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PVxTutt'Elettrico

Massimizzazione dell'efficienza e dell'efficacia nel passaggio dalla trazione diesel alla trazione elettrica

Final Report

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Executive Summary (DE)

Das Projekt PVxTutt'Elettrico stellt Wissen und ein Webtool zur Verfügung, um öffentliche Verkehrsunternehmen beim Übergang zu Elektrobussen zu unterstützen. Dieser Bericht hebt entscheidende Herausforderungen und Strategien für die Elektrifizierung hervor und konzentriert sich auf die Optimierung der Flottenauslastung und die Minimierung der Batterie- und Flottengröße auf der Grundlage betrieblicher Einschränkungen. Außerdem werden optimale Ladestrategien und ihre Auswirkungen auf das Stromnetz sowie die Integration erneuerbarer Energiequellen zur Verbesserung der Netzstabilität und Nachhaltigkeit behandelt.

Das Webtool, das unter pvxte.isaac.supsi.ch zugänglich ist, erermöglicht die Bewertung der Machbarkeit der Elektrifizierung einzelner Buslinien, indem sie die Mindestgröße der Batterie und andere Leistungsparameter in einem Eins-zu-eins-Ersatzszenario analysiert. Sie dient als erster Gradmesser für das Elektrifizierungspotenzial einer Buslinie.

Anhand von zwei realen Fallstudien präsentiert der Bericht eine detaillierte Untersuchung kritischer Herausforderungen und Kompromisse bei der Elektrifizierung von Busflotten, einschließlich Reiseverspätungen, unvorhersehbarem Energieverbrauch und den Auswirkungen des Ladevorgangs auf das Stromnetz. Der Bericht enthält auch eine umfassende Anleitung für Schweizer Verkehrsbetriebe, die die technische und wirtschaftliche Machbarkeit, die Vorbereitung von Ausschreibungen, Anreize und Schulungen abdeckt.

Eine wichtige Innovation ist die Optimierung der Flottendisposition, bei der die Flottengröße, die Batteriegröße und die Fahrpläne aufeinander abgestimmt werden, um die betriebliche Effizienz zu verbessern. Dieser Ansatz ist nicht nur für das Transportunternehmen von Vorteil, da er die Kosten senkt, sondern auch auf die Bedenken der Netzbetreiber eingeht indem er erneuerbare Energiequellen, intelligentes Laden und ein innovatives Reserveflottenmanagement einbezieht.

Insgesamt bietet das Projekt PVxTutt'Elettrico verschiedene strategische EmpfehlungenPortfolio, welche den Übergang zu einer elektrifizierten und netzkonformen Flotte unterstützen. Deranalytische Ansatz des Projekts liefert schrittweise umsetzbare Erkenntnisse und ist damit ein wertvoller wissenschaftlicher Beitrag zum Thema Elektrifizierung des öffentlichen Verkehrs. Das Projekt bewertet die Flottenelektrifizierung umfassend aus der Perspektive des Verkehrsunternehmens und analysiert das Problem aus mehreren Dimensionen, um kritische Kompromisse aufzudecken.

Executive Summary (EN)

The PVxTutt'Elettrico project provides knowledge and a tool to assist public transport companies in the transition to electric buses. This report highlights crucial challenges and strategies for electrification, focusing on optimizing fleet utilization and minimizing battery and fleet size based on operational constraints. It also addresses optimal charging strategies and their impact on the electric system, as well as the integration of renewable energy sources to improve grid stability and sustainability.

A key tool introduced is the pre-feasibility assessment web tool, accessible at pvxte.isaac.supsi.ch. This software helps assess the feasibility of electrifying specific bus routes by analyzing the minimum battery size and other performance parameters in a one-to-one replacement scenario. It serves as an initial gauge for the electrification potential of a bus line.

Using two real case studies, the report presents a detailed investigation of critical challenges and trade-offs in fleet electrification, including travel delays, unpredictable energy consumption, and the impact of charging on the electric system. It also includes comprehensive guidance for Swiss public transport companies covering technical and economic feasibility, tender preparation, incentives and training.

A significant innovation discussed is fleet dispatching optimization, which aligns fleet size, battery size, and trip schedules to improve operational efficiency. This approach not only benefits the transportation company by reducing costs, but also addresses the concerns of grid operators by integrating renewable energy sources, smart charging, and innovative reserve fleet management.

Overall, the PVxTutt'Elettrico project offers a strategic portfolio that supports the transition to an electrified and grid-compatible fleet. The project's step-by-step analytical approach provides actionable insights, making it a valuable scientific contribution to the field of public transport electrification. The project thoroughly evaluates fleet electrification from the perspective of the transportation company, analyzing the problem from multiple dimensions to uncover critical trade-offs.

Executive Summary (IT)

Il progetto PVxTutt'Elettrico fornisce conoscenze e strumenti alle aziende di trasporto pubblico per facilitarne la transizione alla trazione elettrica. Il presente rapporto evidenzia le problematiche principali e le strategie sviluppate nel progetto relative al processo di elettrificazione, focalizzandosi su come si possa ottimizzare l'utilizzo della flotta e al contempo minimizzare le dimensioni delle batterie e della flotta stessa considerando i diversi vincoli operativi. L'importanza delle strategie di ricarica ottimale e del loro impatto sul sistema elettrico sono state considerate, così come l'integrazione di fonti di energia rinnovabile per migliorare la stabilità e la sostenibilità della rete elettrica.

Uno strumento particolarmente importante sviluppato in seno al progetto è l'applicativo *web*: esso ha il fine di valutare la pre-fattibilità del processo di elettrificazione ed è accessibile liberamente all'indirizzo pvxte.isaac.supsi.ch. L'applicativo è inoltre in grado di valutare la fattibilità dell'elettrificazione di specifici percorsi analizzando la dimensione minima della batteria e altri parametri considerando scenari di sostituzione uno-a-uno.

Il rapporto presenta inoltre due casi studio reali al fine di esplorare nel dettaglio le problematiche e i compromessi inevitabilmente legati al processo di elettrificazione, tra cui ad esempio i ritardi nei viaggi, il consumo energetico non prevedibile e l'impatto della ricarica sulla rete elettrica. Il presente documento include inoltre una guida pratico-operativa per le aziende di trasporto pubblico svizzere che copre aspetti tecnici, economici e relativi all'incentivazione e alla formazione del personale.

Un aspetto molto importante descritto nel progetto è il miglioramento nel *dispatching* della flotta, il quale considera la dimensione della stessa e delle batterie e la pianificazione dei viaggi in modo da migliorarne l'efficienza operativa. Questo approccio porta benefici alle aziende di trasporto riducendo i costi e risponde alle esigenze degli operatori di rete integrando energia rinnovabile, ricarica intelligente e una gestione innovativa della flotta di riserva.

Nel suo complesso il progetto PVxTutt'Elettrico fornisce un insieme di strategie che supportano la transizione a una flotta elettrificata sostenibile per la rete elettrica, avendo sviluppato dettagliati approcci analitici che rappresentano un significativo contributo scientifico nel campo dell'elettrificazione dei trasporti pubblici.

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Zusammenfassung

In diesem Bericht werden die wichtigsten Ergebnisse und Erkenntnisse aus dem Projekt PVxTutt'Elettrico vorgestellt. In diesem Bericht nehmen wir den Standpunkt eines öffentlichen Verkehrsbetriebs ein und betrachten einige wichtige technische und wirtschaftliche Herausforderungen, mit denen sie konfrontiert sind, darunter die Notwendigkeit, eine kleinere Busflotte mit kleineren Batterien zu verwalten. Daher stellen wir die Frage: "Welche Kombination von Strategien ermöglicht es einem öffentlichen Verkehrsunternehmen, dieses Ziel zu erreichen"?

Die Antwort auf diese Frage hat mehrere Dimensionen, zumal die öffentlichen Busflotten in einem stark regulierten Umfeld operieren. In integrierten Verkehrssystemen wie in der Schweiz sind die Fahrpläne der Busse, mit denen der anderen Verkehrsträger verknüpft. Um die Qualität des Angebots aufrechtzuerhalten, müssen mögliche Verspätungen von Fahrten und der schwer vorhersehbare Energieverbrauch der Busse sorgfältig berücksichtigt werden. Darüber hinaus muss unsere Elektrifizierungsstrategie auch die Belange anderer Interessengruppen, wie z. B. des Netzbetreibers, berücksichtigen werden.

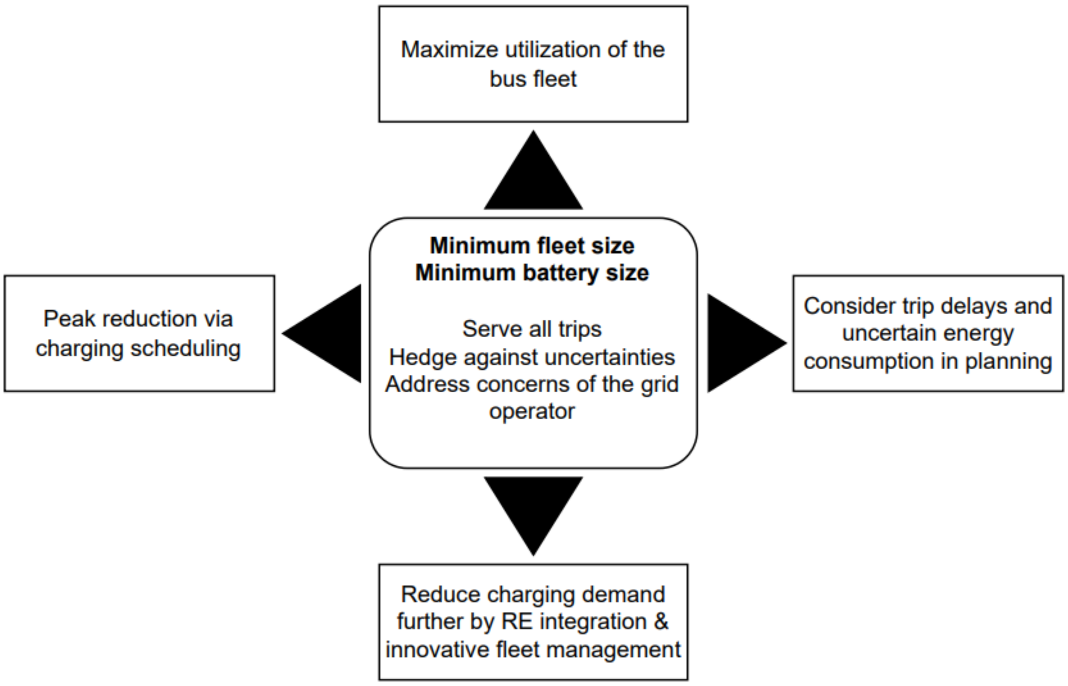

Figure 1: Dimensionen der in dem Bericht dargestellten Erkenntnisse.

Die vier Dimensionen der in diesem Bericht vorgestellten Erkenntnisse sind in Figure 1 grafisch dargestellt.

Die Beantwortung dieser Fragen ist das Ziel der Projektplanungsphase, die mit der Kenntnis der Machbarkeit des Projekts beginnt. Das Webtool zur groben Abklärung der Machbarkeit ist ein konkretes Ergebnis des PVxTutt'Elettrico-Projekts und ermöglicht öffentlichen Verkehrsbetrieben eine erste Bewertung der Elektrifizierung der Fahrzeugflotte, womit sie fundierte Entscheidungen treffen können, bevor sie umfangreiche Ressourcen einsetzen. Viele Unternehmen zögern, beträchtliche Ressourcen bereitzustellen, ohne sich der Durchführbarkeit sicher zu sein. Obwohl das Tool nicht sehr präzise ist und auf eher konservativen Annahmen beruht, ist es ein wichtiges Instrument, das es den öffentlichen Verkehrsbetrieben ermöglicht, anfängliche Vorbehalte zu überwinden und fundierte Entscheidungen für oder gegen ein Elektrifizierungsprojekt zu treffen. Die PVxTE-Webanwendung ist unter der Adresse pvxte.isaac.supsi.ch zugänglich.

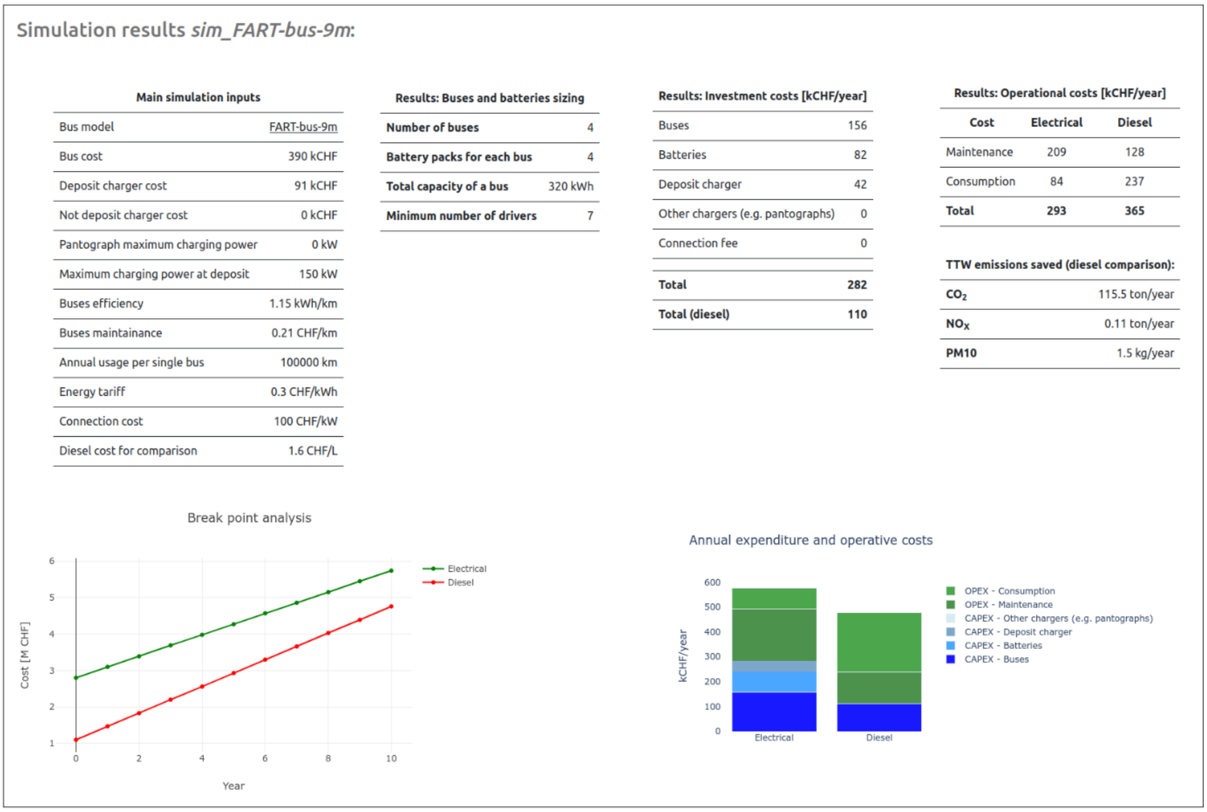

Figure 2: Simulationsergebnisse, wie sie im Webtool erscheinen.

Das Webtool ist einfach aufgebaut und soll nur als vorläufiges Bewertungsinstrument dienen. Das Webtool liefert Antworten auf die folgenden Fragen:

- Ist es machbar, alle Dieselbusse auf einer bestimmten Strecke (eins zu eins) durch Elektrobusse zu ersetzen?
- Wenn dies möglich ist, welche Mindestgröße der Batterie ist erforderlich?
- Wie hoch sind die gesamten und jährlichen Investitionskosten für diese Umstellung auf Elektrobusse?
- Wie hoch sind die jährlichen Kosten für den Betrieb dieser elektrifizierten Busflotte?

Das Webtool berechnet auch einige andere Leistungsindikatoren, darunter die Effizienz der Busse, den jährlichen Energieverbrauch und den Umweltnutzen (Figure 2). Die Simulationszeit variiert je nach Größe der Busflotte und der Anzahl der Fahrten. Für die beiden Fallstudien mit FART und AMSA dauerten die Simulationen jedoch weniger als fünf Minuten.

Eine vollständige Beschreibung des Tools, einschließlich der Einrichtung eines Benutzerkontos und der Erstellung einer neuen Simulation, ist in der Benutzerdokumentation unter dem folgenden Link zu finden: github.com/supsi-dacd-isaac/pvxte-web/blob/main/README.md.

Während das Webtool eine Intuition über die Durchführbarkeit von Elektrifizierungsprojekten liefert, beantwortet es nicht die Fragen "Wie kann es gemacht werden?" oder "Welche Kombination von Strategien kann das Projekt vorantreiben?" Um diese Erkenntnisse zu gewinnen, führen wir detaillierte Machbarkeits- und Wirtschaftsanalysen durch.

In Table 2 werden die wichtigsten Unterschiede zwischen der vorläufigen Durchführbarkeitsstudie und der detaillierten Analyse aufgeführt.

Die detaillierte Durchführbarkeitsanalyse liefert Erkenntnisse über die vier in Figure 1 dargestellten Dimensionen.

Aktuell im Webtool integriertes grobes Machbarkeitsmodell für die Flottenplanung	Detaillierte Machbarkeit des Flottenplanungsmodells
Die Berechnung des Energieverbrauchs für die Fahrt ist vereinfacht, aber vollautomatisch.	Die Berechnung des Energieverbrauchs für die Fahrt ist detailliert. Sie ist nicht automatisiert und beinhaltet die Verarbeitung von Geodaten.
Die Fahrtzeit ist eine feste Eingabe.	Verzögerungen in der Fahrtzeit werden berücksichtigt.
Der Energieverbrauch der Fahrten (bewertet durch das Energieverbrauchsmodell) ist festgelegt.	Der Energieverbrauch auf einer Fahrt kann je nach Wetterbedingungen, Verkehr usw. variieren.
Die Batteriegröße für eine gegebene Busflotte wird unter der Annahme einer Eins-zu-Eins-Ersetzung minimiert.	Das Modell optimiert mehrere Ziele: Batteriegröße, Flottengröße und Fahrtverzögerungen.
Die Einsatzpläne der Busse sind nicht optimiert.	Das Modell optimiert die Einsatzpläne. Auf diese Weise werden Flottengröße und Fahrtverzögerungen für denselben Fahrplan reduziert.
Der gesamte Arbeitsablauf ist von den Eingaben bis zu den Ergebnissen automatisiert.	Einige Schritte der Datenvorverarbeitung und statistischen Modellierung können nicht vollständig rationalisiert werden.
Die Lösungszeit liegt im Bereich von einigen Minuten.	Die Lösungszeit ist wesentlich länger. Sie kann je nach Anwendungsfall zwischen einer halben Stunde und mehreren Stunden liegen.

Table 1: Vergleich der Planungsmodelle, die für die grobe Machbarkeitsstudie und die detaillierte Machbarkeitsanalyse verwendet wurden. innerhalb der Planungsmodelle

Die Ergebnisse verdeutlichen die Bedeutung einer effizienten Flottenauslastung. Ein sichtbares Merkmal einer ineffizienten Flottenauslastung ist die unausgewogene Verteilung der der gefahrenen Strecken. Bei einer ineffizienten Flottenauslastung legen beispielsweise einige Busse deutlich mehr Kilometer pro Tag zurück als andere. Folglich benötigen diese Busse, größere Batterien[1]. Im schlimmsten Fall können solche überdimensionierten Batterien die Elektrifizierung ganz verhindern oder, falls nicht, größere Investitionen nach sich ziehen. In einer effizienteren Umgebung hat jeder Bus eine vergleichbare Auslastung. Infolgedessen ist die Batteriegröße jedes Busses eher kleiner, was für ein öffentliches Verkehrsunternehmen vorteilhafter ist. Eine effiziente Flottenauslastung kann sich auch auf die Mindestanzahl von Bussen (Flottengröße) auswirken, die für die Bedienung einer bestimmten Strecke erforderlich ist. Die Ergebnisse zeigen, dass eine ineffiziente Flottenauslastung zu größeren Flotten führen kann, was für öffentliche Verkehrsbetriebe ungünstig ist.

Enge Busfahrpläne mit wenig oder gar keinem Zeitfenster (Pufferzeit) zwischen zwei Fahrten sind kein Zeichen für eine effiziente Flottenauslastung, da solche Fahrpläne eher zu Verspätungen und Fahrtenausfällen aufgrund von angesammelten Verspätungen führen.

Unsere Strategie zur Verbesserung der Effizienz der Flottenauslastung wird als "Optimierung der Flottenabfertigung" bezeichnet. Obwohl es aufgrund der intermodalen Planung recht schwierig ist, die Fahrpläne zu ändern, haben wir die Möglichkeit zu entscheiden, welcher Bus für die einzelnen Fahrten eingesetzt werden soll. Bei der Optimierung des Flotteneinsatzes geht es darum, diese Entscheidung so zu treffen, dass die erforderliche Batteriegröße, die Flottengröße und die Verzögerungen beim Start der Fahrt minimiert werden können[2].

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[1] Da wir davon ausgehen, dass alle Busse in der Flotte homogen sind, damit sie austauschbar sind und ersetzt werden können, bedeutet eine größere Batteriekapazität in wenigen Bussen, dass alle Busse der Flotte größere Batterien benötigen.

[2] Wir konzentrieren uns auf die Startzeiten der Reisen, da wir diese durch unsere Planung beeinflussen können. Die Verspätungen, die während einer Reise auftreten, sind exogen und liegen oft außerhalb unserer direkten Kontrolle. Daher besteht unsere Strategie darin, uns gegen die Anhäufung solcher Verspätungen abzusichern und danach zu streben, die nächste Reise so pünktlich wie möglich zu beginnen.

Die Bedeutung eines optimalen Flotteneinsatzes hervorzuheben, ist eine der wichtigsten Erkenntnisse dieses Berichts. Es handelt sich dabei um eine Entscheidung, die sich auf viele Bereiche auswirkt und technische und wirtschaftliche Bedenken hervorruft, wie z. B. die Dimensionierung der Batterien, die Größe der Flotte und die Qualität der Dienste, wie z. B. die Robustheit gegenüber Verspätungen.

Die Hervorhebung der Bedeutung einer optimalen Flottenplanung ist eine der wichtigsten Erkenntnisse dieses Berichts. Es handelt sich dabei um eine Entscheidung, die sich auf viele Bereiche auswirkt und technische und wirtschaftliche Bedenken hervorruft, wie z. B. die Dimensionierung der Batterien, die Dimensionierung der Flotte und die Qualität der Dienstleistung, wie z. B. die Robustheit gegenüber Verspätungen.

Die Elektrifizierung von öffentlichen Buslinien erfordert eine sorgfältige Integration in das Stromnetz, um Stabilität und Zuverlässigkeit zu gewährleisten. Ein wichtiger Aspekt in diesem Zusammenhang ist die Bewältigung von Ladespitzen. Unsere Ergebnisse deuten darauf hin, dass sich die Optimierung der Flottendisposition negativ auf den Spitzenlastbedarf auswirken kann, indem sie die Wahrscheinlichkeit der Überschneidungen der Ladepläne von Bussen erhöht (Figure 3, links). Dieses Phänomen wird durch die verlängerten Nutzungsfenster der Busse bei optimaler Disposition verursacht, was zu einer geringeren Streuung der Ankunftszeiten der Busse am Ende des Tages führt. Folglich beginnen die Busse etwa zur gleichen Zeit mit dem Aufladen und haben aufgrund der verlängerten Nutzungsfenster weniger Zeit zum Aufladen über Nacht. Infolgedessen ist der Spitzenladebedarf bei optimaler Flottenverteilung höher als im Basisfall ohne optimale Flottenverteilung. Figure 3 (rechts) zeigt auch die Bedeutung des intelligenten Ladens, das den Spitzenladebedarf durch optimale Neuzuweisung der Ladezeit für jeden Bus reduziert. Wie in der Abbildung zu sehen ist, wird durch intelligentes Laden das Gesamtprofil der Ladeleistung so weit wie möglich abgeflacht.

Aus Sicht des Verkehrsunternehmens kann die Möglichkeit, die Batteriegröße und die Flottengröße mit den damit verbundenen Investitionskosten zu minimieren, den Anstieg des Spitzenladebedarfs überwiegen. Wir verfolgen jedoch weiterhin das Ziel, eine Strategie zu entwickeln, die den Bedenken des Netzbetreibers Rechnung trägt.

