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Title: Technical and economic feasibility of increasing tram system efficiency with EV batteries

Abstract:

Separate and common overhead catenary systems (OCS) are widely utilised on urban light-rail systems. This paper applies Simulink modelling to investigate differences in energy efficiency between two OCS systems, applied to a typical urban tram system. Results suggest common OCS reduces energy demand by 14%, as availability of regenerative braking increases by 297%. This paper predicts number, capacity and best installation locations for energy storage systems (ESSs) on an example system. Greater energy efficiency is achieved by installing ESS on centre stops between adjacent substations, rather than substation stops. Further, an economic study considers net present value, internal rate of return and payback period for a given ESS capacity; and a sensitivity analysis identifies capital cost and battery life as the most influential parameters to economic viability. Finally, using parked EVs as ESS for a tram system is explored to improve the economics.

Keywords: tram system; energy storage system; electric vehicles; energy balance; economic feasibility; light rail

1. Introduction

Saving energy and reducing carbon emissions has become a global mission. In the transportation sector, electrification has long been considered as an important measure to reduce carbon emissions (Butcher et al., 2018). With regards to decarbonising transportation, electrification of rail transport is an important player, along with the contribution from electrified road transport that has been increasing due to the promotion and increasing adoption of electric vehicles (EVs) (European Commission, 2017). In England, for example, a number of major cities (London, Manchester, Sheffield, Newcastle, and Nottingham), have light-rail or tram systems that cover their urban and sub-urban areas (DfT, 2019b). The statistics published by the Department for Transport UK (DFT) show that from 2012 to 2019, the number of passenger journeys provided by the eight English light-rail and tram systems increased by more than a fifth, from 222.5 million to 272.4 million (DfT, 2019a). In the same period, the number of plug-in cars and light good vehicles licensed in England increased by more than 37 fold, from 5,909 to 225,803 (DfT, 2020).

Typically, electrified rail transport utilises dynamic braking, in which the electric motor will work as a generator, upon braking, to convert the kinetic of the tram / train into electricity (González-Gil et al., 2013). However, energy provided from a substation is typically supplied unidirectionally and therefore cannot transfer any excess energy from the catenary back to the utility supply. Therefore, the regenerated energy can only be re-used inside an energy supply section of the rail system which is located between, and powered by, two substations. Generally, a small proportion of the regenerated energy is utilised by the auxiliary loads of the tramcar. The remainder could be utilized to power another accelerating tramcar simultaneously if it is travelling in the same energy supply section, which is commonly referred to as regenerative braking (González-Gil et al., 2013). However, if an accelerating tramcar is not present in the section, to prevent the un-used regenerated energy overly raising the catenary voltage and subsequently causing infrastructure damage, the surplus energy is dissipated as heat via the on-board braking / dump resistor; this is commonly known as resistive braking (González-Gil et al., 2013).

Regenerative braking can therefore offset part of the system energy consumption, and hence the promotion of it elevates the energy efficiency of a light-rail or tram system. Regenerative braking is influenced by the braking energy receiving capacity of the system, and therefore it is affected by the existence, and number, of the nearby accelerating tramcars travelling inside the same energy supply section as the braking tramcar (Zhang et al., 2020). Synchronizing the decelerating and accelerating tramcars through adjusting the timetable is one of the measures to increase the opportunity for regenerative braking (Nasri et al., 2010, Peña-Alcaraz et al., 2012). Aside from timetable adjustments, the energy supply configuration also influences the braking energy receiving capacity. The route network of a light-rail or tram system is commonly configured with dual tracks, each operating in opposing directions (commonly referred to as the uplink and downlink). This paper defines a 'common OCS' as having a substation that exploits the same catenary/cable to power both uplink and downlink tracks. Conversely, a system with a substation that uses separate catenaries/cables to power the uplink and downlink is referred to as a 'separate OCS'. The light-rail or tram network studied in Morita et al. (2008), Chymera et al. (2010), Hirano et al. (2015), and Tian et al. (2016) are separate OCS, and the ones in Açikbaş and Söylemez (2007), López-López et al. (2012) and Teymourfar et al. (2012) are common OCS. The key difference between these two system configurations is that the common OCS allows energy transfer and exchange between uplink and downlink, whereas the separate OCS does not. Consequently, common OCS could have increased instances of regenerative braking, since the accelerating and decelerating tramcar/trains can be traveling on different tracks (in different directions) within the same energy supply section but not be travelling along the same track as the separate OCS requires. The energy balance of separate and common OCS has been well investigated, but there exists little research that directly compares the energy balances based on the same light-rail or tram system.

An energy storage system (ESS) is considered as an effective measure to improve regenerative braking and hence improve the energy balance of a light rail system, as it can store the un-utilized regenerated electricity and feed the stored electricity back to the supply network when needed (Morita et al., 2008, Teymourfar et al., 2012). Morita et al. (2008) conducted a study based on a section of the Osaka Municipal Subway's Chuo Line and reported that an ESS could effectively store the regenerated electricity and the rise of catenary voltage was thereby suppressed simultaneously; the ESS could also provide the stored energy back to the system, which compensated the voltage and reduced energy drawn from the substations. Teymourfar et al. (2012), Ceraolo and Lutzemberger (2014a) and Herrera et al. (2016) studied the light-rail systems in Tehran (Iran), Bergamo (Italy) and Seville (Spain), respectively, and all suggested that ESS capacity positively affects the potential energy saving. Furthermore, in the Tehran study, the ESSs installed at 10 stops located along a 33 km long route are location specific and were tailored with different capacities to achieve different energy savings (Teymourfar et al., 2012). Therefore, both capacity and location are considered important to achieving the energy-saving delivered by an ESS.

However, existing ESS studies tend only to focus on one energy supply section or one single line but seldom cover an entire network that has multiple routes. If such a study solely focuses on a single section of network, the proposed ESS installation might not be at the most optimal location in the network and thus might not lead to the best energy-saving for the whole network. An investigation that focuses on the entire network will resolve this problem.

At the same time, a substantial proportion of the literature regarding adding ESS to a tram network only focuses on the impact on the energy balance side. Whilst some literature will perform economic feasibility studies based on the energy balance studied, the economic study is hardly considered as profound and comprehensive as their energy studies. Streit et al. (2014) discussed the return on the investment, Park et al. (2017) explored the net present value, and Roch-Dupré et al. (2017) looked into both economic parameters on their studies about adding ESS to a rail network, however they did not conduct a sensitivity study to understand the uncertainty and the key influential factor of the economic evaluation. It would be valuable to have a comprehensive economic feasibility study that covers enough potential influential factors and understands their impacts on economics.

The growing number of EVs in general circulation, effectively results in an increasing number of mobile batteries, and thus an increasing flexible energy storage capacity. The concept of using EVs to provide power to specific electric markets and to store excessive energy produced by the grid for levelling the demand and production of the electric system was proposed and known as vehicle-to-grid (V2G) (National Grid plc, 2018, Kempton and Tomić, 2005, Guille and Gross, 2009). In the example of renewable energy generation, its peak generation is not aligned with the peak demand of the grid (Blanco and Faaij, 2018). However, with the introduction of V2G technology, the variability of renewable generation can be smoothed, and hence, the grid can receive more renewable energy, and consequently the generation cost is reduced (Haddadian et al., 2015, Fernandes et al., 2012). The V2G concept can also be exploited at different scales and to various electrical systems because in theory it is still indeed an energy storage technology that can buffer the demand and supply. Gough et al. (2017) studied the technical and economic feasibility of supplying electricity stored (at the off-peak period) in the EV battery to the nearby commercial building at the peak hours via V2G and suggested a promising outcome from both energy and economic perspectives Besides benefiting the electrical system owner, V2G technology also creates financial benefits for the participating EV owners via incentives (Gough et al., 2017, Pelzer et al., 2014, Ma et al., 2012). Therefore, V2G is a promising alternative to the stationary ESS for providing energy storage to an electrified light-rail and tram system.

Therefore, this paper firstly investigates the energy balance of the Sheffield Supertram system based on a common OCS configuration and compares it to its separate OCS configuration (Section 2). Subsequently, based on the comparison as to which one has the better energy balance, a stationary ESS is introduced to the model to determining how installation location, ESS capacity and number of installations impact the energy balance of the entire network (Section 3). Finally, the paper concludes with an economic study based on the stationary ESS option for demonstrating the influential factor of economic evaluation and extrapolates to the significance for the utilization of EVs as ESS on the system (Section 4). This study considers a network of 3 routes, and lines are therefore shared where routes overlap. Therefore, some tram line sections will have tramcars from one single route travelling in it, and some tram line sections will have tramcars from multiple routes travelling over it. The number of tramcars travelling on the tracks directly impacts the energy balance of the given tram line section.

2. Comparison of separate and common OCS configuration

This research focuses on the Sheffield Supertram as a local example to the authors and represents a typical urban light rail tram network. The total route length of the Supertram system is 29 km (Stagecoach, 2020). The latest route map display is shown in Fig. 1. It consists of three lines (or routes) which include 48 stops and 12 substations (red underlined in Fig. 1).

Fig. 1 The route map of the Sheffield Supertram (Substations underlined in red)

Supertram has 12 substations that segregate the network into 11 energy supply sections. Because only the substation stops, and the stop located in the middle of the energy supply section (called centre stop in this paper) are relevant to the modelling and simulation of energy balance, the route map may be simplified. This paper therefore simplifies the route map (Fig. 1) in to Fig. 2, which only highlights the substation stops and centre stops. Both are shown in Fig. 2 with the 12 substation stops and the 11 centre stops highlighted with blue and red dots respectively.

