

Article

Modelling a DC Electric Railway System and Determining the Optimal Location of Wayside Energy Storage Systems for Enhancing Energy Efficiency and Energy Management

Hammad Alnuman 

Department of Electrical Engineering, Jouf University, Sakaka 72388, Saudi Arabia; hhalnuman@ju.edu.sa

Abstract: Global demand for fossil fuels is highly increasing, necessitating energy efficiency to be enhanced in transitioning to low-carbon energy systems. Electric railways are highly efficient in reducing the transportation demand for fossil fuels as they are lightweight and their energy demand can be fed by renewable energy resources. Further, the regenerative braking energy of decelerating trains can be fed to accelerating trains and stored in onboard energy storage systems (ESSs) and stationary ESSs. It is fundamental to model electric railways accurately before investigating approaches to enhancing their energy efficiency. However, electric railways are challenging to model as they are nonlinear, resulting from the rectifier substations, overvoltage protection circuits, and the unpredictability and uncertainty of the load according to the train position. There have been few studies that have examined the ESS location's impact on improving the energy efficiency of electric railways while using specialised simulation tools in electric railways. However, no single study exists that has studied the location impact of stationary ESSs on the energy efficiency of electric railways while the trains are supported by onboard ESSs. Given these goals and challenges, the main objective of this work is to develop a model using commercial software used by industry practitioners. Further, the energy saving is aimed to be maximised using stationary ESSs installed in optimal locations while trains are supported by onboard ESSs. The model includes trains, onboard ESSs, rail tracks, passenger stations, stationary ESSs, and traction power systems involving power lines, connectors, switches, sectioning, and isolators. In this article, a test scenario is presented comprising two trains running on a 20 km with three passenger stations and two substations. The trains and track are modelled in OpenTrack simulation software (Version 1.9) while the power system is modelled in OpenPowerNet simulation software (Version 1.11). The two simulation tools are used in the railway industry and can produce realistic results by taking into account the entire electrical network structure. A stationary ESS is added on the wayside and moved in steps of 1 km to obtain the optimal location before investigating the impact of stationary ESSs on the performance and energy management of onboard ESSs. It is found that the energy saving when installing a stationary ESS at the optimal location is 56.05%, the peak-power reduction of Substation 1 is 4.37%, and the peak-power reduction of Substation 2 is 18.67%.



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1. Introduction

Energy demand is increasing globally due to the growth in the economy and the use of energy-intensive technology. This energy-demand increase causes the global energy demand to rise by a factor of two by the year 2050, which increases CO₂ [1]. Therefore, it is crucial to rely on sustainable energy applications such as electrified public transport. Electric railways' role in reducing CO₂ emissions is decisive as they increase the reliance on public transportation while they can rely on renewable energy resources. Moreover, regenerative braking of electric trains, where their kinetic energy is transferred into electric

energy in order to slow the trains down, is crucial in saving energy. This regenerative energy can be used by the accelerating trains, sent back to the grid, and stored in energy storage systems (ESSs), which increases the energy efficiency of electric railway systems and reduces carbon emissions [2].

The traction DC system involves substations, catenary systems, and pantograph-catenary systems. The substations include transformers to step down the voltage and rectifiers to convert AC voltage into DC voltage. The pantograph-catenary system is a transmission system where there are overhead contact wires that are connected to the train by a mechanical pantograph attached to the roof of the moving train in order to feed the train with current to drive motors [3,4].

The applications of ESSs in electric railways can be stationary or onboard. Onboard ESSs increase the weight of trains, which increases their traction energy demand. Moreover, they can only exchange energy with the same train, which makes them independent of traffic. Stationary ESSs can be located alongside the track and they can exchange energy with multiple trains. Stationary ESSs can support voltage drops at weak points in the rail network, which can reduce the need for installing new substations [5,6]. Further, they can reduce energy consumption and peak-power demands, which is the maximum power that a substation can deliver. Installing stationary ESSs at substation locations or near them can avoid the need for increasing the substations' maximum power size [7]. Properties of ESSs and their applications are described in [8–10].

In stationary ESS applications, the location of ESSs is crucial as it highly affects energy efficiency. Further, defining the optimal ESS location alongside the track is difficult as it depends on traffic density, which can be unpredictable in most railway systems. Therefore, it is essential to install stationary ESSs in optimal locations to ensure their contribution to increasing energy efficiency. In [11], the authors aimed to optimise economic efficiency, voltage regulation, energy management, and ESS location and size. It was concluded that the optimal location of a stationary ESS was at the substation location. The electric railway system was 11.3 km in length with 12 stations and 7 substations. The system was simulated in MATLAB. The same system was investigated in [12], and it was concluded that the optimal location for installing stationary ESSs was at the substation location especially when the distance between the substations was large.

In [13], the objective was to find the optimal ESS size and location to reduce the power peaks caused by the uncertainty of renewable energy sources. It was concluded using the greedy algorithm method that the optimal location was at nodes with the highest load demand. The authors of [14] examined the optimal location of installing a stationary ESS (supercapacitor) alongside a 13-km-long double track with 7 substations. It was aimed to enhance energy management leading to an increase in energy saving. The authors only investigated the installation location at the substations and it was found that the optimal location was at substation 4, which was located at 7.5 km.

In [15], a study on the Rimini-Bologna route, a distance of 115 km, was investigated to discover the optimal location for installing stationary ESSs for recovering braking energy. It was decided that the optimal location was at Faenza station, which was located in the middle of the line. In [16], the authors used three optimisation algorithms to explore the optimal stationary ESS location only within substations. Different locations were found by different optimisation algorithm methods without any preferences. It was decided in [17] that the optimal location was in the middle between two substations that were separated by 2 km. The authors tested the optimal location by placing the ESS at the substations and the midpoint location.

Despite the importance of ESS location alongside the track, there remains a paucity of evidence on the optimal location. Further, there have been few studies that have assessed the role of location on improving the energy efficiency of electric railways while using specialised simulation tools in electric railways. No single study exists that has studied the location impact of stationary ESSs on the energy efficiency of electric railways while the trains are supported by onboard ESSs.

In this work, a 20-km electric railway is modelled in OpenTrack and OpenPowerNet simulators. The model includes two trains, three passenger stations, and two substations. The length of the track line (the distance between the substations) is 20 km in order to meet the typical distance for high DC voltage applications, which is 20–30 km [7]. To enhance energy efficiency, energy management, and voltage regulation, a stationary ESS is installed on the wayside. Thereafter, the ESS location impact on the electric railway's energy efficiency is examined by moving it alongside the rail track and analysing the power flow. Finally, the impact of the stationary ESS on the energy stored in the onboard ESS is investigated. Table 1 provides a comparison between the literature and the main contributions of this research article.

Table 1. Comparison of the proposed contribution with the existing literature.

Reference	Simulation Method	Uses Both Stationary and Onboard ESSs	Energy Saving	Peak-Power Reduction
[11]	MATLAB	No	16.56%	----
[12]	MATLAB	No	4.88%	----
[13]	MATLAB	No	----	5.4%
[14]	Numerical analysis	No	17.04%	----
[15]	Numerical analysis	No	30%	----
[16]	Realistic Railway Simulator	No	----	----
[17]	ETAP Simulator (version 20.0.4)	No	52.56%	----
Proposed	OpenTrack and OpenPowerNet	Yes	56.05%	12.17%

The main contributions of this article are summarized as follows:

- The DC electric railway model is modelled by OpenTrack and OpenPowerNet commercial simulation tools. The simulation tools support complex railway technology problems and they are used by the railway supply industry.
- The optimal location for installing ESSs is examined in a practical scenario without simplifications.
- The stationary ESSs' impact on the energy efficiency of the electric railway is examined while the trains are supported by onboard ESSs. Further, the impact of installing stationary ESSs on the energy management of the onboard ESSs is investigated.

This paper is organized as follows: Section 2 presents the modelling approach. Section 3 shows the analysis and results of the railway model.

2. Modelling Approach

The trains and track are modelled in OpenTrack simulation software while the power system is modelled in OpenPowerNet simulation software. The main modules of OpenTrack are shown in Figure 1, where it shows three modules, rolling stock, infrastructure, and timetable, that should be entered by the user. The simulation is performed by continuously solving the differential equations representing the train's movements that are combined with discrete signal information. OpenPowerNet is a simulator that is developed as an extension of OpenTrack. The two simulators interact during the simulation where OpenTrack simulates the course operation control and the driving dynamics while OpenPowerNet simulates voltages of the electrical network with respect to the course current consumption and position. Then the engine in OpenPowerNet simulates the requested current and achieved effort with respect to the available line voltage at the course position. The simulation philosophy is explained in Figure 2, where the advanced train model (ATM) simulates the propulsion and auxiliary systems. The ATM also calculates the train's current demand

when the power supply calculation (PSC) feeds into the tractive/braking effort. If the PSC feeds into the train's current demand, the ATM calculates the tractive/braking effort. It is worth mentioning that the trains are modelled as current sources. Screen captures of the OpenTrack and OpenPowerNet simulation tools are shown in Figures 3 and 4, respectively.

The presented model includes trains, tracks, timetables, and power systems, where the user enters information before running the simulation. Locomotives and wagons form trains and the user needs to enter the information on tractive/braking effort, weight, length, load, and adhesive values. The track is modelled by forming track segments, signals, stations, vertices, and routes. The user can assign length, gradient, curvature, and maximum speed of track segments. Rectifier substations are connected to the power system through line feeders (busbars), including busbars with line conductors (rails, contact wires, and messenger wires). The user needs to set the parameters of the power system, such as the type of substation; nominal voltage; the position of the substations; the feeding scheme; and the number, length, and cross section of the feeding and return current cables. The stationary ESS should be placed at locations alongside the track and its attributes and SoC limits are specified.