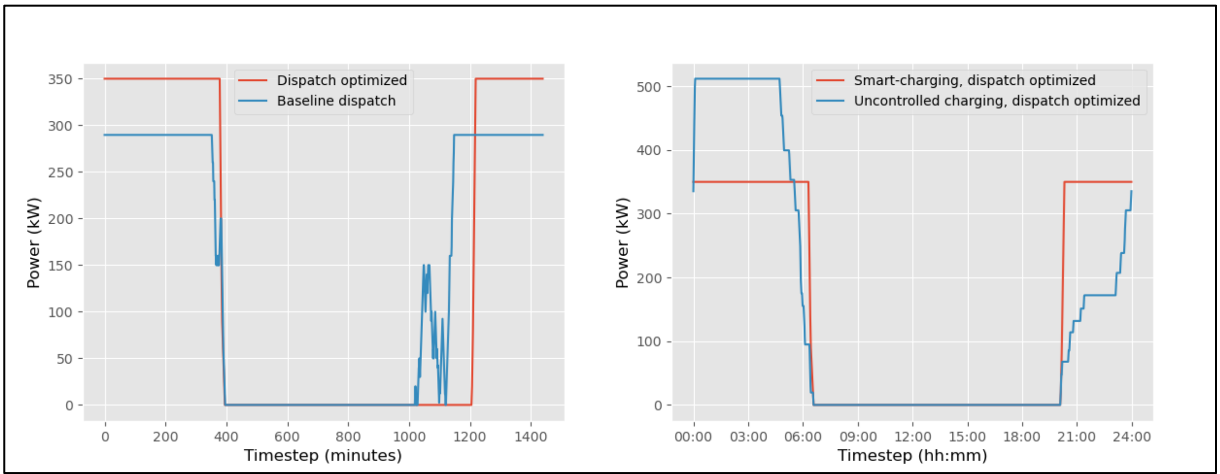


Figure 3: Die Optimierung des Flotteneinsatzes kann aufgrund von Überschneidungen im Ladeplan und einer geringeren Verfügbarkeit von Ladezeiten zu einem höheren Spitzenladebedarf führen (links). Intelligentes Laden reduziert die Spitzenladeleistung, selbst im Falle einer abrufoptimierten Flotte (rechts). Die Bilder entsprechen dem Anwendungsfall der AMSA

Unsere Analyse zeigt, dass es möglich ist, eine für beide Seiten vorteilhafte Elektrifizierungsstrategie zu entwickeln, welche die Interessen des Transportunternehmens und des Netzbetreibers in den Vordergrund stellt. Die von uns vorgeschlagene Lösung beinhaltet die Integration von erneuerbaren Energien. Unser Ziel ist es, einen Teil des nächtlichen Ladebedarfs auf den Tag zu verlagern, der mit Hilfe von Photovoltaikanlagen vor Ort gedeckt werden kann. Wir schlagen innovative Flottenmanagement-Strategien vor, die die Reserve-Busflotte nutzen, um dieses Ziel ohne zusätzliche Investitionen in einen stationären Batteriespeicher für die Nachfrageverlagerung zu erreichen.

Bei der in Abschnitt 4.3.8 vorgestellten Strategie handelt es sich um einen einfachen und unbegrenzt wiederholbaren Algorithmus, bei dem eine ausgewählte Anzahl von Bussen zwischen der Haupt- und der Reserveflotte rotiert. Die Reservebusse laden sich tagsüber vollständig mit Photovoltaik auf und ersetzen die gleiche Anzahl von Bussen der Hauptflotte, die sich nachts nur bis zu 50 % mit Netzstrom auflädt (Figure 8). Daher arbeiten die Reservebusse im Wesentlichen als stationäre Batteriespeicher für die Nachfrageverschiebung, und diese Strategie eliminiert die nächtliche Nachfrage in Höhe von 50 % der von den rotierenden Bussen der Hauptflotte benötigten Energie. Die Einfachheit des Algorithmus macht ihn aus Sicht der Personalschulung und des Managements für öffentliche Verkehrsunternehmen attraktiv.

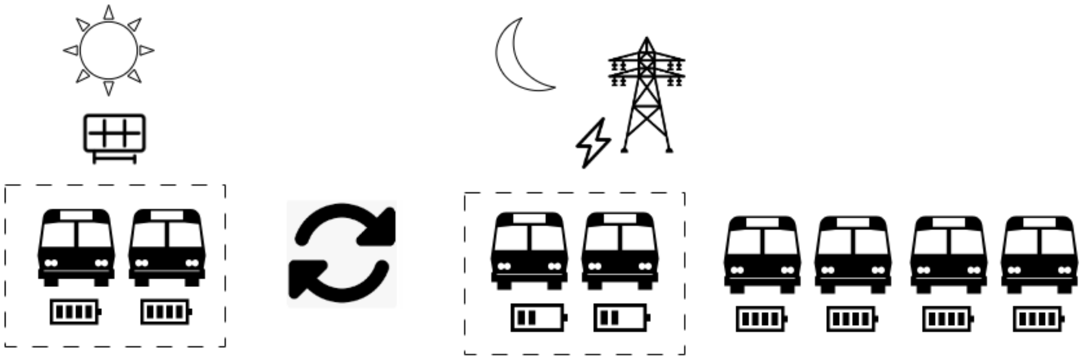


Figure 4: Grafische Darstellung der PV-Integrations- und Reserve-Bus-Management-Strategie

Die potenzielle Bedeutung dieser Studie liegt in der Einfachheit und Kohärenz der vorgeschlagenen Strategien. Die Einfachheit steht im Einklang mit unserem Ziel, öffentliche Verkehrsbetriebe bei der Elektrifizierung ihrer Flotten zu unterstützen, während die Kohärenz dazu beiträgt, mehrere gewünschte Ziele mit einer Strategie zu erreichen, z. B. die Optimierung des Flotteneinsatzes.

Darüber hinaus haben wir im Rahmen des PVxTutt'Elettrico-Projekts eine Datenbank mit Kosten, wie durchschnittlichen Buspreisen, Infrastrukturkosten und Wartungskosten konsolidiert, die zur Schätzung von Investitionen und Betriebskosten erforderlich sind (Anhang 4). Der im Rahmen des Projekts entwickelte praktische Betriebsleitfaden dient als umfassendes Hilfsmittel für öffentliche Verkehrsbetriebe in der Schweiz, dass sie dabei unterstützt, die Effizienz und Effektivität beim Übergang zu Elektrobussen zu maximieren. Der Leitfaden deckt die technische und wirtschaftliche Machbarkeit, die Vorbereitung von Ausschreibungen, Kompensations- und Anreizverfahren sowie die Änderung interner Prozesse mit Schwerpunkt auf der Personalschulung ab.

Insgesamt sind wir der Meinung, dass die in diesem Bericht, dem Webtool, den unterstützenden Datenbanken und den praktischen Betriebsleitfäden vermittelten Erkenntnisse den öffentlichen Verkehrsbetrieben in der Schweiz als wertvolle Ressourcen dienen und sie in die Lage versetzen, ihre Projekte zur Elektrifizierung ihrer Flotte erfolgreich durchzuführen.

Summary

This report presents the key results and insights generated during the PVxTutt'Elettrico project. We take the public transportation company's point of view and examine some important technical and economic challenges they face, including the imperative to manage a smaller bus fleet with smaller batteries. Therefore, we ask the question, "What combination of strategies enables a public transportation company to achieve this objective?"

The answer to this question has multiple dimensions, especially as the public bus fleets operate in a highly constrained environment. For example, in integrated transportation systems like those in Switzerland, the bus timetables are interlinked to those of other transportation modes. To maintain the quality of service, careful consideration must be paid to potential delays of trips and the energy consumption of buses, which is hard to predict. Moreover, our electrification strategy must address the concerns of other stakeholders, such as the grid operator.

The four dimensions of the insights presented in this report are shown graphically in Figure 5.

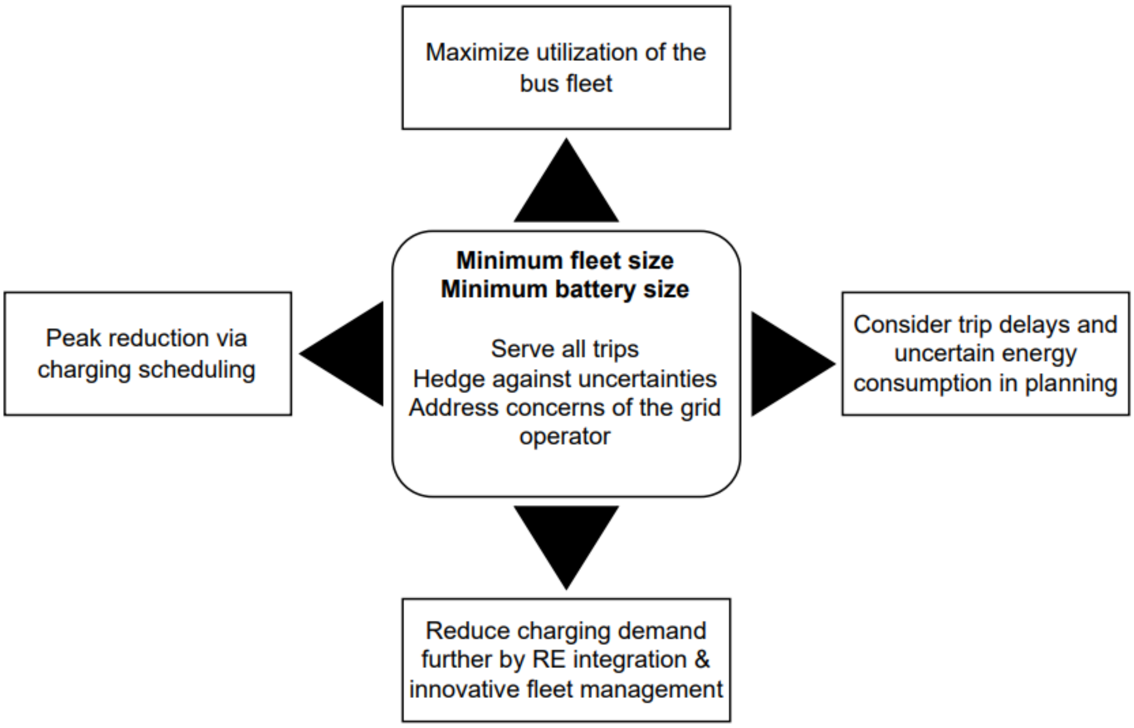
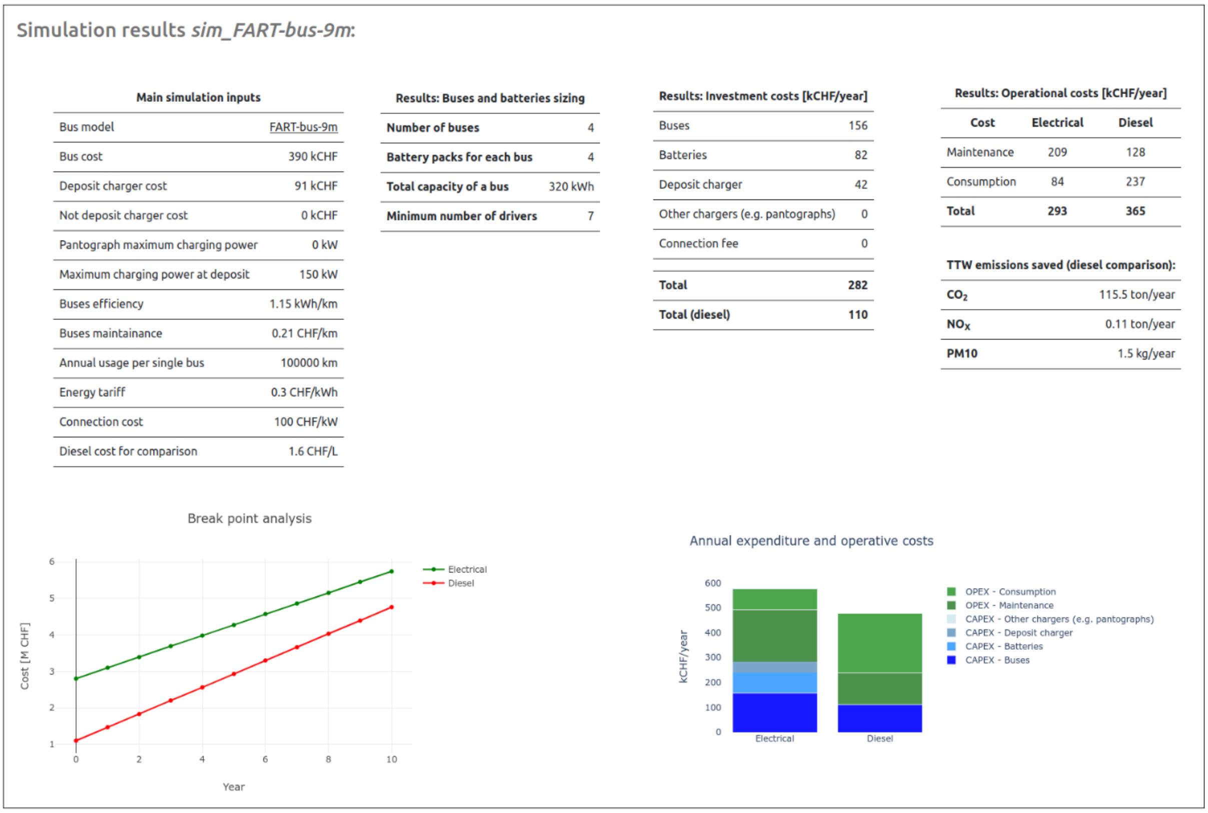


Figure 5: Dimensions of the insights presented in the report.

Addressing these concerns is the objective of the project planning stage, which begins with knowing the feasibility of undertaking the project. The pre-feasibility assessment web tool, an outcome of the PVxTutt'Elettrico project empowers public transportation companies with an initial assessment of the feasibility of fleet electrification projects, allowing informed decisions before substantial resource commitments. Many companies hesitate to allocate significant resources without a level of feasibility assurance. Although the web application is not highly precise and incorporates some conservatism, it is



Main simulation inputs	
Bus model	FART-bus-9m
Bus cost	390 kCHF
Deposit charger cost	91 kCHF
Not deposit charger cost	0 kCHF
Pantograph maximum charging power	0 kW
Maximum charging power at deposit	150 kW
Buses efficiency	1.15 kWh/km
Buses maintainance	0.21 CHF/km
Annual usage per single bus	100000 km
Energy tariff	0.3 CHF/kWh
Connection cost	100 CHF/kW
Diesel cost for comparison	1.6 CHF/L

Results: Buses and batteries sizing	
Number of buses	4
Battery packs for each bus	4
Total capacity of a bus	320 kWh
Minimum number of drivers	7

Results: Investment costs [kCHF/year]	
Buses	156
Batteries	82
Deposit charger	42
Other chargers (e.g. pantographs)	0
Connection fee	0
Total	**282**
Total (diesel)	**110**

Results: Operational costs [kCHF/year]		
Cost	**Electrical**	**Diesel**
Maintenance	209	128
Consumption	84	237
Total	**293**	**365**

TTW emissions saved (diesel comparison):	
CO_2	115.5 ton/year
NO_X	0.11 ton/year
PM10	1.5 kg/year

Figure 6: Simulation results as they appear on the webtool

an important tool that enables public transportation companies to overcome initial reservations and make informed go/no-go decisions regarding electrification projects. The PVxTE web application, accessible at the address pvxte.isaac.supsi.ch, enables public transport companies to assess the pre-feasibility of converting to electric buses.

The web tool is simple by design and intended to be a preliminary assessment tool only. The web tool provides answers to the following questions:

- Is replacing all diesel buses of a particular route (one-to-one) with electric buses feasible?
- If this is possible, what minimum battery size is required?
- What are the total and annual investment costs of this electrification project?
- What are the annual operating costs of running this electrified bus fleet?

The web tool also calculates some other performance indicators, including the efficiency of the buses, annual energy consumption, and environmental benefits (Figure 6). The simulation time varies depending on the size of the bus fleet and the number of journeys. However, for each test case involving FART and AMSA, simulations took less than five minutes.

A complete description of the tool, including how to set up a user account and create a new simulation, can be found in the user documentation at the following link: github.com/supsi-dacd-isaac/pvxte-web/blob/main/README.md.

While the web tool provides an intuition about the feasibility of electrification projects, it does not answer the questions "How can it be done?" or "What combination of strategies can drive the project forward?" For those insights, we perform detailed feasibility and economic analyses.

Table 2 distinguishes between the main differences between the pre-feasibility and the detailed analysis.

Pre-feasibility fleet planning model, currently integrated in the web tool	**Detailed feasibility fleet planning model**
Trip energy consumption calculation is simplified, but fully automated.	Trip energy consumption calculation is detailed. It is not automated and involves geo-data processing.
Trip time is a fixed input.	Delays in trip time are considered.
Trip energy consumption (computed by the simplified energy consumption model) is fixed.	Trip energy consumption can vary depending on reasons such as weather conditions, traffic, etc.
Battery size for a given bus fleet is minimized under one-to-one replacement assumption.	The model optimizes for multiple objectives: battery size, fleet size, and trip delays.
Dispatch schedules of the buses are not optimized.	The model optimizes for the dispatch schedules. In this way, the fleet size and trip delays for the same trip timetable are reduced.
The entire workflow is automated, from inputs to results.	Some data pre-processing steps and statistical modeling cannot be fully streamlined.
Solution time is in the range of several minutes.	Solution time is substantially longer. Depending on the specific use case, it can range from half an hour to several hours.

Table 2: Comparison of the planning models used for the pre-feasibility study and the detailed feasibility analysis. Within the planning models

The detailed feasibility analysis provides insights along the four dimensions presented in Figure 5. The results highlight the importance of efficient fleet utilization. A visible characteristic of inefficient fleet utilization is the imbalance in workload distribution. For example, in an inefficient fleet utilization, some buses cover considerably more kilometers per day than others. Consequently, the buses that cover longer distances per day require larger batteries[3]. In the worst case scenario, such over-sized batteries can prohibit electrification entirely and, if not, incur larger investments. In a more efficient setting, each

[3] Since we expect every bus in the fleet to be homogeneous for interchangeable use and replacement purposes, larger battery capacity in few buses means all buses in the fleet needing larger batteries.

bus has a comparable workload. As a result, the battery size of each bus is relatively equal and smaller, which is more favorable for a public transportation company. Efficient fleet utilization may also influence the minimum number of buses (fleet size) required to service a particular route. The results show that inefficient fleet utilization can lead to larger fleets, an unfavorable condition for public transportation companies. Tight bus schedules with little or no window (buffer time) for buses between two trips are not a sign of efficient fleet utilization, as such schedules are more likely to cause delays and trip cancellations due to accumulated delays.

Our strategy for improving fleet utilization efficiency is called "fleet dispatch optimization." While it is quite challenging to change trip timetables due to intermodal planning, we have a choice in deciding which bus should be dispatched to serve each trip. Fleet dispatch optimization refers to making this decision in such a way that enables us to minimize the required battery size, fleet size, and trip starting time delays[4].

Highlighting the significance of optimal fleet dispatch is one of the main insights of this report. It is one decision that trickles down and causes technical and economic concerns in many areas, such as battery sizing, fleet sizing, and the quality of service, such as robustness against delays.

Electrification of public bus lines requires careful integration with the power system to maintain stability and reliability. A primary consideration to this effect is the management of peak charging demand. Our findings indicate that fleet dispatch optimization may adversely impact peak charging demand by increasing the chance of charging schedule overlaps of buses (Figure 7, left). This phenomenon is caused by the extended utilization windows of the buses under optimal dispatch schedules, which leads to less spread-out arrival times of the buses at the end of the day. Consequently, the buses start charging around the same time, and they have less time to charge overnight due to the extended utilization of windows. As a result, the peak charging demand under optimal fleet dispatch schedules is higher than a baseline case without optimal fleet dispatch. Figure 7 (right) also shows the importance of smart charging, which reduces the peak charging demand by optimally reallocating the charging time for each bus. As shown in the figure, smart charging effectively flattens the aggregate charging power profile as much as possible.

From the transportation company's point of view, the opportunity to minimize battery size and fleet size with their associated investment costs may outweigh the increase in peak charging demand. However, we proceed with our objective of having a strategy that addresses the concerns of the grid operator.

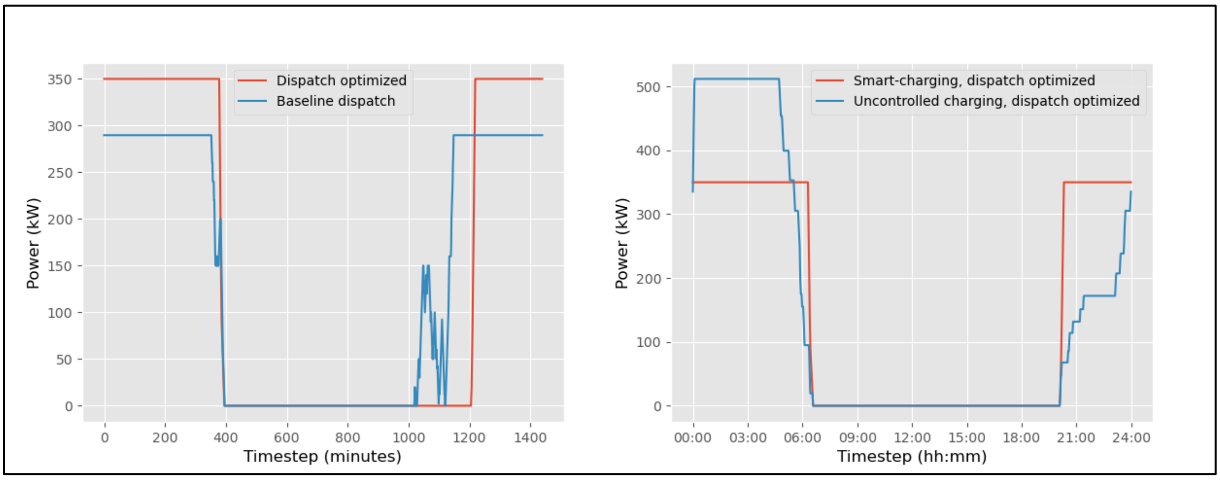


Figure 7: Fleet dispatch optimization can cause higher peak charging demands due to increase in charging schedule overlaps and lower charging time availability (left). Smart charging reduces the peak charging power, even in the case of dispatch optimized fleet (right). Images correspond to the use case of AMSA.

Our analysis shows that it is possible to engineer a mutually beneficial electrification strategy that prioritizes the interests of the transportation company and the grid operator. The solution we propose involves integrating renewable energy. We aim to shift part of the overnight charging demand to daytime, which can be covered using onsite solar photovoltaic generation. We propose innovative fleet

[4] We focus on trip starting times, because this is something we can influence through scheduling. The delays that occur during a journey are exogeneous and often out of our direct control. Therefore, our strategy is to hedge against accumulation of such delays and strive to start the next trip on time as much as possible.

management strategies using the reserve bus fleet to achieve this goal without additional investments in a stationary battery storage unit for demand shifting.

The strategy presented in section 4.3.8, is a simple and infinitely repeatable algorithm that rotates a selected number of buses between the main and reserve fleets. The reserve buses charge fully with photovoltaic during the day, and they replace the same number of buses in the main fleet, which only charges up to 50% during the night with grid energy (Figure 8). Therefore, the reserve buses essentially work as stationary battery storage for demand shifting, and this strategy eliminates the nighttime demand equal to 50% of the energy required by the rotated buses of the main fleet. The algorithm's simplicity makes it attractive for public transportation companies from the staff training and management perspective.

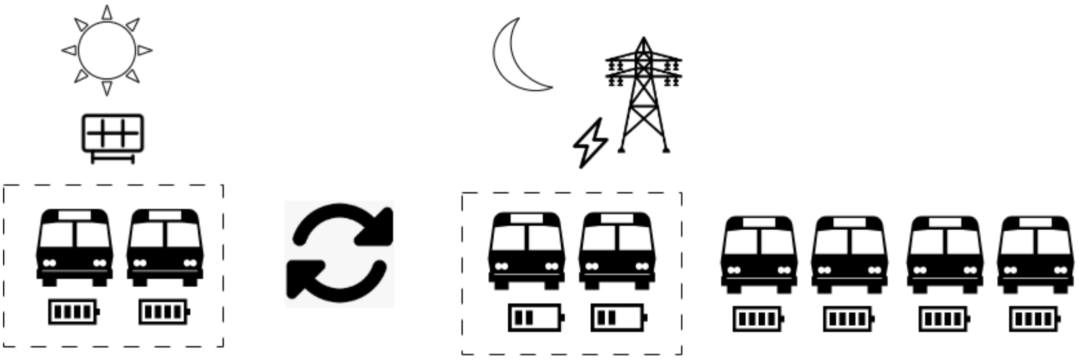


Figure 8: Graphical representation of the PV integration and reserve bus management strategy.

The potential significance of this study is the simplicity and cohesiveness of the proposed strategies. Simplicity aligns well with our aim to enable public transportation companies in their efforts to electrify their fleets, while cohesiveness leverages achieving multiple desired outcomes with one strategy, e.g., fleet dispatch optimization.

In addition, as a part of the PVxTutt'Elettrico project, we have consolidated a database of costs such as average bus prices, infrastructure costs, and maintenance costs required to estimate investments and operative expenses (Appendix 4). The practical-operational guide developed during the project serves as a comprehensive resource for public transport companies in Switzerland, helping them maximize efficiency and effectiveness in the transition to electric buses. The guidelines document covers technical and economic feasibility, preparation for tendering, compensation and incentive procedures, and changes to internal processes, focusing on personnel training.