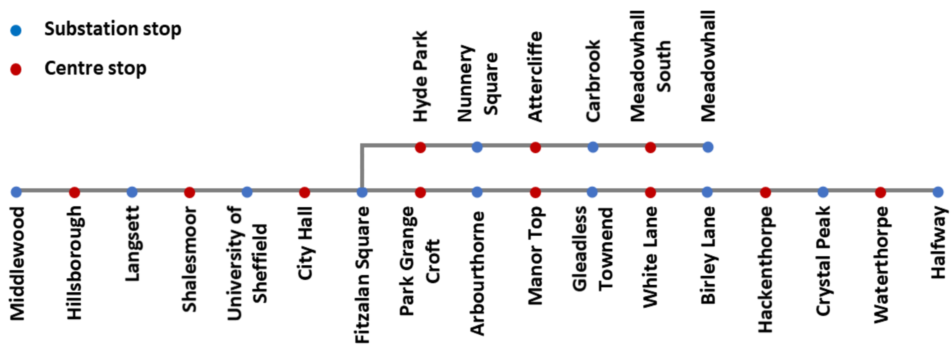

Fig. 2 The substation stops and the centre stops of the energy supply sections in the Supertram network

2.1 Introduction of energy supply modes

The rated voltage of the Supertram system is 750 Vdc, and the LV distribution voltage of the UK utility grid is 11 kV ac. Hence, the substations transform the 11 kV ac into 750 V dc to supply the catenary and power the trams. The substations utilise a bilateral power supply approach. Namely, each substation provides power to the two adjacent rail supply sections. The substation can use either a separate overhead catenary system (OCS) or a common OCS to transmit the energy to the tramcar, as illustrated in schematic in Fig. 3.

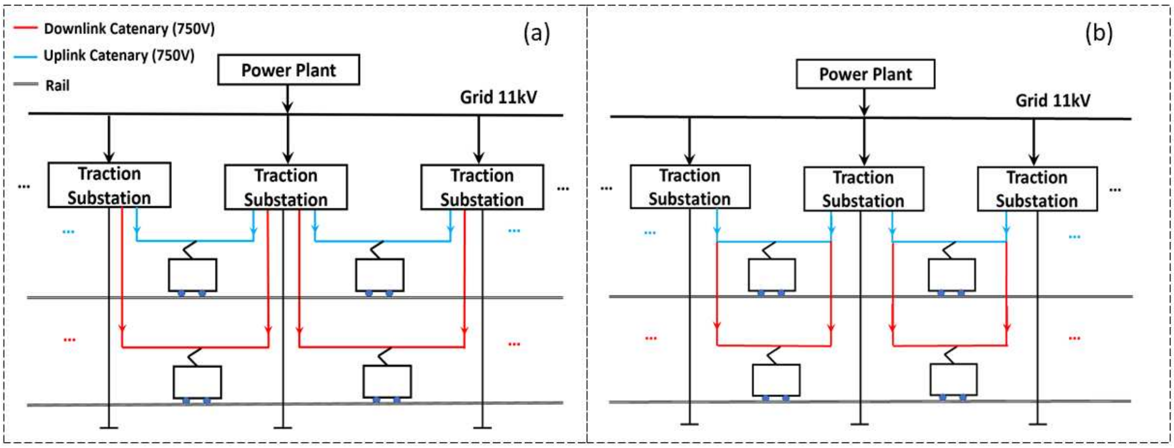

Fig. 3 Schematic of separate OCS (a) and common OCS (b)

In the separate OCS, the substation has two independent cables to power the uplink catenary/tram-travel and downlink catenary/tram-travel, and the two cables are not connected (being fed from their own rectifier), as shown in Fig. 3(a). But, in the common OCS system, the substation uses the same cable to power both the uplink and downlink and hence the uplink and downlink catenaries are connected, as shown in Fig. 3(b).

The application of common OCS or separate OCS determines whether energy flows between uplink and downlink catenaries, between different tramcars and substations, and furthermore, between individual tramcars. Choosing between common OCS or separate OCS could potentially lead to a variation on the energy consumption. Therefore, it is worth knowing the effect on the energy use of the two alternative operating modes. This paper thereby presents a model created to represent the common OCS mode that is fundamentally based on the Supertram network, and subsequently compares its energy balance to the model that was also built from the Supertram network but represents the separate OCS mode (Zhang et al., 2020).

2.2 Simulation method of energy balance

This paper estimates the energy requirement for the Sheffield Supertram network, based on simulation of tram operations, utilising real GPS data of tram journeys and the operational timetable. This mirrors the approach used in Zhang et al. (2020). The overall simulation includes the construction of a model and the data input, and can be described in four main steps:

1. The distance, speed, acceleration and altitude data of example tram journeys that covers all the routes and stops was collected, initially on a second by second basis via a dedicated

GPS device, with data collection covering both morning (08:00-12:00) and afternoon (14:00-18:00) travel patterns, on three different weekdays in June 2018.

2. This data was subsequently used to calculate both the distance moved per second and the force generated or absorbed by the electric motor, on a second by second basis, during the tram journey.
3. Both the distance and force data obtained from the example tram journeys that travel both the uplink and the downlink of all the stops and routes, and the operational timetable, are incorporated into a Matlab model for integration into the system. The model aims to replicate the operational profile of the tramcar for every tram journey during a typical weekday.
4. Based on the operational profile of every tram journey made during a day (from the Matlab model), the Simulink model will simulate the daily energy balance of the tram system.

2.3 Energy balances of the two energy supply modes

The energy balances presented in this paper consider three factors: the energy supplied from substation (E_{sub}), the energy lost in the braking resistors (via resistive breaking, E_{res}), and the regenerated energy re-used (via regenerative breaking, E_{reg}). Table 1 presents the energy balances of the common OCS, simulated based on 6 independent data sets collected. As can be seen, there is little variation in the results simulated from these different data sets. The percentage standard deviation of the energy supplied from substation, the energy lost in resistor, and the regenerated energy re-used are 1.2%, 2.1% and 2.9%, respectively. This phenomenon is in good agreement with the result of separate OCS presented in Zhang et al. (2020). Hence, this paper used the mean values of the energy balance of the two systems for comparison.

Table 1 Daily energy balances of common OCS system simulated from different data sets

	Day 1 Morning (kWh/d)	Day 1 Afternoon (kWh/d)	Day 2 Morning (kWh/d)	Day 2 Afternoon (kWh/d)	Day 3 Morning (kWh/d)	Day 3 Afternoon (kWh/d)	Mean (kwh/d) *
Energy supplied from substations	28974	29934	29317	29836	29732	29309	29517±342 (±1%)
Energy lost in resistor	12665	13284	12839	13260	12912	12567	12921±272 (±2%)
Regenerated energy re-used	7084	7284	7034	7486	7607	7130	7271±212 (±3%)

*：the value shown in the () is the percentage standard deviation

As mentioned in Section 2.1, the separate OCS prevents the energy transferring between the tramcars travelling on the uplink and the downlink within the same energy supply section, but the common OCS allows it. In the common OCS, more tramcars are therefore able to access and utilize the braking energy produced, and this leads to a greater value of the regenerated energy being re-used. In turn, this results in a smaller amount of energy lost in the braking resistor, and thus less energy is required from the substations. As shown in Fig. 4, the regenerated energy re-used from the common OCS is 297% greater than that of the separate OCS. Consequently, the common OCS also has a 27% smaller energy lost in resistor and requires 14% less energy supplied from substation.

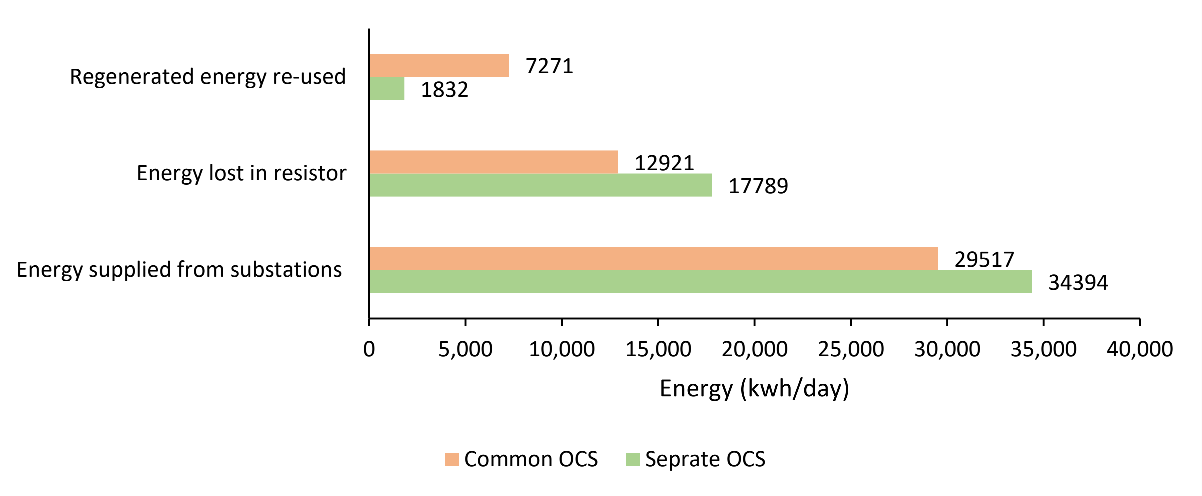

Fig. 4 Comparison of the energy balances of Separate OCS and Common OCS

From the mean results presented in Fig. 4, the energy from the substations, E_{sub} of the common OCS is 34,394-29,517=4,877 kWh/day less than the E_{sub} of the separate OCS, and the re-used braking energy, E_{reg} of common OCS is 7,271-1,832=5,439 kWh/day greater than that of the separate OCS. This suggests that the reduction of the substation energy supply, E_{sub}, can be completely compensated for by the increase in re-use of the braking energy, E_{reg}. Although the increase of the E_{reg} is similar to the reduction of the E_{sub}, the former is still about 10% greater than the latter. This indicates part of additional E_{reg} was potentially lost in the catenary resistance during its transmission from one tramcar to another.

