus recharges at the hub (or at the terminus) every time it stops at the terminal/recharging hub (apart from the first and last pass through the terminus just before leaving the depot/just before returning to the depot).
- Depots:
  - each bus line is always associated with one depot;
  - ‘overnight’ does not only mean recharging during night-time: the e-bus can also return to the depot to recharge during the day, as it currently occurs in the baseline. The assumption here is that an e-bus returns to the depot if the time between the two service blocks (*block_id* of the GTFS) is at least 4 h;
  - it is assumed that the e-bus starts charging as soon as it arrives at the depot (no waiting time);
  - each depot maximum capacity has been put as a constraint for the number of vehicles charging and recovering in each depot.

Results

A first significant result of the developed DST is the possibility to



Energy request (kWh) in zone #100143
(where Gerbido depot is located)

Peak power (kW) in zone #100143
(where Gerbido depot is located)

Number of charging vehicles in zone #100143
(where Gerbido depot is located)

Fig. 5. Energy demand (kWh), peak power (kW) and number of charging vehicles: hourly profile for a specific Turin zone (where Gerbido depot is located) in a typical weekday.

perform what-if simulations on the bus lines that the local PTO is willing to electrify.

As an example, Fig. 4 represents the SoC (State of Charge, in orange) of a vehicle on line 71, which the local PTO intends to electrify soon. In Scenario 1 (upper part of Fig. 4), this line is assumed with an overnight-only charging mode at the depot and, based on the daily distance travelled in the GTFS for this vehicle, this e-bus arrives at the end of service at the depot at around 9 p.m. with a SoC of around 5 %, thus with an almost completely discharged battery. In Scenario 4 (lower part of Fig. 4), with the same operating service (i.e. the same trips made by this vehicle during the day), it is assumed that opportunity charging can be carried out at the Porta Susa hub (see map in Fig. 6 for its localization), in the proximity of the line's terminus. In this case, the vehicle takes advantage of the waiting time at the terminus (about 10 min) to recharge at the hub station, and thus makes short and frequent charging sessions at the hub (average charging time: 5 min), with a SoC that never goes below 80 %. Consequently, when arriving at the depot at the end of the service at around 9 p.m., this vehicle requires only 11 min of charging time (with the same power of Scenario 1) to restore the SoC to 100 %, whereas in Scenario 1 the same vehicle required 2.5 h of charging at the depot.

Similarly, another vehicle of the same bus line in Scenario 1 would not be able to arrive at the end of the service due to a completely discharged battery (i.e. vehicle range less than bus-km day). In Scenario 4, on the other hand, thanks to short and frequent opportunity charging sessions distributed throughout the day, the same vehicle returns to the depot at the end of its service with a SoC of >90 per cent. These last results are quite compliant with ones observed in a similar context still located in the Northern part of Italy where the progressive conversion of conventional bus fleets into full-electric fleets is analysed (Di Martino et al., 2023). According to the specificity of that case study, the benefit offered by opportunity charging is capable in fact of reducing the minimum SoC reached by e-buses at the end of service from 9.7 % to around 33 %.

Regarding energy demand in the city of Turin, in the baseline (current situation) it is about 4 MWh. Simulation results show that the energy demand related to LPT electrification in the city of Turin (on a typical weekday) will be about 45 MWh in 2030 (40 % e-bus) and about 90 MWh in 2040 (100 % e-bus).

In the case of the all-electric fleet (2040) and in accordance with the assumptions detailed in Section 4.2, this energy demand is concentrated at depots, with values ranging between 70 % (Scenario 4, with three charging hubs) and 90 % (Scenario 3, without charging hubs) of energy demand at depots (given a power output of 100 kW per single infrastructure), and the remainder distributed throughout the day at charging terminals/hubs.

More distributed charging throughout the day allows for a dampening of the energy/power peaks required at the depot with overnight charging mode alone: in fact, a reduction of up to 27 % of energy demand can be achieved in depots thanks to opportunity charging (difference between scenario 3 and 4). Furthermore, it is noted how on average each e-bus charging at a terminus / charging hub leads to a reduction in energy demand of about 150 kWh at the depot at the end of the day (load shifting).