Altogether, we believe that the insights provided in this report, the web tool, supporting databases, and practical operational guidelines shall serve as valuable resources for public transportation companies in Switzerland and empower them to succeed in their fleet electrification projects.

Sommario

Questo rapporto presenta i risultati principali del progetto PVxTutt'Elettrico, in cui sono state considerate le problematiche inerenti la transizione alla trazione elettrica dal punto di vista di un'azienda di trasporto pubblico, esaminando aspetti significativi sia tecnici che economici, tra cui ad esempio l'approcio ottimale per di gestire una flotta di autobus più piccola con batterie a capacità minore. In generale durante il progetto si è cercato di rispondere alla domanda seguente: "Quale combinazione di strategie consente ad un'azienda di trasporto pubblico di elettrificare la propria flotta in modo ottimale"?

La risposta a questa domanda deve essere fornita considerando diversi aspetti, essendo le flotte di autobus pubblici operanti in un ambiente altamente vincolato. Ad esempio, in sistemi di trasporto integrati come quelli svizzeri, gli orari degli autobus sono legati a quelli di altri mezzi. Per mantenere la qualità del servizio occorre così prestare attenzione ai potenziali ritardi delle corse e al consumo energetico degli autobus, che è difficile da prevedere. Inoltre, la nostra strategia di elettrificazione deve tenere conto degli interessi di altri soggetti coinvolti, come ad esempio il gestore della rete elettrica.

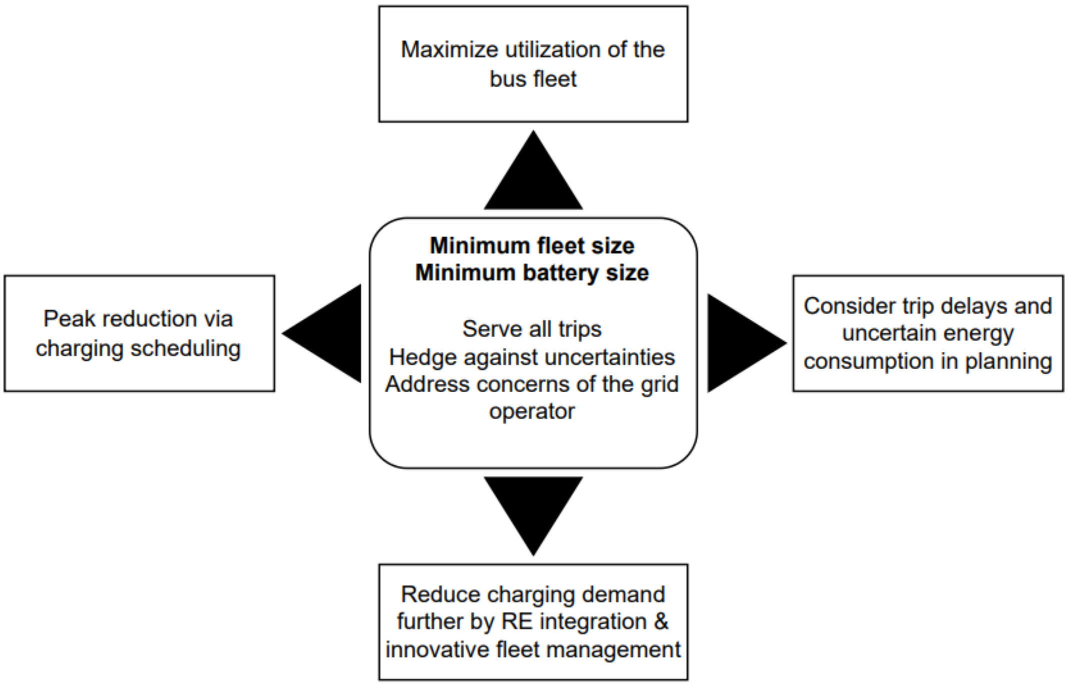


Figure 9: Aspetti rilevanti considerati nel rapporto per gestire in modo ottimale la transizione alla trazione elettrica

La Figure 9 mostra gli aspetti più significativi che sono stati tenuti in conto nel progetto e che saranno presentati nel rapporto.

Il primo elemento da considerare è l'obiettivo della fase di pianificazione del progetto, il quale inizia con la conoscenza della fattibilità del progetto. L'applicazione web sviluppata durante le attività del progetto risponde appunto all'esigenza di poter valutare la pre-fattibilità della transizione alla trazione elettrica, consentendo alle aziende di trasporto di effettuare una valutazione iniziale e, più in generale, di prendere decisioni preliminari ma al contempo informate. Molte aziende esitano infatti ad allocare una quantità significativa di risorse senza avere un certo grado di sicurezza. Sebbene l'applicazione non sia estremamente precisa e abbia un approccio di tipo conservativo, essa è uno strumento utile che consente alle aziende di superare le riserve iniziali relative al processo di elettrificazione fornendo delle informazioni di tipo fattibile o non fattibile.

Simulation results *sim_FART-bus-9m*:

Main simulation inputs	
Bus model	FART-bus-9m
Bus cost	390 kCHF
Deposit charger cost	91 kCHF
Not deposit charger cost	0 kCHF
Pantograph maximum charging power	0 kW
Maximum charging power at deposit	150 kW
Buses efficiency	1.15 kWh/km
Buses maintainance	0.21 CHF/km
Annual usage per single bus	100000 km
Energy tariff	0.3 CHF/kWh
Connection cost	100 CHF/kW
Diesel cost for comparison	1.6 CHF/L

Results: Buses and batteries sizing	
Number of buses	4
Battery packs for each bus	4
Total capacity of a bus	320 kWh
Minimum number of drivers	7

Results: Investment costs [kCHF/year]	
Buses	156
Batteries	82
Deposit charger	42
Other chargers (e.g. pantographs)	0
Connection fee	0
Total	282
Total (diesel)	110

Results: Operational costs [kCHF/year]		
Cost	**Electrical**	**Diesel**
Maintenance	209	128
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Total	**293**	**365**

TTW emissions saved (diesel comparison):	
CO_2	115.5 ton/year
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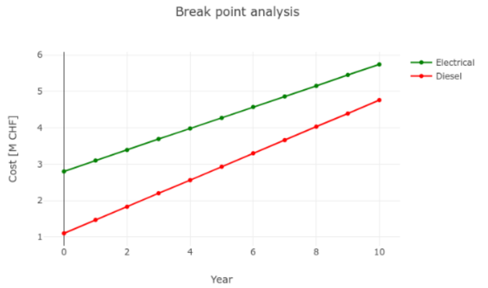
PM10	1.5 kg/year



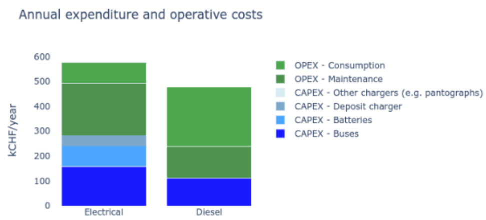


Figure 10: Risultati di una simulazione eseguita dall'applicazione web

L'applicazione PVxTE, accessibile gratuitamente all'indirizzo pvxte.isaac.supsi.ch, è stata progettata in modo da essere semplice per poter rispondere alle seguenti domande:

- Dato un percorso è fattibile la sostituzione uno a uno di tutti gli autobus *diesel* con dei corrispettivi elettrici?
- In caso positivo, qual è la dimensione minima necessaria delle batterie degli autobus?
- Quali sono i costi di investimento totali e annuali?
- Quali sono i costi operativi annuali di gestione della flotta di autobus elettrici?

L'applicazione *web* è in grado di calcolare vari KPI, tra cui l'efficienza degli autobus, il consumo energetico annuale e i benefici ambientali, come mostrato in Figure 10. Naturalmente Il tempo di simulazione varia a seconda delle dimensioni della flotta di autobus e del numero di viaggi; tuttavia, per ogni caso di test che ha coinvolto FART e AMSA, le simulazioni hanno richiesto meno di cinque minuti.

Una descrizione esaustiva dell'applicazione si trova nella documentazione per l'utente al seguente link: github.com/supsi-dacd-isaac/pvxte-web/blob/main/README.md.

È bene considerare come, sebbene lo strumento *web* fornisca una valutazione preliminare sulla fattibilità dei progetti di elettrificazione, esso non risponda a domande importanti quali "Come si può fare?" o "Quale combinazione di strategie può portare avanti il progetto?". Per questi approfondimenti è così necessario effettuare delle analisi di fattibilità tecniche ed economiche maggiormente dettagliate.

La Table 3 mostra le principali differenze tra l'analisi di pre-fattibilità che può essere ottenuta tramite l'applicazione e l'approccio più dettagliato.

Modello di pianificazione della flotta di pre-fattibilità, attualmente integrato nell'applicazione *web*	**Modello di pianificazione della flotta di fattibilità dettagliata**
Il calcolo del consumo energetico dei percorsi è semplificato, ma completamente automatizzato.	Il calcolo del consumo energetico dei percorsi è dettagliato. Non è automatizzato e richiede l'elaborazione di dati geografici.
I tempi di percorrenza di un viaggio sono input fissi.	Vengono considerati i ritardi nei tempi di percorrenza.

Il consumo energetico di un viaggio (calcolato dal modello di consumo energetico semplificato) è fisso.	Il consumo energetico del viaggio può variare a seconda di motivi come le condizioni meteorologiche, il traffico, ecc.
La dimensione della batteria per una data flotta di autobus è minimizzata sotto l'ipotesi di sostituzione uno-a-uno.	Il modello ottimizza per obiettivi multipli: dimensione della batteria, dimensione della flotta e ritardi nei viaggi.
I turni macchina degli autobus non sono ottimizzati.	Il modello ottimizza i turni macchina. In questo modo, la dimensione della flotta e i ritardi nei viaggi per lo stesso orario di viaggio sono ridotti.
L'intero flusso di lavoro è automatizzato, dagli input ai risultati.	Alcuni passaggi di pre-elaborazione dei dati e modellazione statistica non possono essere completamente standardizzati.
Il tempo di soluzione è nell'ordine di alcuni minuti.	Il tempo di soluzione è sostanzialmente più lungo. A seconda del caso d'uso specifico, può variare da mezz'ora a diverse ore.

Table 3: Confronto tra i modelli di pianificazione utilizzati

L'analisi di fattibilità dettagliata fornisce approfondimenti sulle quattro dimensioni mostrate nella Figure 9. In generale i risultati evidenziano l'importanza di un utilizzo efficiente della flotta. Una caratteristica visibile di un sfruttamento inefficiente della flotta è infatti lo squilibrio nella distribuzione del carico di lavoro, che si può avere ad esempio quando alcuni autobus percorrono molti più chilometri al giorno rispetto ad altri. Di conseguenza, gli autobus che coprono distanze maggiori richiedono batterie più grandi[5]. Inoltre nel peggiore dei casi queste batterie sovradimensionate possono impedire del tutto l'elettrificazione e in generale comportare investimenti maggiori. In un contesto più funzionale ogni autobus ha invece un carico di lavoro paragonabile a quello degli altri e di conseguenza la dimensione della batteria di ogni autobus è sostanzialmente simile, più piccola e in generale più economica. L'utilizzo ottimale della flotta può inoltre influenzare il numero minimo di autobus necessario per servire un determinato percorso. I risultati ottenuti mostrano infatti come un utilizzo inefficiente della flotta possa portare ad un dimensionamento maggiore delle flotte e così a maggiori costi di investimento. Un altro aspetto riguarda gli orari delle tabelle di marcia, il dimensionamento non ottimale delle finestre temporali tra due corse comporta infatti maggiori probabilità di ritardi e cancellazioni a causa dei ritardi accumulati.

La strategia definita nel progetto cerca di ottimizzare il dispacciamento della flotta considerando come sia in generale complesso modificare gli orari delle corse, ma al contempo come si possa decidere quale autobus deve essere utilizzato per ogni viaggio. L'ottimizzazione del dispacciamento si riferisce di conseguenza alla definizione di una strategia volta a minimizzare i seguenti aspetti: il numero di automezzi, la dimensione delle batterie e i ritardi[6].

La strategia ottimale di distribuzione della flotta è una degli aspetti principali descritti nel presente rapporto in quanto si tratta di una decisione avente molteplici conseguenze tecniche ed economiche, tra cui il dimensionamento della batteria e della flotta, la qualità del servizio, la robustezza del sistema di trasporto rispetto ai ritardi.

L'elettrificazione delle linee di autobus pubblici richiede un'attenta integrazione con la rete elettrica al fine di mantenerne la stabilità e l'affidabilità. Una considerazione primaria relativa a questo aspetto riguarda la gestione dei picchi di domanda di ricarica: i nostri risultati indicano come l'ottimizzazione del dispacciamento della flotta possa avere un impatto negativo sulla domanda di picco, aumentando la possibilità di sovrapposizione degli orari di ricarica degli autobus (Figure 11, a sinistra). Questo fenomeno è causato dalle finestre di utilizzo più ampie degli autobus che si possono avere in base al dispacciamento ottimale, i quali portano a orari di arrivo degli autobus meno distribuiti alla fine della giornata. Di conseguenza, gli autobus iniziano a caricarsi più o meno alla stessa ora e hanno meno tempo a disposizione durante la notte a causa dell'estensione delle finestre di utilizzo, di conseguenza

[5] Supponendo che gli autobus della flotta siano omogenei tra loro, una maggiore capacità della batteria distribuita su pochi mezzi significa che gli automezzi della flotta necessitano di batterie più grandi.

[6] L'attenzione è focalizzata sui tempi di partenza del viaggio, essendo questo un aspetto che può essere influenzato dal dispacciamento. I ritardi che si verificano durante un viaggio sono esogeni e spesso fuori dal controllo diretto; pertanto, la nostra strategia consiste nell'evitare l'accumulo di tali ritardi e nel cercare di iniziare il viaggio successivo il più possibile in orario.

il picco di domanda tende ad essere più alto rispetto al caso base senza dispacciamento ottimale. La Figure 11 (a destra) mostra invece l'importanza della ricarica intelligente, la quale riduce il picco di domanda riallocando in modo ottimale il tempo di ricarica per ogni bus. Come mostrato nella figura, la ricarica intelligente appiattisce efficacemente il profilo di potenza.

È importante notare come, dal mero punto di vista dell'azienda di trasporto, l'opportunità di minimizzare le dimensioni della batteria e della flotta, con i relativi costi di investimento, può essere più importante dell'aumento della domanda di picco di ricarica. Tuttavia, è opportuno tenere in conto anche degli aspetti relativi alla rete elettrica nella valutazione del processo di elettrificazione.

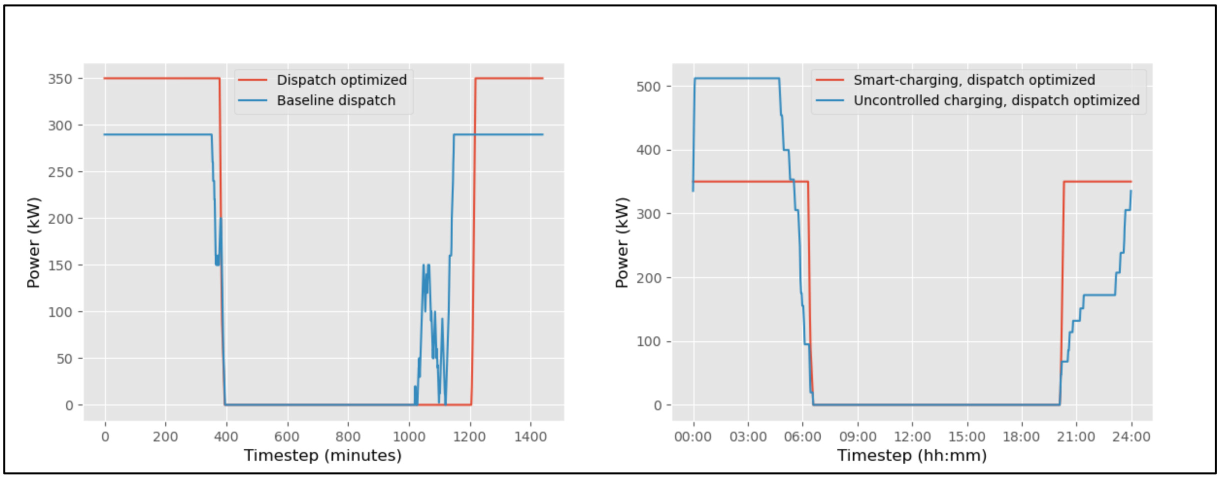


Figure 11: L'ottimizzazione del dispacciamento della flotta può causare richieste di picco più elevate a causa dell'aumento delle sovrapposizioni dei programmi di ricarica e della minore disponibilità di tempo di ricarica (sinistra). La ricarica intelligente riduce il picco di potenza, anche nel caso di una flotta ottimizzata per il dispacciamento (destra). Le immagini corrispondono al caso d'uso di AMSA

L’analisi svolta mostra come sia possibile elaborare una strategia di elettrificazione in grado di considerare sia gli interessi dell'azienda di trasporto che dell'operatore di rete. La soluzione proposta prevede l'integrazione dell'energia rinnovabile, puntando a spostare parte della domanda di ricarica notturna verso le ore diurne, che possono essere coperte utilizzando l’energia solare fotovoltaica prodotta localmente. Sono così state sviluppate strategie innovative di gestione della flotta, le quali utilizzano gli autobus di riserva per raggiungere l’obiettivo dello spostamento della domanda, in modo da non richiedere investimenti aggiuntivi come ad esempio un'unità di accumulo composta da batterie stazionarie.

La strategia presentata nella sezione 4.3.8 è un algoritmo semplice e potenzialmente ripetibile in modo indefinito che fa ruotare un numero selezionato di autobus tra la flotta principale e quella di riserva. Gli automezzi di riserva si caricano completamente grazie alla produzione fotovoltaica durante il giorno e sostituiscono poi l’equivalente numero di elementi della flotta principale; questa si carica solo fino al 50% durante la notte grazie all'energia fornita dalla rete (Figure 14). In questo modo gli autobus di riserva funzionano essenzialmente come accumulatori stazionari per la gestione dello spostamento della domanda, questa strategia elimina il 50% della domanda notturna per quanto riguarda l'energia richiesta dagli autobus della flotta principale. La semplicità dell'algoritmo lo rende interessante per le aziende di trasporto pubblico anche dal punto di vista della formazione e della gestione del personale.

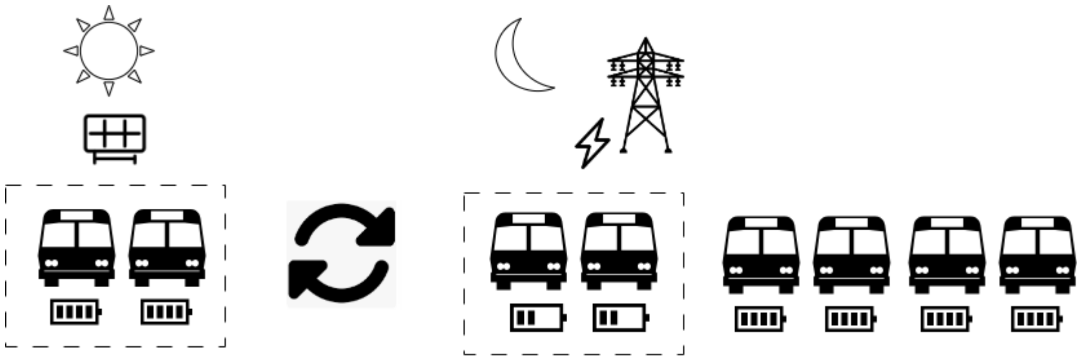


Figure 12: Rappresentazione grafica della strategia di integrazione della produzione di energia fotovoltaica locale con la gestione dei bus di riserva

L'importanza potenziale di questo studio risiede principalmente nella semplicità e nella coerenza delle strategie proposte. In generale la semplicità si allinea bene con l'obiettivo di aiutare le aziende di trasporto pubblico nei loro sforzi per elettrificare le flotte, mentre grazie al secondo aspetto è stato possibile conseguire più risultati con un'unica strategia, come ad esempio nel caso dell'ottimizzazione del dispacciamento della flotta.

Inoltre nell'ambito del progetto è stata progettata ed implementata una banca dati relativa ai costi relativi ai processi di elettrificazione, contenente informazioni preziose come i prezzi medi degli autobus, i costi delle infrastrutture e i costi di manutenzione, tutti elelmenti necessari per stimare gli investimenti e le spese operative (Appendice 4).

Infine la guida pratico-operativa redatta funge da risorsa completa per le aziende di trasporto pubblico in Svizzera, aiutandole a massimizzare l'efficienza e l'efficacia nella transizione agli autobus elettrici. Il documento copre aspetti molteplici e variegati, come la fattibilità tecnica ed economica, la preparazione per le gare d'appalto, le procedure di incentivazione e le modifiche ai processi interni, con una particolare attenzione alla formazione del personale.

Nel complesso riteniamo che i risultati ottenuti nelle attività del progetto e descritti nel presente rapporto, lo strumento *web*, i database dei costi e la guida pratico-operativa saranno risorse preziose per le aziende di trasporto pubblico in Svizzera aiutandole nei loro progetti di elettrificazione delle flotte.

1. Initial situation

Road traffic is one of the main sources of CO_2 emissions and thus contributes to climate change. In recent years, the electrification of the transport sector has become increasingly important as a possible solution for reducing greenhouse gas emissions. Electrification is climate-friendly and can reduce air pollution, noise, and operating costs, making it an attractive choice for many transportation companies. With this in mind, FART and AMSA, two transport companies in Ticino, have also undertaken preliminary work to electrify their fleets. However, to speed up the process and ensure that the goal of fleet electrification is achieved from both a technical and economic point of view, FART and AMSA needed further advice and support, which was the original motivation for the PVxTutt'Elettrico project.

The main objectives of the project are threefold:

- Provide a practical-operational guide to define the transition strategy for the electrification of urban bus lines, tested on the AMSA and FART cases and replicable in other contexts, to reduce economic-financial losses due to potential disinvestment of diesel bus fleets and optimize self-consumption of electricity from renewable photovoltaic sources;
- Provide an analysis of the feasibility of a new electric bus fleet for AMSA and FART urban lines and the development of a tool to analyze the feasibility of the electrification of a generic line;
- Provide an analysis of the impact on the electricity grid and the development of smart charging algorithms to optimize the reduction of power peaks and self-consumption of photovoltaic systems.

These project objectives concern the following aspects of the electrification of public buses.

- Public transport operators lack internal skills or capacity to perform techno-economic analysis related to fleet electrification, especially in connection with the integration of renewable energy and the impact on the electricity grid;

- There is a lack of simple tools that transport operators can use for an initial assessment at the start of an electrification project;
- There is a lack of sound and practical guidelines to support and empower public transport operators wishing to electrify their bus fleets.

2. Aims of the work

We present the goals and expected results of the study under the following four main sub-themes.

1. **Conduct a feasibility analysis for fleet electrification options for FART and AMSA:**
   - For a given line (FART or AMSA), whether there is a feasible option for one-for-one replacement of diesel buses with electric buses;
   - If there is a feasible option, the minimum battery size required for such a conversion;
   - Integration of the simplified version of the optimization algorithm used in this analysis into a web interface that other transit agencies can use as a tool for pre-feasibility assessment.
2. **Evaluate the impact on the electricity grid and optimal charging strategy:**
   - An evaluation of the appropriate charging strategy minimizing the impact on the power grid,
   - Investigation of renewable energy integration scenarios and strategies to increase self-consumption;
   - Estimating the impact of electric bus charging (peak power flow at the point of common coupling of the distribution grid) under different scenarios and the impact on transformer dimensioning.
3. **Conduct economic and environmental analysis:**
   - A reference database for investment and operating costs and government incentives for bus electrification;
   - Investment and operating cost analysis for the bus electrification scenarios of FART and AMSA under optimal bus fleet configuration (minimum number of buses, battery sizes, etc.)
   - Calculation of the climatic and atmospheric effects of the transition.
4. **Provide a practical and operational guide for public bus electrification:**
   - Outline activities and processes related to bus fleet electrification in public transport operators;
   - Identify critical and practical points that public transport companies need to consider during the process.

Public transit companies such as FART and AMSA lack internal capabilities or capacity to conduct techno-economic analyses related to fleet electrification, especially in conjunction with renewable energy integration and impacts on the electricity system. Consequently, the concrete results of the PVxTutt'Elettrico project have the following relevance for our direct stakeholders (FART and AMSA) and the broader public transportation community. Table 4 reports the relevant aspects for AMSA and FART and other generic public transport companies.

