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Research Paper

Energy Storage for High Speed Trains: Economical and Energy Saving Evaluation

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A R T I C L E I N F O	A B S T R A C T
	Increasing the utilization rate of regenerative braking energy in rail systems is one of the ongoing applications increasing in significance in recent years. In rail systems, braking is made with two ways, mechanical and electrical. While the energy released due to mechanical braking cannot be recovered, the energy released due to electrical braking can be reused as regenerative braking energy. This regenerative braking energy varies according to the dynamics of the system and it can be given back to the grid, stored in storage devices or burned in resistors (it is not desired). This study develops a novelty algorithm within the scope of this objective and provides the calculation of the regenerative braking energy recovery rate and then making a decision for storage or back to grid of this energy. Afterwards, the regenerative braking energy was calculated with the help of this algorithm for Eskisehir-Ankara and Ankara-Eskisehir trips in two different passengers (load) scenarios, using the YHT 65000 high-speed train, which was chosen as a case study. Then, with a decision maker added to this classical regenerative braking energy algorithm, it will be decided whether this energy will be stored or forward back into the grid for the purpose of providing non-harmonic energy to the grid.

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1. Introduction

In rail systems, there are two energy storage types according to storage location; one is on the vehicle (on-board energy storage) and the other is on the wayside. If the two energy storage systems are compared:

- *In on-board energy storage, transmission losses related to where the train is located do not need to be taken into account.*
- *On-board energy storage makes it possible to travel without a catenary on the train.*
- *On-board energy storage causes the weight of the train to increase, this results in energy losses.*
- *In on-board energy storage, there is a disadvantage in that the train only meets its own energy requirement, without giving it to other trains on the line.*

Applications with short distances between stops is another important factor which leads to an optimum use of installed energy storage components against stored energy, because the braking energy can be stored and reused more often than in other applications with longer distances (Steiner et al., 2001). The absolute value of the braking energy is less important since the weight and costs for the energy storage are more or less proportional to the absolute storage amount of the energy storage (Hentschel et al., 2000). Therefore, generally, high-speed trains, as well as vehicles with good regeneration performance, such as regional and suburban EMUs (Electrical Multiple Units), do not belong to these preferred applications (Ghahremani Nahr et al., 2022). However, this issue must also be researched because of changing and developing technology. The use of regenerative braking is beginning to extend to many railway systems, especially in metro systems (Falyo et al., 2010; Killer et al., 2012). The new traction systems with energy storage leads to an energy saving of up to 30% and a reduced peak power demand from the line of about 50% compared to a modem regenerative light rail vehicle. The saved emissions of CO2 per train are in the range of l00 t per year (Sertsöz, 2021; Ellwanger, 2005).

In railway systems, two different energy storage types generally (Li-ion batteries, Ultra-capacitors) are used. A technical comparative table (Energy Density, Energy Efficiency, Charge/Discharge Cycle, Total Project Cost and Life) will be given in Part 4.2. Determining of the regenerative braking energy is the essential point for energy storage systems in trains. However, this system has many different inputs as load, train movement resistance, speed, line conditions. The aim of this study was to see how much regenerative braking energy can be utilized according to different working conditions.

The paper is planned as follows: The comparative advantages and disadvantages of storage types in rail systems, features of storage devices have been summarized in the Introduction section. Applications in the world, the algorithm for this issue and information about the principle of storage energy in railways is given in the Recoverable Energy in Trains section, below. The regenerative energy of vehicles and their mathematical equations are given in the Methods section. The algorithm for calculation of regenerative braking energy is given and added a novelty decision-maker section to the algorithm to decide of this energy to storage or forward back to the grid in Proposed Algorithm and Selection of Storage Type section. The outcomes of the two algorithms, both of the decrease in energy cost and the best option for storage selection, are handled in the Comparative Results section, and finally, the results are interpreted and suggestions are presented in the Conclusions section.