As shown in Fig. 4, the braking energy, being the sum of E_{reg} and E_{res}, for the two systems were found to be similar, but the common OCS is slightly higher (by 3%) than the separate OCS. Any braking energy generated could also be consumed by the 'hotel loads' (Lighting, heating, air conditioning etc.) on the tramcar, in addition to the dissipation in the dump resistor. Therefore, some degree of self-consumption will take place of the resistive braking energy. However, the largest difference between the common OCS and separate OCS is that the former has more braking energy flowing to the catenary and less braking energy flowing to the resistor than the latter.

Although a common OCS is found to be more energy efficient than a separate OCS, the resistive ‘dumped’ energy, $E_{res,}$ of both systems are still equivalent to about half of their own power supply requirements, E_{sub}. This indicates that there is an enormous unrecovered energy reserve in the tram system, and the successful recovery of this could lead to a significant benefit on the energy-saving, potential cost-saving, and ultimately carbon emissions, for the tram system operation.

3. Impact of ESS installation on energy balance of the tram network

Zhang et al. (2020) studied the impact of an ESS installation location on the improvement of energy balance and suggested the installation of the ESS at the centre stop between two substations could lead to the best improvement in system efficiency. However, this conclusion was reached based on the modelling of an isolated energy supply section in a separate OCS. By extending the scale and scope of this investigation from one energy supply section to the whole tram network, then the substation stop ESS will serve two adjacent energy supply sections. Therefore, this paper presents the results from a simulation model of the energy balance across the entire network, including the introduction of centre stop ESS and/or substation ESS, with a common OCS configuration that allows a substation based ESS to serve at its maximum function. This work then enables the potential energy saving generated by both the centre stop ESS, and substation ESS to be compared; and the impact of differing ESS capacities on the improvement of the energy balance across the network to be studied.

3.1 Modelling of ESS installation

Having compared the separate and common OCS, we will now consider the implication of locating a possible ESS at various locations within the whole network. To this end, an ESS is modelled at each of the 12 substation stops, and on the 11 centre stops of each energy supply section shown in Fig. 2, in turn, to assess the overall effect on the whole system energy use.

Fig. 5 shows the Simulink model of a substation stop ESS installation. The model consists of 4 steps, after the data collection and scaling for the overall routines:

1. The modules tram1P to tram4P and tram1N to tram4N are responsible for the modelling the operation of tramcars
2. The modules sub1 to sub3 are responsible for modelling the substations
3. The modules PR1 to PR6 and NR1 to NR6 are responsible for modelling the line resistance
4. The module ESS serves as the energy storage facility.

The ESS module is able to absorb the braking energy generated from two adjacent energy supply sections. In this section, an ESS with a limited discharge rate of 2 C and capacities of 1,000 Ah, 500 Ah, and 100 Ah were installed on the substation stop and centre stop of each energy supply section in turn to determine the effect on the system energy use. These example capacities were based on currently available EV battery capacities which ranges from 40 kWh (i.e. Nissan Leaf) to 100 kWh (i.e. Tesla). Therefore, a 100 Ah battery (49kWh at 400V) can be considered to equate to an EV with a relatively small battery. Multiples of these EVs will give increasingly large available capacity, and from Zhang et al (2020), 1,000Ah is a large enough capacity to provide sufficient energy saving capacity to achieve our goals. Hence, the 500Ah is taken as an intermediate value approximately reflective of 5 available EV's for the study.

The ESS performance evaluation mainly focuses on examining how the introduction of the ESS changes the regenerated energy re-used, the energy lost on the resistor, and the energy supplied from the substation on a daily basis. The study also investigates how ESS battery capacity and installation location further impacts the ESS performance.

3.2 Single ESS installation

The simulation results indicate that the introduction of ESS, regardless of its placement on either substation stops or centre stops of an energy supply section, increased the re-use of regenerated energy, reduced the energy lost in the braking resistors, and consequently reduced the energy supplied from the substations. Table 2 shows the increase in the re-use of the regenerated energy ($+E_{reg}$), the reduction the energy lost in the resistors ($-E_{res}$), and consequently the reduction of the energy supplied from the substation ($-E_{sub}$) if one ESS, modelled with various storage capacities was installed at different locations, in turn. Table 2 categorizes the results based on the ESS battery capacity, and ranks them in a descending order based on the reduction of the energy supplied from the substations ($-E_{sub}$), for each of the stops in Fig. 2

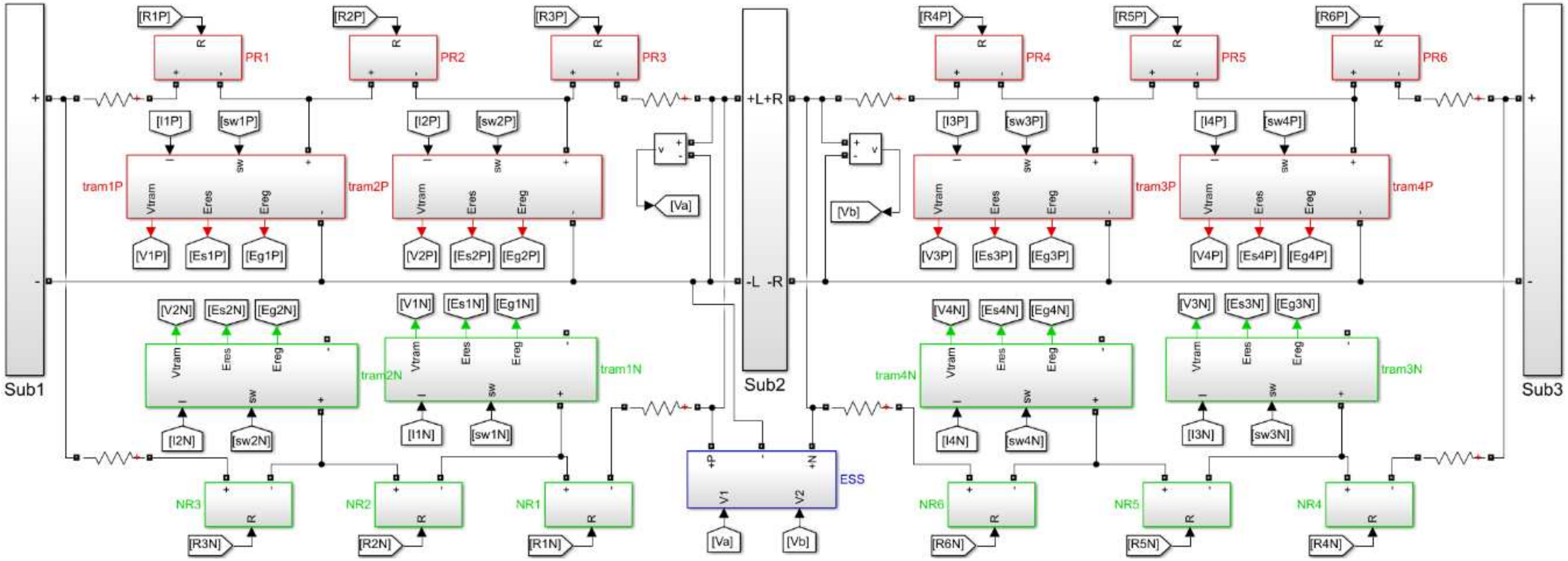

Fig. 5 Model of ESS installation on substation stop

Table 2 The change of energy balance caused by using ESS with different battery capacities

	ESS battery capacity: 1,000 Ah					ESS battery capacity: 500 Ah					ESS battery capacity: 100 Ah				
Ranking	**Tram Stop**	**Type***	**-Esub**	**-Eres**	**+Ereg**	**Tram Stop**	**Type***	**-Esub**	**-Eres**	**+Ereg**	**Tram Stop**	**Type***	**-Esub**	**-Eres**	**+Ereg**
1	Park Grange Croft	C	1205	1194	1207	Park Grange Croft	C	1130	1161	1170	Park Grange Croft	C	609	621	630
2	Shalesmoor	C	1084	1155	1156	Shalesmoor	C	964	1048	1042	Shalesmoor	C	607	635	631
3	Manor Top	C	1004	836	844	Manor Top	C	931	829	831	Manor Top	C	566	535	528
4	Hillsborough	C	985	1108	1063	Hillsborough	C	923	1024	979	Fitzalan Square	S	562	608	587
5	City Hall	C	882	1087	1069	City Hall	C	876	984	959	Hillsborough	C	552	637	588
6	Attercliffe	C	833	902	922	Attercliffe	C	770	823	868	The University	S	531	585	538
7	Hackenthorpe	C	678	852	870	Hackenthorpe	C	676	752	772	City Hall	C	518	549	543
8	Waterthorpe	C	675	860	867	Waterthorpe	C	668	753	754	Attercliffe	C	481	488	504
9	Fitzalan Square	S	622	796	773	Fitzalan Square	S	618	726	700	Langsett	S	425	469	439
10	The University	S	607	773	733	The University	S	604	713	669	Hackenthorpe	C	407	410	435
11	Langsett	S	487	656	626	Langsett	S	481	595	566	Waterthorpe	C	401	418	426
12	Hyde Park	C	457	624	651	Hyde Park	C	450	530	560	Arbourthorne	S	370	380	394
13	Arbourthorne	S	435	604	608	Arbourthorne	S	431	533	535	Gleadless Townend	S	337	319	345
14	Gleadless Townend	S	426	527	550	Gleadless Townend	S	423	411	436	Hyde Park	C	326	320	355
15	Meadowhall South	C	386	552	576	Meadowhall South	C	382	472	496	Crystal Peak	S	319	333	350
16	White Lane	C	371	517	546	White Lane	C	368	449	481	Meadowhall South	C	304	311	334
17	Crystal Peak	S	333	538	550	Crystal Peak	S	321	422	438	Nunnery Square	S	299	308	332
18	Nunnery Square	S	318	491	507	Nunnery Square	S	310	408	425	White Lane	C	295	305	322
19	Birley Lane	S	277	400	420	Birley Lane	S	272	338	367	Birley Lane	S	269	275	297
20	Halfway	S	169	384	394	Halfway	S	163	260	275	Halfway	S	160	172	188
21	Middlewood	S	144	330	303	Middlewood	S	141	250	225	Middlewood	S	139	193	171
22	Meadowhall	S	109	304	318	Meadowhall	S	102	198	220	Meadowhall	S	96	107	132
23	Carbrook	S	90	240	262	Carbrook	S	83	176	201	Carbrook	S	61	70	98