Objective (number from the list above)	Relevance for FART and AMSA	Relevance for public transit companies
1	Understand the feasibility of electrifying the bus fleet, Understanding the possible configuration of the bus fleet.	Publicly accessible web interface that can be used to assess the pre-feasibility of a bus electrification project.
2	The assessments/results presented in the study are directly relevant for FART and AMSA to make strategic decisions on the dimensioning of charging stations, PV systems, and grid connections.	The methodology and workflow for assessing the impact on the network and the optimal charging strategy presented in this report are also relevant for other bus electrification projects.
3	The evaluations/results presented in the study are directly relevant for FART and AMSA to make strategic decisions on the economic feasibility of their fleet electrification projects.	The reference database provides a basis for calculating CAPEX and OPEX during the project evaluation. The economic and environmental impact assessment workflow presented in the study is also relevant for other bus electrification projects.
4	The practical and operational guide contains information on incentives, operation and maintenance and provides valuable information for FART and AMSA.	The practical and operational guide for the electrification of regular-service buses is designed as a manual for every public transport company to explain the details of fleet electrification.

Table 4: Relevant aspects for AMSA/FART and for generic public companies

3. State of the art

Our research problem falls into the broad class of optimization problems commonly referred to as "Vehicle Scheduling Problems (VSP)". The task of a VSP is to allocate a set of buses to serve a certain number of trips according to a specified schedule and other practical requirements. The optimization goal is to minimize the fleet size, battery size, or a function that defines the total cost.

Early research on the vehicle scheduling problem (VSP) used formulations such as minimum cost flow, linear allocation, and quasi-allocation methods, as documented by [1], [2], [3], [4]. Several extensions were developed based on this fundamental work, such as the Capacitated Vehicle Scheduling Problem (CVSP) and the Time-Window Vehicle Scheduling Problem (TVSP). CVSP considers capacity constraints for vehicles, while TVSP considers time constraints based on schedules (e.g. [5]). Borcinova et al [6] treated CVSP with time window constraints, resulting in an asymmetric MILP formulation.

Another extension of the CVSP relates to electric vehicles. Since electric vehicles have a limited range, additional constraints for charging and discharging the battery and additional time requirements must be included in the model. The typical way range constraints are described in the transportation modeling literature is to define a maximum driving distance [7] or a maximum driving time [8] for each vehicle after a recharge.

The number of depots is a critical parameter that determines the simulation time. It is known that the multi-depot VSP problem is NP-hard, while the single-depot problem has a complexity of polynomial order [9], [10]. In practice, the single-depot problem is the typical use case for transportation companies, considering the planning of one bus line at a time. The elimination of subtours, a common subproblem when solving the mixed-integer formulation of VSP, is another computational bottleneck since the number of constraints required to eliminate subtours grows exponentially with the number of nodes. However, we circumvent this problem by using a strictly decoupled formulation of start and end nodes for each trip (versus finding a Eulerian path) and the time window constraints.

Regarding economic analysis, a literature review was conducted to obtain investment and operating costs related to electric and diesel buses (see paragraph 4.2). This allows for an analysis that includes all the costs that a company must face over the entire ownership period, from purchase to use. By doing so, it is possible to focus on the expenditures (or outflows) of money, thus not considering cash inflows. Additional variables such as the number of passengers carried, ticket prices, government funding and other related financial factors are in fact unknown and therefore excluded from the analysis. The same documents also provided interesting comments and considerations useful for economic analysis and evaluations that a transportation company should consider.

Some recent examples of case studies representing public bus electrification are presented by [11], [12], [13], [14]. The study by Kunith et al. [11] is a mixed-integer optimization model that simultaneously optimize the quantity and placement of fast charging stations, along with determining the necessary battery size for each electrified bus line for an urban bus network under the constraints given by the daily trip timetable, network layout, and battery capacity. The study focuses on 17 bus lines with 134 buses, all originating from the same depot. Each bus exclusively operates on a fixed route, resulting in independent fleets for each bus line. The model takes deterministic inputs such as daily trips, travel times, and energy consumption. Another case study that focuses on a single existing bus route in Jeju, Korea is presented by [12]. The proposed solution method is a two-stage optimization strategy aimed to jointly optimize for fleet size, battery capacity, and cost of charging infrastructure. The two-stage method decomposes the large optimization problem into two smaller problems that are more tractable. Rogge et al. [14] presents an MILP optimization study that minimizes the total cost of ownership (TCO) of electric bus systems considering the assignment of trips to buses, charging events, and charging infrastructure scheduling. The study presents two case studies, both single-depot scenarios consisting of three bus lines (case study 1) and one bus line (case study 2). We also recognize the study by Lotfi et al. [13], which although do not present a case study specific to a real-world transportation system, provides valuable insights about electrification of generic public transportation lines. The study presents three generic urban and suburban bus line archetypes characterized by the average distance between stops and average daily travel distance. Since the study specifically focuses on charging infrastructure planning, it needs to address the considerations related to optimal fleet and battery sizing.

4. Results

The results reported in the following of the present chapter are based on two case studies corresponding to two public transportation companies of Ticino, FART (fartiamo.ch) and AMSA (www.amsa.ch). The former operates multiple public transportation lines surrounding Locarno, lake Maggiore, and the valleys nearby. The latter provides transportation services to the inhabitants in the municipalities of the Chiasso–Mendrisio region. AMSA also provides special transportation services to schoolchildren from home to home.

In the PVxTutt'Elettrico project, we chose four lines belonging to FART and seven lines operated by AMSA as our use cases. The choice of the lines was based on the requests made by the two companies that are partners of the project who partially funded project, based on their future fleet electrification plans. The seven lines of AMSA cover their entire operations in the Mendrisiotto region, while the four lines of FART cover their operations in the urban and suburban regions. The rural lines of FART that serve the localities in the Centovalli region are not included in the analysis.

Some of these lines, for example, FART 301 and 307, operate as standalone lines, which means these lines have a dedicated bus fleet that does not operate on any other line. On the other hand, integrated lines, such as FART 303 and 304, operate a shared bus fleet, which means these buses operate on both lines at different times of the day.

Table 5 provides an overview of each bus line we analyzed during the project.

4.1. Web tool for assessing the pre-feasibility of fleet electrification for a generic bus line

The PVxTE web tool has the main capability of simulating a generic bus line; it is available for public use at the following link: pvxte.isaac.supsi.ch. Users can determine whether a particular type of bus with a specific charging system is suitable for the service in question by inputting generic information about a line, such as route, schedule, and number of buses. A graphical summary of the PVxTE workflow is shown in Figure 13. A complete description of the required user inputs is available in Appendix 1.

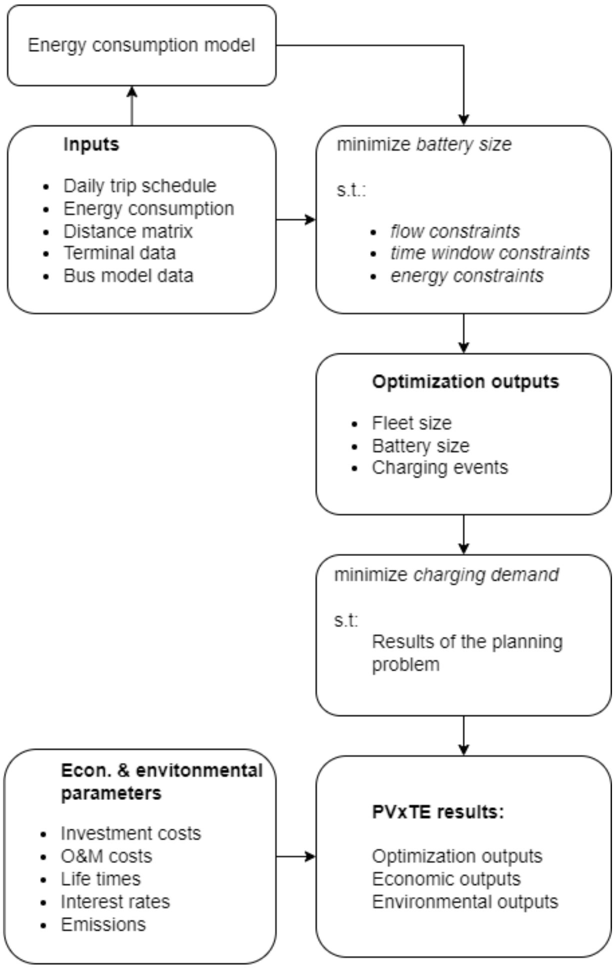


Figure 13: PVxTE web tool graphical summary.

The engine behind the tool is a mixed-integer nonlinear optimization model (MINLP). This model expands on the classical vehicle scheduling problem by incorporating additional time windows and constraints related to battery charge and discharge. The mathematical formulation of the model is a directed decision graph, where each node represents an event or decision, and the arcs represent the sequence of decisions for each bus from the time it leaves the depot until its return at the end of the day. All inputs are defined as deterministic to ensure the online tool is user-friendly and runs within a reasonable runtime. Moreover, we coupled a simplified energy consumption model to automate the estimation of the energy consumption of each bus.

Due to its simplified nature, which is necessary for computational reasons, we recommend using it as a pre-feasibility assessment tool that provides an initial go/no–go evaluation. If the pre-feasibility is positive, the transportation company can consult a subject matter expert for a comprehensive feasibility assessment, including studying potential extreme scenarios.

For an exhaustive description of the mathematical basis behind PVxTE, please refer to Appendix 3, while the details of the energy consumption estimation model are provided in Appendix 2. The complete user guide of the tool is accessible at the following link: github.com/supsi-dacd-isaac/pvxte-web, where it is also possible to find the source code.

The urban lines of Locarno (FART) and Mendrisio (AMSA) served as test cases for the development and validation of the web tool.

As the first step, we defined the scope of the study based on client consultation. We highlighted some key requirements and decisions made during the client consultation phase that directly influenced how we framed the optimization problem.

1. **Battery recuperation happens only at the depot** – The pre-feasibility confirmed that opportunity charging is not required for the bus lines operated by FART and AMSA. There were also concerns from FART and AMSA related to space requirements and public opinion when installing fast-charging pantographs. Therefore, the rest of the analysis is carried out for overnight charging (at the depot) only.
2. **Battery energy is used exclusively for the buses' motion while auxiliary energy is provided through a separate source** – Many electric buses have a small diesel engine for heating and cooling. Examples of more advanced technologies include infrared heating and heat pumps. In our use case, FART and AMSA, in consultation with the bus manufacturers, agreed to use a separate energy source for heating and cooling.
3. **The length of the buses operating in each line is given and cannot be changed** – The length of the buses is determined by the passenger load and route characteristics.

Company	Bus line	Terminal stations	Number of weekday trips	Total distance covered on a weekday (km)	Size of the current fleet on the line	Standalone/ integrated
FART	301	Losone – Gordola	170	2474.9	10	Standalone
	303	Delta Maggia – Brione	65	532.5	4	Integrated with each other
	304	Residenza Lido – Brione	74	484.7		
	307	Locarno – Losone	174	1076.1	6	Standalone
AMSA	502	Cantine di Sotto – Chiasso FFS	71	972.0	6	Integrated with each other
	504	Chiasso FFS – Cantine di Sotto	61	649.9		
	503	Morbio Posta – Cantine di Sotto	56	475.3	2	Standalone
	505	Chiasso FFS – Morbio Posta	61	257.6	5	Integrated with each other
	507	Crocione – Morbio Serfontana	56	353.0		
	508	Chiasso FFS – Morbio Serfontana	28	167.0		
	511	Vacallo – Seseglio	36	294.2		

Table 5: Summary information about each of the bus lines evaluated in the project

How do these decisions affect the modeling strategy? Limiting the charging strategy to overnight charging eliminates other charging options, reduces the search space for solutions, and improves the solution time[7]. The decision regarding the auxiliary power source only affects the input parameter for trip energy and has no other effect on the modeling strategy.

Table 6 summarizes the one-to-one replacement feasibility of the bus lines operated by FART and AMSA. The maximum allowable battery size reported in the table is a technical specification of the bus model. We noted that AMSA line 511 did not meet the feasibility requirements due to the large battery capacity needs. One of the ways to deal with this situation is to increase the number of buses that serve line 511 (more accurately, the integrated lines 505, 507, 508, and 511). Changing the fleet size automatically requires updating the dispatch schedules of the buses.

[7] PVxTE web tool provides the option for enabling fast-charging (pantograph) option at terminal stations as a pre-feasibility option. The recommended workflow is to evaluate if there is a feasible solution with pantograph option disabled and if not, enable the pantograph option at a desired terminal station. More information can be found in the web tool documentation.

Line #	Bus type x # buses	Max. battery size allowed (kWh)	1-1 replacement feasibility	Comments
FART 301	18m x 10	704	YES	Under dispatch optimization, the fleet size can be reduced to 9[8]
FART 303,304	12m x 4	528	YES	
FART 307	18m x 6	704	YES	
AMSA 502,504	12m x 6	528	YES	
AMSA 503	12m x 2	528	YES	
AMSA 505,507,508,511	9m x 5	352	NO	A bus that operates in line 511 requires a minimum battery capacity of 567 kWh, which is more than the maximum battery size allowed for 9m buses by the manufacturer[9].

Table 6: Pre-feasibility results regarding one-to-one replacement of the bus lines operated by FART and AMSA

Table 7 below shows the minimum battery size, number of battery packs, and the maximum passenger carrying capacity for each bus in the feasible lines.

Bus ID	Maximum passenger capacity	Min. battery size (kWh)	Number of battery packs[10]
FART 301	113	622.2	8
FART 303-304	68	423.4	5
FART 307	131	512.6	6
AMSA 502-504	68	420.9	5
AMSA 503	68	353.2	5

Table 7: Minimum battery size, number of battery packs, and the maximum passenger carrying capacity for each bus in the feasible lines

4.2. Economic and environmental impact assessment for fleet electrification

This paragraph describes a method for calculating and analyzing capital expenditure (CAPEX) and operating expenditure (OPEX) for evaluating the transition from diesel traction to electric traction. The calculation has been integrated in the web tool described in Section 4.1, aiming to be used by operators when evaluating different fleets and bus compositions.

Various studies on the subject were analyzed to gather comments, collecting and calculating costs, required to estimate capital expenditure (CAPEX) and operating expenditure (OPEX). The aim is therefore to have sufficiently robust information to calculate average buses price, infrastructures cost, maintenance costs and energy costs. Clear and organized information on investment (CAPEX) and operating (OPEX) costs is normally not freely available. This is due to various reasons that can be assumed in a relatively new and constantly evolving market and competition between suppliers, with the considerable possibility of customization of products and services. Costs are generally mainly

[8] Refer to the results of the detailed feasibility study.
[9] Since line 511 is integrated with the three other lines, the infeasibility of one line affects all the lines they share buses with.
[10] The standard size of one battery pack in this study is 88 kWh as per the communication with the bus manufacturer Solaris.

identifiable based on contact with manufacturers or from documents compiled by research institutes that are normally based on public tenders (mandatory in some country).

The energy-economic calculation presented in this section assesses and quantifies the costs over the years for the replacement of diesel vehicles with electric ones, considering component lifetimes, interest discounting, annual operational and energy costs.

The environmental impacts of a change from diesel to electric vehicles are as well calculated, considering the tank-to-wheel (TTW) impact. The savings in atmospheric emissions of carbon dioxide (CO_2), particulate matter (PM10) and nitrogen oxides (NO_x) are then estimated.

The diagram shown in Figure 14 visually represents the content discussed in this chapter. It begins with a literature analysis that furnishes both data and commentary, leading to the formulation of an economic and environmental model. Subsequently, the model can be applied to practical scenarios using the web tool described in the previous paragraph 4.1 (the application of the model to a real case is carried out in paragraph 4.3).

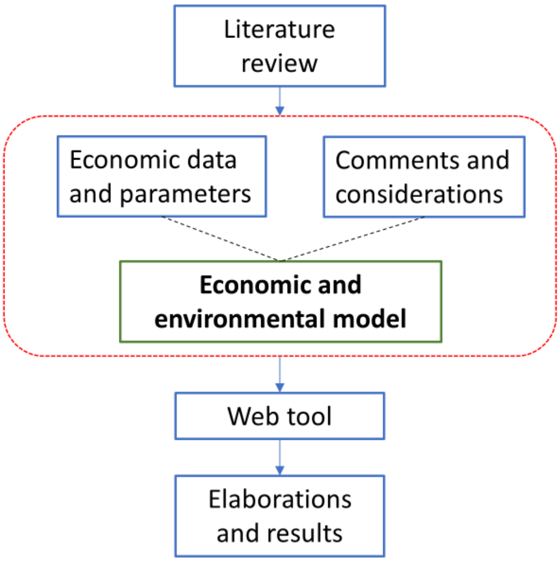


Figure 14: Diagram describing paragraph 4.2

4.2.1. Investigated databases and data source

In this work, an analysis of available public documentation was made, based mainly on public literature of recent years. The details of the individual databases, with their corresponding links for downloading the documents and their main contents, are described in Appendix 4.

Based on the analyzed documents, cost equations have been created and directly integrated within the web tool relating investment and operational costs. The user utilizing the web tool always has the option to modify and enter different values if they are deemed more correct and accurate.

The analyzed documents are reported in Table 8.

Most of the cost data found in the literature reviewed and used in the tool for economic evaluations refer to different European public tenders. The only reference source that explicitly refers to the Swiss market is the Swiss Federal Council's 2020 report, but it contains few information that can be used (limited bus lengths, no information on batteries, limited information on chargers).

The strong fluctuations that characterize market trends in recent years could greatly affect e-bus prices, as well as charging infrastructure and batteries, and the purchase prices of energy carriers (electricity and diesel). In addition, almost all of the information collected refers to pre-pandemic and pre-war time frames. These considerations can lead to uncertainties and predictions that are very difficult to implement. In this regard, the development and definition of future prices is indeed to be elaborated. Beside there are numerous parameters that influence the price of a bus, the main ones are the battery capacity, provision for a charging infrastructure and connections to the power grid. The prices found, although efforts have been made to classify them as much as possible into sub-categories, could vary to a greater or lesser extent in each of these categories.

a	Finance, B. N. E. Electric buses in cities: Driving towards cleaner air and lower CO_2. Bloomberg 2019
b	Baccelli, O. (2021). Scenari e prospettive dell'elettrificazione del trasporto pubblico su strada: Un'innovativa analisi di benchmark: Il TCRO-Total Cost and Revenues of Ownership. Bocconi 2021
c	Rapporto del Consiglio federale in adempimento del postulato 19.3000 CTT–N del 15/1/2019. "Promuovere l'affermazione dei vettori di trasporto non fossili nei trasporti pubblici su strada". Berna, 12/3/2020. Rapporto del consiglio federale Svizzero, 2020
d	National Academies of Sciences, Engineering, and Medicine 2018. Battery Electric Buses State of the Practice. Washington, DC: The National Academies Press. TCRP 2018
e	RSE, Ing. C. Carlini, Mobilità sostenibile nel TPL Valutazione economica e prospettive dagli orientamenti istituzionali in tema di energia. Mobility Innovation Tour, 11/6/20. RSE 2020
f	Valentini, M. P., & Conti, O. (2016). Procedure di supporto alle decisioni nei processi di elettrificazione del servizio di Trasporto Pubblico Locale su gomma. Report RdS/PAR2015/205. ENEA 2016
g	Abschätzung des Einsatz- und CO_2-Reduktionspotenzials durch Busse mit nicht fossi- len Antriebstechnologien und Fördermöglichkeiten. Grundlagestudie und Zusatzstudie im Auftrag des Bundesamtes für Energie. INFRAS 2020

Table 8: List of publications analyzed to obtain investment and operating costs, as well as remarks and recommendations

In this regard, a major source of error is mainly due to the fact that it is not always recognizable whether the battery is included in the bus cost or not, and which its capacity is (as well as the possibility of having different batteries on the same vehicle). This lack of information contributes to the failure to break down the two cost items in detail.

4.2.2. Main comments and remarks from the literature necessary for economic evaluations

The literature highlights three key categories deemed most significant in terms of economic considerations: batteries, charging infrastructure, and operating costs.

Concerning <u>batteries</u>. The durability of a battery is normally defined and measured in two main ways:

- The number of years for which a battery can operate is called "lifetime";
- The number of cycles a battery is capable of performing is defined as " life cycle".

A battery is generally considered to have reached its end of life when it has less than 80% of its original capacity. However, many battery warranties define end of life as when the battery capacity drops to 60-80% of original capacity. Guaranteed end-of-life capacity is an important factor to consider because the lower the end-of-life capacity, the fewer distances an e-bus can travel.

The lifetime of batteries is due to the continuous chemical reactions that occur within them. These occur regardless of use, but can be aggravated by exposure of the battery to unfavorable conditions, such as high temperatures. When used regularly, batteries can have a lifetime of more than 10 years. However, if they are not used regularly (less than once every 3 months), battery life can be drastically reduced. Since e-buses are expected to be used daily, this should not be a problem for e-bus operators.

The choice of battery size for an e-bus depends largely on the required range and the number of daily kilometers it will need to travel. In larger cities, where the daily distance driven by a bus can often exceed 300 km per day, operators might be more likely to deploy e-buses with larger batteries. Medium and small cities, with average driving distances of about 160 km per day, are likely to be better served by more economical e-buses with smaller batteries.

The battery size of an electric bus therefore requires careful analysis so that the investment is not overly penalized, as finding the right balance is crucial to maximize vehicle efficiency and range.

Concerning <u>charging infrastructures</u>. "Opportunity charging" and "combi-charging" are in general carried out by using charging pantographs at the terminals and in depots, with also the possibility of manual recharging. If these electric solutions are adopted, special attention should be given to the time required for approval, construction and grid connection of charging facilities placed along the route. In fact, real case studies from literature indicate that this process takes time and efforts and suggest that it should be started at least one year before the buses are delivered.

If the "in-motion-charging" option is chosen, overhead cables should be installed for at least 50% of the track. This is the option more invasive and that requires high investments in the supporting infrastructure.

Less conventional "Opportunity charging, combi-charging and in-motion-charging" solutions, as compared to those with manual charging, require investments that are difficult to standardize and predict, and can only be estimated with a good accuracy case-by-case.

Concerning operative costs. The cost items defined as OPEX (operating costs, operation, maintenance, etc.) are very often not addressed and not evaluated in the literature and databases considered. This is most likely due to lack of historical information, experience of manufacturers, variability and uncertainty about future costs (energy, raw materials, etc.), market evolution. In addition, some firms include maintenance contracts in tenders, for which it is, however, difficult to unbundle and trace how and what is included.

4.2.3. Energy and economic analysis

Transitioning from diesel to electric traction of buses offers several economic benefits, including lower operating costs (fuel savings and lower maintenance costs), tax incentives and subsidies, cost stability due to reduced dependence on oil prices, improved corporate image, and reduced risks associated with fuel price fluctuations. These benefits may vary according to specific circumstances, but they contribute significantly to the overall analysis of switching to electric traction.

In general, electric buses typically have higher initial costs than diesel buses, mainly due to electric batteries and charging infrastructure. On the other hand, however, they have lower operating costs over their life cycle. In fact, the energy cost per kilometer of an electric bus is generally cheaper than a diesel bus, and electric buses require less maintenance because of the simplicity of electric motors and less wear and tear on components. When considering the adoption of electric buses, it is therefore important to conduct an economic analysis over several years that considers all the costs over the lifetime of the vehicles. This type of analysis can demonstrate whether and under what conditions the reduced operating costs of electric buses offset the difference of higher initial costs already in the short to medium term.

The cost classification is normally made into two broad categories, CAPEX and OPEX. The former is related to expenses that a company capitalizes over a certain period related to investments and which, after the lifetime of the components, it will have to provide for again. Instead, the latter refers to all the ongoing costs for running the system, including maintenance, cost of energy purchased, insurance, personnel costs.

Whitin this paragraph a method, adopted by different studies and supported by regulations, is described to analyze and compare CAPEX and OPEX costs. This method is usually named Total Cost of Ownership (TCO) and includes all the costs the owner or a company has to face over the entire ownership period, from purchase to use. Because of a matter of second life of components and residual value of investments, those related to disposal are not counted as cost equations in this calculation.

Description of the proposed method

The introduction of electric buses into a public transport company's fleet requires a systemic approach, as it involves different considerations related to the economic evaluation of TCO, with a significant shift towards CAPEX and OPEX expenses, and, consequently, greater attention to the vehicle's useful life.

For the implementation of the energy-economic model, the annualized investment and expenditure method was adopted. It consists of offsetting all temporal misalignments of monetary flows associated with a techno-economic activity, bringing them all back to "time zero" of the operation. Each annual operating expense is calculated and estimated, considering it representative of each year of operation.

This approach allows capital and interest to be combined, along with ongoing costs, resulting in a constant annual rate over time. The lifetime of components is an important element to consider when conducting an energy-economic analysis. Component lifetime refers to the length of time for which a component or equipment will remain functional before requiring replacement or major maintenance. This information is crucial for making informed economic decisions in various contexts.

In general, longer component lifetimes normally reduce long-term costs, but may result in higher initial investments. It is important to conduct a comprehensive cost-benefit analysis in the specific context of the application to make informed economic decisions.

When conducting an economic analysis, it is important to consider major cost items with different life spans, with the aim of planning for their replacement during their useful life and thus keeping the annual cash flow constant and on different time scales of analysis.

Regarding electric buses, the main cost items (macro-categories) with the ranges of different lifetime are reported in Table 9.