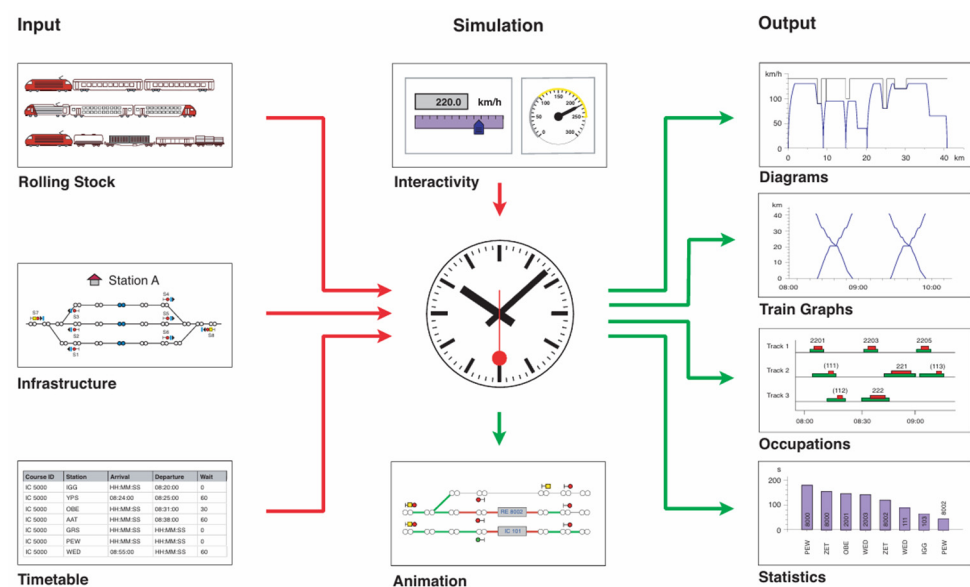


Figure 1. Operation process of the OpenTrack simulation tool. Reprinted with permission from Ref. [18].

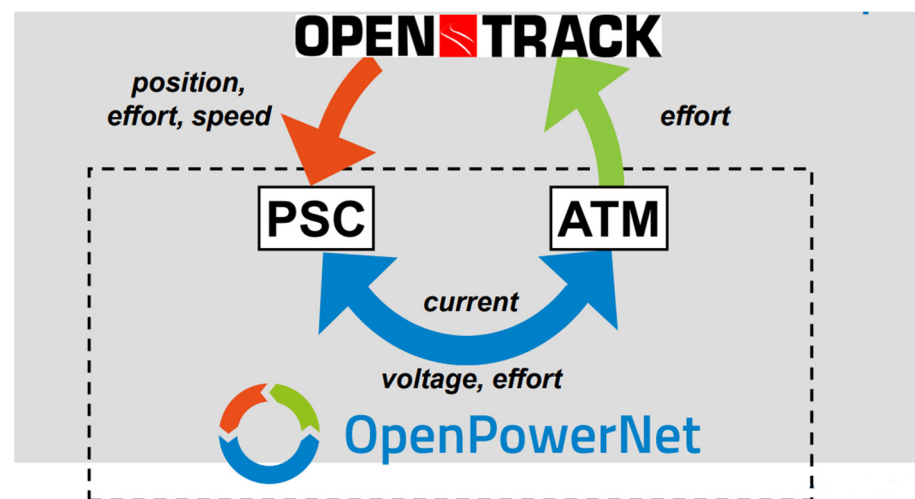


Figure 2. Simulation philosophy. Reprinted with permission from Ref. [18].

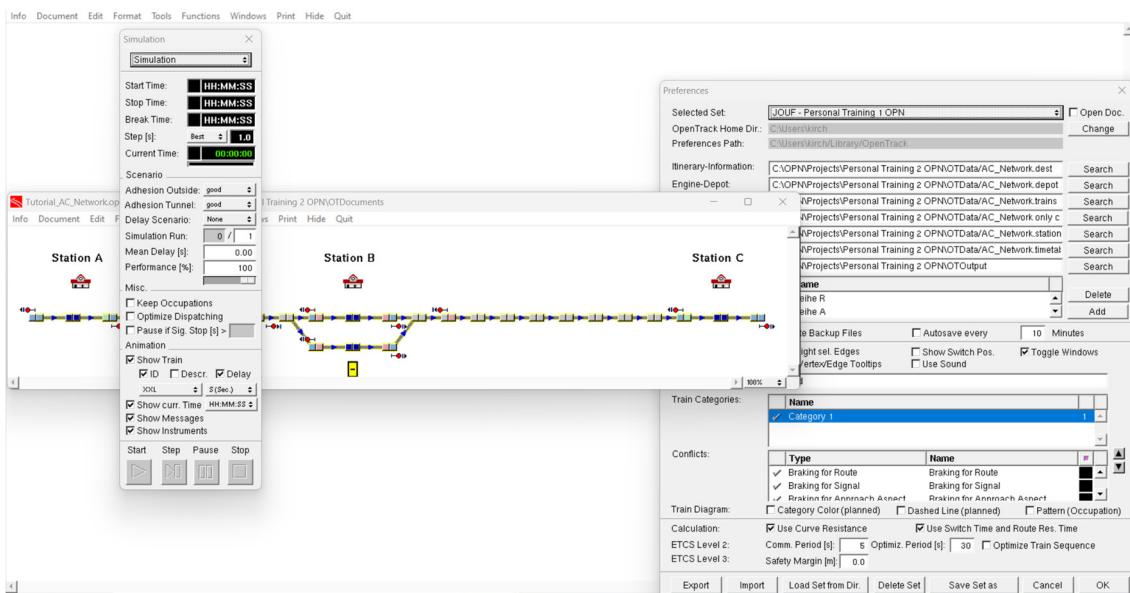


Figure 3. Screen capture of the OpenTrack simulation tool.

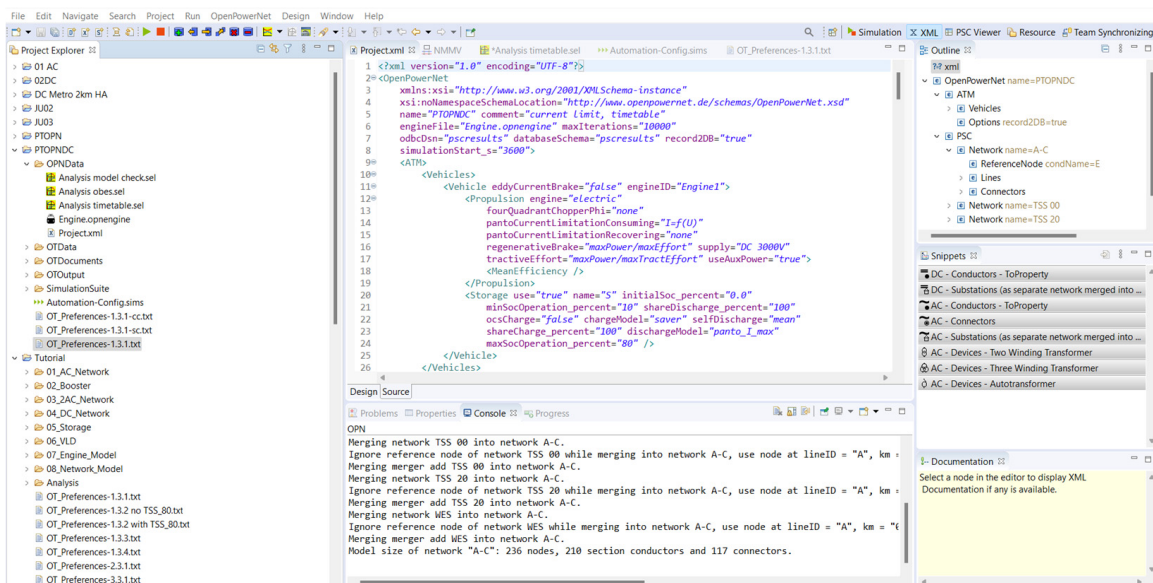


Figure 4. Screen capture of the OpenPowerNet simulation tool.

The representation of the modelled railway track system is shown in Figure 5, where there are three passenger stations (the place where the trains load and unload passengers) and two running trains. The alignment, gradients, curvature, speed limits, occupation constraints of tracks, and signalling are defined within the track infrastructure in the OpenTrack simulation tool. The total length of the railway track is 20 km where Station A is located at 0 km, Station B is located at 10 km, and Station C is located at 20 km. The train diagrams are shown in Figure 6 and the timetable is presented in Table 2. Train 1 travels from west to east while Train 2 travels from east to west. The trains are supplied by DC traction where the maximum tractive/braking power is 5560 kW and the auxiliary power is 100 kW. The trains are equipped with onboard ESSs that are 50 kWh in size and charge and discharge with a maximum power of 2000 kW.

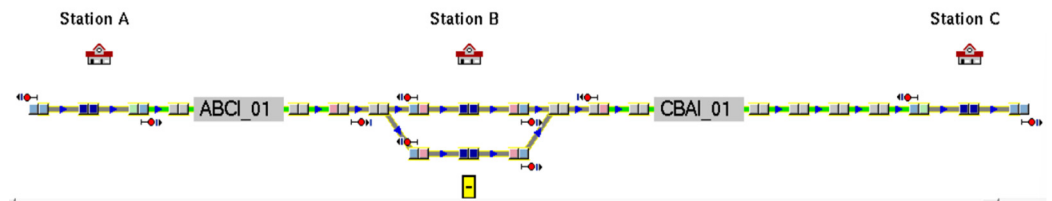


Figure 5. Layout of the railway track with three passenger stations and two travelling trains.