2. Recoverable Energy in Trains

There are many different ways to recover energy from trains. However, especially saving energy which gets from regenerative braking has two ways. One of them is reversible substations the other one is energy storage. High-speed trains are supplied with AC power. Then the use of regenerative braking is direct, being possible to send the power back to the electric grid. However, it is reported that most of the energy generated during

braking is used by other trains on lines where trains are operated for 3 minutes or less (Albrecht, 2010). In lines where trains are not operated frequently, most of the energy is burned in resistors. In this context, it is thought that significant energy savings can be achieved in terms of operating costs through energy storage technologies (Najafi et al., 2022; Nozari et al., 2022). High-speed trains use AC power and send the power back to the electric grid. There are not any requirements and losses for additional pieces of equipment. However, using a reversible transformer does not seem logical as the next train will not arrive in 3 minutes.

There are two types of energy storage in railways. These are for High Speed and Conventional Train and Urban train. Studies in this field are given below separately.

2.1. High Speed and Conventional Trains

The International union of railways (UIC) observed that 2.9% of the energy drawn from the pantograph will be lost if regenerative braking is stored on the high-speed train. A unique feature of each application is how it will be stored and used in high-speed trains or urban systems. Therefore, it is necessary to know the system and its use. Ceraolo et al. (2016) has shown that the addition of energy recovering capability to high-speed railway lines can bring a significant amount of energy-saving when one stationary storage system is installed in correspondence of one Energy Storage System (ESS) located in correspondence of the entrance in a railway junction. In a realistic case study, involving a 728 kWh storage and only considering trains moving on the DC high-speed line, payback time is expected around five years, for a system that is expected to stay in service ten years. There are also algorithms that have been created for utilizing regenerative braking energy around the world. Researchers at Xi'an Jiaotong-Liverpool University's Suzhou campus developed an algorithm intended to optimize the storage and reuse of braking energy. The name of the algorithm is XJTLU (wang et al., 2022). In research paper, stationary and on-board batteries and super capacitors have been considered. The analysis has shown that braking energy recovery is able to provide significant energy and costs saving even in DC high-speed railway systems, opening new research opportunities for the future (Ceraolo et al., 2016). The proposed simulation tool (Pugi et al., 2014) completely developed in Matlab-Simulink is designed as a modular system that should be easily customized in order to fit different traction and braking system layouts.

2.2. Urban Trains

There have been important studies on energy storage in rail systems globally. The first is the MITRAC train. The MITRAC train is called an energy saver. MITRAC can minimize the environmental effect and reduce energy consumption costs, which are very important issues for public transport. The MITRAC Energy Saver is based on a series connection of high-performance EDLCs (Electric Double Layer Capacitors). A characteristic of EDLCs is that they can be quickly charged, (when the train is accelerating), and discharged, (when the train is decelerating). The single line schematic of the MITRAC energy saver is shown in Figure 1 (Steiner et al., 2007; Ratniyomchai et al., 2014). In the braking phase, the train stores some of the regenerative energy, and in the acceleration phase, this energy is used in the power supply of the train as with all-electric vehicles. The aims of the MITRAC Energy Saver are energy savings, power supply optimization, reduced infrastructure investment, catenary-free operation, and performance-boosting (Transportation, 2009).

The MITRAC Energy Saver was installed onboard as a prototype of a light rail vehicle (LRV) for public transport by the German operator Rhein-Neckar-Verkehr Gmbh in Mannheim, Germany from September 2003 to 2008. In the future, for metro systems, it is estimated that about 40% of braking energy can be saved and 21% of the total energy can be saved for acceleration (Transportation, 2016).
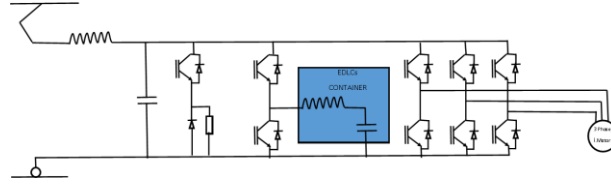
Fig. 1. Schematic of MITRAC Energy Saver Modified

In Figure 1, a general schematic of Mitrac can be seen. In this figure, there is an EDLCs Container paralleled to network. In this way, the three-phase Induction motor's energy requirement can be met by both the EDLCs Container and/or network. Algorithms of this system make choices for how much energy will be recover from two different sources.