	Lifetime [years]
Bus (diesel / electric)	10 – 12
Battery	8 – 10
Charger at the depot	10 – 12
On route charger - pantograph	10 – 12
On route charger - infrastructure	14 – 18
Power grid connection	20 – 25

Table 9: Lifetime ranges of macro-categories for investment cost calculations

Operational expenditures (OPEXs) encompass the aggregate of all annual operating costs, covering various ongoing expenses incurred in the day-to-day functioning of a system or project. On the other hand, capital expenditures (CAPEXs) represent the total of all annualized investments, encapsulating the costs. The following formulas briefly describe these concepts:

$$CAPEX = \sum_{i=o}^{n} a_i \, C_i$$

$$OPEX = \sum_{j=o}^{m} C_{j_OP}$$

Where:

- a_i: annualization of each i-investment;
- C_i: cost of each i-investment;
- C_{j_OP}: each j-operative cost;
- n: number of investment costs;
- m: number of operative costs.

In detail, the annualization of the investment "*a*" has been calculated with the following equation.

$$a = \frac{q^t \cdot i}{q^t - 1}$$

Where:

- a: annuality
- q: factor 1+i
- i: annual interest
- t: duration of the investment – according to lifetime of the components (years)

SIA 480 proposes using a value of 3% for the annual interest, to be reduced by 0.5% for public investments and 1% for national investments.

Based on the costs calculated by web tool described in Section 4.1, through the input data entered by the user, it is then possible to annualize the CAPEXs so that they can be compared with the corresponding OPEXs.

Regarding OPEXs, the tool annually calculates energy costs and propose typical maintenance costs (expressed in CHF/km). Energy costs depend on the size of the bus, its efficiency, the kilometers driven, and the altitude difference. All these values are calculated by the tool that multiplies the energy needed to operate the bus at a corresponding and defined electricity price (in CHF/kWh).

<u>Consideration of the Electricity costs</u>

In Switzerland, the price of electricity consists mainly of three components: the tariff for energy consumed, the tariff for grid usage and the tariff for system-related services.

In 2009, the Swiss market was partially liberalized: companies whose consumption is more than 100'000 kWh per year are free to choose who they supply electricity to, on whom they then depend for the consumption-related component. Concerning small consumers, or the ones who decides not to enter the free market, the prices of this component can vary greatly depending on the region and the electric company involved. For the other components of the energy price, the consumer must follow what is set by Swissgrid and the local electric utilities, respectively.

For an overall energy-economic analysis, it is sufficient to consider the total electricity price, keeping in mind, however, that price optimizations can be implemented, particularly for the "energy tariff" component, as well as the fact that all components can be influenced by different energy, economic and technical policies at the company, regional and national levels.

In addition to all these tariffs, connection fees must be added, which can be influenced by various factors, especially in the case of large powers. Consequently, it is advisable that this type of expense should be negotiated in advance with the power company, which may need specific improvements (installation of a new transformer, increased cable size, power availability, etc.).

In this project, tariffs corresponding to the 2023 averages of a Ticino energy company were used to achieve realistic results and reported in Table 10. These values are indicative and modifiable by the user in the web tool: once the local electric utility is contacted, the user can then modify these values and adjust their calculation respectively.

	Value	**Units**
Connection fee 20 kW (50 A)	5’000	CHF
Connection fee 150 kW (240 A)	28’800	CHF
Connection fee 450 kW (720 A)	100’800	CHF
Tariff energy depending	0.30	CHF/kWh
Tariff power depending	72	CHF/kW (year)

Table 10: Typical connection costs and electricity tariffs

in Canton Ticino it is optionally possible to connect directly to the medium voltage, under the responsibility of AET, the cantonal TSO. In this case the connection fees would presumably be reduced, but on the other hand there would be a need to equip with one's own electric transformer. In the present paper, no insights have been made regarding these aspects, for which ad-hoc evaluations have to be made.

<u>Graphical views of the analysis</u>

Based on the considerations and formulations previously described, it is then possible to calculate and differentiate the annualized cost items concerning the necessary investment and operation of the vehicles. Corresponding cost equations were found for each cost item and integrated into the web tool. The cost estimations are based on the tables of Appendix 5 but, if available, more specific values provided by sales companies can be used.

Energy and fuel prices are highly varying and unpredictable over time. Interest in one technology over another is closely related to the relative operating costs. A simplified way is to impose current energy costs (cost of electricity and cost of diesel) and at the same time set an annual increase in the purchase price of energy, with the aim of achieving greater sensitivity on the two different solutions.

Figure 15 depicts a typical trend of OPEX and CAPEX over a 20-year period, assuming an increase in electricity (CHF/kWh) of 1% per year and diesel (CHF/liter) of 2% per year. The calculation was done on a single 12-meter bus, with a charger in depot, and a running route of 100’000 km per year.

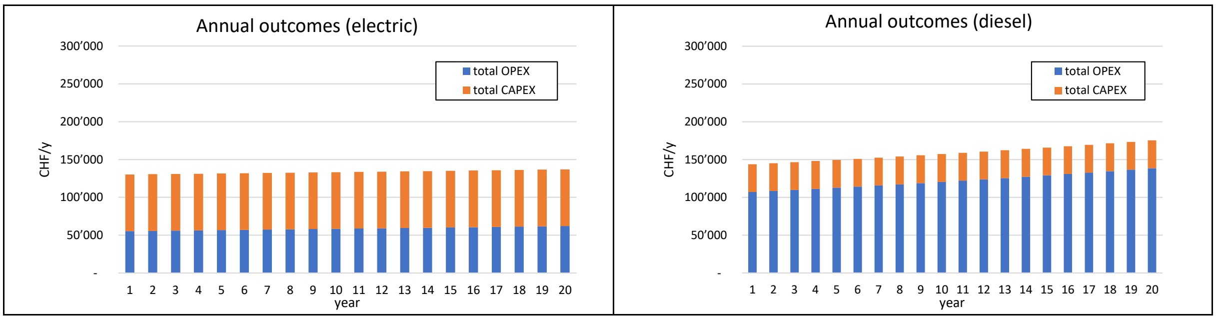


Figure 15: CAPEX and OPEX annual outcomes for an electric bus and a similar diesel bus (example)

Results show that electric traction, compared with diesel traction, has higher annual investment costs but lower operating costs. For a different reading and interpretation of the results, the two calculations can be combined to compare the two options, considering the recurrence over the years of certain investments.

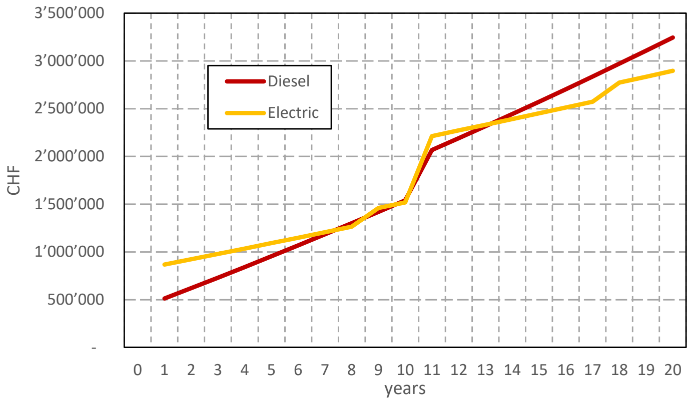


Figure 16: Example of "Break-even point of the cost analysis" comparing diesel bus with electric bus

Figure 16 shows the "break-even point" method, an approach to determine in how many years one investment will become cost-effective over another. It starts with “year 0”, considering the present value of the investments, and continues in subsequent years by analyzing the trend of operating costs, possibly repeating investments if they reach their end of life. If, for simplicity's sake, the repetition of investments is not to be considered in the evaluation, it is advisable to limit the analysis to a period of no more than 10 years.

4.2.4. Environmental analysis

The transition from diesel to electric traction of buses brings significant environmental benefits, including reduced pollutant and greenhouse gas emissions, a lower dependence on fossil fuels markets, less noise emission, and more sustainable management of energy resources, helping to preserve the environment and public health. Reducing pollutant and greenhouse gas emissions is one of the most significant aspects of the switch from diesel to electric traction in buses. Diesel engines emit a variety of air pollutants, including nitrogen oxides (NO_x), fine particulate matter (PM), carbon monoxide (CO), and hydrocarbons (HC). These emissions can have adverse effects on human health, causing respiratory problems, heart disease and other ailments. Electric buses, being exhaust-free, do not produce these emissions on-site, thus improving air quality in urban areas and reducing health risks to residents and transportation workers. In addition, the emission of greenhouse gases such as carbon dioxide (CO_2), are responsible for climate change by contributing to the greenhouse effect. Since electric buses use electricity, their greenhouse gas production is significantly lower than diesel buses. In addition, if the electricity used is generated from low-carbon sources, such as hydropower or solar power, the overall environmental impact is significantly reduced even further. This is fundamental to achieve the goals of reducing CO_2 emissions and mitigating climate change.

Environmental impact assessment is therefore essential when comparing electric buses and diesel buses. For this purpose it is common to conduct well-to-wheel (WTW) and tank-to-wheel (TTW) analyses, which refer to two different approaches for assessing the environmental impact of vehicles, including electric buses. These two approaches are used to measure the energy efficiency and GHG emissions associated with electric transportation, but they consider different aspects of the vehicle life cycle and associated infrastructure, as described in the list below:

1. TTW: This approach evaluates the energy efficiency and emissions of the electric vehicle from the "tank" to the "wheel," that is, from the moment energy is delivered to the vehicle until it is used to move the vehicle on the road. In the case of electric buses, TTW considers the efficiency of the electric motor, capacity of the battery, energy consumption during charging and any energy loss in the drive system. This approach is primarily oriented toward the vehicle itself and its use.
2. WTW: This methodology assesses the overall environmental impact of an electric vehicle, including the processes for producing the energy used to power the vehicle. This approach takes into account the entire life cycle of energy, from the point at which it is extracted (e.g., electricity generation from fossil or renewable sources) to its final use in the vehicle. Thus, for electric buses, the emissions calculation in the WTW approach would include electricity generation, transmission, distribution, and vehicle efficiency.

The main difference between TTW and WTW is that the former considers only the efficiency and emissions directly related to the use of the electric vehicle, while the latter takes into account the entire life cycle of energy, including how it is generated and distributed. Both approaches are important for assessing the overall environmental impact of electric vehicles and for making informed decisions about the transition to low-carbon electric transportation.

In the project the environmental analysis was conducted through the TTW methodology. A comparison was then made between electric and diesel traction by representing the local emissions avoided annually, considering an annual mileage of 100,000 km for each bus. In the analysis, the focus was on emissions of carbon dioxide (CO_2), nitrogen oxides (NO_x) and fine particulate matter (PM10).

Table 11 shows the considered emission indices according to the INFRAS database (please refer to Annex C for details) and an example calculation considering a 12-meter bus travelling 100’000 km per year.

Pollutant	Emission coefficient (diesel Euro VI)	Amount of pollutant saved per year
CO_2	1’155 gCO_2/km	1'732 tonn CO_2/y
NO_x	1.1 gNO_x/km	1.7 tonn NO_x/y
PM10	0.015 gPM10/km	11.5 kg PM10/y

Table 11: Emission indices according to INFRAS database and 12-meter bus travelling 100'000 km per year

Multiplying emission indices by the distance traveled by diesel buses for an equivalent comparison to electric traction is a direct approach to quantify locally avoided emissions. This type of assessment gives a clear idea of the environmental and health benefits, the latter particularly from harmful emissions of nitrogen oxides and particulates.

More specifically CO_2 emissions can be considered completely saved from a global point of view if the electricity used to supply the electric buses is produced entirely from renewable energy sources. This statement assumes a 100% renewable energy mix for power generation, which can vary greatly by various factors such as regional or national renewable energy mix, presence of local PV and subsequent self-consumption, purchase of certified green electricity, etc. Due to the level of detail required to assess these issues, in the present study this topic was not particularly explored in detail.

4.2.5. Comments useful for feasibility evaluations

Determining bus fleet replacement plans to meet electrification targets is a complex task because of a number of normally interconnected aspects.

Firstly, the time to purchase electric buses has to be taken into account. Battery prices have in fact steadily decreased over the last decade, while their specific energy (which directly influences the driving range of buses) and lifespan have improved. This could be an incentive to wait as long as possible before making significant bus purchases, in order to benefit from lower or similar purchase costs, and on the other hand to avoid missing out on further technological improvements. An improvement in the energy density of batteries is expected in the coming years without, however, any particular reduction in the associated costs.

Secondly, the alternative with large batteries avoids the costly investments associated with charging infrastructure along the route, but negatively affects the purchase cost of the vehicles and the number of passengers they can carry (and thus the routes the buses can serve). In addition, having to charge large batteries in a depot can reduce the time the buses can operate, thus trying to charge at night when the buses are not running or are running limited. The alternative of small batteries has opposite pros and cons: lower purchase costs, higher usable passenger loads and fewer time constraints due to depot charging, but possible need for investment in charging infrastructure along the route. In addition, charging batteries during the night, when buses are normally more often stationary in depots, does not allow the use of any photovoltaic systems on garage roofs, which would reduce the energy cost of charging.

Therefore, the introduction of electric buses in a transport company's fleet requires a system view, as different approaches to economic evaluations are required, with a strong shift to CAPEX over OPEX and consequently a greater focus on the useful life of the vehicle. As mentioned previously, the useful life of electric vehicles is often estimated at 15 years, with a battery replacement in the eighth year; experience with electric buses is, however, very limited to date. Many companies, in order to offer their customers buses that are not too worn and outdated, prefer to replace the vehicles around their tenth year of life. It has not yet been fully clarified how to handle battery replacement, and whether the efficiency and battery life between the eighth and tenth year will still be adequate for the routes required by the specific buses.

When evaluating the transition from a diesel fleet to an electric fleet, it is necessary to carefully consider all the many parameters that can affect annual costs. The method proposed here focuses on the expenditure (or output) of money, thus not considering cash inflows. Additional variables such as the number of passengers carried, ticket prices, public funding and other related financial factors are in fact unknown and therefore excluded from the analysis. The inclusion of electric buses in a public transport company's fleet requires a systemic view over the years, as it requires an approach to economic evaluations touching a significant number of parameters, and in general with a strong initial shift to investment costs versus operating costs.

Regarding environmental analysis, given the complexity of the electric market and on global pollutant emissions, it is suggested that for feasibility analysis we focus mainly on TTW impacts. Compared to diesel traction, electric buses are in fact ninefold better in terms of reducing local pollutants (mainly particulate matter and nitrogen oxides) and noise.

4.3. Feasibility study

We dedicate this section to present the results related to the detailed feasibility study carried out for FART and AMSA.

4.3.1. Uncertainty modeling

The detailed study incorporates trip times and energy consumption uncertainties compared to the pre-feasibility study.

Figure 17 shows the estimated best-fit probability distribution for the residual trip times based on the measurements provided by FART and AMSA. Due to the lack of measurements, a combined data set is used for our analytical purposes, which may under-represent reality, especially the extremities. Therefore, we recommend carrying out this analysis with a more representative data set after a long-term measurement campaign by FART and AMSA.

Under infinitely many independent observations, we expect the distribution to approximate a Gaussian according to the central limit theorem. However, the dataset we received for approximating the trip delays contained only 1065 records corresponding to two days of measurements. The effect of the small number of observations is visible, particularly in the right extremity of the distribution, where we see the presence of outliers.

Unlike the residual trip durations, we do not have any measured data to estimate a probability distribution for energy consumption. As such, assuming prior knowledge about the minimum, maximum, and likely outcomes of key variables, we develop an approximation method that we describe in detail in Appendix 2. The resulting histograms of Δe (the difference between actual and planned energy consumption) for FART bus lines are shown in Figure 18 as an example.

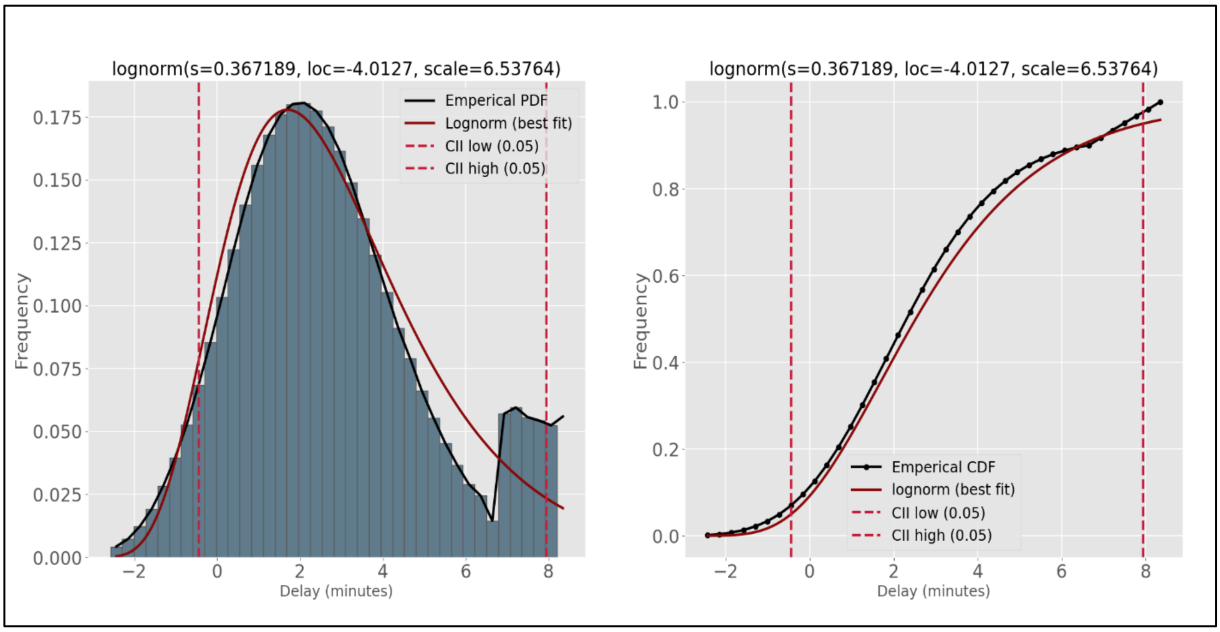


Figure 17: Fitted log-normal distribution of the residual trip durations.
The red dotted lines indicate the confidence intervals

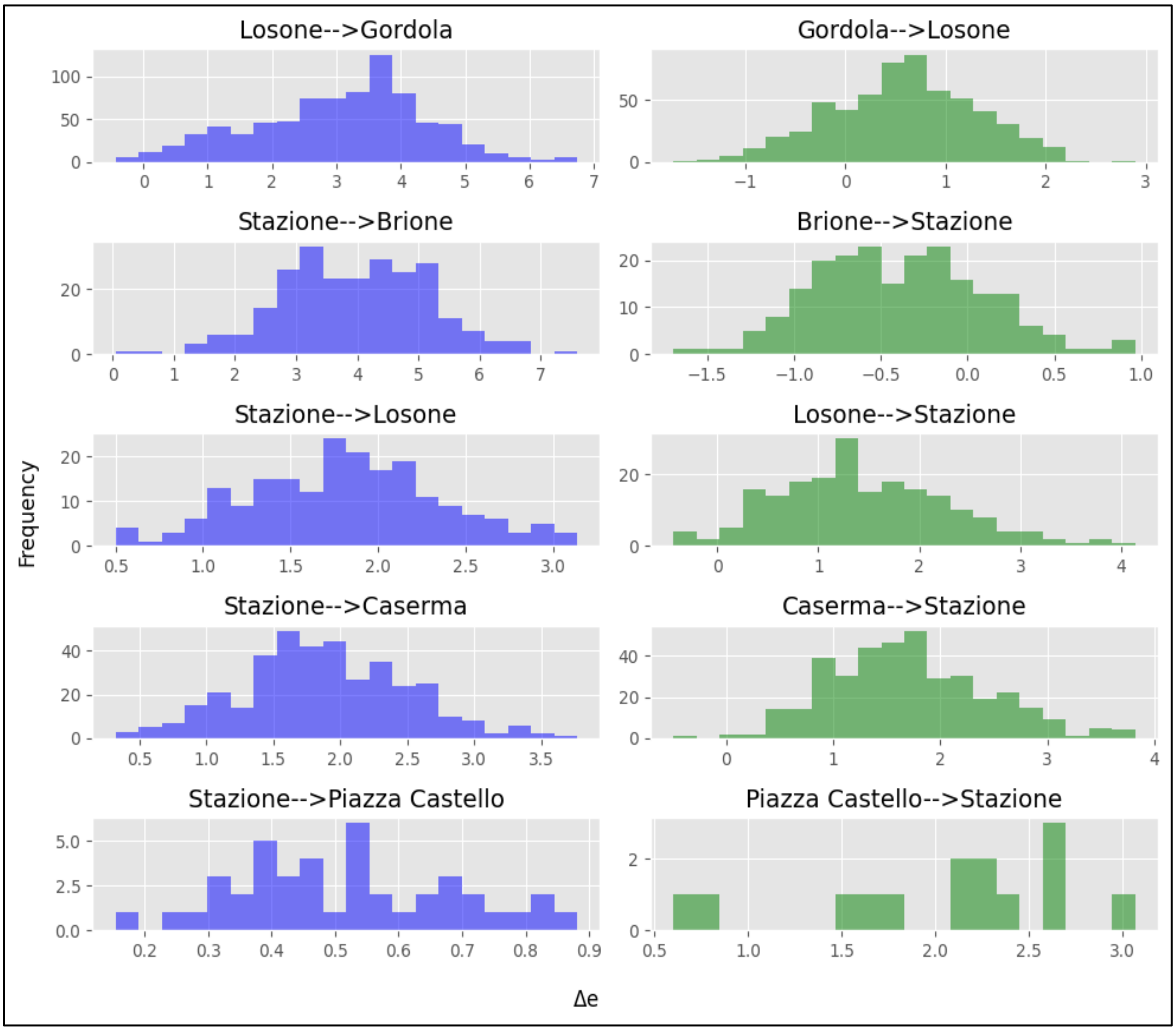


Figure 18: The histograms of Δe (the difference between actual and planned energy consumption in kWh), in different travel directions related to FART bus lines. The distribution estimated using data from a short measurement campaign

4.3.2. Robust vehicle scheduling problem

Based on the state-of-the-art, we define the mathematical form of the problem as a MINLP (mixed integer non-linear problem). Moreover, we remove the one-to-one replacement constraint from the pre-feasibility analysis, allowing the optimizer to find the minimum fleet size under the given constraints. It is also clear that if we intend to optimize for the fleet size, there needs to be some degree of freedom to reevaluate the operating sequences of each bus. Please refer to Appendix 3 for more details about the optimization model.

Public transportation companies develop daily operating schedules in consultation with regional transportation authorities, which is a fixed input to our optimization algorithm. Therefore, to get the degree of freedom we need for optimizing, we define the term “dispatch schedules,” which refers to a mapping between a bus and the sequence of trips the bus operates during the day. For example, consider a fleet of three buses serving nine trips. Figure 19 shows three dispatch schedules by which these three buses can serve the nine trips, given time windows between two trips are not violated.

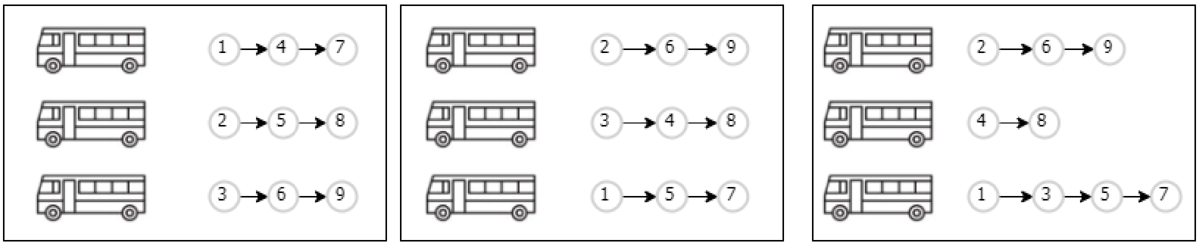


Figure 19: Example of different dispatch schedules. In the three cases shown, the three buses serve nine trips. However, the sequence of trips operated by the buses are different, hence different dispatch schedulesHowever, the sequence of trips operated by the buses are different, hence different dispatch schedules.

The robust optimization problem for fleet planning ensures that the electrified bus fleet operates reliably under time and energy consumption uncertainties. Each battery has a usable capacity of 80% of its rated capacity and an 80% depth-of-discharge (DoD)[11]. Each bus is fully charged (up to 100% of the usable capacity) before leaving the depot in the morning. Battery recuperation happens only at the depot at a maximum charging power of 150kW. Moreover, battery energy is used exclusively for the buses' motion, while auxiliary energy is provided through a separate source.

The worst-case solution time for the robust optimization problem in our use cases is approximately 30 minutes.

4.3.3.Business-as-usual and optimal dispatch

The optimal dispatch strategy gives a balanced workload distribution between all the buses serving a particular line**.** In other words, if the *business-as-usual operation* leads to some buses operating for longer hours/distances than others, those buses will require larger batteries. On the other hand, if we try to maintain the maximum battery size below a feasible upper limit, uneven usage of buses can lead to larger fleets.