Similar results were pointed out in Hasan et al. (2021) where a smart combination of opportunity and depot charging can reduce the grid impact of the charging sessions for the e-bus fleet at the depot in the city of Gothenburg.

Furthermore, a distributed charging infrastructure allows shorter and more frequent charging sessions at the hub/terminal distributed throughout the day, instead of a single charging session at the depot at the end of the service. For example, the e-bus average SoC (State of Charge) at the end of the day is 24 % in the case of overnight charging only, compared to 91 % in the case of joint overnight and opportunity charging. Furthermore, the average energy demand per charging session at the depot (overnight only) is about 200 kWh, compared to 20 kWh in the combined overnight / opportunity case. Finally, the average charging time at the end of the day is 2 h in the case of overnight recharging only, compared to 13 min in the case of combined overnight / opportunity.

Fig. 5 provides another example of output of the developed DST: the hourly profile of energy demand, peak power and number of charging

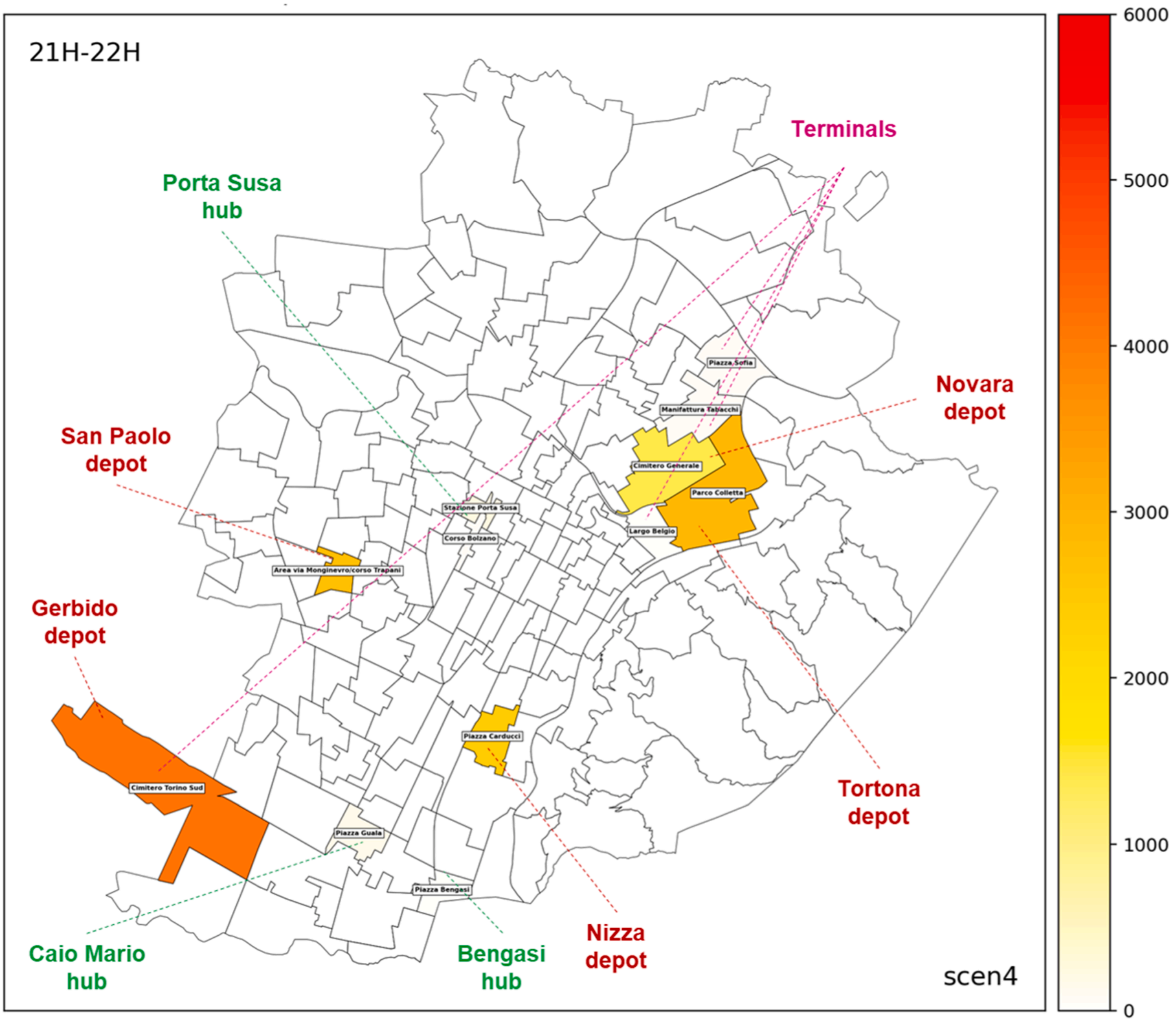


Fig. 6. Map visualisation of energy demand (kWh) in each zone of the municipality of Turin in the timeslot h. 21–22 (typical weekday) for Scenario 4.

vehicles are represented for a specific zone of Turin, where one of the city's six depots (i.e. Gerbido) is located (see map in Fig. 6 for its localization).

Again, it can be seen that the power peaks are lower in Scenario 4 than in Scenario 3, due to the charging available at the hubs. Note, moreover, a slight peak between h. 10 and h. 12, corresponding to the depot charging during the day between two blocks of trips (GTFS block id), when the time between blocks is >4 h.

In aggregate, over the whole city of Turin, at peak energy demand times there is a 13 % reduction in recharging vehicles in the most 'distributed' scenario (Scenario 4) compared to the most 'centralised' scenario (Scenario 3).

In addition, the DST also provides hourly visualisations on maps. For example, Fig. 6 shows the energy demand (kWh) in each zone of the municipality of Turin in the timeslot h. 21–22 for Scenario 4. The same representation has also been prepared for the other impact indicators on the electric network computed within the DST.

Conclusions

The tool described in this paper provides support for guiding strategies for the implementation of the electric network for recharging LPT vehicles, making it possible to assess the impact of different strategies for the development of fleets and recharging infrastructure.