*: C = centre stop, and S = substation stop

As shown in Table 2, for the same installation location, a higher battery capacity tends to have a greater influence on the amount of regenerated energy re-used, as well as having a greater reduction the energy lost on resistor, and a greater reduction of the energy supplied from the substation. It is worth noting that the ESS state of charge is set 50% at the beginning of the simulation (namely at the start of a day) regardless of the actual capacity (Ceraolo and Lutzemberger, 2014b). Assuming the ESS is half full, this would allow the ESS to either store or feed energy from/to the network initially. Additionally, with this initial condition, the ESS has the capacity to either store excess energy, or supply energy to the tram system over the course of the day, this being reflected in the final state of charge of the ESS at the end of the days operation. From the data shown in Table 2, if the increase of the regenerated energy re-used (E_{reg}) is greater than the reduction of the energy supplied from the substation (E_{sub}), then the ESS receives a net input of braking energy. Conversely, if the increase of E_{reg} is less than the reduction of energy from E_{sub}, then the ESS provides its own energy to the tram. Whether the ESS will have a net input or output may be impacted by the tram sharing the road network, thus could be attributed to the road traffic condition at different times of day and the frequency of braking and acceleration occurring when a tram passes through a busy area.

From Table 2 it may be seen that there is little difference in the ranking of the 1000 Ah category and the 500 Ah category. However, there is a noticeable difference in the rankings of the 100 Ah category from the first 2 columns. Some substation stop ESS installations ranked higher in the 100 Ah category than in the other two categories, for example, an installation on Fitzalan Square went from the 9th to the 4th ranking when comparing the 100Ah column with the other ESS sizes; and the installation on University of Sheffield went from 10th to 6th. To understand how battery capacity impacts the overall savings for the centre and substation stop ESS installations, the mean value of the reduction of energy supply from substation, the reduction of energy lost in resistor, and the increase regenerated energy re-used was calculated for both centre stop ESS installations and for substation stops ESS under different ESS battery capacities. Results indicating these mean values and the trends are shown in Fig.6.

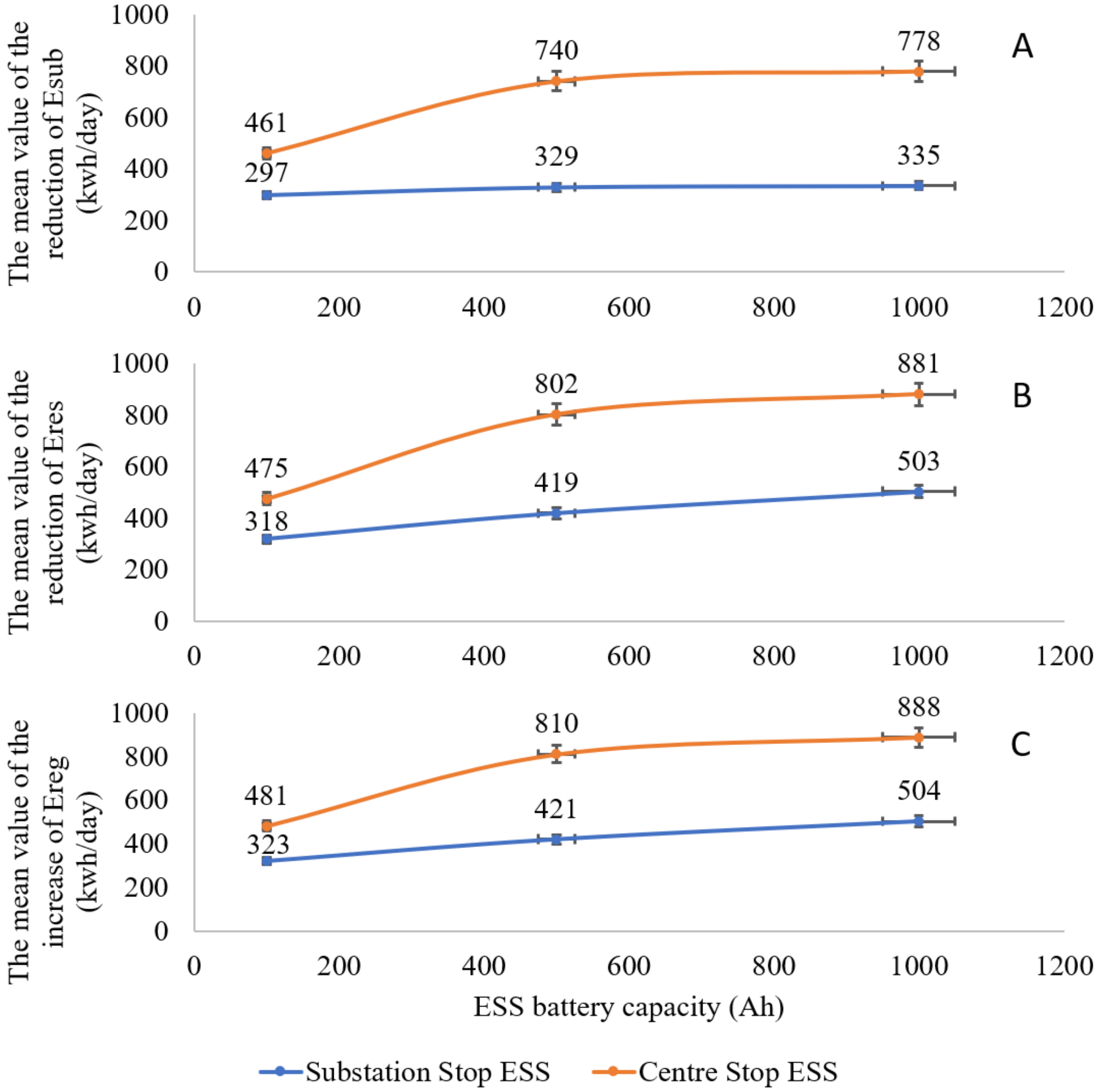

Fig. 6 Mean values (with percentage error bars) of the change of energy balance of substation ESS and centre stop ESS

As can be seen, the centre stop ESS installation consistently has a greater reduction of E_{sub}, a greater reduction of E_{res}, and a greater increase of E_{reg} than the substation stops ESS installation. The difference varies from 55-132% on the reduction of E_{sub}, 49-91% on the reduction of E_{res}, and 49-92% on the reduction of the E_{reg}. For the same battery capacity, the centre stops ESS installation leads to a better energy balance than the installations at substation stops.

Although the ESS battery capacity is found to positively impact the system energy balance, it has a stronger impact as a centre stop ESS than as a substation stop ESS. The centre stop ESS covers the tracks on both sides but the substation ESS only covers the tracks on one side.

Therefore, the centre stop ESS covers a longer length of track and thereby a greater distance of tram journey than the substation ESS does. Consequently, the accessible braking energy to the substation stop ESS and the centre stop ESS being different, with the latter being likely to be substantially higher than the former. For the substation stop ESS, the lowest simulated ESS capacity of 100 Ah is likely to be sufficient to absorb most of the available braking energy. Thus, increasing ESS battery capacity will only reduce the E_{sub} slightly. However, for the centre stop ESS, this capacity is possibly too small to fully store or utilize the majority of the available braking energy. The increasing ESS battery capacity could increase the degree of utilization substantially and thereby the result is a sharper reduction of the $E_{sub.}$

3.3 Multiple ESS installations

In practice, based on the modelling of the entire tram network, multiple ESS could be installed to maximise the energy-saving and cost saving. Table 2 could be used to support decision making for determining at which locations to best install an ESS. The working logic is simply to install at the higher energy-saving locations (the reduction of energy supplied from substation, E_{sub}) first, namely, to pick the installations shown in Table 2 ranked in descending order.

There are two types of ESS installations studied in this paper, the ESS at substation stops and the ESS at centre stops. Both types of installation have different distinguishing features, the centre stop ESS is installed inside an energy supply section, and since each energy supply section is isolated from the others, if multiple ESSs are installed on various centre stops respectively, each ESS would work independently. However, if the ESSs are installed on both the substation stop and the centre stop in the same energy supply section, they are likely to influence each other, as the braking energy generated could flow to both ESSs simultaneously, and hence each ESS could receive less braking energy than if it is working independently, and ultimately the energy-saving delivered together could be different from the energy-saving delivered independently.