To understand this idea, refer to Figure 20 that depicts the final state-of-charge of all buses of FART 301 bus line under business-as-usual operation. Some buses (3, 4, 5, and 6) operate more than other buses while bus 9 is clearly not used that often.

[11] To increase the longevity of the battery, manufacturers recommend charging the battery only up to 80% of the rated capacity, which is called the usable capacity of the battery.

Another potential issue with business-as-usual dispatch schedules is that sometimes they do not have enough buffer time to deal with trip delays.

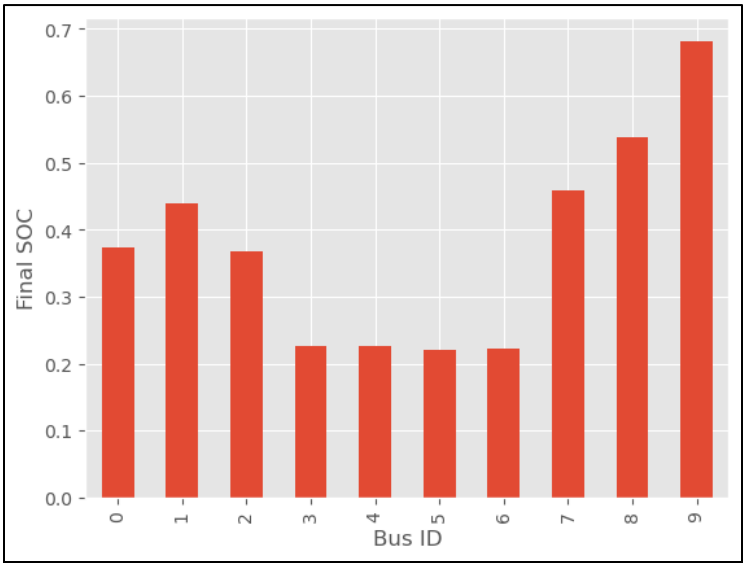


Figure 20: The final SOC of the FART line 301 bus fleet. We see the uneven utilization of the bus fleet from this figure as some buses have SOC level as low as 20% while some buses have SOC levels > 50%

Some of the consequences of maintaining business-as-usual dispatch schedules based on the feasibility study for FART and AMSA are highlighted in Table 12.

Line	Impact
FART 301	Time-window infeasibilities Larger fleet size
FART 303,304	Time-window infeasibilities Min. required battery size exceeds EOL capacity[12].
FART 307	Time-window infeasibilities Min. required battery size exceeds EOL capacity.
AMSA 502,504	Time-window infeasibilities
AMSA 503	Time-window infeasibilities
AMSA 505,507,508,511	Time-window infeasibilities Min. required battery size exceeds maximum allowed capacity.

Table 12: Consequences of maintaining the business-as-usual dispatch schedule.

As reported in Table 12, replacing diesel buses with electric buses in line 511 was infeasible, and due to the bus-sharing nature of these four lines, the infeasibility of one line affected all four integrated lines. A plausible strategy to address this situation is to increase the number of buses that operate on these lines, which also means updating the dispatch schedules[13].

[12] End-of-life capacity allows for battery degradation during its useful life. Therefore, when the minimum required battery capacity exceeds the EOL capacity, it suggests that sometime during the operation, there is the risk of deep discharge of batteries due to degradation.
[13] Earlier, we defined the term "dispatch schedules" as a mapping between a bus and the sequence of trips that the bus operates during the day.

4.3.4.Bus types and battery sizes

The main outcome of the feasibility study is the fleet configuration for each bus line. Note that FART 303,304, AMSA 502,504, and AMSA 505-511 are interconnected lines that share buses.

It is impossible to directly compare the pre-feasibility and detailed feasibility results as the differences in input parameters. For example, the pre-feasibility study uses deterministic inputs, while the energy and time inputs used in detailed feasibility are random variables. However, we highlight some key observations below based on the results in Table 13.

1. As a result of dispatch schedule optimization, the fleet size of FART line 301 is reduced to 9 instead of 10 buses,
2. AMSA 505-511 lines can be electrified with a fleet of 7 buses (two additional buses to the current fleet) equipped with a battery pack of at least 274 kWh (nearest standard size 352 kWh).

AMSA lines 505, 507, 508, and 511 require a minimum battery size of 274 kWh and the nearest standard battery size is 352 kWh, which is also the maximum allowable battery size (according to technical specifications by the manufacturer) for 9-meter buses. We observe that the minimum required battery size is greater than the end-of-life battery size of the 352 kWh battery, which is 260.8 kWh. Therefore, careful monitoring of battery degradation is essential for this bus line to avoid deep discharge and, as a result, service interruptions due to battery degradation.

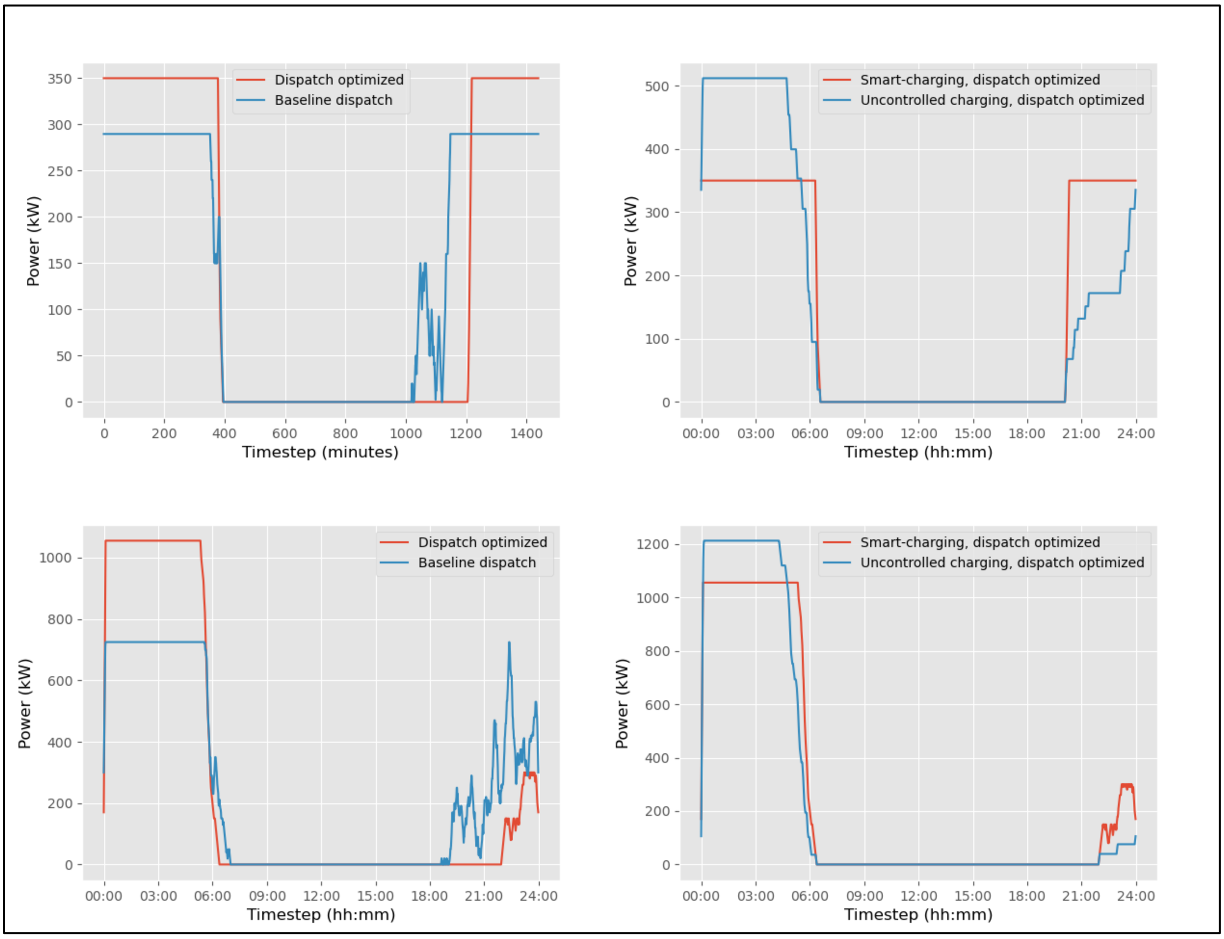


Figure 21: Comparison of the overnight charging profiles of AMSA (top) and FART (bottom) under optimized dispatch (left) and uncontrolled charging (right).

Line #	Bus type x # buses	Minimum battery size (kWh)	Nearest Standard Battery size (kWh)	Usable size (kWh)	EOL battery size (kWh)
FART 301	18m x 9	500.7	704	563.2	521.6
FART 303,304	12m x 4	389.3	528	422.4	391.2
FART 307	18m x 6	376.4	528	422.4	391.2
AMSA 502,504	12m x 6	341.5	528	422.4	391.2
AMSA 503	12m x 2	316.6	528	422.4	391.2
AMSA 505,507,508,511	9m x 7	274.0	352	281.6	260.8

Table 13: Optimal fleet configuration results of the detailed feasibility study

4.3.5. Intelligent charging algorithms and analysis of the impact on the grid

The overnight charging strategy for electric buses involves supplying them at the depot during the night using chargers with a maximum power output of 120-150 kW. The typical charging time takes several hours. To optimize the overnight charging schedule, we aim to minimize the peak charging demand, allowing us to determine the optimal size for the service transformer. We also must ensure that all buses are fully charged to their maximum usable capacity before they begin their first shift the following day. We restrict the maximum power ramp to 20 kW per minute to prevent detrimental effects on battery life, as extreme power fluctuations and ramp rates can harm the battery.

Figure 21 (right) shows the overnight charging profiles of AMSA and FART compared against an uncontrolled charging strategy. For the same fleet and dispatch schedule, the proposed smart charging strategy results in a lower peak charging demand.

4.3.6. Impact of business-as-usual dispatch on smart-charging

Let us observe the impact of business-as-usual dispatch on the overnight charging profile. Figure 21 (left) depicts the comparison between the charging profiles under optimized and business-as-usual fleet dispatch. We observe that the peak charging demand is lower under business-as-usual dispatch schedules, particularly in the case of FART. This observation is linked to the uneven workload distribution and more spread-out start and return times of the buses.

We already observed that business-as-usual dispatch generates uneven workload distribution between the buses (Figure 20). Consequently, some buses have short operating shifts, allowing them to leave the depot late and return early. As a result, under business-as-usual dispatch, there is less charging overlap, which leads to lower peak charging demands. Therefore, there are trade-offs related to dispatch scheduling that public transportation companies must evaluate, and we summarize them in the Table 14.

These results highlight one of the most important dimensions of fleet electrification: the potential conflicts of interest between the transportation company and the energy supplier. From the point of view of the public transportation company, it is advantageous to maximize the utilization of the buses. Maximizing the utilization is advantageous in two ways. Firstly, it reduces the required minimum battery size (as explained earlier), and it also reduces the minimum size of the fleet to serve the same number of trips in a day. However, this self-interest conflicts with the interest of the grid operator as it leads to higher charging peaks due to increased charging schedule overlaps.

In this report, we start by looking at this problem from the perspective of the public transportation company. That means we are trying to find a solution that enables public transportation companies to achieve their self-interest. A part of this endeavor is to find a suitable compromise with the grid operator. Therefore, in the following sections, we describe in detail how renewable energy integration and some innovative fleet management strategies as a strategy to address the peak charging demand concerns of the grid operator.

Optimized dispatch schedules	Business-as-usual dispatch
Leads to smaller battery sizes.	Battery capacity increases and, in the worst case, may lead to project infeasibility.
Leads to smaller fleet sizes.	Sometimes, this results in larger fleet sizes.
Allows better handling of trip delays.	There can be less flexibility to deal with trip delays.
It can cause higher peak charging demands.	Peak charging demand can be lower due to less charging overlap.
Larger transformer sizes and grid connection costs.	Smaller transformer sizes and grid connection costs.

Table 14: Trade-offs related to dispatch scheduling.

4.3.7. Transformer sizing

To determine the appropriate transformer size, we assume a transformer efficiency of 95%. Generally, the maximum transformer loading is limited to 80% of its rated capacity. The power factor at the secondary side of the transformer is assumed to be 0.99, and we disregard any losses associated with AC/DC conversion. Consequently, under the scenario where the entire fleet is electrified, the transformer sizes needed by AMSA and FART are 484 kVA and 1376 kVA (nearest standard size 500 kVA and 1500 kVA), respectively.

Let us denote the peak charging demand as P_{max}. Also, we use η to denote the transformer efficiency, τ for maximum transformer loading and φ for the power factor. Then, the required transformer size KVA is given by,

$$KVA = \frac{1}{\eta\tau\cos\varphi}\mathrm{P_{max}}$$

4.3.8. Advanced fleet management strategies

Earlier, we discussed an important trade-off between grid impacts and fleet configuration. We showed that dispatch scheduling resembles a tuning knob that allows us to balance fleet parameters such as battery size and fleet size and the grid impacts. In this study, we discuss two strategies that enable us to achieve smaller battery and fleet sizes and, at the same time, lower the charging impact on the power system. Firstly, we demonstrate a strategy based on the use of reserve buses. In the following subsection, we discuss renewable energy integration as a strategy to reduce the burden on the power system further.

Every public transportation company typically maintains a small reserve bus fleet. These reserve buses are sometimes assigned to small tasks such as school bus services. They also serve as replacement buses when another bus has to undergo maintenance.

We use the spare bus fleet of AMSA as an exemplary use case to demonstrate the proposed strategy. AMSA has a reserve fleet of three buses, which is expected to increase. At present, the spare buses have a regular schedule to transport school children, but the future schedules for the expanded reserve bus fleet are currently unavailable. Therefore, we make the following assumptions.

- Each reserve bus takes three round trips per day, which is similar to the average number of round trips performed by the current reserve bus fleet,
- The start and end times of these trips are shifted by 5 minutes compared to the current schedules,
- The round-trip distances of the future reserve buses are similar to the round-trip distances performed by the current reserve bus fleet,
- The energy intensity of each trip is 1.2 kWh/km, a rough average of the scheduled trips.

The strategy is as follows.

- **Step 1:** Ensure *k* reserve buses are fully charged by the time the rest of the fleet returns to the depot at the end of the daily operations. While charging reserve buses, maximize PV self-consumption and utilize grid energy only if necessary.

- **Step 2:** The last *k* buses to arrive at the depot[14] are charged up to 50% of their usable capacity[15]. These buses will be used as reserve buses the next day. The regular operating fleet for the next day consists of the buses arriving early and the *k* number of fully charged reserve buses.
- **Step 3:** The *k* number of buses that arrived last at the depot shall serve as reserve buses the next day. Note that they are charged up to 50% overnight.

The above strategy is infinitely repeatable, given that we allow the *k* number of reserve buses to charge with renewable and grid energy. It is also very simple to implement, as it is a simple set of instructions that a technician can learn easily.

4.3.9. Renewable energy integration potential

In the previous section, we devised a strategy using reserve buses to shift some of the overnight charging demand to the daytime, reducing the peak charging demand. Shifting the overnight charging demand to daytime also enables us to use the available solar photovoltaic generation potential on-site. As a first step, we perform a PV potential analysis.

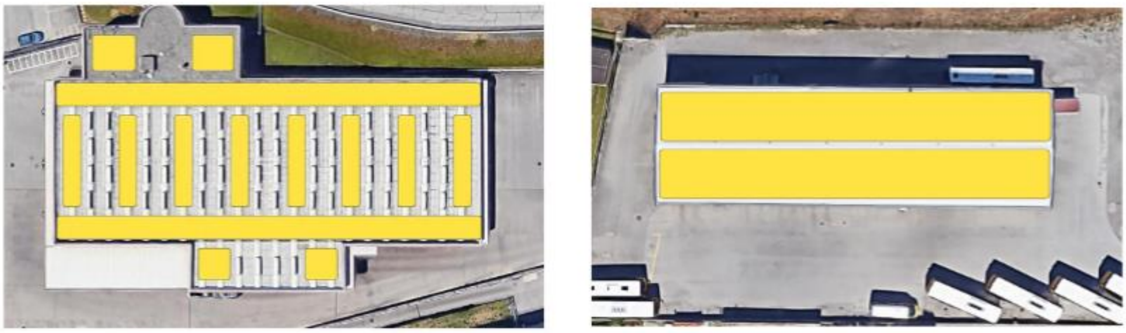


Figure 22: Exemplary solar photovoltaic module layouts on (left) the AMSA main office roof in Balerna and (right) the maintenance building. The area covered in each building is approximately 800 m^2

Figure 22 illustrates exemplary photovoltaic module arrangements for the depot and maintenance building. The depot serves as an overnight parking facility for buses, while the maintenance building provides temporary accommodation for buses undergoing repair or maintenance. The PV generation at the maintenance building cannot be directly used to charge reserve buses. It can be sold to the grid operator at a negotiated feed-in tariff. Conversely, the PV energy generated at the depot can be utilized to charge the reserve buses during the daytime, aligning with our strategy of maximizing the self-consumption of this local renewable energy source.

Given the proximity of the two buildings and the similarity in PV-covered areas, we analyze the PV potential of the depot and assume that the results apply equally to the maintenance building. The exemplary roof-mounted PV design comprises 414 modules of 1.93 m^2 each. The results indicate that the total PV generation potential is about 600 kWh on an average day. If the seasonal irradiation levels worsen, such as in January, the PV generation potential reduces to about 195 kWh. The annual PV generation potential is 135 MWh.

Table 15 describes the technical parameters of the exemplary PV module used for the PV potential analysis. We generate PV generation profile for three exemplary days corresponding to worst-case, average-case, and high PV scenarios. The TMY weather profiles corresponding to each scenario are extracted from meteonorm (meteonorm.com). The PV potential analysis was carried out using the PVLib library (pvlib-python.readthedocs.io/en/stable/#), a popular Python library first developed at the Sandia National Laboratories. Figure 23 shows three PV generation profiles representing worst, average, and best-case scenarios.

[14] Based on the timetables of AMSA (available at amsa.ch), the last buses arriving at the depot are the ones serving lines 502 and 504.
[15] We propose 50% because it is a reasonable state-of-charge for a reserve bus to start operation next day. However, based on practical experience, it is possible to adjust this parameter to a more profitable and operationally convenient value.

Parameter	Value
Model	Suniva OPT300-60-4-1B0
Type	Monocrystalline Silicon
STC rated power	300 W
STC power per unit area	184.4 W/m^2
Cells in series	72
Area	1.93 m^2
Peak efficiency	18.44%
Maximum system voltage	1000 V

Table 15: Technical parameters of the exemplary PV module used in the PV potential analysis.

Advanced fleet management with PV self-consumption

Based on the advanced fleet management strategy introduced earlier, we need to evaluate the number of reserve buses we should use in rotation to shift overnight charging demand and increase PV self-consumption. The expanded reserve bus fleet has seven buses, and our objective is to find the number of buses that enable us to maximize PV self-consumption. We assume that the selected k buses have a battery capacity of the buses serving lines 502 and 504.

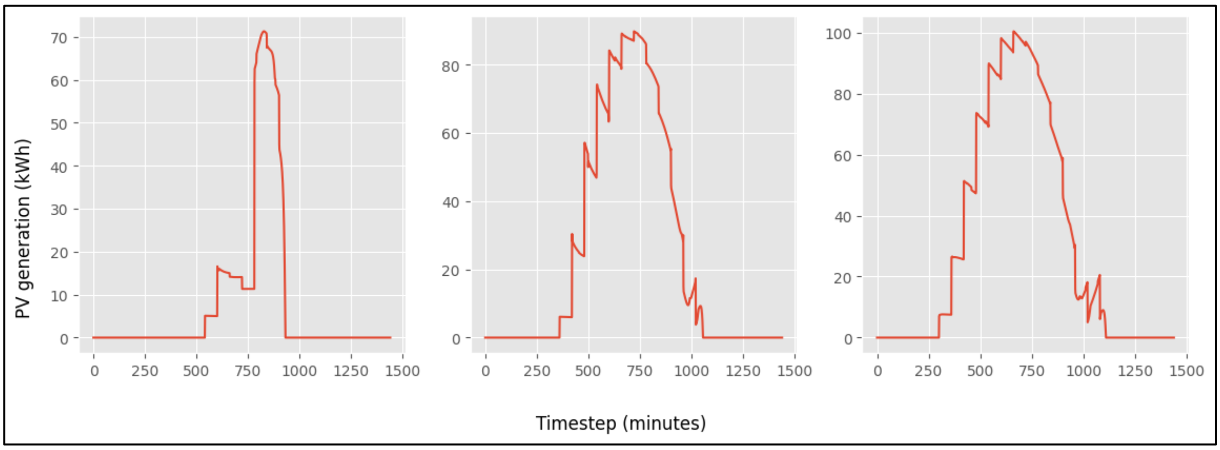


Figure 23: PV generation profile for three exemplary days, (left) January 12th, which refers to the worst-case PV scenario; (middle) April 9th, which refers to an average PV scenario; and (right) May 25th, which refers to a high PV scenario.

Table 16 summarizes the PV self-consumption potential and the share of energy supplied by PV and the grid under different scenarios.

	No. buses = 2			**No. buses = 3**		
	Average	**High**	**Low**	**Average**	**High**	**Low**
Charging demand (kWh)	541.6	541.6	541.6	809.0	809.0	809.0
PV generation (kWh)	599.6	743.7	194.6	599.6	743.7	194.6
PV consumed (kWh)	525.6	540.3	194.6	596.2	721.3	194.6
Grid consumption (kWh)	16.0	1.3	347.0	212.8	87.7	614.4
% PV energy	97.0%	99.8%	36.0%	73.7%	90.0%	24.0%
% Grid energy	3.0%	0.2%	64.0%	26.3%	10.0%	76.0%
PV self-consumption	0.88	0.73	1.0	0.99	0.97	1.0

Table 16: PV self-consumption and share of energy supply from PV and grid under different numbers of electric reserve buses and PV seasonal availability scenarios

Opting for three electric buses is an ambitious choice that yields exceptionally high PV self-consumption levels under all seasonal conditions. However, during winter, the daytime charging energy demand from the distribution grid can increase to 614 kWh daily. A more conservative approach is to plan for two electric reserve buses that still yield quite good PV self-consumption levels but at a lower energy demand from the grid in the winter.

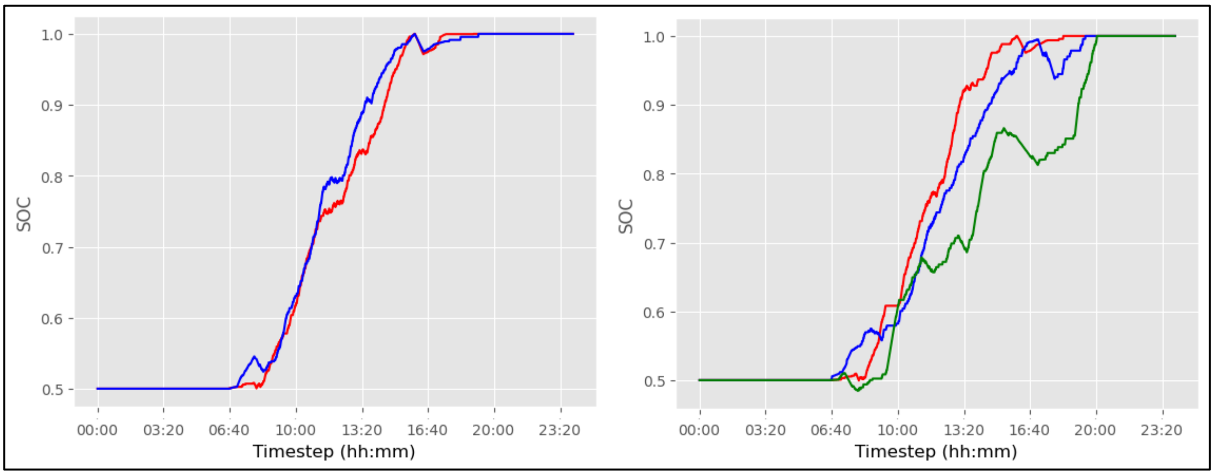


Figure 24: State-of-charge profiles for reserve buses used for demand shifting and self-consumption maximization. (Left) The scenario where only two reserve buses are used, (Right) The scenario where three reserve buses are used.

Figure 24 shows the daytime SOC profiles of the electric reserve buses under the average seasonal availability of PV. We observe that they start with 50% SOC according to the strategy mentioned above. The SOC drops when the reserve buses are dispatched to transport the school children and the SOC improves when they return to the depot and start charging with the onsite generated PV.

Considering the demand-shifting possibility of using reserve buses, the peak charging demand can be reduced to 326 kW (two electric reserve buses) or 306 kW (three electric reserve buses). Consequently, the required transformer size is reduced to 450 kVA.