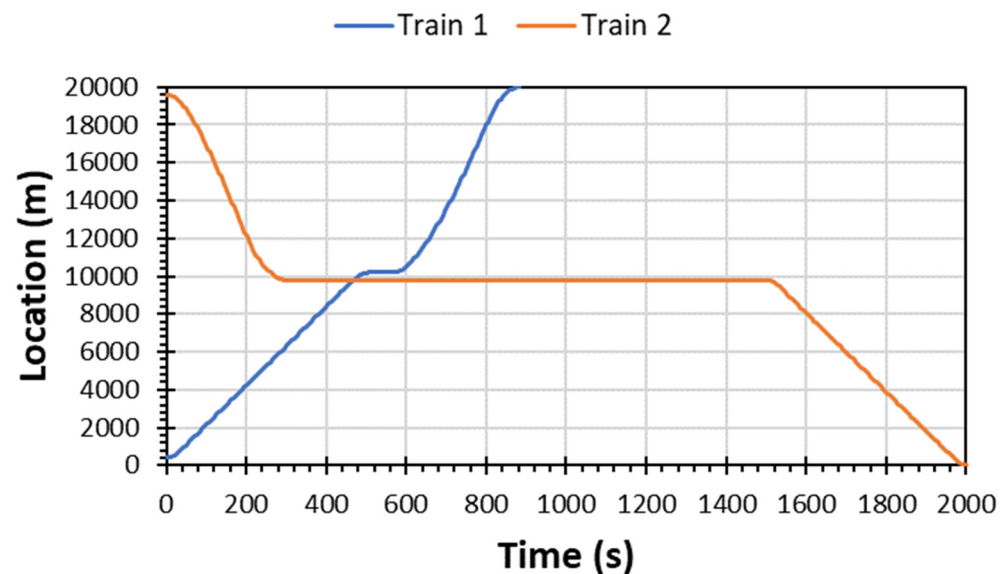


Figure 6. Train diagrams of two trains running on a railway track serving three passenger stations.

Table 2. Train timetable.

Train Number	Passenger Station	Arrival	Departure
Train 1	A	HH:MM:SS	01:00:00
Train 1	B	01:08:25	01:09:25
Train 1	C	01:14:16	HH:MM:SS
Train 2	C	HH:MM:SS	01:00:00
Train 2	B	01:04:52	01:25:00
Train 2	A	01:33:25	HH:MM:SS

There are two traction substations. Substation 1 is located at 0 km while Substation 2 is located at 20 km. It is decided to locate substations at the passenger stations except for the middle, where there is a passenger station without a substation in order to simulate both practical cases. Further, this assumption allows for the analysis of the impact of stationary ESSs when they are located in the middle of two substations. The substations are rectifiers, meaning that the power is unidirectional. However, they could be supported by renewable energy sources. The substations have a no-load voltage of 3.3 kV and an internal resistance of 10 mΩ. The power lines are formed of contact wires with a resistance of 65.8 mΩ/km and a return conductor rail with a resistance of 15.3 mΩ/km. Figure 7 shows the modelling approach of the substations and power lines in the OpenPowerNet simulation tool. It is worth mentioning that the power lines are divided into slices that directly affect the size of the calculation matrix and analysis speed. There are conductors that are perpendicular to the track and connected at the slices' locations. These are called connectors and they are used to analyse the data between different conductors. In this study, the distance between slices is set to 500 m, which depends on the size of the network, the length of the line, the

number of conductors, and the speed of the trains. The leakage between the rail and the earth is modelled along the line.

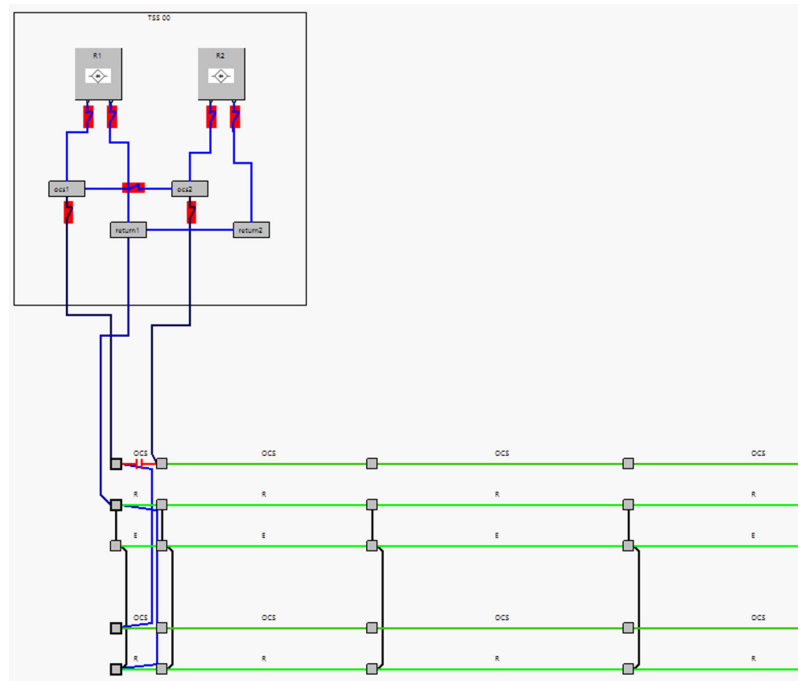


Figure 7. Screen capture of the substation and power lines modelled in the OpenPowerNet simulation tool.

The trains are modelled in OpenTrack and OpenPowerNet, which deal with a train file containing all of the train's data. The mechanical power demand for traction and braking is fed into the OpenPowerNet simulator before calculating the electrical power demand based on the efficiency of parts such as the transformer, chopper, inverter, motor, and gearbox. The train power demand consists of traction, auxiliaries, eddy current brake (the train tries to achieve the requested braking effort by the regenerative braking and when it cannot achieve it, the eddy current is activated, and if it is still not enough, then mechanical braking is activated), and onboard ESS charging power demand. The priority of collecting power from the pantograph is given to the auxiliary power, traction power, and charging the onboard ESS, respectively. In the discharging mode, the auxiliary is prioritised over the traction power demand.

The distribution of power available at the pantograph is always prioritised as follows: 1. Auxiliary power 2. Traction power 3. ESS charging power. During regenerative braking, the ESS is prioritised over recovery to the power supply network. Inside catenary-free sections, all consumed power will be provided by the ESS to the highest possible extent. The auxiliary power demand is always prioritised over the traction power demand. The ESS will provide power if the pantograph current limitation is applied, meaning that the ESS is discharged only when the maximum allowed pantograph current is exceeded.

The train driving dynamics, such as mass, length, adhesion, driving resistance (Davis formula), and limits of acceleration and deceleration, are entered in OpenTrack. The train dynamics are studied based on Newton's Second Law, given as follows:

$$Force(F) = mass(m) \cdot acceleration(a) \quad (1)$$

$$F(v) - B(v) = m \cdot a \quad (2)$$

$$F(v) - B(v) = m \cdot \frac{dv(t)}{dt} \quad (3)$$

where v is train velocity, $F(v)$ is tractive force in kN and $B(v)$ is braking force in kN.

The drag force $Q(v)$ in kN is represented by the Davis equation:

$$Q(v) = \alpha \cdot M + \beta \cdot M \cdot v + \gamma \cdot v^2 + \frac{\tau}{r} \quad (4)$$

where α represents bearing resistance in kN and it is dependent on the vehicle mass. β denotes rolling resistance in kNs/m, and γ represents air resistance in kNs²/m². M is the vehicle mass and r is the radius of the track curvature. The rotating components add resistance to the train that is expressed as follows:

$$M^* = M \cdot (1 + \lambda_w) \quad (5)$$

The rotary allowance λ_w is a constant that is 1.06 in this study and depends on the ratio of the number of motored axles over the number of axles, the gear ratio, and the type of train construction [19]. It is worth mentioning that the number of trailers in each train is 15 with a length of 25 m for each trailer. Therefore, the motion of a train is described as follows:

$$m \cdot \frac{dv(t)}{dt} = F(v) - B(v) - Q(v) \quad (6)$$

The mechanical traction power is calculated by multiplying the train speed by the tractive force: $(P = m \cdot \frac{dv(t)}{dt} \cdot v)$.

To study the location impact of a stationary ESS on the energy consumption of the electric railway, an 800 kWh ESS is added on the wayside. The ESS is generic and could be batteries, ultracapacitors, flywheels, fuel cells, etc. The ESS self-discharge power is 50 W, the efficiency of charge/discharge is 98%, and the maximum charge/discharge current is 2000 A. The stationary ESS charges when the track voltage is above 3.3 kV and it discharges when it is below 3.3 kV. Figure 8 shows the modelling approach of the stationary ESS in the OpenPowerNet simulation tool. The parameters describing the modelled electric railway system are detailed in Table 3.

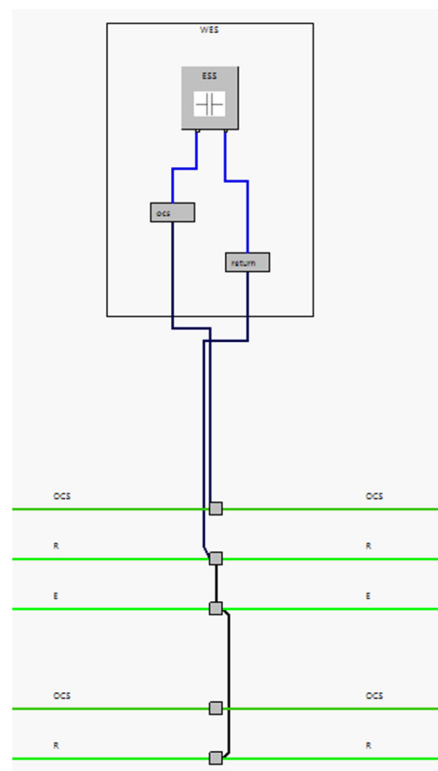


Figure 8. Screen capture of the stationary ESS modelled in the OpenPowerNet simulation tool.