As shown in Table 2, the ranking of the 1000 Ah and 500 Ah capacity ESS are identical and the centre stop ESSs are apparently delivering greater energy-saving than the substation stop ESSs. If a small number of installations are required, the centre stop ESSs are more preferable locations than the substation stop ESSs. However, in the case of 100 Ah capacity ESS, since some substation stop ESS ranked higher, the small number of installation may involve both the centre stop ESS and substation stop ESS. To address this, simulation results from simultaneous ESS installation on the centre stop and substation stop is presented, illustrating the effects on the total energy saving, based on the 100 Ah ESS.

If only three ESSs are required across the entire Supertram network, the top three locations, Park Croft Grange (1st), Shalesmoor (2nd), Manor Top (3rd) would logically be chosen. If four ESSs are required, Fitzalan Square (4th) would then be initially included as a location. Yet, Park Grange Croft and Fitzalan Square are both located in the same energy supply section as shown in Fig. 2, the former is the centre stop and the latter is a substation stop. Independently, they can deliver energy-savings of 609 kWh/d and 562 kWh/d, respectively. However, after ESSs are installed on both stops simultaneously, the simulation result suggested the two ESSs would only deliver a saving of 1078 kWh/d, which is 93 kWh/d smaller than the sum (1171 kWh) of their independent energy-saving. Therefore, two options for the installation of 4 ESSs have been established as shown in Table 3. The difference between these is that option 2 replaces the Fitzalan Square installation (4th) with Hillsborough installation (5th) that is a centre stop and has no conflict with the other centre stops selected for installation. As shown in Table 3, option 2 delivers 83 kWh/d more energy saving than option 1.

Table 3 Options for four ESSs installations

Option 1			**Option 2**		
Location	**Ranking***	**Type****	**Location**	**Ranking***	**Type****
Park Grange Croft	1st	C	Park Grange Croft	1st	C
Shalesmoor	2nd	C	Shalesmoor	2nd	C
Manor Top	3rd	C	Manor Top	3rd	C
Fitzalan Square	4th	S	Hillsborough	5th	C
Energy Saving (kWh/d)	2252		Energy Saving (kWh/d)	2335	

*: Ranking based on reduction of energy supplied from substation shown in Table 2
**: C = centre stop, and S = substation stop

In another scenario, if five ESS installations are required, there are three options that could be considered that comprise the top locations (shown in Table 2). As shown in Table 4, Fitzalan Square and Park Grange Croft in option 1 are in the same energy supply section. Meanwhile, Shalesmoor and the University of Sheffield in option 2 are also in the same energy supply section. Compared to option 1 and option 2, option 3 only consists of centre stop ESS installations and includes a low-ranking location City Hall (7th). However, due to cross influences between ESS in the same energy supply sections, option 3 generates the highest energy saving amongst the three options.

Table 4 Options for five ESSs installation

Option 1 Location	**Ranking** *	**Type** **	**Option 2** Location	**Ranking***	**Type** **	**Option 3** Location	**Ranking***	**Type** **
Park Grange Croft	1st	C	Park Grange Croft	1st	C	Park Grange Croft	1st	C
Shalesmoor	2nd	C	Shalesmoor	2nd	C	Shalesmoor	2nd	C
Manor Top	3rd	C	Manor Top	3rd	C	Manor Top	3rd	C
Fitzalan Square	4th	S	Hillsborough	5th	S	Hillsborough	5th	C
Hillsborough	5th	C	University of Sheffield	6th	C	City Hall	7th	C
Energy Saving (kWh/d)	2804		Energy Saving (kWh/d)	2743		Energy Saving (kWh/d)	2853	

*: Ranking based on reduction of energy supplied from substation shown in Table 2
**: C = centre stop, and S = substation stop

The two examples provided above indicate that when two ESSs are installed on the substation stop and the centre stop located in the same energy supply section, the energy saving achieved becomes smaller than the sum of their independent installations. Therefore, if multiple ESS installations are required, the final solution tends to only have centre stop installations regardless of some independent substation stop installations actually ranking higher in terms of energy balance shown in Table 2. Thus, this paper considers that the best installation locations for multiple ESS on a network are always at the centre stops. Interpreted from Table 2, Fig. 7 shows the potential best energy-saving corresponding to each number of ESS installations.

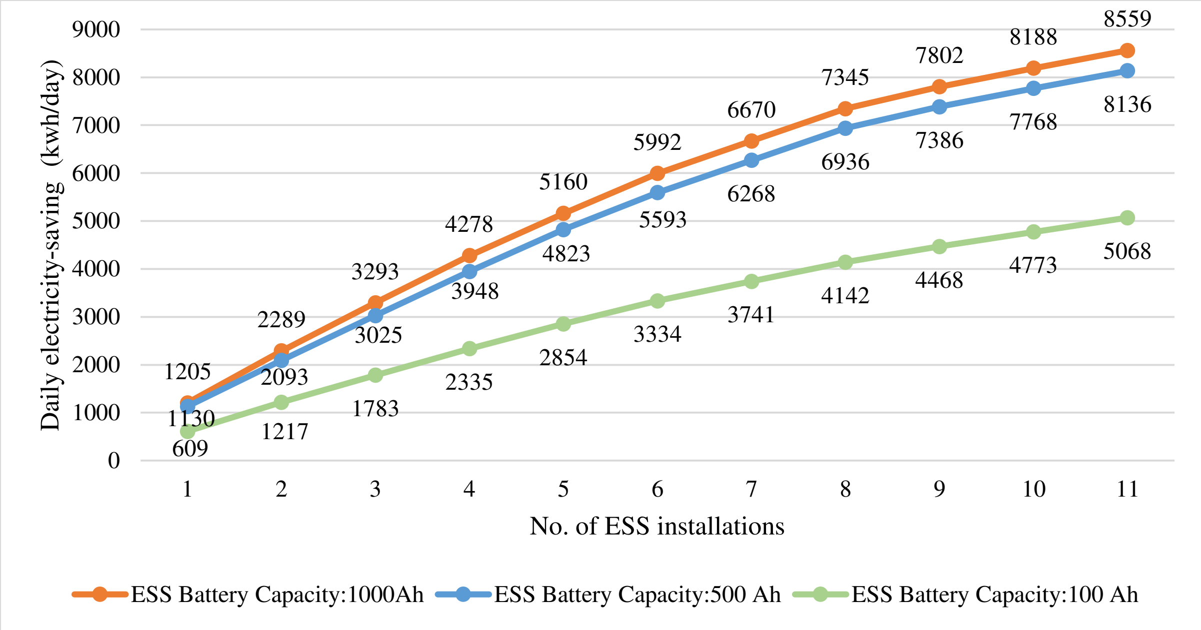

Fig. 7 Daily electricity saving of centre stop ESS installations with different battery capacity

4. Economic feasibility of applying ESS for tram system

The introduction of ESS can effectively deliver an energy-saving to the Supertram network, however the costs of the systems have not been addressed. Thus an economic evaluation has been conducted on ESS installations with different capacities and number of installations. Subsequently, a sensitivity study is presented to identify the influential factors to the economic evaluation. Since the final aim of this paper is to integrate EVs as part of the ESS with the tram network, a further economic study was conducted to illustrate the economic benefit brought by utilizing the EVs batteries for the energy storage of the tram system.

4.1 Method of economic evaluation

The economic evaluation explores three aspects, payback period, net present value (NPV) and internal return rate (IRR). It aims to demonstrate when the investment will likely be recovered, how much profit will be generated at the end of the project, and determine the rate of return on the investment. The fundamental elements used to conduct the economic evaluation are the cost of installation and income generated. The cost includes the capital expenditure (CAPEX) and operational expenditure (OPEX), and income was considered as the monetary saving brought about by the energy saving. The details of the cost and income are described in Section 4.2.

Net Present Value

NPV is the difference between the present value of cash inflows and the present value of cash outflows over a period of time (Žižlavský, 2014). It assumes the buying power of the same amount of money reduces in the future, and hence, the future income needs to be discounted accordingly for bringing it back to today's value (Žižlavský, 2014). The discount rate could be simply the inflation rate (San Ong and Thum, 2013). Alternatively, investors would assume their money can be invested elsewhere that generates profit. The discount rate then becomes the expected interest rate of the potential investment and is usually called, and used as, the nominal discount rate (Žižlavský, 2014). The NPV of an investment project is calculated via Equation 1 adapted from San Ong and Thum (2013) and Žižlavský (2014).

Equation 1

$$NPV = \sum_{t=0}^{n} \frac{R_t}{(1+i)^t}$$

Where $\boldsymbol{t}$ is the number period in the unit of year, $\boldsymbol{R}$ is the net cash inflow during a single period of $\boldsymbol{t}$, and $\boldsymbol{i}$ is the discount rate. The $\boldsymbol{t}$ ranges from 0 to 5 or any given asset life. For the discount rate $\boldsymbol{i}$, it has been reportedly taken as 10-15% for big corporate projects, and was also set between 5-9% on some solar photovoltaic projects (San Ong and Thum, 2013, Žižlavský, 2014, Lipu and Jamal, 2013). This paper examined a moderate value of 6% for the discount rate.

A positive NPV demonstrates that investment is economically feasible as profit is generated (San Ong and Thum, 2013). However, it only provides the absolute amount of profit generated during the appraised period and is not able to indicate the rate of return (Juhász, 2011). If two investments have the same amount of initial investment and the same estimated NPV but a different time scale, the one with a shorter time scale generates the profit quicker, and it is thereby potentially more preferable. Solely using the NPV is not able to provide an indicative comparison of the two investments (Lipu and Jamal, 2013).

Internal Rate of Return

The IRR is the rate of return of the current investment and is commonly used together with the NPV (Juhász, 2011, Gallo, 2019). IRR is calculated when the NPV is zero, and it can be expressed as Equation 2, that is adapted from Equation 1.