4.3.10. Economic and environmental calculations applied to AMSA fleet

Based on the information evaluated in the project context, which concerns investment cost estimates for the various components (bus and batteries), the estimated investment is approximately CHF 8.6 million. This investment should also add to the expense of purchasing and installing chargers. Each of them can handle a maximum power of 150 kW per bus, but thanks to the management algorithms developed as part of the project, the total power required never exceeds the maximum value of 400 kW. The resulting projected expense for the chargers in storage amounts to about CHF 1.4 million. The connection expense required by the power company, which was requested based on the maximum power of 400 kW, is around 100‘000 CHF.

As for annual operating costs, these are calculated based on the total vehicle distance of about 1 million km, corresponding to the current utilisation of the analysed buses under analysis. Considering an estimated electricity cost of 0.28 CHF/kWh, a total annual operating cost of about 320’000 CHF is estimated. In addition, yearly costs related to maintenance of the 15 buses are expected to be about 180’000 CHF.
The economic analysis described in Section 4.2 was then applied to AMSA bus fleet. The comparison was made by considering equivalent diesel buses.

		Electric buses expeditures [CHF/y]	Diesel buses expeditures [CHF/y]
OPEX	Travel costs	316'027	815'517
	Bus maintenance costs	167'333	354'200
	Chargers maintenance costs	28'050	-
CAPEX	Bus investment (no battery)	651'657	551'806
	Battery investment	292'001	-
	Chargers investment	147'411	-
	Electric connections	1'718	-

Table 17: Detailed annual operative and investment costs

The graphs reported in Figure 25 show the trend of OPEX and CAPEX over a 20-year period considering diesel busses and electric busses, assuming an increase in electricity (CHF/kWh) of 1% per year and diesel (CHF/liter) of 2% per year.

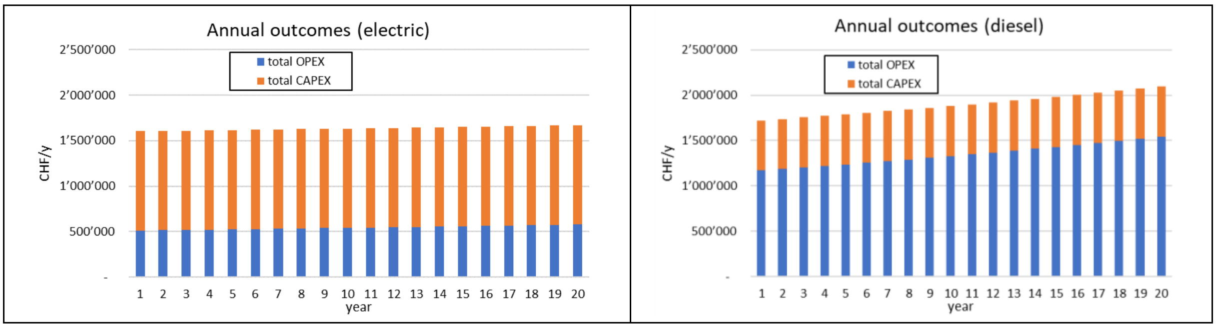


Figure 25: CAPEX and OPEX annual outcomes for a fully electrified bus fleet and fully diesel one (AMSA case study)

The "break-even point" method was additionally calculated allowing to see the flow of investment coupled with the flows of operating expenses.

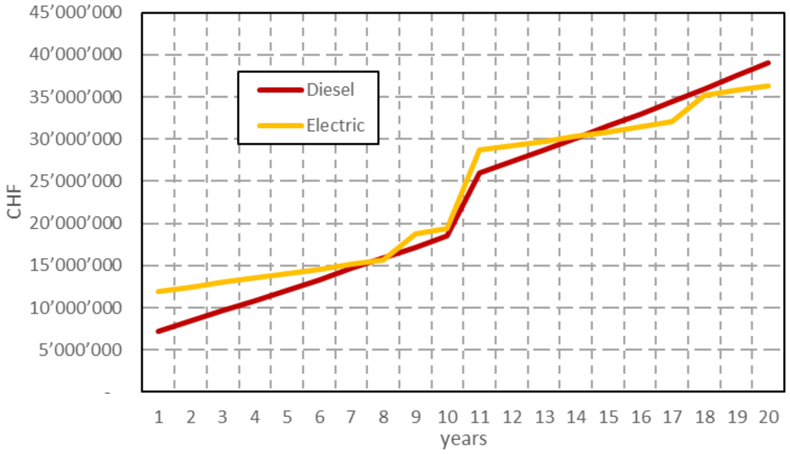


Figure 26: "Break even" analysis comparing a fully electrified bus fleet and fully diesel one (AMSA case study)

Always for the same bus fleet, the environmental emissions (TTW, Tank-To-Wheel) were analysed by comparing electric and diesel traction, and the following figures represent the local emissions avoided annually, considering the total mileage of all 15 buses.

Pollutant	Saved quantity
CO_2	1155 ton/year
NO_x	1.1 ton/year
PM10	15.0 kg/year

Table 18: Saved quantities of pollutants emissions (AMSA case study)

4.4. Practical-operational guide for public transportation companies on the strategy for electrification of public bus fleets.

In WP4, we built upon the work carried out in the previous work packages to develop a comprehensive strategy for electrifying public transport fleets. Activities performed in the WP include:

- Mapping out all activities and processes related to the transition to electric traction, considering technological, organizational, and financial aspects.
- Estimating timelines for each activity, listing potential suppliers, and identifying any potential challenges due to the complexity of the transition.

The results of the analysis are condensed into guidelines that public transportation companies - including our project partners FART and AMSA - can use to plan the electrification of their fleet.

The deliverable for this work package is a practical operational guide that serves as a comprehensive resource for public transport companies in Switzerland, helping them to maximize efficiency and effectiveness in the transition to electric buses. The guidelines document covers technical and economic feasibility, preparation for tendering, compensation and incentive procedures, and changes to internal processes, focusing on personnel training. The document includes a case study on the AMSA transport company and an infographic detailing the main steps in the transition to electric traction.

We compare two other guidelines for bus electrification to elaborate on where the practical-operational guide developed within PVxTuttelettrico stands.

Leitfaden Flottenelektrifizierung für Busbetriebe [15]

This guideline summarizes the generally applicable findings from an analysis for fleet electrification involving Regionalverkehr Bern-Solothurn (RBS) and Busbetrieb Solothurn und Umgebung (BSU), two public transportation companies in Bern and Solothurn areas. The analysis covers specific technologies relevant to the two public transportation companies but provides an overview of other available technologies. The guide includes topics/ suggestions related to network/ energy consumption analysis, charging options, infrastructure requirements, grid integration, safety, economic and environmental considerations, etc.

Guideline for transit electrification (Oregon Department of Transportation) [16]

This guide is designed to provide transit agencies with information and recommendations for vehicle electrification. It covers only battery electric buses[16]. The document summarizes lessons learned from transit agencies in Oregon that have already piloted or deployed electric buses. It also incorporates information from state, national, and international studies on electric buses and provides advice for transit agencies interested in electrification.

The guideline accompanies a quantitative tool for life-cycle cost estimation for alternative fuel transit buses. Compared to the above references, the guide developed within the PVxTuttelettrico project is more oriented toward practical application by public transportation companies, highlighting the action steps and workflows. During our discussions with project partners, this aspect emerged as quite crucial from the point of view of public transportation companies. We also highlight relevant remuneration/ incentive schemes available for fleet electrification projects and provide specific guidelines for preparing documents for tenders, which is another domain where public transportation companies require more guidance and support.

[16] Future editions are expected to address buses of other fuel types.

5. Discussion

Electrifying public bus fleets holds significant benefits by reducing carbon emissions, mitigating air pollution, and contributing to cleaner urban environments. The “PVxTutt'Elettrico” project is designed to enable public transportation companies interested in fleet electrification to realize their objectives by providing tools, insights, and guidelines.

Electrification is an endeavor that involves substantial resource commitment. Therefore, from a transportation company’s viewpoint, it is beneficial to have an initial evaluation of the project's success before committing substantial financial or non-financial resources. This is the objective of the PVxTE web tool, whose simplicity makes it easy to use for any person with reasonable experience in the field of public transport.

The web tool is limited in its inaccuracy due to the compromise made to maintain simplicity and affordable computational resources. Even though the tool suggests feasibility, the public transportation company is strongly advised to perform a detailed feasibility analysis covering topics such as robustness. This analysis can be highly customized based on the context and the company's needs. The following topics were considered in the case studies in which we looked at:

- Robustness of the solution under uncertainty,
- Charging requirements and impacts on the power system,
- Renewable energy integration,
- Strategies to minimize peak charging demand and maximize renewable energy use,
- Economic and environmental impacts of fleet electrification.

Another limitation of the web tool is that it is limited to evaluating single-depot problems. For the vast majority of practical applications concerning urban and suburban bus lines, this is not a problem. Even in a rare multi-depot scenario, if all buses return to the same depot they originate from, we can disaggregate the multi-depot problem into several single-depot problems as a workaround. The cases in which a bus may not return to the same depot it originates from are typical use cases for long-distance buses, such as FlixBus, which is beyond the scope of this project.

Uncertainty related to energy consumption and trip delays plays a crucial part in planning electric bus fleets. Failure to adequately account for these uncertainties can lead to under-sizing the battery systems and fleets and over-estimating the available charging windows. These oversights can lead to operational challenges, e.g., trip delays, cancellations, and service interruptions that are resource-intensive to correct later.

A key challenge to finding robust solutions is the data inputs required to statistically quantify the uncertainties. Some public transportation companies (as we encountered during the project) do not keep track of the operational data related to service delays and energy consumption. As a result, one has to either make assumptions or conduct a short measurement campaign to collect a dataset, as we did during the project, which leads to inaccurate solutions and conservatism. Therefore, we make the following important recommendations regarding operational data management:

1. Public transportation companies must be encouraged to monitor and maintain operational data such as service times/ delays and energy consumption,
2. If this information is not sufficiently available during project planning and estimations/ assumptions have to be made, the public transportation company must cross-check the validity of the estimates/ assumptions made during the project planning process during the implementation and commissioning stages. If there are major discrepancies, their impacts must be evaluated, and corrective actions must be taken.

In Switzerland (and many other countries), bus timetables are linked to the ones of other modes of transportation, such as trains. Therefore, the flexibility to optimize or update the timetables is quite limited. However, to optimize the operation of an electrified fleet, we may require some extra degrees of freedom. Some examples are given below, including some use cases we did not encounter with our case studies.

- To make sure the required battery sizes are not too large by equally dividing the workload among each bus,
- To make sure there is sufficient buffer time between trips to compensate for potential trip delays and make sure delays do not accumulate,
- To make sure there is sufficient buffer time to minimize accumulated trip delays, such that buses do not lose a significant amount of overnight charging time,

- To ensure the availability of sufficient charging time at a terminal stop for fast charging using a pantograph.

Finding that extra degree of freedom while keeping the same bus timetables is challenging. The strategy we proposed in the project, dispatch schedule optimization, involves finding a better mapping between buses and the trips they will serve. The analyses we performed showed the effectiveness of this approach in reducing the fleet size, distributing the workload, and improving the robustness of the solution under uncertainty.

Public transportation services operate within a tightly constrained environment, characterized by thin margins for flexibility. This constraint arises from the intricate interconnection of multi-mode transportation services and the need to enhance economic efficiency. The results underscore the significance of transcending this status quo to facilitate innovative and efficient fleet transition strategies. However, a notable barrier to progress is the absence of thorough internal assessments by public transportation companies regarding their operational processes and practices.

Conducting such assessments is crucial as it provides vital insights into existing processes and practices, especially to understand the relevance of the existing practices for the future. This understanding is pivotal in determining the extent to which process innovation can be incorporated to overcome potential obstacles related to fleet electrification. The analyses and feedback derived from these assessments serve as valuable inputs for expert consultants and research institutes like ours. For instance, these inputs enable the development of more effective scenario studies, identify the most critical decision variables, assign appropriate degrees of freedom in modeling tasks, and narrow down the solution space to search for the most efficient solutions in the shortest amount of time.

A significant practical constraint against dispatch schedule optimization is related to drivers. At present, the dispatch schedules of the buses and the driver schedules are tightly linked. Decoupling the two within the restrictions of the labor law requirements for working hours and rest times might increase staff requirements for public transportation companies. On the other hand, there is the inconvenience factor of changing the status quo for public transportation companies and drivers. However, we recommend that public transportation companies explore this avenue during the electrification project by having an effective dialogue with the drivers to see to what extent a change is possible.

Another key consideration is the systemic view required in transitioning to electric buses. The focus shifts significantly from operational expenditures (OPEX) to capital expenditures (CAPEX), underscoring the importance of evaluating the vehicle's entire lifecycle, particularly its useful life and battery replacement strategies. Electric buses typically have a projected life of 15 years, with a mid-life battery replacement around the eighth year. However, practical experience with electric buses is still limited, and strategies for efficient battery replacement and performance maintenance in the later years of operation need further exploration. This emphasizes the need for transportation companies to adopt a comprehensive and forward-thinking approach in planning their fleet electrification.

A crucial aspect to consider in fleet electrification is the evolution of battery technology. Over the last decade, battery prices have steadily decreased, while their energy density and lifespan have improved. This presents a strategic challenge in timing bus purchases: delaying acquisitions could leverage cost benefits and technological advancements, but also risks missing out on current technological capabilities. Furthermore, the trade-off in battery size impacts both the vehicle cost and charging infrastructure requirements. Larger batteries reduce the need for extensive charging stations but increase vehicle costs and limit passenger capacity. Conversely, smaller batteries necessitate additional charging infrastructure but are more economically feasible and operationally flexible. This highlights the importance of a balanced approach in deciding battery specifications and infrastructure investments.

A thorough examination of the various parameters that influence annual costs is essential in evaluating the transition from a diesel to an electric fleet. Factors such as initial investment, maintenance expenses, energy consumption, and environmental impact are crucial considerations in determining the cost-effectiveness of electric buses.

Transitioning to electric buses can substantially reduce local pollutants like particulate matter and nitrogen oxides, offering a ninefold improvement over diesel traction. This not only contributes to cleaner urban environments but also aligns with broader environmental sustainability goals. Therefore, when assessing the feasibility of electrification, focusing on 'Tank-to-Wheel' (TTW) impacts can provide a more targeted understanding of the environmental benefits. This approach underscores the importance of incorporating environmental considerations into the overall strategy for fleet electrification.

The PVxTE web tool can estimate investment and operative costs in the case of a one-to-one replacement scenario. Coupled with detailed energy and technical analyses, this application enables a nuanced understanding of the potential long-term benefits of switching from a diesel bus fleet to an electric counterpart. By delving into these assessments, transport companies can make informed decisions that not only align with their economic considerations but also contribute to sustainable and environmentally friendly transportation solutions. This strategic approach ensures that the transition to electric buses is not merely a modernization of the fleet but a well-informed and forward-thinking investment in the future of transportation.

Local PV production is an environmentally and economically attractive option for public transportation companies. A key challenge we discuss in the project is integrating local PV generation under an overnight charging strategy. When charging occurs during nighttime, directly utilizing PV generation to offset a portion of the charging energy demand becomes more challenging. For example, a strategy that stores daytime PV generation in large battery storage for use at night is quite a high investment. Instead, we propose a strategy in which we make use of the storage capacity of the reserve bus fleet. By strategically alternating their utilization between the reserve and regular operating fleets, we can shift some of the charging demand to daytime and maximize the self-consumption of renewable energy.

Several parameters are associated with the proposed demand-shifting strategy. We list them below and discuss how significant they are if other public transportation companies adopt the same strategy.

1. PV generation potential –
    a. It is influenced by the design and location of the depot where the chargers are located.
    b. A PV potential analysis must be carried out to estimate the best, average, and worst-case scenarios for onsite PV integration.
2. The number of reserve buses used in a rotating manner –
    a. This depends on the PV generation potential and the available daytime charging windows.
    b. Reserve buses may carry out daytime tasks such as transporting school children, and such activities must be considered during the analysis.

6. Conclusions and recommendations

Public transit companies often lack internal capabilities or capacity to conduct techno-economic analyses related to fleet electrification, especially in conjunction with renewable energy integration and impacts on the electricity system. This serves as a motivating factor for us to develop essential tools, guidelines, and pertinent use cases. While the PVxTutt'Elettrico project is one such attempt, we see it as a continuous process where more tools, especially within an integrated framework, become available, tested, and validated in the future.

The multidimensional nature of fleet electrification projects is highlighted, addressing various concerns ranging from improving transportation service quality (e.g., minimizing service delays and interruptions) to minimizing the burden on local power systems and maximizing the use of renewable energy sources. The presented case studies demonstrate that careful planning at the initial stages of a project enables the simultaneous achievement of diverse objectives. The report emphasizes that a robust planning approach mitigates the risk of service quality degradation resulting from unforeseen delays or energy consumption.

A pivotal observation is the need to reassess conventional practices during the electrification process, particularly in dispatch schedules closely tied to drivers' work schedules. Changing the status quo often requires the engagement of the stakeholders at different levels of the organizational hierarchy, and the practical and operational guide encourages public transportation companies to appeal to everyone's participation and engagement from the initial stages of the electrification project.

Furthermore, optimal charging schedules are emphasized to ensure on-time fleet readiness, minimize peak charging loads on the power system, and maximize the utilization of renewable energy sources. Opportunity charging may not be required for many urban and suburban transportation lines due to relatively short travel distances, short buffer times between trips, and space and investment constraints to install fast-charging stations at terminal stations. Therefore, whenever technically feasible, overnight charging is the least resistance avenue for a public transportation company to electrify their fleets.

When evaluating the transition from a diesel fleet to an electric fleet from an economic perspective, it is necessary to carefully consider and be aware that there are several parameters that can affect annual costs. Several parameters crucial for economic analysis lack detailed information, including the lifespan of investments or future replacement costs. Furthermore, obtaining precise data such as maintenance costs or future energy expenditures is difficult. However, it is essential to work with the available information, make informed assumptions, and be mindful of potential variations to assess their impact on return on investment.

Integrating on-site PV generation under an overnight charging strategy addresses a vital concern. While installing a large stationary battery storage is a solution, we show that there are more economical ways of doing that by strategically integrating the use of the main and reserve fleets. Such innovations require the flexibility of public transportation companies to rethink their current operating methods and practices, once again highlighting the importance of managing the change process effectively within the organization.

Overall, embracing the recommendations provided in this report and other supporting resources such as the PVxTE web tool, accessible at address pvxte.isaac.supsi.ch, and the practical and operational guide will position public transit companies to successfully navigate the challenges and reap the benefits of a sustainable and electrified transportation future.

List of symbols and abbreviations

Hier sind die im Bericht verwendeten Symbole und Abkürzungen (mit den dazugehörigen Einheiten oder Definitionen) zusammenzustellen.

Symbol / abbreviation	**Description**
AMSA	Autolinea Mendrisiense SA
BAU	Business As Usual
BSU	Busbetrieb Solothurn und Umgebung
CAPEX	Capital Expenditure
CO	Carbon Monoxide
CO_2	Carbon Dioxide
CVSP	Capacitated Vehicle Scheduling Problem
DoD	Depth of Discharge
EOL	End Of Life
FART	Società per le Ferrovie Autolinee Regionali Ticinesi
GHG	Greenhouse gas
HC	Hydrocarbons
MINLP	Non Linear Mixed Integer
NOx	Nitrogen Oxides
NP	Nondeterministic Polynomial
PM10	Fine Particulate Matter
PV	Photovoltaic
OPEX	Operating Expenditure
RBS	Regionalverkehr Bern-Solothurn
TCO	Total Cost of Ownership
TVSP	Time-Window Vehicle Scheduling Problem
TTW	Tank-to-Wheel
VSP	Vehicle scheduling problem

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Appendix 1: Inputs for the PVxTE web-tool

This section provides a description about the input requirements for the PVxTE web-tool.

Bus model description:

- Bus model identifier (string) – A name to uniquely identify the bus model,
- Bus length in meters (integer),
- Empty weight of a bus without battery in kg (integer),
- Maximum passenger capacity (integer),
- Minimum number of battery packs required (integer),
- Maximum number of battery packs allowed (integer),
- Size of one battery pack in kWh (integer),
- Bus life time in years (integer),
- Life time of a battery pack in years (integer),
- Investment cost of a bus in CHF (real),
- Investment cost of a battery pack in CHF (real)

Schedule, terminal, and distance information:

- Terminals file (CSV format described in tool documentation) providing elevation and charging infrastructure availability at each terminal location,
- Distance matrix (CSV format described in tool documentation) providing distances between each pair of terminal stations,
- Charging power in kW (real),
- Daily trips schedule (CSV format described in tool documentation).

Other inputs:

- Investment cost of a charger in CHF (real),
- Grid connection cost in CHF/ kW (real),
- Lifetime of a charger in years (real),
- Lifetime of the transformer in years (real),
- Interest rate as a percentage (real),
- Bus maintenance cost in CHF/km (real),
- Charging efficiency (real),
- Annual usage per single bus in km (integer),
- Energy cost in CHF/ kWh (real),
- Annual increase in energy cost in percentage,
- Demand tariff in CHF/ kW (real),
- Diesel cost in CHF/liter (real),

Appendix 2: Approximate modelling of stochastic energy consumption

If we break down each trip into a set of trip segments K, the planned energy consumption of a trip is the sum of energy consumption at each trip segment. A separate diesel engine supplies the auxiliary energy consumption; hence it is not included in the optimization model.

$$e = \sum_{k \in \mathcal{K}} \frac{s_k}{\eta} \left(mg \sin \alpha_k + mgC_r \cos \alpha_k + \frac{1}{2} \rho v_k^2 A_f C_d \right) + e_{hvac} + e_{other} \quad (1)$$

Equation 1 describes the energy consumption model where *mg* is the weight of the bus (including passenger weight), A_f is the frontal area of the bus, α_k is the inclination of the road segment $k \in \mathcal{K}$, C_r is the rolling resistance of the tires, C_d is the drag coefficient, ρ is the air density, η is the overall efficiency of the bus allowing for all complexities, and s_k is the length of the trip segment *k* [17]. We assume constant travel speed within a trip segment. This approximation excludes the effect of acceleration, but it is widely used in the scientific literature to model time-varying traffic conditions [18].

Assuming we possess knowledge or a reasonable approximation of a random variable's minimum, maximum, and likely outcomes, we may represent its distribution using a triangular distribution.

The parameters used to estimate the triangular distributions are outlined in
Table 19. Subsequently, we calculate the energy consumption for trips over a seven-day period using Equation 1 for randomly sampled velocities and passenger capacities. We also have the planned energy consumption for each trip, enabling us to set up a stochastic distribution for the difference between actual and planned energy consumption Δe.

	Minimum	**Likely**	**Maximum**
Passengers	20% of the max. passengers	50% of the max. passengers	80% of the max. passengers
Velocity	$0.5V_{avg}$	V_{avg}	V_{max}

Table 19: Minimum, likely, and maximum passenger capacity and velocity values. v_max is the maximum speed limit of the road segment, and v_avg is the average speed of the road segment

Appendix 3: Optimization model

In this appendix, we describe the optimization models developed during the project.

1. The deterministic mixed integer optimization model associated with the PVxTE web-tool,
2. The robust mixed-integer optimization model (an extension of the deterministic model) used for the comprehensive feasibility study of FART and AMSA.

The deterministic mixed integer optimization model associated with the PVxTE web-tool

The mathematical core of our research problem is an extension to the Vehicle Scheduling Problem (VSP) with additional constraints for time windows and battery charging/ discharging. Similar problems have been studied in the past by various scientists, and we use the method proposed by [1], [9] called the transportation (quasi-assignment) model as the basis for our approach. The key idea is to model the problem as a series of decisions or events that can be mathematically represented as a directed decision graph.

Sets, variables, and parameters:

Sets:	
N	Set of nodes that describe the trips
D	Set of nodes that describes start and end depots
C	Set of nodes that describe charging actions at a terminal station
W	Set of nodes that describes dead-heading and charging at the depot
B	Set of bus indices
V	Set of all nodes
T	Set of time steps
Parameters:	
$\mathrm{T_{i,j}}$	The sum of the planned service time of trip i and relocation time from destination node of i to start node of j
t_i^s	Planned start time of trip i
$E_{i,j}$	Energy consumption of serving trip i and relocation to the starting node of trip j
ψ_i	Energy required to recharge bus i
u	Maximum ramp rate
Variables:	
$x_{i,j}^k$	The binary variable is equal to one if the bus k travels the arc (i,j)
soc_i	SOC at node i
Δsoc_i	SOC change that corresponds to the charging event at or depot charging node i
c_{bat}	Battery size
ζ_i	Charging time at charging or depot charging node i
p_i^c, p_i^d	Charging powers at charging and depot charging nodes

Table 20: Sets, parameters and variables of the optimization model

Based on the definitions above, we formalize the mathematical representation of the problem as follows.