A second example is the STEEM project. The circuit layout of the onboard EDLC modules of the STEEM project is similar to the MITRAC Energy Saver shown in Figure 1. The objectives of this project were to enhance the energy efficiency of tramway systems and to support catenary-free vehicles (Moskowitz & Cohuau, 2010). This project is an example of wayside energy storage. Turkey also used a train energy storage and management system with a piece of software named TROBES developed by kebede et al. (2022). Modular energy storage infrastructure that can be configured with battery and/or supercapacitor. TROBES provides up to 30% energy savings.

Portuguese trains have an energy saver program in which they increase the use of regenerative braking energy (PORTUGAL, 2016). In this work (Pugi et al., 2018), it was presented and successfully applied to a benchmark test case, a model for simulation and optimization of tramway lines. In this study, the Simulink model was used for energy storage or energy management: energy management that have been developed by García et al. (2013) for electric power system of tramways.

3. Methods

The technical information of high-speed train used in this study is given in Table 1:

Table 1. Technical Information of High Speed YHT 65000 Train *

Main Characteristics	YHT 65000
Power	38400 kW
Locomotive Load	297.25 Ton
Axle Load	17 Ton
Axle Type	-
Maximum Velocity	275 km/h
Line Gap	1435 mm
Catenary Type	AC 25 kV, 50 Hz
Traction Motor Power	AC 4800 kW

*Obtained from TCDD (Turkish State Railways).

The aim of this study was to see how much regenerative braking energy can be utilized according to different working conditions. However, in order to realize the objectives, firstly a mathematical expression of the E68000 High Speed Train is needed. There are two main approaches for the transient modeling of electric rail vehicles (Kulworawanichpong, 2015; Khodaparastan & Mohamed, 2018).

- *Cause-effect or forward-facing method. In this method, the power consumed by the vehicle is used as an input to determine the speed of the wheel.*
- *Effect-cause or backward-facing method. In this method, the speed profile and vehicle properties are used as inputs to determine the input power to the train.*

In this paper, the effect-cause approach is used to model the electric rail vehicle. The modeling process is presented in Figure 2. In this model, the speed of the train is taken as an input, and is calculated with the vehicle dynamic equations represented in (1):

$$P_T = P_R \tag{1}$$

P_T: Total power

P_R: Wheel force power caused by movement

Wheel force is defined as the summation of all resistive forces against the motion of the train, which can be expressed as F_{RT}. Wheel force occurs only if power is applied to the axle of that wheel. The power applied to the axle is called the traction motor power, which can be shown by equation (2).

$$P_R = \frac{F_{RT} \cdot V}{367} (kW) \tag{2}$$

F_{RT}: Wheel force

F_{RT} consists of five different resistances: cruise, acceleration, aerodynamics, curves, and ramp resistances. In this study, the cruise, curve, and ramp (Başeğmez, 2018; Akbayir & Çakir, 2017) and acceleration resistances of the selected high-speed train E68000 were taken into account. However, aerodynamic resistance was neglected.

As a result of empirical studies, train resistance is expressed by a second order polynomial depending on speed and consists of 3 terms. This equation, denoted by equation 3, is generally called the Davis equation. In the literature, this equation is also called the von Borries Formel, Leitzmann and Barbier equation (2):

$$F_R = AV^2 + BV + C \, (daN/ton) \tag{3}$$

Where A, B and C are constants that depends of the type of railway.

This equation with the calculated coefficients A, B and C for YHT 65000 is as follows (Sertsöz & Fidan, 2020):

$$F_R = 0.0006V^2 - 0,071V + 1,3953 \, (daN/ton) \tag{4}$$

The following result was reached when curves, ramp, and acceleration resistances, together with vehicle mass were also included in the equation, giving the total resistance force:

$$F_{RT} = \left((0.0006V^2 - 0,071V + 1,3953) + \frac{65}{(R-55)} + S + \frac{3.85(V_2^2 - V_1^2)}{X} \right) M \, (daN) \tag{5}$$

R: Curve (m)

S: ‰ ramp level (daN/ton)

M: load (ton)

V: speed (km/h)

X: Covered distance (km)

V_1 = First speed (km/h)