Equation 2

$$0 = \sum_{t=0}^{n} \frac{R_t}{(1+IRR)^t}$$

Where t is the number period in the unit of year that leads to a NPV is zero, R is the net cash inflow during a single period of t.

In this paper, the IRR was determined via the Excel IRR function. If the IRR is equal or greater than the discount rate, the return of the current investment meets or exceeds the investor's expectation, and hence the economic viability is proven (Lipu and Jamal, 2013).

Using the same example given in the NPV section, if two investments have the same amount of initial investment and the same estimated NPV but a different time scale, the one with a shorter time scale will have a higher IRR than the one with a longer time scale. Besides, if two investments have the same time scale and the same estimated NPV but a different initial investment, the one with a smaller initial investment will have a higher IRR than the one with a greater initial investment. Thus, IRR can be used to assess which investment is able to return quicker and better (Gallo, 2019).

However, IRR is not able to be used on its own because it is not able to explain the absolute amount of profit generated (Juhász, 2011). If two investments have the same time scale and the same estimated IRR but a different initial investment, the one with a greater initial investment will have a higher absolute profit generated (NPV) than the one with a smaller initial investment.

Discount Payback Period

The discounted payback period (DPP) indicates the time taken to recover the initial investment with regards of potential depreciation over time. The annual income and annual OPEX are expected to be uniform before being discounted, and hence, the annual cash flow, which is the different between the annual income and annual OPEX, is expected to be uniformed as well. The DPP is calculated via Equation 3 (Marshall, 1984).

Equation 3

$$DPP = \frac{ln[1 \div (1 - CAPEX \div ACF \times i)]}{ln(1 + i)}$$

where the ACF is the annual cash flow before being discounted and i is the discount rate.

In this study, the asset life, which is battery life, was primarily assumed as five years. A DPP that is smaller than the asset life helps to demonstrate economic feasibility. However, the DPP is not able to estimate any potential net income generated after the initial investment is recovered.

This paper considers that the economic feasibility is proven if the DPP is smaller than the asset life (battery life), the net income and NPV are both positive, and the IRR is greater than the discount rate, simultaneously.

4.2 Cost and income

The CAPEX of the ESS considers the cost of the battery, the cost of the other components (i.e. converter, control units, site wiring, etc.), and the cost of installation. According to the economic analysis of energy storage system installation reported in various literatures (Ardani et al., 2016, Cole and Frazier, 2019, Mongird et al., 2019, Goldie-Scot, 2019, Li et al., 2018), this paper gives a reasonable assumption of:

- The unit cost of the battery is estimated at £133 per kWh
- The cost of the other components is estimated to be 80% of the cost of the battery
- The cost of installation is estimated as £10,000 per ESS

Therefore, the CAPEX of each ESS installation can be calculated via Equation 4.

Equation 4

$$CAPEX = n \times [(1 + 80\%) \left(\frac{133 \times Battery\ Voltage \times Battery\ Capacity}{1000}\right) + 10000]$$

Where ***n*** is the number of ESS that will be installed, ***battery voltage*** is set as 390 V, ***battery capacity*** varies from 100 Ah, 500 Ah and 1000 Ah, and ***1000*** is the conversion ratio between W to kW.

The OPEX per annum only considers the maintenance of the ESS and is assumed as 3% of the CAPEX (Rahmann et al., 2017, Wingren and Johnsson, 2018). Therefore, the costs per ESS with different capacity are shown in Table 5.

Table 5 The costs per ESS

Capacity of battery	Cost of battery	Cost of other components	Cost of installation	CAPEX	OPEX per Annum
1000Ah (390kWh)	£51,870	£41,496	£10,000	£103,366	£3,101
500 Ah (195kWh)	£25,935	£20,748	£10,000	£56,683	£1,700
100 Ah (39kWh)	£5,187	£4,150	£10,000	£19,337	£580

The income is considered as the money-saving due to the electricity saved. The unit cost of electricity for this study is set at £53 per MWh (West, 2017). The annual income related to the electricity-saving is calculated via Equation 5.

Equation 5

$$Annual\ Income = \frac{Daily\ Electricity\ Saving\ \times 365\ \times 53}{1000}$$

where the ***Daily Electricity Saving*** of each ESS installation appraised is in the unit of kWh and is shown in Fig.7, ***53*** is the price (£) per MWh electricity, and ***1000*** is the conversion ratio from kWh to MWh.

4.3 Economic feasibility

The economics of different numbers of ESS installations are shown in Table 6. As shown, it is economically feasible to install ESSs with 500 Ah battery capacity at the top 6 identified best centre stops, and it is economically feasible to install ESSs with 100 Ah battery capacity on all centre stops. However, no 1000 Ah ESS installation has been found to be economically viable. It is worth noting that, in order to demonstrate the impact of the different parameters on the economic evaluation, Table 6 and Table 8 to Table 14 highlight the NPV, IRR and DPP results, the uneconomic results (with NPV<0, IRR<6% and/or DPP>5) being highlighted by a superscript 'N'.

Table 6 The economics of different numbers of ESS installation with different ESS battery capacity

No. of ESS	ESS Battery Capacity:1000Ah			ESS Battery Capacity:500Ah			ESS Battery Capacity:100Ah		
	NPV (£)	IRR (%)	DPP (year)	NPV (£)	IRR (%)	DPP (year)	NPV (£)	IRR (%)	DPP(year)
1	-£18,251[N]	-6.4%[N]	5.1[N]	£28,219	15.9%	2.8	£27,879	41.9%	1.7
2	-£46,339[N]	-8.2%[N]	5.4[N]	£42,895	12.3%	3.1	£55,594	41.8%	1.7
3	-£80,945[N]	-9.6%[N]	5.7[N]	£54,931	10.6%	3.2	£79,953	40.3%	1.8
4	-£117,099[N]	-10.5%[N]	5.9[N]	£66,290	9.6%	3.3	£103,162	39.1%	1.8
5	-£161,696[N]	-11.7%[N]	6.1[N]	£73,787	8.6%	3.3	£123,626	37.7%	1.8
6	-£210,269[N]	-12.8%[N]	6.4[N]	£72,646	7.1%	3.5	£141,025	36.0%	1.9
7	-£271,489[N]	-14.3%[N]	6.7[N]	£63,878[N]	5.4%[N]	3.6[N]	£152,419	33.6%	2.0
8	-£332,897[N]	-15.5%[N]	7.1[N]	£54,466[N]	4.1%[N]	3.8[N]	£163,283	31.7%	2.0
9	-£412,102[N]	-17.3%[N]	7.6[N]	£27,249[N]	1.8%[N]	4.0[N]	£168,100	29.2%	2.1
10	-£497,068[N]	-19.1%[N]	8.1[N]	-£5,453[N]	-0.3%[N]	4.3[N]	£171,100	27.0%	2.2
11	-£583,288[N]	-20.6%[N]	8.6[N]	-£39,335[N]	-2.2%[N]	4.5[N]	£173,367	25.1%	2.3

[N]: uneconomic results

Two most noticeable phenomenon found from Table 6 are that:

- The greater the ESS battery capacity, the lower the economic feasibility
- A greater number of ESS installations will also lower the economic feasibility

The ESS installation on Park Grange Croft (top 1 ESS installation shown in Table 2) is used as an example for demonstration. When the ESS battery capacity increases from 100 Ah to 1000 Ah, the energy-saving (shown as -Esub in Fig. 7) increases by 97%, and the CAPEX and OPEX per annum shown (in Table 5) both increase by 435%. When the ESS battery capacity increases, the energy-saving increases at a slower rate over time than the cost. Therefore, a greater ESS battery capacity will worsen the economic feasibility.

Regarding the second trend discovered, it could be attributed to multiple ESS installations consisting of the highest energy-saving centre stop ESS installations first. When the number of ESS installations increase, the total ESS battery capacity increases positively and linearly at the same time, and so does the cost related CAPEX and OPEX. But regarding the income related energy saving, when the number of ESS installations increase, more centre stop ESS installations with lower energy-saving are included, thus the increase of the total energy-saving and the income is thereby relatively slower. Therefore, when the number of ESS installations increase, the cost increases faster than the income, and hence leads to worse economics.

The economic evaluation aims to assist decision making over potential investment options. In the example where a single ESS installation is required, 500 Ah ESS has a higher NPV but a smaller IRR than 100 Ah ESS. This means that the 500 Ah ESS will generate a greater profit than 100 Ah ESS at the end of the asset life, but its rate of return on investment is slower since it uses a higher CAPEX. This indicates that a potential investor could thereby decide which option to invest in according to his/her own preference on the absolute value of profit or the flexibility of reinvestment.

4.4 Sensitivity study

In the economic evaluation, three variables could have substantial uncertainty and hence could heavily impact upon economic evaluation. They are the battery price which affects the cost of battery, the installation cost, the ratio between OPEX and CAPEX, electricity price, the battery life, and discount rate. The sensitivity study aims to examine the impact of these three variables on economic parameters, and subsequently to discover what is required and how to improve the economics.

The sensitivity study only used the second highest energy saving case of one ESS installation on Shalesmoor (shown Table 2) as an example for illustration. The approach is to change one variable in turn, and a ±33% was given to the discount rate and a ±20% was given to the remaining variables, as the variation. The CAPEX and annual OPEX of the ESSs to install at Shalesmoor have been listed in Table 5, and the undiscounted annual income and annual cash flow related to those ESS additions are listed in Table 7.