Table 3. Parameters of describing the modelled electric railway system.

Quantity	Value
Davis equation constant coefficient	3.3 kN
Davis equation linear term coefficient	0.02422 kNs/m
Davis equation quadratic term coefficient	0.000552 kNs ² /m ²
Train mass	355,000 kg
Train maximum speed	250 km/h
Maximum tractive/braking force	250 kN
Resistance factor	3.3
Rotating mass factor	1.06
Train length	375 m
Maximum acceleration	3 m/s ²
Maximum deceleration	−0.6 m/s ²
Substation DC voltage	3300 V
Substation internal resistance	10 mΩ
Contact wire resistance	65.8 mΩ/km
Rail electrical resistance	15.3 mΩ/km
Voltage threshold for braking resistor activation	3600 V
Maximum power of the train inverter	5560 kW
Onboard ESS size	50 kWh
Maximum charging/discharging current of the onboard ESS	1000 A
Maximum charging/discharging power of the onboard ESS	2000 kW
Stationary ESS size	800 kWh
Maximum charging/discharging current of the stationary ESS	2000 A
Maximum charging/discharging power of the stationary ESS	6569 kW

The substation parameters and voltage threshold for braking-resistor activation are decided according to EN 50163 international standards for DC traction systems with a length of 20 km that are displayed in [20]. The train, track, and power system parameters are taken from a case scenario provided in [21].

3. Simulation Results

To study the location impact of a stationary ESS, it is decided to move the ESS alongside the track in steps of 1 km. Figures 9 and 10 show that installing the ESS at the substation location contributes positively by reducing the substation power demand. It is noticed that when installing the ESS at Substation 1, the impact on Substation 2 is negligible. Similarly, when installing the ESS at Substation 2, the impact on Substation 1 is negligible. When installing the ESS at Substation 1, the energy from the traction power supplies to the catenary system is 1051 kWh, energy from the catenary system to the stationary ESS is 31 kWh, energy from the stationary ESS to the catenary system is 117 kWh, energy from the catenary system to the vehicle pantographs is 1041 kWh, energy from the vehicle pantographs to the catenary system is 60 kWh, energy from the vehicles to the onboard ESS is 99 kWh, energy from the onboard ESS to the vehicles is 8 kWh, and total losses in the catenary system is 156 kWh (losses in the substation feeder cables are 4 kWh, losses in the contact wires are 127 kWh, losses in the rails are 21 kWh, and losses in the connectors are 4 kWh). When installing the ESS at Substation 2, the energy from the traction power supplies to the catenary system is 1007 kWh, energy from the catenary system to the

stationary ESS is 50 kWh, energy from the stationary ESS to the catenary system is 163 kWh, energy from the catenary system to the vehicle pantographs is 1041 kWh, energy from the vehicle pantographs to the catenary system is 77 kWh, energy from the vehicles to the onboard ESS is 91 kWh, energy from the onboard ESS to the vehicles is 8 kWh, and total losses in the catenary system are 156 kWh (losses in the substation feeder cables are 4 kWh, losses in the contact wires are 127 kWh, losses in the rails are 22 kWh, and losses in the connectors are 4 kWh). When there is no stationary ESS installed, the energy from the traction power supplies to the catenary system is 1165 kWh, energy from the catenary system to the vehicle pantographs is 1042 kWh, energy from the vehicle pantographs to the catenary system is 31 kWh, energy from the vehicles to the onboard ESS is 101 kWh, energy from the onboard ESS to the vehicles is 9 kWh, and total losses in the catenary system is 154 kWh (losses in the substation feeder cables are 4 kWh, losses in the contact wires are 126 kWh, losses in the rails are 21 kWh, and losses in the connectors are 4 kWh).

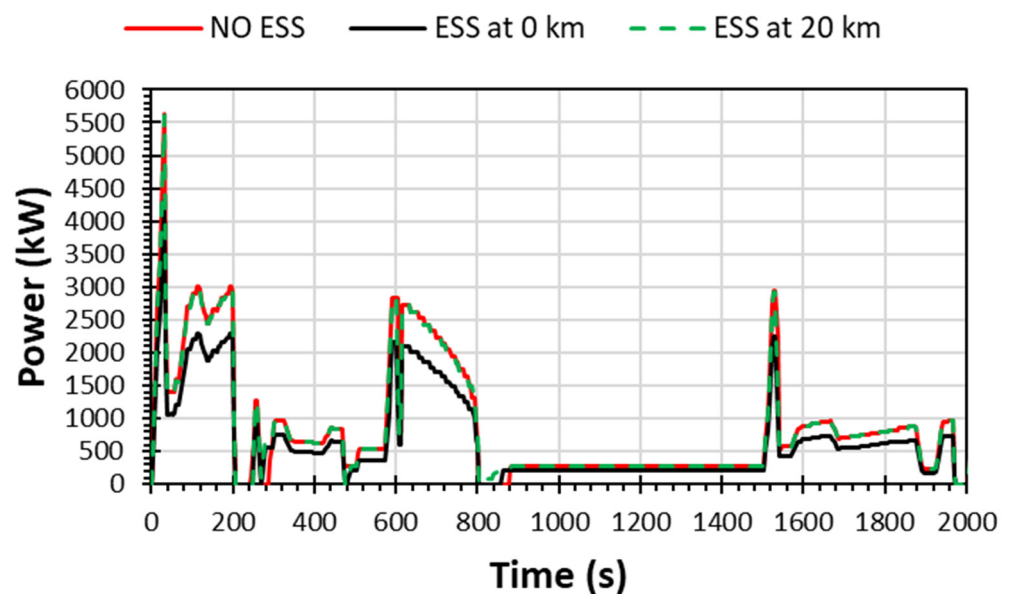


Figure 9. Power profiles of Substation 1 with respect to changing the location of the stationary ESS.

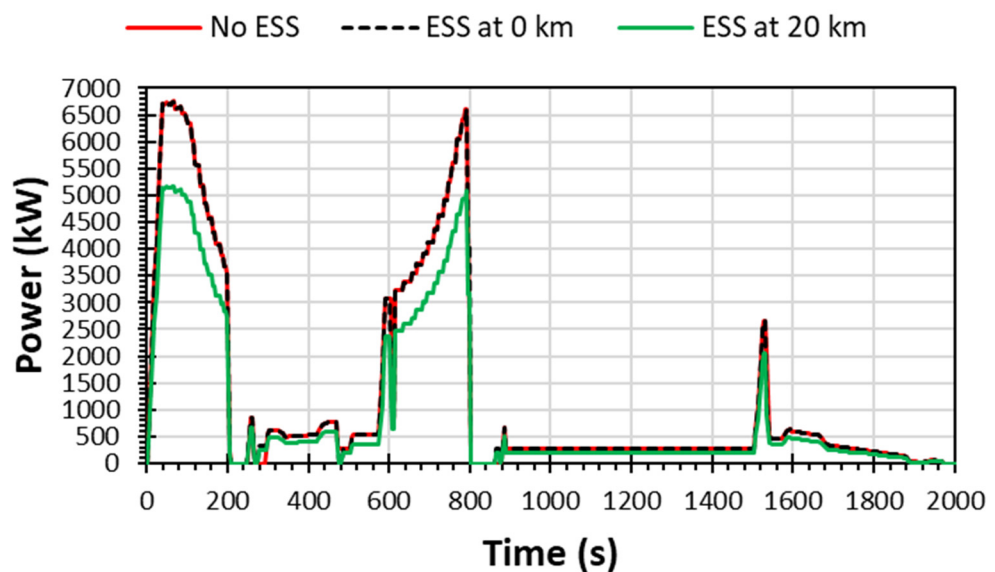


Figure 10. Power profiles of Substation 2 with respect to changing the location of the stationary ESS.

Figure 11 shows the total energy at the traction power supplies, which represents the energy leaving the traction power supplies to the catenary system. The figure shows that installing the stationary ESS contributes positively by reducing the substation's energy demand. It is noticed that the worst location to install the ESS is at the location of the substations. The more you move the stationary ESS away from the substations, the better in terms of energy saving. The figure shows that the optimal location is at 15 km, which reduces the energy supplied by the traction substations by 56.31% (656 kWh) compared to the traction system when there is no stationary ESS installed. When installing the ESS at the location 15 km away from Substation 1, energy from the traction power supplies to the catenary system is 509 kWh, energy from the catenary system to the stationary ESS is 61 kWh, energy from the stationary ESS to the catenary system is 646 kWh, energy from the catenary system to the vehicle pantographs is 1106 kWh, energy from the vehicle pantographs to the catenary system is 95 kWh, energy from the vehicles to the onboard ESS is 97 kWh, energy from the onboard ESS to the vehicles is 7 kWh, and total losses in the catenary system is 82 kWh (losses in the substation feeder cables are 5 kWh, losses in the contact wires are 64 kWh, losses in the rails are 13 kWh, and losses in the connectors are 1 kWh).