The VSP can be written as a directed graph $\mathrm{G} = (\mathrm{V}, \mathrm{A})$ where $\mathrm{V} = \mathrm{N} \cup \mathrm{C} \cup \mathrm{D} \cup \mathrm{W}$ represents the set of all nodes. $\mathrm{A} = \{(\mathrm{i},\mathrm{j}) : \mathrm{i},\mathrm{j} \in \mathrm{V}, \mathrm{i} \neq \mathrm{j}\}$ represents the set of arcs in the network where each arc (i,j) denotes the servicing of trip j after a trip i. We define a binary decision variable $\mathrm{x_{i,j}^k}$ that takes the value one if the arc (i,j) in the graph is served by bus k and zero otherwise. Figure 27 shows a VSP with two trip nodes and the corresponding charging events (nodes).

If $\mathrm{D} = \mathrm{D}_{\mathrm{s}\backslash\mathrm{cupD}_\mathrm{d}}$ where $\mathrm{D_s}$ and $\mathrm{D_d}$ are the sets of start and end depot indices[17], a valid schedule of a bus;

- Must start from the origin depot and end with the destination depot,
- Must visit all trip nodes exactly once,
- May visit any number of depot charging nodes, but a depot charging node can be visited only from its corresponding trip node,
- May not arrive at a depot charging node from the origin depot node,
- May not return to the destination depot node from a depot charging node.

A feasible schedule $(\mathrm{d_s} - \mathrm{n_0} - \mathrm{c_0} - \mathrm{n_1} - \mathrm{d_d})$ that respects the above constraints is shown in red arrows in Figure 27.

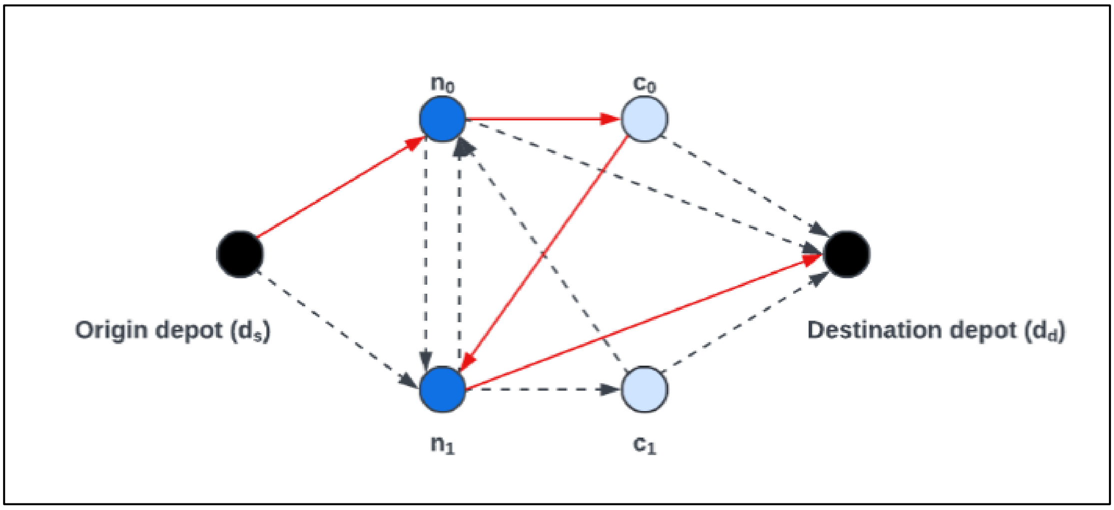

Figure 27: Feasible schedule respecting the constraints described above (red arrows)

The time-window feasibility of two trips (i,j) can be defined as follows.

$$\left(t_i^s + T_{i,j} - t_j^s\right)\sum_{b\in B} x_{i,j}^k \leq 0;\ \forall\ \mathrm{i},\mathrm{j} \in N, k \in \mathrm{B}$$

Time-window constraints with charging time apply for every arc that starts at a trip node and ends at another trip node while passing through a charging or depot charging node. These constraints ensure the existence of a sufficient time window between the two trips, given the respective trip time, relocation time(s), and charging time. The following constraint gives the dynamics of the energy consumption of the buses. We also define a the lower bound of the state-of-charge as a model constraint.

$$\left(soc_i + \frac{E_{i,j}}{c_{bat}}\right)x_{i,j}^k = \mathrm{soc}_j x_{i,j}^k;\ \forall i,\mathrm{j} \in N \cup D, \mathrm{k} \in \mathrm{B}$$

$$\mathrm{soc}_i \geq soc_{min}; \forall i \in V$$

The following constraint describes the charging dynamics of a bus entering the charging node c_i.

$$\mathrm{soc}_i + x_{i,j}^k \Delta\mathrm{soc}_i = \mathrm{soc}_j; \forall i \in N, \mathrm{j} \in C, \mathrm{k} \in \mathrm{B}$$

We can write a similar constraint for depot charging as well. Then it is straightforward to calculate the charging duration $\zeta_i, \mathrm{i} \in C \cup W$, assuming constant charging power during a charging event.

$$\zeta_i p_i^c = c_{bat\Delta so} c_i; \forall i \in C$$

The next set of constraints (below) are the flow constraints. They state that each trip node must be visited exactly once and there must be continuity of flow between a starting node and a terminal node.

$$\sum_{i\in D_s \cup C \cup W b\in B} x_{i,j}^k = 1; \forall j \in N$$

[17] For the single depot scenario, the set $\mathrm{D_s}$ comprises solely of one element. The cardinality of $\mathrm{D_d}$ is the maximum number of vehicles, which is predetermined to be sufficiently large for the model to be feasible.

$$\sum_{i \in D_s \cup C \cup W} x_{i,j}^k = \sum_{p \in V} x_{j,p}^k \; ; \forall j \in V \setminus D, \forall k \in B$$

$$\sum_{i \in D_s, j \in N k \in B} x_{i,j}^k = \sum_{i \in N \cup C, j \in D_d k \in B} x_{i,j}^k$$

The objective function of this optimization model is to minimize the battery size.

The robust mixed-integer optimization model

The robust model extends the previously described deterministic model and integrates the effects of uncertainties related to energy consumption and trip times.

The key differences between the two models are listed below.

- We hedge against the trip delays and uncertainties of the energy consumption in the robust model,
- We use a detailed energy consumption estimation model using the method described in [17],
- Instead of minimizing the battery size, we have a multi-objective cost function.

Hedging against the uncertainties of trip time and energy consumption requires public transportation companies to collect real-world observations and define the appropriate uncertainty sets based on the distribution of the observations. This is a task that could be confusing for many public transportation companies. Therefore, we exclude robustness considerations in the simplified model version of the PVxTE web tool.

According to the method described in [17], each trip is divided into a series of smaller segments, and the energy consumption for traveling each smaller segment is evaluated separately, taking into account variables such as speed, elevation profile of the road, etc. However, applying the method requires manipulating a large amount of geo-data[18] as a pre-processing step to set up the required inputs to the optimization model. Due to the complexity of this endeavor, we adhere to a simplified (and automated) energy consumption model in the web tool version. The simplified model does not divide the trip into a sequence of smaller segments but treats the entire trip length as a single segment.

Since we consider the uncertainty of the trip time in the robust optimization model, the service time delay component is also included minimization objective.

In the robust optimization model, the parameters $T_{i,j}$ and $\mathrm{E}_{\mathrm{i,j}}$ are defined as random variables from distributions that we estimate using data. In our robust model, we define box uncertainty sets for both energy consumption and trip delays hedging against 75th percentile value of the energy consumption and 95th percentile value of trip delays.

Let γ_i be a decision variable that denotes the actual departure time of the trip i that cannot be less than the planned departure time.

$$\gamma_i \geq t_i^s ; \forall i \in N$$

Using $\widehat{T_{i,j}}$ to denote the 95th percentile value corresponding to the sum of service time of trip i and relocation time from destination node of i to start node of j, , we can write the following.

$$\left(\gamma_i^s + \widehat{T_{i,j}} - \gamma_j^s\right) \sum_{b \in B} x_{i,j} \leq 0; \; \forall \, \mathrm{i}, \mathrm{j} \in N$$

Similarly,

$$\left(soc_i + \frac{\widehat{E_{i,j}}}{c_{bat}}\right) x_{i,j} = \mathrm{soc}_j x_{i,j}; \; \forall i, \mathrm{j} \in N \cup D$$

$\widehat{E_{i,j}}$ denotes the 75th percentile value of the energy consumption of serving trip i and relocation to the starting node of trip j. Observe that the decision variable x no longer spans over the set B. This demonstrates the degree of freedom that allows the optimization model to find the optimal sequence of trips for the minimum bus fleet.

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[18] A key challenge of working with open geo-data such as open-street maps is the inaccuracies and incompleteness that often can be verified only by manual checks.

The total time delay is denoted by κ and is given by the following equation.

$$\kappa = \sum_{i \in N} (\gamma_i - t_i^s)$$

To calculate the fleet size λ, we sum the number of flows that originate from the nodes is set D.

$$\lambda = \sum_{i \in D_s, j \in N} x_{i,j}$$

Finally, the optimization problem is set to minimize the size of the electric bus fleet, maximum battery size, and total service delay time over the optimization horizon. Therefore, our objective function is a linear combination of the costs related to fleet size, battery size, and trip delays.

$$minimize\ O = r_1\lambda + r_2 c_{bat} + r_3\kappa$$

Overnight charging management

The optimal overnight charging schedule is a charging schedule for each bus that minimizes the peak charging demand during the overnight charging period. The overnight charging scheduling problem is formulated as linear mixed integer problem subject to the optimal solution to fleet planning problem (deterministic or the robust) described earlier. Together, they form a two-stage optimization problem that we solve sequentially.

Let $\mathcal{T}$ be the set of time steps belonging to the charging duration and $\mathcal{P}$ be the set of indices corresponding to each electric bus[19]. Then, the sum of charging power over the charging horizon should be equal to the energy required to recuperate the batteries of each bus i to their total capacity denoted by ψ_i.The value of ψ_i is determined based on the optimal solution to fleet planning problem.

$$\sum_{t \in \mathcal{T}} p_t^i = \psi^i; \forall i \in \mathcal{P}$$

The aggregate charging profile (the power flow at the coupling point) is given by y_t and it is the sum of individual charging power of the buses. Let the upper bound of y_t be Φ.

$$\sum_{i \in \mathcal{P}} p_t^i = y_t; \forall t \in \mathcal{T}$$

$$\sum_{i \in \mathcal{P}} p_t^i \leq \Phi; \forall t \in \mathcal{T}$$

To limit extreme charging power fluctuations that could reduce the battery lifetime, we assume the maximum ramp rate u to be 20 kWh/min per time step in both directions.

$$-u \geq p_t^i - p_{t+1}^i; \forall t \in \mathcal{T}, \forall i \in \mathcal{P}$$

$$u \leq p_t^i - p_{t+1}^i; \forall t \in \mathcal{T}, \forall i \in \mathcal{P}$$

Finally, we state the objective function as,

$$\text{minimize } \Phi$$

The objective function finds the minimum upper bound to the aggregate charging power.

Economic and environmental calculations:

The economic and environmental calculations are carried out as a post-processing step based on the results of a planning model. When using the PVxTE web tool, the economic and environmental calculations are streamlined into the same work flow and it is fully automated requiring no further user engagement.

Let M and N be the sets of project elements, components, or equipment for which the annualized investment cost and operational expenditure are evaluated. Then;

[19] The cardinality of this set is determined by the solution to the fleet planning problem.

$$CAPEX = \sum_{i \in M} a_i \, C_i; \forall i \in M$$

$$OPEX = \sum_{j \in N} C_{j_{OP}}\,; \forall j \in N$$

a_i is the annualization factor of the i^{th} investment component and C_i is the cost of the i^{th} investment. $C_{j_{OP}}$ is the cost of j^{th} operating cost element.

Given i is the interest rate and t is the duration of the investment, the annualization factor of an investment is defined as follows.

$$a = \frac{(1+i)^t \cdot i}{(1+i)^t - 1}$$

The environmental emissions are indicated by their emission intensities, i.e., amount of emissions per unit consumption of fuel. For example, α is the CO_2 emission intensity of diesel (in kg/ liter) and L is the total diesel consumption (liters), then the emissions W_{CO_2} are calculated as;

$$W_{CO_2} = \alpha L$$

Appendix 4: Detail of the investigated databases

a) Bloomberg, 2019

Source	Finance, B. N. E. Electric buses in cities: Driving toward cleaner air and lower CO_2 .
Year of ref.	2018
Link	assets.bbhub.io/professional/sites/24/2018/05/Electric-Buses-in-Cities-Report-BNEF-C40-Citi.pdf
Description	Overview of the e-bus industry, including a description of business models, an overview of existing e-bus manufacturers, and a detailed analysis of the costs associated with operating e-buses. The report also discusses how different types of cities can best utilize electric buses.
Content	- List of major e-bus manufacturers and characteristics of their respective flag models (Tab. 1, p. 6) - Market price trends for lithium-ion batteries (chap. 6.2) - Average battery life analysis related to the most popular e-bus models (Table 5) - Total Cost of Ownership (TCO) scenarios for different route scenarios (small, medium and large city) (Ch. 8.2)
Pro	- Solid reference for price trends and business plan - Takes into account different annual travel scenarios
Against	- Reference year 2018 - Costs referred mainly to the U.S. context - Lack of disaggregated prices of e-buses, components, and infrastructure

b) Bocconi, 2021

Source	Baccelli, O. (2021). Scenari e prospettive dell'elettrificazione del trasporto pubblico su strada: Un'innovativa analisi di benchmark: Il TCRO-Total Cost and Revenues of Ownership.
Year of ref.	2021
Link	www.enelfoundation.org/content/dam/enel-foundation/topics/2021/11/Report%20su%20TCRO_ITA_def.pdf
Description	TCRO (Total Cost and Revenues of Ownership) analysis of major TPL (Local Public Transport, in Italian "Trasporto Pubblico Locale") solutions.
Contents	- Review of the main studies available in the literature on TPL (fig. 16, p. 34) - Current costs per km and projections to 2030 for all major types of public road transport (Full electric, Diesel, CNG, fossil LNG, biomethane LNG and hydrogen) in terms of costs for vehicle purchase, maintenance, consumption and infrastructure (Fig. 6, p. 11) - Bidding basis and price (bus and maintenance) of Consip tender "Autobus 3" and "AQ Urban Bus" for 10m, 12m and 18m CNG, hybrid, diesel and full electric buses - Summary pros and cons for each bus category (Fig. 19, p. 42) - E-bus market analysis for different battery lengths and capacities (Fig. 33) - Trend analysis and projections to 2030 battery cost (Fig. 34 and 35, p. 56) - Full service e-bus maintenance cost analysis (ch. 3.4.3) - Recharge infrastructure cost analysis (ch. 3.4.5) - Indications on bus service life with different engines (Fig. 43)
Pro	- Very robust data because it is based on actual tenders awarded - Very recent data (calls for tenders in the last 6/7 years)
Against	- Mainly referred to the Italian market - Data are disaggregated from tenders awarded, lacking a proper price "list" for buses, batteries, etc.

c) Swiss Federal Council Report, 2020

Source: Rapporto del Consiglio federale in adempimento del postulato 19.3000 CTT–N del 15/1/2019. "Promuovere l'affermazione dei vettori di trasporto non fossili nei trasporti pubblici su strada". Berna, 12/3/2020

Year of ref.: 2019

Link: www.newsd.admin.ch/newsd/message/attachments/65688.pdf

Description: Analysis of the i potentials for reducing CO_2 and air pollutant emissions in the short, medium, and long term for switching from current diesel buses to propulsion technologies that do not use a fossil energy and estimating the associated additional costs

Contents:

- Purchase costs according to bus type and propulsion technology (2020 price). Source: INFRAS 2020 (tab. 1, p. 11)
- Regulatory framework and information regarding incentive opportunities in Switzerland (Ch. 4)
- Estimated profitability due to transition to an electric fleet (aggregate data) (Ch. 3.4). The analysis takes into account the following cost categories:
  - Infrastructure along lines and in depots or workshops (investment and service/maintenance costs)
  - Vehicles with battery included: purchase and maintenance costs
  - Energy costs
  - Additional costs for driver personnel due to the operational impacts of the individual option (e.g., higher vehicle turnover due to charging processes).

Pro:

- Analysis based on an updated database (INFRAS 2020, limited access)
- Keeps track of all relevant expense items
- Includes review of regulatory environment and incentive possibilities (included in WP objectives)
- Exclusively referred to the Swiss context

Against:

- Net of a table, there is no disaggregated data, for which it would be interesting to be able to consult INFRAS reports
-

d) TCRP, 2018

Source: National Academies of Sciences, Engineering, and Medicine 2018. Battery Electric Buses State of the Practice. Washington, DC: The National Academies Press. doi.org/10.17226/25061 .

Year of ref.: 2018

Link: nap.nationalacademies.org/catalog/25061/battery-electric-buses-state-of-the-practice

Description: State of the art of transportation systems in planning, procurement, infrastructure installation, operation and maintenance of battery electric buses (BEBs).

Contents:

- Case studies with investment and operational costs based on actual surveys provided by the transportation agencies involved in the study (Ch. 6)

Pro:

- Real case studies with real CAPEX and OPEX

Against:

- Entirely referred to U.S. context

e) RSE, 2020

Source: RSE, Ing. C. Carlini, Mobilità sostenibile nel TPL Valutazione economica e prospettive dagli orientamenti istituzionali in tema di energia. Mobility Innovation Tour, 11/6/20

Year of ref. 2020

Link www.autobusweb.com/wp-content/uploads/2020/06/Presentazione-rse_corretta.pdf

Description Presentation of an RSE study (full report not available) regarding the techno-economic evaluation of 4 case studies in Italy on integration of electric buses in the fleet of urban transport companies

Contents
- Costs of purchase, maintenance, and charging infrastructure for 4 case studies in Italy (Bolzano, Turin, Milan, and Bergamo)
- TCO assessment compared with fossil alternatives in the fleet of the transport companies analyzed

Pro
- Real case studies with real CAPEX and OPEX

Against
- Entirely referred to Italian context
- The characteristics of the means purchased are not stated (only battery capacity)

f) ENEA, 2016

Source Valentini, M. P., & Conti, O. (2016). Procedure di supporto alle decisioni nei processi di elettrificazione del servizio di Trasporto Pubblico Locale su gomma. Report RdS/PAR2015/205..

Year of ref. 2015

Link www.enea.it/it/Ricerca_sviluppo/documenti/ricerca-di-sistema-elettrico/adp-mise-enea-2015-2017/mobilita-elettrica/RdS_PAR2015-205.pdf

Description Final report of an ENEA research aimed at developing decision-support software for use by LPT Companies to identify which lines are best suited, both technically and economically, for possible use of battery-powered vehicles and for which technological solutions preferably

Contents
- List prices of some buses distinguished by size class and power supply. Prices net of VAT referring to period from 2011 to 2015. (tab. 14 and tab.15)
- Unit costs of on-board storage systems in €/kWh and charging infrastructure from various sources + assumptions market evolution (tab. 16 and tab. 17)
- Data sheets of electric buses considered in the study (no prices) (Ch. 11.1)
- Data sheets with prices of many examples of CNG and diesel buses (useful as a benchmark) (p. 115)
- Technical details for 27 e-bus specimens (fig. 46, p. 118)

Pro
- Excellent support for development of later project phases, fleet sizing, and progressive integration of electric vehicles
- Input data for the software seem very robust and can be used to enrich the database that is to be developed

Against
- Not recent (2015)
- Part of the sources refer to market surveys conducted by agencies in the U.S. territory

g) INFRAS, 2020

Source INFRAS 2020. Abschätzung des Einsatz- und CO_2-Reduktionspotenzials durch Busse mit nicht fossi- len Antriebstechnologien und Fördermöglichkeiten. Grundlagestudie und Zusatzstudie im Auftrag des Bundesamtes für Energie (Stima del potenziale di utilizzo e di riduzione di CO_2 da parte dei bus con tecnologie di propulsione non fossili e possibilità di promozione. Studio di base e supplementare su incarico dell’Ufficio federale dell’energia). Zurigo

Year of ref. 2020

Appendix 5: Detail of the costs implemented and used in PVxTE

This annex is based on the databases analyzed and described in Annex C. From these, costs relating to the investment and operation of electric and diesel buses were extracted. The costs of electric buses include not only their initial investment and operating costs, but also the costs associated with recharging infrastructure. Due to the fluctuation of the euro franc exchange rate, and the current value, the euro is considered equal to the Swiss franc.

Based on these data, cost equations were created and entered into the "PVxTE web tool for energy and economic evaluations of a bus fleet".

Electric buses:

CAPEX:

Electric bus (without battery):

8 m bus	390'000	€==CHF
12 m bus	440'000	€==CHF
18 m bus	690'000	€==CHF

Table 21: Electric bus investment costs (without battery)

Battery:

200 kWh	70'000	€==CHF
350 kWh	122'500	€==CHF
550 kWh	192'500	€==CHF

Table 22: Electric batteries investment costs

The "residual value at end-of-life for batteries" was not taken into account. This value is very variable and could change over the next few years. However, a sensible current value could be around CHF 100/kWh, which corresponds to the value that the company can recover from the sale of the batteries at end of life. If the user wants to take it into account, it has to be subtracted from the initial investments shown in the tables above.

Charging infrastructure:

Slow depot (with installation) – about 70 kW_{el}	60'000	€/unit
Fast terminal (with installation) – about 200 kW_{el}	110'000	€/unit
On-route (with installation) – about 200 kW_{el}	350'000	€/unit
Pantograph On-route (with installation)	200'000	€/unit

Table 23: Charging infrastructure investment costs

Protoscar provided costs of charging stations as a function of power. In addition to these costs, the final cost should be increased by about 20%, value due to supply, installation, prepayments, etc.

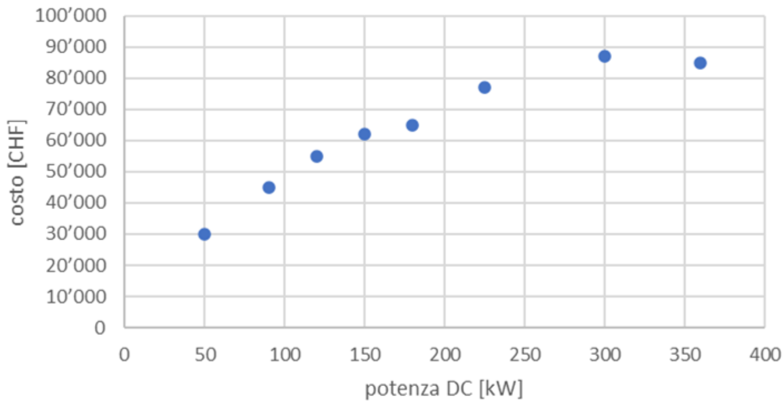

Figure 28: Charging stations investments costs

The figure above, provided by Protoscar shows the relations between the DC power if the charging infrastructure and the costs. The points depicted in the graph show basically a linear behaviour until 250-300 kW, then no significant cost increases are observed.

Electric company fees:

Fee for a 150 kW connection (240A)	28'800	CHF
Fee for a 450 kW connection (720A)	100'800	CHF
Fee for a 20 kW connection (50A)	5'000	CHF

Table 24: Electric company fees (local company values)

Values based on online information from a local electricity company. Depending on necessary investments in the grid infrastructure and availability of grid power, these values can vary considerably.

OPEX:

The following bus efficiency values were found in the literature. The "PVxTE web tool" also calculates these values for electric buses, so they are not used by the tool.

8 m bus efficiency	1.11	kWh/km
12 m bus efficiency	1.15	kWh/km
18 m bus efficiency	1.63	kWh/km

Table 25: Efficiencies of electric buses

Instead the following table report typical maintenance values found in literature.

8 m bus maintenance	0.13	€/km
12 m bus maintenance	0.21	€/km
18 m bus maintenance	0.28	€/km

Table 26: Maintenance costs of electric buses

As mentioned in section 4.4, the electricity market is heterogenous and can be complex, as consequently the related cost calculation. Due to the large amount of energy consumed annually, and the large amount of power that is expected to be concerned, it is recommended to make contact with the local company or optionally consider entering in the «free electricity market». In this study a unique value has been taken into account (overall typical average value in Ticino is 0.3 CHF/kWh). However, tariffs related to the grid costs and the power consumption can also be considered.

Energy tariff	*tbd*	CHF/kWh
Grid tariff	*tbd*	CHF/kWh
Power tariff	*tbd*	CHF/kW/year

Table 27: Electric tariffs composition (simplified)

Diesel buses:

CAPEX:

Purchase 8 m bus (total)	250’000	€==CHF
Purchase 12 m bus (total)	350’000	€==CHF
Purchase 18 m bus (total)	500’000	€==CHF

Table 28: Diesel bus investment costs

OPEX:

The following tables show typical efficiency and maintenance costs of diesel buses. The user can enter the corresponding purchase value per litre of automotive diesel.

8 m bus efficiency	0.352	kWh/km
12 m bus efficiency	0.584	kWh/km
18 m bus efficiency	0.746	kWh/km

Table 29: Efficiencies of diesel buses

Maintenance 8 m bus	0.30	€/km
Maintenance 12 m bus	0.38	€/km
Maintenance 18 m bus	0.5	€/km

Table 30: Maintenance costs of diesel buses

Fuel cost	1.6	CHF/l

Table 31: Diesel cost