Table 7 The undiscounted annual income and annual cash flow related to the ESSs installed on Shalesmoor

Capacity of battery	Undiscounted Annual Income	Undiscounted Annual Cash Flow
1000Ah (390kwh)	£20,972	£17,871
500 Ah (195kwh)	£18,641	£16,940
100 Ah (39kwh)	£11,750	£11,170

Impact of battery price

The economic evaluations obtained for different battery prices are shown in Table 8. As can be seen, battery price substantially impacts the economics of the bigger capacity ESSs, but less-so, on the 100 Ah ESSs. This is because the battery cost contributes more to the capital costs of the 1,000 Ah ESS and 500 Ah ESS.

Table 8 The economic evaluation based on different battery price

Battery Price (£/kWh)	ESS Battery Capacity:1000Ah			ESS Battery Capacity:500Ah			ESS Battery Capacity:100Ah		
	NPV (£)	IRR (%)	DPP (year)	NPV (£)	IRR (%)	DPP (year)	NPV (£)	IRR (%)	DPP (year)
£106	-£7,054[N]	-2.9%[N]	5.5[N]	£25,192	16.9%	3.1	£29,819	48.7%	1.7
£133*	-£28,087[N]	-10.1%[N]	7.3[N]	£14,676	8.6%	3.8	£27,716	41.7%	1.9
£160	-£49,120[N]	-15.5%[N]	9.4[N]	£4,159[N]	2.2%[N]	4.7[N]	£25,612	35.8%	2.1

*: Base case, [N]: uneconomic results

Impact of installation cost

The economic evaluations obtained from different installation costs are shown in Table 9. Opposite to the battery price, the installation cost impacts more on the 100 Ah ESSs, but less on the 500 and 1000 Ah capacities. This is because the installation cost is assumed to be a fixed cost and has a higher proportion of the capital cost in the 100 Ah ESSs.

Table 9 The economic evaluation based on different installation cost

Installation Cost (per ESS)	ESS Battery Capacity:1000Ah			ESS Battery Capacity:500Ah			ESS Battery Capacity:100Ah		
	NPV (£)	IRR (%)	DPP (year)	NPV (£)	IRR (%)	DPP (year)	NPV (£)	IRR (%)	DPP (year)

£8,000	-£25,834^N^	-9.4%^N^	7.1^N^	£16,929	10.2%	3.7	£29,968	49.3%	1.7
£10,000*	-£28,087^N^	-10.1%^N^	7.3^N^	£14,676	8.6%	3.8	£27,716	41.7%	1.9
£12,000	-£30,340^N^	-10.7%^N^	7.5^N^	£12,423	7.1%	4.0	£25,463	35.4%	2.1

*: Base case, ^{N}: uneconomic results

Impact of OPEX

The economic evaluations obtained from different OPEX to CAPEX ratio cost are shown in Table 10. The higher the ratio, the worse the economic evaluation result. However, its impact on the economics is minor.

Table 10 The economic evaluation based on different OPEX to CAPEX ratio

OPEX: CAPEX	ESS Battery Capacity:1000Ah			ESS Battery Capacity:500Ah			ESS Battery Capacity:100Ah		
	NPV (£)	IRR (%)	DPP (year)	NPV (£)	IRR (%)	DPP (year)	NPV (£)	IRR (%)	DPP (year)
2.4%	-£25,475^{N}	-9.1%^{N}	7.0^{N}	£16,109	9.4%	3.8	£28,204	42.4%	1.9
3.0%*	-£28,087^{N}	-10.1%^{N}	7.3^{N}	£14,676	8.6%	3.8	£27,716	41.7%	1.9
3.6%	-£30,700^{N}	-11.1%^{N}	7.6^{N}	£13,243	7.8%	3.9	£27,227	41.1%	1.9

*: Base case, ^{N}: uneconomic results

Impact of electricity price

The economic evaluations obtained from different battery price are shown in Table 11. A higher electricity price leads to a higher current expenditure. Consequently, the same energy-saving would result in a higher cost saving. The electricity price substantially impacts upon all ESS regardless of capacity. In the base case, the electricity price is considered as a contract price which is discounted from normal market price. If the UK average non-domestic electricity price of 2019, £122/MWh, is applied, the economics will be promoted greatly (BEIS, 2020).

Table 11 The economic evaluation based on different electricity price

Electricity Price (£/ MWh	ESS Battery Capacity:1000Ah			ESS Battery Capacity:500Ah			ESS Battery Capacity:100Ah		
	NPV (£)	IRR (%)	DPP (year)	NPV (£)	IRR (%)	DPP (year)	NPV (£)	IRR (%)	DPP (year)
£42.4	-£45,755^{N}	-17.3%^{N}	10.4^{N}	-£1,028^{N}	-0.6%^{N}	5.1^{N}	£17,817	28.0%	2.4
£53.0*	-£28,087^{N}	-10.1%^{N}	7.3^{N}	£14,676	8.6%	3.8	£27,716	41.7%	1.9
£63.6	-£10,419^{N}	-3.6%^{N}	5.7^{N}	£30,380	17.0%	3.1	£37,615	54.7%	1.5
£122.0	£86,923	25.8%	2.5	£116,903	57.7%	1.5	£92,154	121.7%	0.8

*: Base case, ^{N}: uneconomic results

Impact of battery life

The economic evaluations obtained from different battery life lengths are shown in Table 12. Battery life impacts both the NPV and IRR of all the ESS installations substantially but does not affect the payback period. This is because it controls the income-generating period, and hence controls the total amount of income generated during the battery life. However, it does not influence the rate of income generation and hence it will not change when the investment is recovered. Battery life is likely affected by the number of charging cycles. Battery life, and thereby the economics, could be potentially improved if the numbers of charging cycles can be reduced via a better system control and design.

Table 12 The economic evaluation based on different battery life

Battery Life (year)	ESS Battery Capacity:1000Ah			ESS Battery Capacity:500Ah			ESS Battery Capacity:100Ah		
	NPV (£)	**IRR (%)**	**DPP (year)**	**NPV (£)**	**IRR (%)**	**DPP (year)**	**NPV (£)**	**IRR (%)**	**DPP (year)**
4	-£41,44^{N}	-18.2%^{N}	7.3^{N}	£2,017^{N}	1.5%^{N}	3.8^{N}	£19,369	36.3%	1.9
5*	-£28,087^{N}	-10.1%^{N}	7.3^{N}	£14,676	8.6%	3.8	£27,716	41.7%	1.9
6	-£15,489^{N}	-4.7%^{N}	7.3^{N}	£27,274	13.2%	3.8	£40,314	46.2%	1.9

*: Base case, ^{N}: uneconomic results

The sensitivity study suggests that both the electricity price and battery life can substantially impact the economics of ESS with different battery capacities. When examining the overall costs of deploying an ESS at a location, the installations costs are relatively fixed, whilst the costs of the actual battery is dependent on the size of the storage, therefore for smaller ESS capacities, the installation costs dominate, and for larger ESS, the battery cap costs dominate. The ratio between OPEX and CAPEX influence the economics slightly.

Impact of discount rate

The economic evaluations obtained from different battery lifetimes are shown in Table 13. A low discount rate leads to a less predicted depreciation when the future annual cash flow is discounted into the present value. Thus, a lower discount rate will lead to a better NPV and IRR and a shorter DPP. Moreover, the discount rate will have a greater impact on the high CAPEX project. In the examples of the 500 Ah battery ESS and 100 Ah battery ESS, the former has a higher annual cash flow than the latter as shown in Table 7. When the discount rate was reduced from 8% to 4%, the NPV of the former increased by £7,777 (71%), and of the latter increased by £5,129 (20%). Consequently, the 500 Ah battery ESS had a higher percentage increase on the IRR and a higher percentage reduction on the DPP than the 100 Ah battery ESS, when the discount rate reduces. A lower discount rate will improve the economics of the high cash flow project at a greater extent.

Table 13 The economic evaluation based on different discount rate

Discount Rate	ESS Battery Capacity:1000Ah NPV (£)	IRR (%)	DPP (year)	ESS Battery Capacity:500Ah NPV (£)	IRR (%)	DPP (year)	ESS Battery Capacity:100Ah NPV (£)	IRR (%)	DPP (year)
4%	-£23,808^{N}	-8.3%^{N}	6.7^{N}	£18,732	10.7%	3.7	£30,391	44.4%	1.8
6%*	-£28,087^{N}	-10.1%^{N}	7.3^{N}	£14,676	8.6%	3.8	£27,716	41.7%	1.9
8%	-£32,013^{N}	-11.7%^{N}	8.1^{N}	£10,955	6.6%	4.0	£25,262	39.1%	1.9

*: Base case, ^{N}: uneconomic results

4.5 The potential merit of using EV for energy storage to the tram network

The battery price is found to be an influential factor in the economic feasibility of ESS usage. As the battery price is determined by the production technology and the market, it cannot be reduced or changed from the customer perspective. However, if EVs or the second-life EVs batteries can be used as part of the ESS, the capital investment costs can be substantially reduced. A further economic feasibility on the single ESS installation at Shalesmoor was conducted to illustrate the potential merit of incorporating EVs into the energy storage system on the tram network. The EV batteries are expected to deliver the same energy storage capacity and the same energy-saving as the corresponding stationary ESS does.

Taking this approach the initial cost of the ESS is reduced (shown in Table 5) and therefore the CAPEX and the OPEX related to maintenance is reduced. However, exploiting an EV battery as the ESS for the tram network is expected to contribute additional operating cycles to the EV battery which could potentially degrade the battery life quicker than seen in normal EV use. Therefore, this research assumes that the tram service provider would provide the EV owners, who allow their EVs to be used as energy storage for the tram network, with incentives (e.g. discounted travel perhaps) to compensate for the extra degradation of the EV battery. The undiscounted annual cash flow of using EV battery as the energy storage for the tram system ($\boldsymbol{ACF_{EV}}$) is therefore calculated via Equation 6.