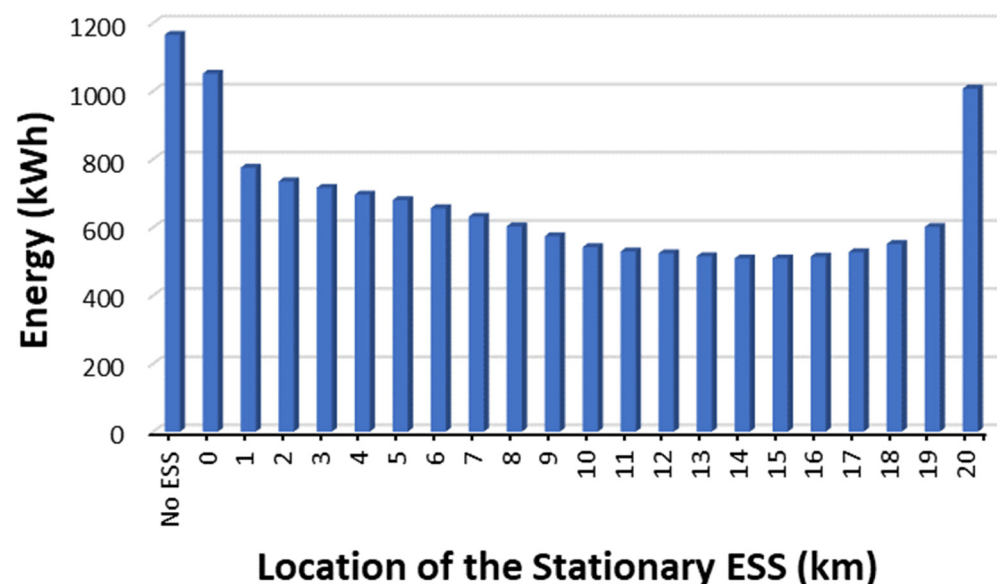


Figure 11. Total energy supplied by the substations with respect to the location of the stationary ESS.

Logically, the optimal location should be at the midpoint, especially when the two modelled trains are identical. However, since there is a passenger station at the midpoint, where trains must stop, the optimal location is found to be 15 km. Further, the two trains do not run simultaneously according to the timetable shown in Table 2, which shows that the two trains travel faster between Passenger Stations B and C than between Passenger Stations A and B. Therefore, the trains would need extra energy in the second track section, which should be the optimal location for installing the ESS.

The tractive/braking force, voltage, speed, and power of Train 1 and Train 2 are shown in Figures 12–15. The sections between passenger stations are divided into speed segments, where the speed limit between Station A and B is 200 km/h while it is 75 km/h between Station B and C. The trains run in a driving style known as flat-out operation, where the trains try to achieve the target speed limits with respect to constraints such as maximum acceleration, minimum safe distance between consecutive trains, allowable travel time, and passenger comfort criterion. Train 1 travels from west to east in 14 min and 16 s. The energy consumed by a vehicle at the pantograph increases from 430 kWh to 468 kWh after installing the stationary ESS. However, energy recovered by the catenary system at the pantograph increases from 11 kWh to 48 kWh and the degree of consumed energy

regenerated at the pantograph increases from 3% to 10%. Further, the energy losses in the braking resistors decrease from 23 kWh to 0 kWh. Train 2 travels from east to west in 33 min and 25 s. The energy consumed by a vehicle at the pantograph increases from 612 kWh to 638 kWh after installing the stationary ESS. However, energy recovered by the catenary system at the pantograph increases from 20 kWh to 47 kWh and the degree of consumed energy regenerated at the pantograph increases from 3% to 7%. Further, the energy losses in the braking resistors decrease from 22 kWh to 4 kWh.

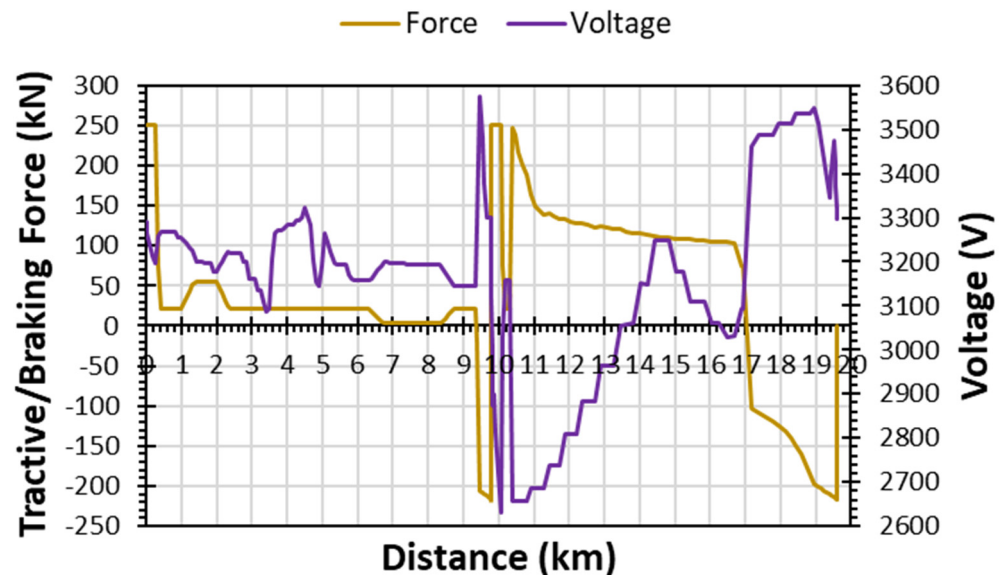


Figure 12. Train 1 tractive/braking force and pantograph voltage.

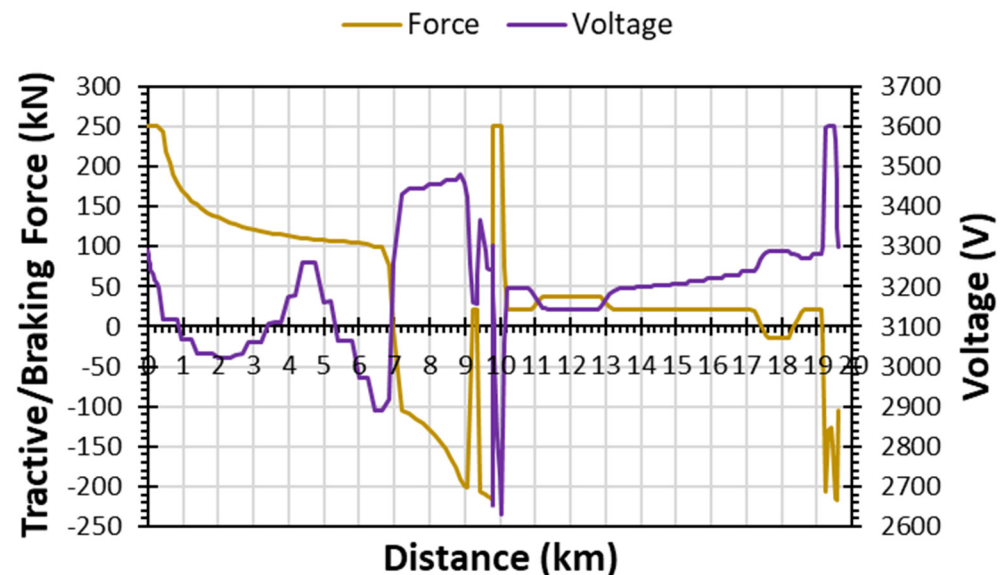


Figure 13. Train 2 tractive/braking force and pantograph voltage.

It is noticed in Figures 16–19 that the power and voltage profiles of the substations reduce significantly when placing the stationary ESS at the location of 15 km. The peak power of Substation 1 reduces from 5624 kW to 5378 kW (4.37% reduction) while the peak power of Substation 2 reduces from 6754 kW to 5493 kW (18.67% reduction). The average of the peak-power reduction of the two substations is 12.17%. The impact of the stationary ESS on the substation's peak-power reduction is high because the ESS charging voltage setpoint is very low, above 3.3 kV (the substation has no-load voltage). The impact on Substation 2

is significantly higher than that on Substation 1 because the ESS is installed at 15 km, which is closer to Substation 2 than to Substation 1. Further, when locating the stationary ESS at Substation 1 (0 km), the peak-power demand of Substation 1 reduced from 5624 kW to 4308 kW (23.4% reduction) while the peak-power demand of Substation 2 reduced from 6754 kW to 6748 kW (0.09% reduction). When locating the stationary ESS at Substation 2 (20 km), the peak-power demand of Substation 1 reduced from 5624 kW to 5607 kW (0.3% reduction) while the peak-power demand of Substation 2 reduced from 6754 kW to 5178 kW (23.3% reduction). Therefore, it is evident that the impact of the stationary ESS on reducing the substation peak-power demand is highly related to the location of the ESS installation, see Figure 20 for further details.

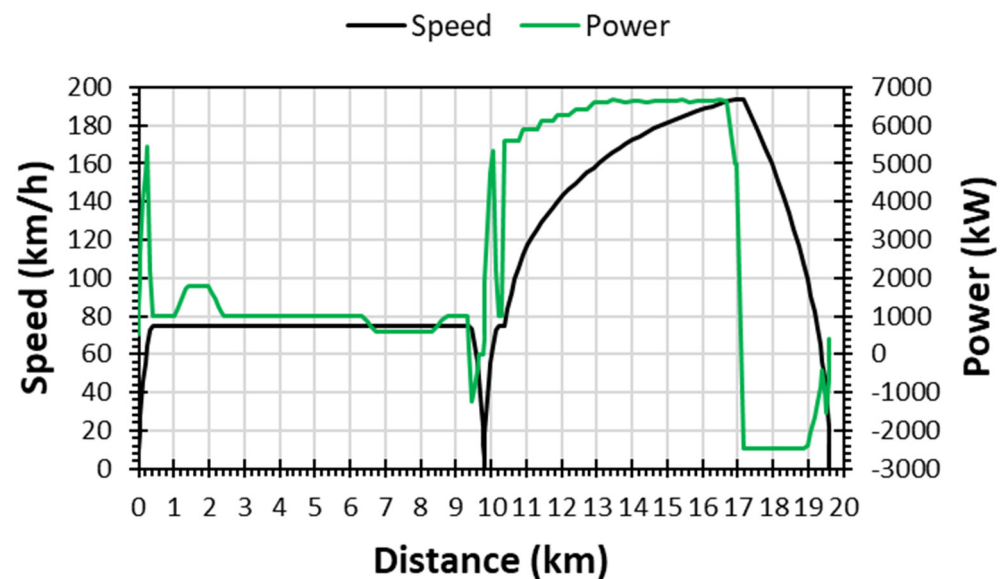


Figure 14. Train 1 speed and power profiles with respect to the travelled distance.