V_2: Second speed (km/h)

Power spent in resistors:

$$P_R = \frac{F_{RT} \cdot V}{360} = \frac{\left((2 + 0.0008V_1^2) + \frac{65}{(R-55)} + S + \frac{3.85(V_2^2 - V_1^2)}{X} \right) M \, V}{360} (kW) \tag{6}$$

When braking the train, it releases energy as regenerative braking (E_{RG}). This energy can be explained as Newton's 2nd law, principle of motion:

$$E_{RG} = \frac{1}{2} M(V_2^2 - V_1^2) \text{(joule)} \tag{7}$$

Regenerative braking energy is caused by acceleration; the algorithm is given below, figure 4 depend on this theory and Newton's 2nd law. The conditions for storing regenerative braking energy are given in the algorithm below:
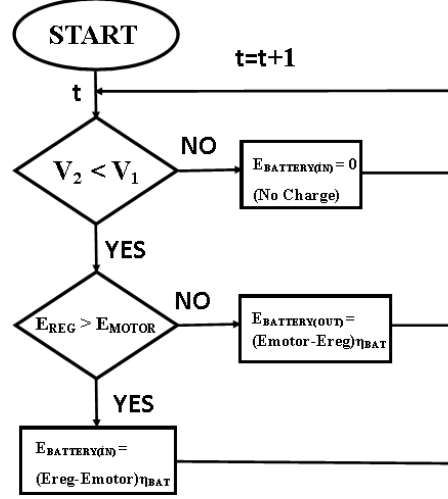

Fig. 2. Algorithm of Regenerative Braking Recover in Storage Devices

In the algorithm described in Figure 2, the first question is whether the speed of V2 is greater than V1. It is not important the value of the speeds, there is an only comparison. This is actually questioning whether regenerative energy is available or not, in other words, is the train slowing down? If the train does not slow down, there is no energy input into the battery, it is not charged. However, if the train is slowing, there is regenerative braking. If the regenerative braking energy value is greater than the energy required by the motor, the battery is charged, which is performed based on the charging efficiency of the battery after the motor's need has been met from the regenerative energy. Alternatively, the battery is discharged, so energy required by the motor is derived from regenerative energy and the discharged battery. Here it is assumed that the battery has sufficient capacity when it is being charged and discharged, because energy storage is carried out on the wayside, not on the vehicle. Thus, there is no possibility for the train to increase its weight. This algorithm continues until the end of journey time with each "t" time increasing by one.

4. Proposed Algorithm and Selection of Storage Type

There are two related studies in this section. The first is to find the effect of load parameter in regenerative braking energy with the aim of proposed algorithm in section 3; the second one is the evaluation of storage device selection according to this calculated energy amount using Net Present Value Analysis (NPVA). Route information is used in this study in below:

Fig. 3. Route Information of the Line used in this study (Sheikholeslami, 2022)

The route given in Figure 3 presents the 245 km route travelled by the YHT 65000 train; which performs five departures and five return trips per day. As seen in the figure, there are four stations, namely Eskişehir, Polatlı, Eryaman and Ankara. Comparing this to other high-speed train examples in the world, four stops seem to be too many for this short distance. This route was chosen for the study as this line, where stopping is high, allows the utilization of regenerative braking energy.

4.1. Calculation of Regenerative Braking According to Different Load Scenarios Using Proposed Algorithm

The algorithm detailed in section 3 was run and two studies with different load scenarios were carried out. In both scenarios, the speeds of the trains were specified at 1-minute intervals, and this process continued until the end of the journey process, the 91st minute. The speeds were always the same in both scenarios.