Equation 6

$$ACF_{EV} = Annual\ Income - \ OPEX_M - OPEX_C$$

where $\boldsymbol{OPEX_M}$ is the annual OPEX related to maintenance, and the $\boldsymbol{OPEX_C}$ is the annual OPEX related to the compensation provided to the EV owners.

This research estimates the compensation via multiplying the energy-saving delivered, which can be considered as the braking energy firstly stored in the EV battery and subsequently discharged back to the tram network, with the degradation cost per unit electricity discharge

(C_D, in the unit of £/kWh$_{ED}$ or £/MWh$_{ED}$) from the EV batteries. Zhou et al. (2011) reported that, in concept, the C_D can be estimated by dividing the cost of the battery with the battery cycle life. The battery cycle life could be prolonged if the depth of discharge (DoD) is small, for example, Miao et al. (2019) reported that reducing the DoD from 20% to 10% will increase the potential life cycles of Li-ion battery from 2,000-9,000 from 6,000-15,000. Zhou et al. (2011) reported a C_D of approx. £0.040-0.060/kWh$_{ED}$ (£40-60/MWh$_{ED}$) for the Li-ion battery based on a battery cost of £128/kWh and a life cycle of 2,200 estimated from a rated DoD of 95%. This research assumes:

- the DoD of the EV battery exploited for energy storage for the tram network could be regulated <20%
- the life cycle of the EV battery for this application is at a reasonable value of 6,000
- the life cycle is directly inversely proportional to the C_D

Hence, the estimated C_D could be potentially reduced to 2,200/6000=36.6% as £0.015-0.022/kWh$_{ED}$ (£15-22/MWh$_{ED}$). A C_D of £0.018/kWh$_{ED}$ with a ±20% variation is then used for studying the economics of using EV batteries as ESS for the tram network and the impact of the compensation cost on economics. Results are shown in Table 14.

Table 14 The economic evaluation based on ESS battery gets replaced by the EV battery

Battery Cost (£/kWh) and C_D (£/kWh$_{ED}$)	ESS Battery Capacity:1000Ah			ESS Battery Capacity:500Ah			ESS Battery Capacity:100Ah		
	NPV (£)	IRR (%)	DPP (year)	NPV (£)	IRR (%)	DPP (year)	NPV (£)	IRR (%)	DPP (year)
£0, £0	£30,338	18.6%	3.0	£43,888	41.6%	1.9	£33,558	65.3%	1.3
£0, £0.015	£5,891[N]	3.9%[N]	4.4[N]	£22,159	22.4%	2.7	£19,861	40.9%	1.9
£0, £0.018	-£221[N]	-0.1%[N]	5.0[N]	£16,727	17.3%	3.1	£16,437	34.5%	2.1
£0, £0.022	-£6,332[N]	-4.4%[N]	5.8[N]	£11,294	11.9%	3.5	£13,013	28.0%	2.4
£133, £0*	-£28,087[N]	-10.1%[N]	7.3[N]	£14,676	8.6%	3.8	£27,716	41.7%	1.9

*: Base case, [N]: uneconomic results

As can be seen from Table 14, using the EV battery for energy storage could improve the economics if the C_D that is equal to or lower than the base case value of £0.018/kWh$_{ED}$, especially for the big capacity applications. The C_D that relates to the OPEX on compensation to EV owners has a bigger influence on economics than the OPEX on maintenance does. Using the EV battery for energy storage will reduce the CAPEX and the annual OPEX on maintenance by 27-50%. At the same time, it also introduces additional OPEX for compensating the EV owners. Consequently, replacing the stationary ESS with EV battery will change the nature of the investment. As illustrated via the application with 500 Ah capacity and/or a C_D=£0.018/kWh_{ED} in Fig. 8,

- In the stationary ESS case, the OPEX is only spent on maintenance and contributes 11% of the cost throughout the project
- In the EV battery case, the total OPEX contributes 50% of the cost throughout the project due to the additional OPEX spent on compensation

Therefore, the C_D is considered an influential factor to the economic feasibility of using EV as the energy storage of the tram network.

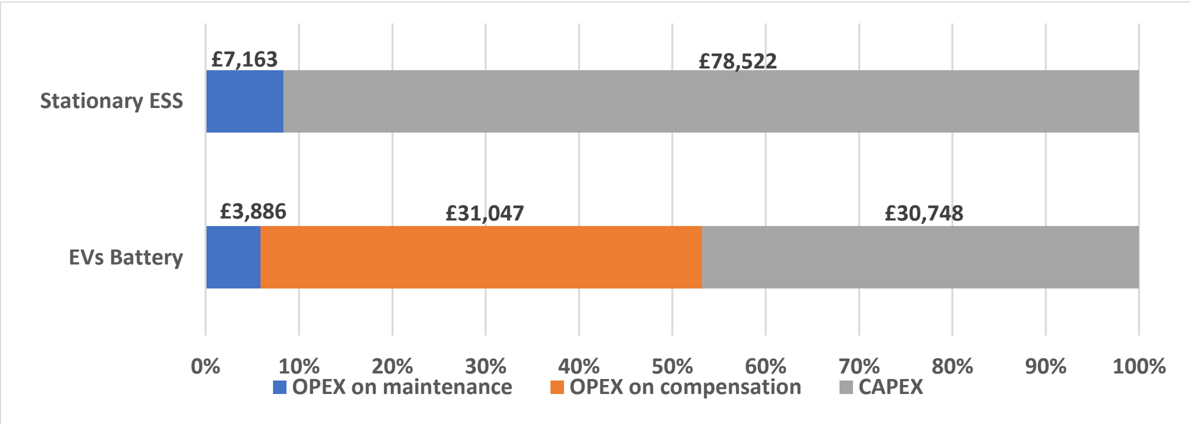

Fig. 8 The breakdown of CAPEX and OPEXs of using Stationary ESS and EV battery for energy storage for the tram network

The determination of the C_D is profound as it requires comprehensive modelling and simulation of the state of charge (SoC), DoD, and the related potential degradation of capacity, etc. of the battery, that is tailored for different specific energy-storage exploitations. Besides, apart from the C_D, various factors could also impact the OPEX on compensation, for instances, the reward (i.e. free parking or free tickets) to the EV owner, and/or the potential net electricity (from the braking energy of tram network) remained in the batteries, etc. If such rewards to the EV owner fully cover the loss due to the degradation of the EV battery, then the OPEX on compensation could be erased, and finally, the economics could be further improved, as shown as the case with a battery cost of £0 and a C_D £0 in Table 14. This research considers using the EV battery as energy storage for the tram network is a promising option that could lead to better economic feasibility. Still, to provide a more reliable and comprehensive feasibility study for this exploitation, it requires further research on

- investigating the SoC and DoD of the battery,
- determining the battery degradation,

- developing an intelligent control method that prevents the range anxiety of the EV and minimises the battery degradation (Uddin et al., 2018, Guenther et al., 2013, Geske and Schumann, 2018), and
- studying the economic feasibility with careful considerations of all the available incentives to the EV owner (Parsons et al., 2014).

5. Conclusion

This paper firstly applies the same method and data set used in Zhang et al. (2020) to study the energy balance of the Supertram network in a common OCS configuration. From the perspective of energy, the common OCS is more advantageous than the separate OCS because it requires 16% less energy supplied from the substations than the separate OCS does (Zhang et al., 2020).

This paper subsequently presents the results of a study of ESS based on the common OCS system. It illustrates how ESS battery capacity and/or installation location influence the energy-saving delivered by the introduction of ESSs to the example tram network, based on the network-wide scale rather than on one single energy supply section. Similar to the finding reported in Zhang et al. (2020), a higher ESS battery capacity and an ESS installed on the centre stops of an energy supply section commonly results in a better energy saving. ESS battery capacity is more influential on the energy saving when it is installed at the centre stops than at substation stops. This is because the accessible braking energy is distributed to the two locations differently. The centre stops can potentially access a greater reserve of braking energy, and hence potential energy-saving is limited by battery capacity. When the capacity rises from below the optimal level, the energy-saving obtained will increase substantially, but the increase becomes more subtle once the capacity passes the optimum level. For the substation stops, the tested ESS battery capacity seems already to be at or greater than the optimal level, and hence, the change of capacity only slightly influences the energy saving. Further, this paper studies the optimal location and number of ESS installations that that could maximise the energy savings across an entire tram network. The simultaneous ESS installations on substation stops and centre stops located in the same energy supply section have been found to result in a smaller energy saving than the corresponding independent installations. Therefore, this paper recommends that ESSs are only installed on centre stops where multiple ESS installations are required.

Each multiple ESS installation scenario with the best potential energy-savings was examined for economic feasibility. Results suggest that the economics stay viable when the number of 100 Ah ESS installations fully reaches the 11 available locations on the network, and the number of 500 Ah ESS installations reaches 6. However, no 1000 Ah ESS installations were found to be economically feasible under the base case assumptions. From the sensitivity study, both the higher electricity price and longer battery life are found to have positive impact on the economics of all ESS installations with various battery capacities. The higher battery price and the higher installation cost both negatively impact the economics, the former has a greater impact on ESS with higher capacity, and the latter has a bigger influence on ESS with lower capacity. When the ESS battery was replaced by EV batteries, and the cost of the battery was thereby waived, the economic feasibility improved substantially. High battery capacity installation would be able to generate a similar or greater profit compared to the low battery capacity ones. Using EVs for energy storage to the tram network could be more advantageous on the economic feasibility than the stationary ESS, but work is still ongoing in this area. The work presented can be generalised to any tram network through the adoption of the processes outlined in the paper for the specific network.

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