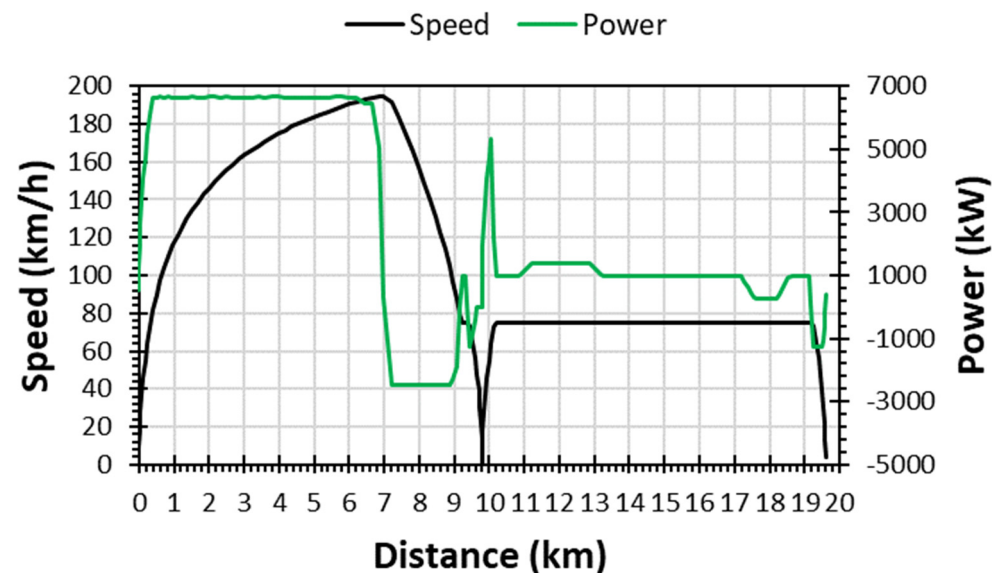


Figure 15. Train 2 speed and power profiles with respect to the travelled distance.

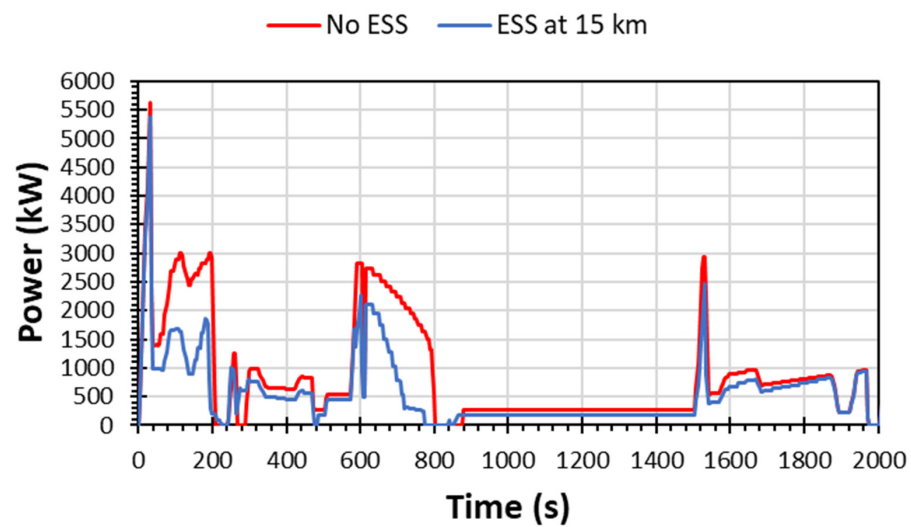


Figure 16. Power profiles of Substation 1 with respect to installing the stationary ESS at the location of 15 km.

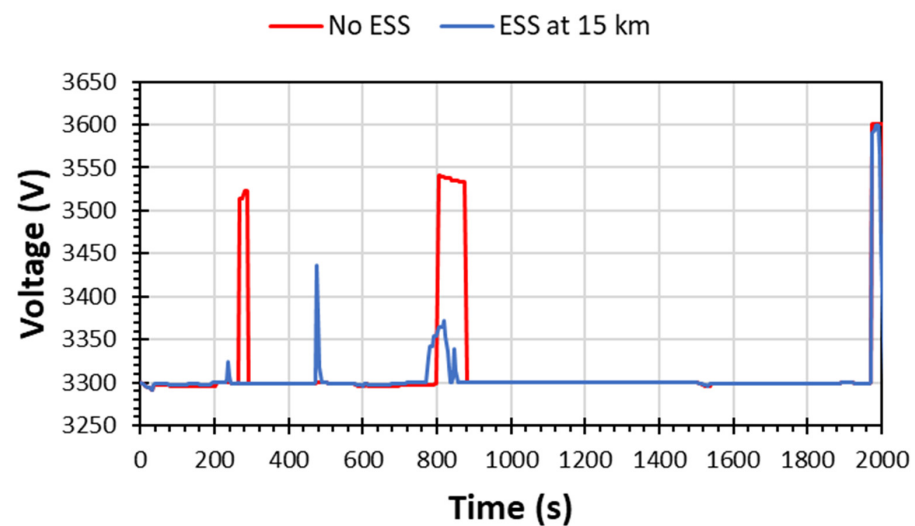


Figure 17. Voltage profiles of Substation 1 with respect to installing the stationary ESS at the location of 15 km.

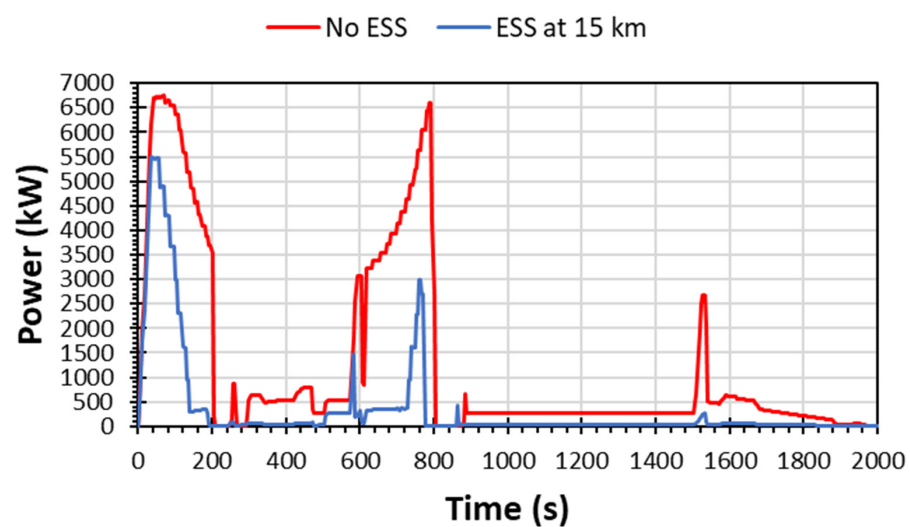


Figure 18. Power profiles of Substation 2 with respect to installing the stationary ESS at the location of 15 km.

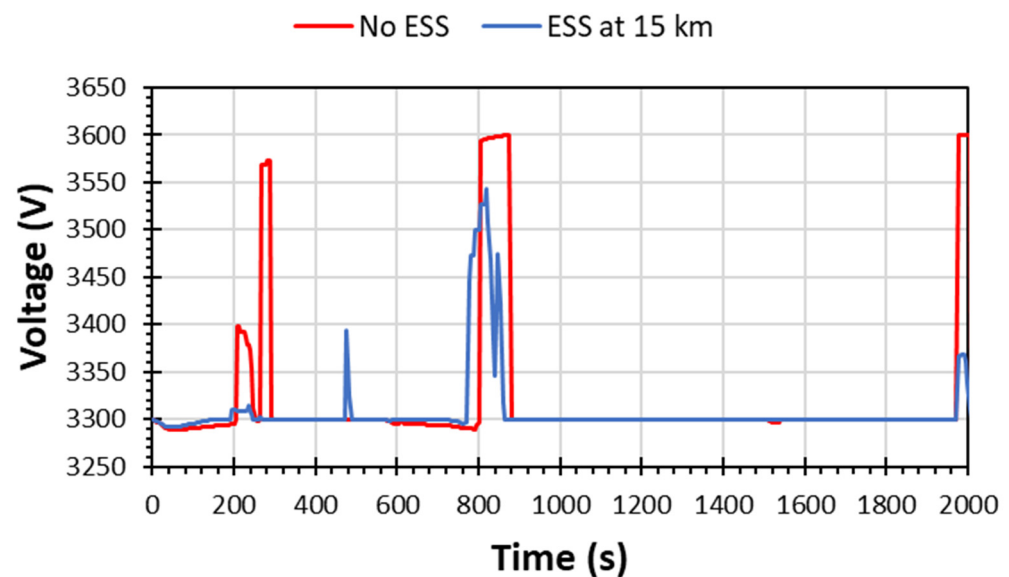


Figure 19. Voltage profiles of Substation 2 with respect to installing the stationary ESS at the location of 15 km.