The results have been quantified for the city of Turin in four scenarios with different share of e-buses and different charging strategies, considering GTFS data (related to the PT service), e-bus technical characteristics (i.e. driving range, battery capacity and energy consumption) and different typologies of charging infrastructure in terms of charging power. Results in terms of energy demand, peak power, number of e-buses being charged, and the total duration of the charging sessions have been gathered both on hourly basis and in a disaggregated form for each zone of the city.

As detailed in the previous section, in a typical working day with a fully electrified bus fleet, LPT can achieve significant benefits thanks to distributed charging infrastructures (opportunity charging): up to 27 % reduction in peak power, higher average SoC at end of the service (estimated close to 91 %, while 27 % if only overnight charging is performed), reduction of the average energy demand for each charging session at depots from 200 kWh (only overnight charging) to 20 kWh (overnight + opportunity charging) and, consequently, reduction of the average duration of charging sessions at depot (from 2 h to 13 min).

The described tool could be useful for both DSOs and PTOs to anticipate the effect of future electromobility development on the power grid of a city, considering the evolution of the electricity market, the evolution of charging infrastructure and the possibilities of smart management of the distribution network. Nevertheless, the proposed methodology has some limitations. Firstly, since the tool has no one-stop shop nature but only supplies guidelines and suggestions for PTO and DSO through a what-if analysis, have a limited capability to catch possible impacts on the urban distribution grid due to opportunity or hub charging, while it can better explore the impacts at depots. Secondly, smart charting is not currently implemented as an option of the tool, so possible further actions for reducing peak demand at depots are not included. In future work, hence, the inclusion of smart charging options will be included, as well as the possibility of modifying current LPT supply (e.g. changing the path of a bus route) and, finally, a suggestion for the end user of the location for the charging hubs.

CRediT authorship contribution statement

Brunella Caroleo: Writing – review & editing, Writing – original draft, Supervision, Software, Methodology, Investigation, Data curation, Conceptualization. **Paolo Lazzeroni:** Writing – review & editing, Writing – original draft, Methodology, Conceptualization. **Maurizio Arnone:** Writing – review & editing, Supervision, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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