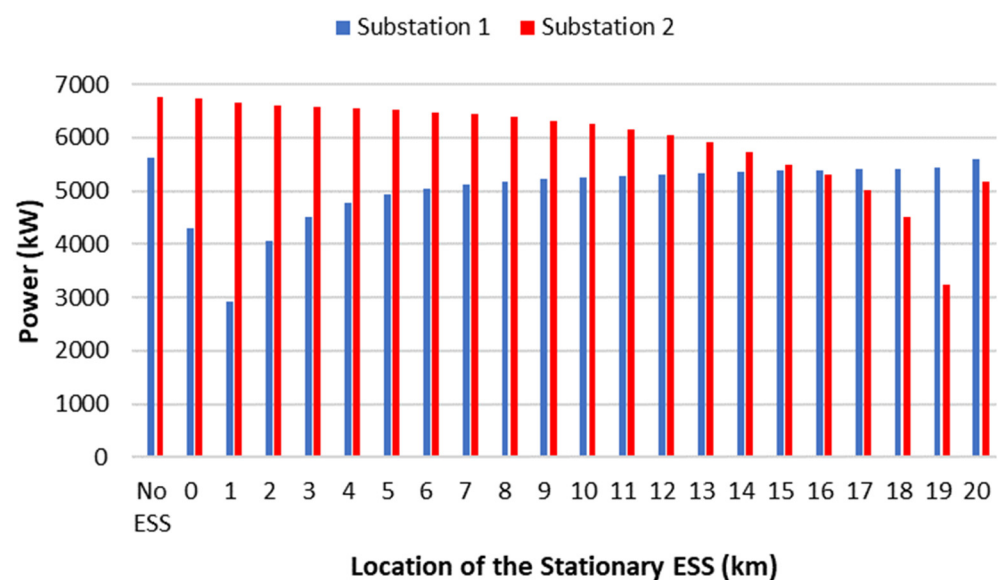


Figure 20. The substation's peak-power demand with respect to the location of the stationary ESS.

The energy demand of Substation 1 reduces from 484 kWh to 316 kWh (34.71% reduction) while the energy demand of Substation 2 reduces from 681 kWh to 196 kWh (71.22% reduction). Although the stationary ESS contributes effectively to reducing the energy demand of both substations, the impact is higher on Substation 2 as it is closer in distance to the ESS location.

Figure 21 shows the SoC and voltage of the stationary ESS when it is located at 15 km. The figure shows that the voltage drops down when it is discharging and rises up when it is charging. Figure 22 shows the SoC and current of the stationary ESS when it is located at 15 km. The figure shows that the current is positive when it is discharging and positive when it is charging. The maximum discharging current is 2000 A while the maximum charging current is 558 A. The stationary ESS internal losses are 14.9 kWh. The discharged energy is higher than the charged energy as the ESS discharges 659.5 kWh and charges 59.5 kWh.

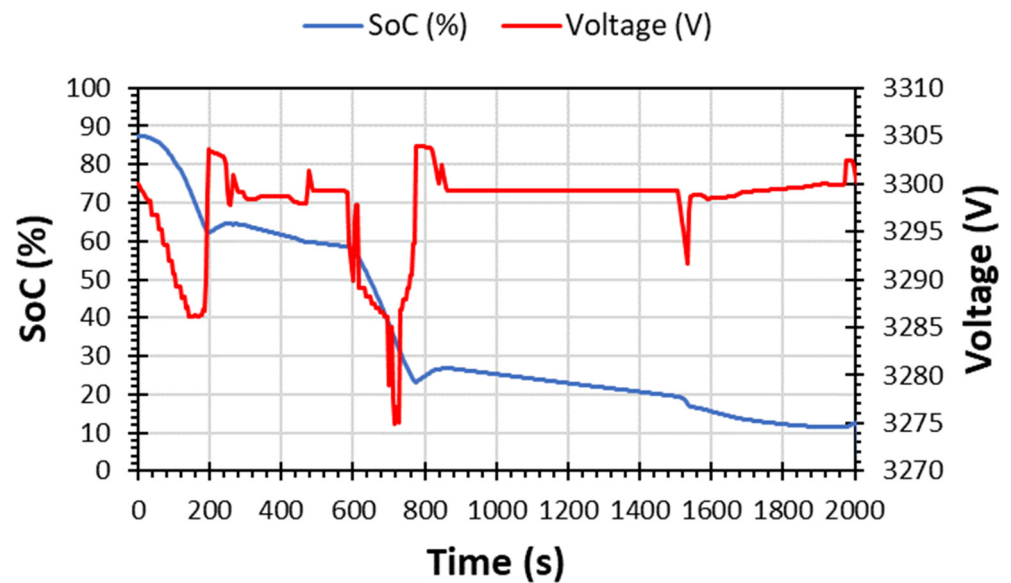


Figure 21. SoC of the stationary ESS and its voltage when it is located at 15 km.

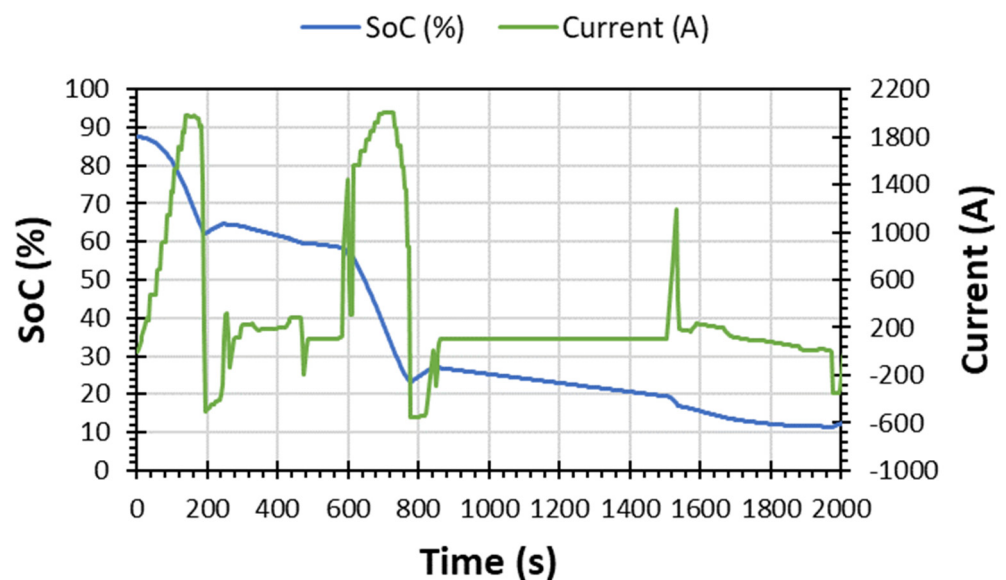


Figure 22. SoC of the stationary ESS and its current when it is located at 15 km.

Figure 23 shows the SoC of the onboard ESS of Train 1 with respect to changing the location of the stationary ESS. The figure shows that the final SoC is 80%. The energy consumed by storage from the engine at the terminals is 55 kWh while the energy recovered from storage to the engine at the terminals is 8 kWh when there is no stationary ESS installed. The energy consumed by storage from the engine at the terminals is 52 kWh, while the energy recovered from storage to the engine at the terminals is 6 kWh when the stationary ESS is installed at 0 km, 15 km, and 20 km. Figure 24 shows the SoC of the onboard ESS of Train 2 with respect to changing the location of the stationary ESS, where it shows that the final SoC is 80%. The energy consumed by storage from the engine at the terminals is 46 kWh while the energy recovered from storage to the engine at the terminals is 0 kWh when there is no stationary ESS installed, that is the same result when the stationary ESS is installed at 15 km. The energy consumed by storage from the engine at the terminals is 48 kWh, while the energy recovered from storage to the engine at the terminals is 2 kWh when the stationary ESS is installed at 0 km and 20 km. It is concluded that the location of the stationary ESS has a negligible impact on reducing the size of the onboard ESSs.

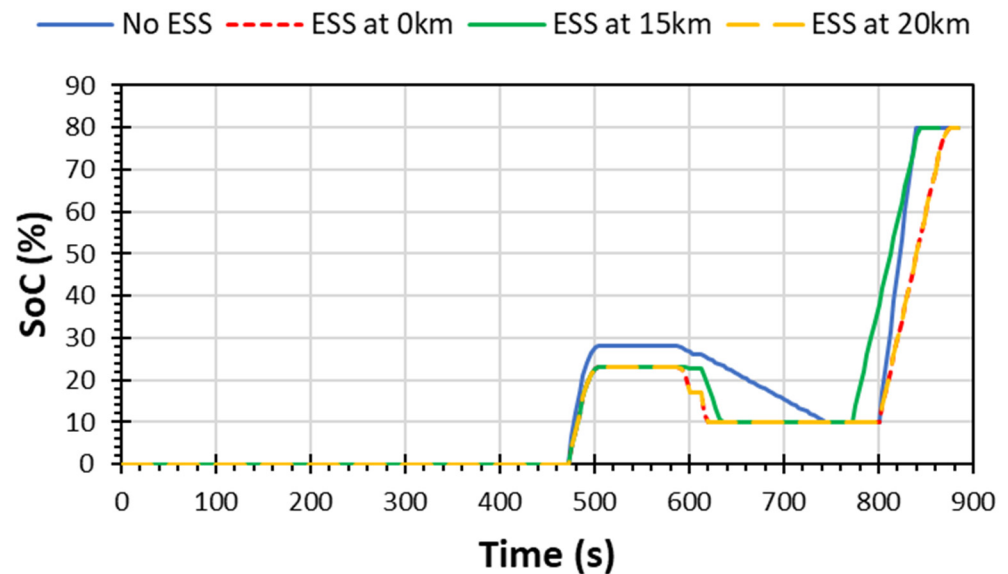


Figure 23. SoC of the onboard ESS of Train 1 with respect to changing the location of the stationary ESS.

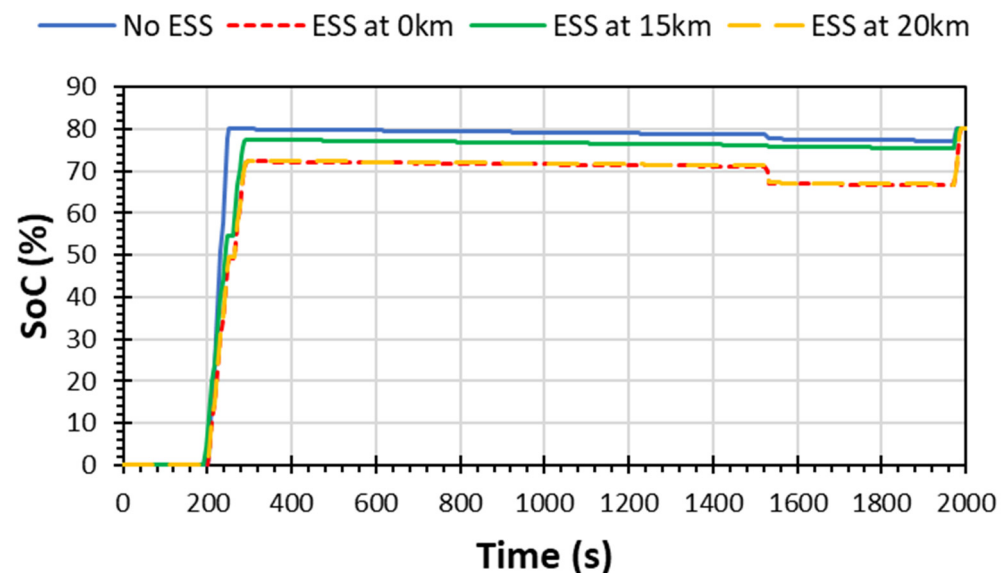


Figure 24. SoC of the onboard ESS of Train 2 with respect to changing the location of the stationary ESS.

Electric railways are challenging to model as they are nonlinear and time variant. Further, it is more challenging when they include multiple trains and ESSs. The common numerical methods are Gauss-Seidel, Newton-Raphson, and current injection methods. However, these methods require complex formulation, especially with large electric railway systems. Therefore, existing studies simplify the complexity of the traction system by not involving all features (rectifier substations, onboard ESSs, offboard ESSs, regenerative braking systems, overvoltage protection circuits, and neutral sections) in the same model [7]. Therefore, the presented results in this article could not be compared with other studies. However, the OpenTrack and OpenPowerNet simulation tools are certified according to the European Regulations for Conformity Assessment (ERC) and validated for multi-conductor models in the DC and AC voltage systems that meet the requirements of EN 50641:2020 standard [22].

The energy balance can be used as a method of validation as shown in Figure 25. The figure shows the generated data by the simulation tool at the end of the simulation

process with respect to installing the stationary ESS at 15 km. The data shows that the energy supplied by substations (509 kWh) and the energy supplied by the stationary ESSs (585 kWh) are equal to the sum of the energy consumed by the trains (1012 kWh) and total losses (82 kWh). Further, another case scenario is examined with respect to installing the stationary ESS at 7 km, as shown in Figure 26. The data shows that the energy supplied by substations (631 kWh) and the energy supplied by the stationary ESSs (500 kWh) are equal to the sum of the energy consumed by the trains (1003 kWh) and total losses (128 kWh).

Energy Overview, feeder, current limit, wes, obes, timetable

Network A-C, 01:00:00 - 01:33:32

Total energy at traction power supplies	509 kWh
Energy from traction power supplies to catenary system	509 kWh
Energy from catenary system to traction power supplies	0 kWh
Total energy at stationary energy storages	-585 kWh
Energy from catenary system to stationary energy storages	61 kWh
Energy from stationary energy storages to catenary system	646 kWh
SoC balance of stationary energy storages	-600 kWh
Total energy at vehicle pantographs	1,012 kWh
Energy from catenary system to vehicle pantographs	1,106 kWh
Energy from vehicle pantographs to catenary system	95 kWh
Total energy at vehicle energy storages	91 kWh
Energy from vehicles to energy storages	97 kWh
Energy from energy storages to vehicles	7 kWh
SoC balance of vehicle energy storages	79 kWh
Total losses in catenary system	82 kWh
Losses in substation feeder cables	5 kWh
Losses in substation busbar connectors	0 kWh
Losses in contact wires	64 kWh
Losses in rails	13 kWh
Losses in earth wires	0 kWh
Losses in connectors	1 kWh

(a)

Vehicle Overview, feeder, current limit, wes, obes, timetable

A-C, Aggregation Course, 01:00:00 - 01:33:32

Course	Formation	Engines	TKT	Δt	$U_{\text{U-limit1}}$	$U_{\text{U-limit2}}$	E_{Panto}	E_{Spec}	E_{Con}	E_{Rec}	ξ_{reg}	E_{BrReq}	E_{BrAch}	E_{BrRes}	ξ_{br}	ξ_{brNet}	E_{AUX}	E_{Loss}	U_{imu}	$ U_{\text{Panto}} _{\text{zmin}}$	$ U_{\text{Panto}} _{\text{zmin}}$
			tkm	hh:mm:ss	s	s	kWh	Wh/tkm	kWh	kWh	%	kWh	kWh	kWh	%	%	kWh	kWh	V	V	V
Total		2	13,915	00:47:56	-	-	1,012	73	1,106	95	9	300	257	4	86	32	415	99	3,196	-	-
Maximum		1	6,958	00:33:28	2	6	591	85	638	48	10	150	130	4	87	32	290	50	3,156	2,869	3,272
Minimum		1	6,957	00:14:28	0	3	420	60	468	47	7	149	127	0	84	31	125	50	3,124	2,816	3,222
ABCL_01	Train long	1	6,958	00:14:28	2	6	420	60	468	48	10	149	130	0	87	32	125	50	3,124	2,816	3,222
CBAI_01	Train long	1	6,957	00:33:28	0	3	591	85	638	47	7	150	127	4	84	31	290	50	3,156	2,869	3,272

(b)

Figure 25. Screenshots of the generated data by the OpenTrack and OpenPowerNet simulation tools with respect to installing the stationary ESS at the location of 15 km, where (a) energy overview of the power traction system; (b) energy overview of trains.

Energy Overview, feeder, current limit, wes, obes, timetable

Network A-C, 01:00:00 - 01:33:32

Total energy at traction power supplies	631 kWh
Energy from traction power supplies to catenary system	631 kWh
Energy from catenary system to traction power supplies	0 kWh
Total energy at stationary energy storages	-500 kWh
Energy from catenary system to stationary energy storages	44 kWh
Energy from stationary energy storages to catenary system	544 kWh
SoC balance of stationary energy storages	-512 kWh
Total energy at vehicle pantographs	1,003 kWh
Energy from catenary system to vehicle pantographs	1,081 kWh
Energy from vehicle pantographs to catenary system	78 kWh
Total energy at vehicle energy storages	91 kWh
Energy from vehicles to energy storages	97 kWh
Energy from energy storages to vehicles	6 kWh
SoC balance of vehicle energy storages	79 kWh
Total losses in catenary system	128 kWh
Losses in substation feeder cables	4 kWh
Losses in substation busbar connectors	0 kWh
Losses in contact wires	102 kWh
Losses in rails	20 kWh
Losses in earth wires	0 kWh
Losses in connectors	2 kWh

(a)

Vehicle Overview, feeder, current limit, wes, obes, timetable

A-C, Aggregation Course, 01:00:00 - 01:33:32

Course	Formation	Engines	TKT	Δt	t_{U-Umin}	t_{U-Umax}	E_{Panto}	E_{Spec}	E_{Con}	E_{Rec}	ξ_{reg}	E_{mbr_req}	E_{mbr_ach}	E_{strRes}	ξ_{br}	ξ_{br_net}	E_{AUX}	E_{loss}	U_{mu}	$ U_{panto} _{min}$	$ U_{panto} _{max}$
			tkm	hh:mm:ss	s	s	kWh	Wh/tkm	kWh	kWh	%	kWh	kWh	kWh	%	%	kWh	kWh	V	V	V
Total			2	13.915	00:48:00	-	-	1,003	72	1,081	78	7	285	238	13	83	27	416	95	3,194	-
Maximum			1	6.958	00:33:28	9	4	582	84	629	47	7	144	126	12	88	33	290	49	3,131	3,303
Minimum			1	6.957	00:14:32	4	4	422	61	453	31	7	141	111	1	79	22	126	46	3,096	3,273
ABCI_01	Train long		1	6.958	00:14:32	9	4	422	61	453	31	7	141	111	12	79	22	126	46	3,096	3,273
CBAI_01	Train long		1	6.957	00:33:28	4	4	582	84	629	47	7	144	126	1	88	33	290	49	3,131	3,303

(b)

Figure 26. Screenshots of the generated data by the OpenTrack and OpenPowerNet simulation tools with respect to installing the stationary ESS at the location of 7 km, where (a) energy overview of the power traction system; and (b) energy overview of trains.

4. Conclusions

The purpose of the work presented in this article is to model an electric railway system accurately in order to investigate the energy management, energy efficiency, and voltage regulation when installing a stationary ESS that is placed on the wayside, and its location is moved in steps of 1 km. The electric railway model is 20 km in length including two trains, three passenger stations, and two substations. The system is modelled in OpenTrack and OpenPowerNet simulation tools. It is found that the least optimal location is at the substations' location while the most optimal location is at 15 km, which is in the middle between Passenger Station B and C. The energy saving when installing the stationary ESS at 15 km is 56.05% (656 kWh), the peak-power reduction of Substation 1 is 4.37% (246 kW), and the peak-power reduction of Substation 2 is 18.67% (1261 kW). Further, the impact of installing ESSs on the performance of onboard ESSs is investigated. It is found that installing the stationary ESS reduces the energy consumed by storage from the engine and the energy recovered from storage to the engine; however, the location has a negligible impact on the size of the onboard ESS with respect to energy charged and discharged.

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