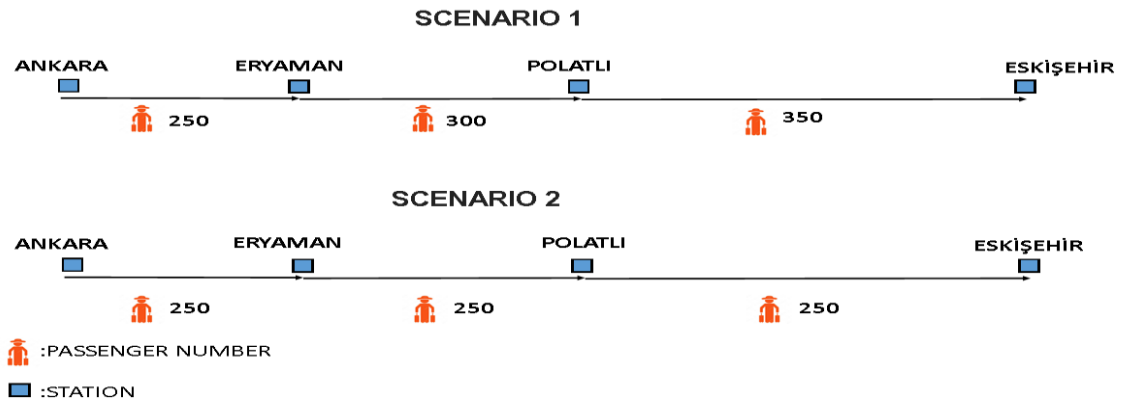It is possible to give the difference between the two scenarios as follows:

Fig. 4. Passenger Number According to Scenarios

Considering Figure 4, for the first scenario, the number of passengers in the Ankara-Eryaman trip is 250, between Eryaman and Polatlı 300, and finally, this number is 350 between Polatlı and Eskişehir. In the second scenario, on the Ankara-Eryaman trip, the number of passengers starts with 250, and this number is not changed until the last stop without making any stops at the stations.

As a result of proposed algorithm, energy gain from regenerative energy was found as 31.86% for the first scenario and as 30.57% for the second scenario. These two different values are based on the effect of the load in acceleration resistance. In other words, it is due to the change in the acceleration capacity under different loads because of the Newton's 2nd Law.

These values corresponded to 5087.34 kWh for the first scenario and 5302.66 kWh for the second scenario after the losses were removed, (generator and transmission losses). These values represent a single trip of YHT between Ankara and Eskişehir. In this way, there is a linear relationship between increasing passenger

number (load) and regenerative energy gain. However, it does not have a huge impact in energy consumption compared with huge energy requirement in high-speed trains.

4.2. Storage Device Selection and Investment Accounts

When choosing the storage device, energy density (Wh/kg), and the charge / discharge cycle must be checked (Møller et al., 2017). In addition, the Net Present Value Analysis should also be calculated well since it is suitable for the financial investment. The main alternatives to be used in the recovery of energy from regenerative braking are batteries (Gao et al., 2017; Irena, 2017), supercapacitors (Killer et al., 2012; Lin et al., 2016) and flywheels (Gee et al., 2014; Spiryagin et al., 2015). Below is a table of parameters used for investment and capacity calculations of these storage devices (li-ion was selected as the battery type) (Sabihuddin et al., 2014; Shan et al., 2022):

Table 2. Some Parameter Values for Different Storage Devices

	Energy Density (kWh/m³)	Char./Disc. Cycle	Energy Efficiency (%)	Total Project Cost in 2025 ($/kWh)	Average Calendar Life (years)
Li-ion Batteries	94.00-500.00	900	70-100	362	10
Ultra-cap.	1.00-35.00	1 million	65-99	66,640	16

According to the regenerative power gains given in section 4.1; 5302.66 kWh is chosen due to the because the higher energy will need more storage space. This value is for a single trip. This train set makes five departures and five return trips per day, thus the train makes a total of 3650 trips per year. In this case, the annual regenerative power gain is:

5302.66x365x10=19354.709 MWh regenerative energy gain per year

19354709 kWh x **0, 0589$/kWh (energy price in Turkey) ≈1,140,000**$ financial gain per year

In order to store this power, one of the two storage devices given in Table 2 will be preferred. The NPVA will be used to ensure that investment cost does not exceed economic limits. The formula for this analysis is as follows (Whitman & Terry, 2012):

$$\text{NPVA} = -\text{Initial Investment Cost} + \text{Annual Gain}\frac{(1+i)^n - 1}{i(1+i)^n} \tag{8}$$

Here i is the interest rate; n represents its economic life. The interest rate of 0.79% has been chosen, as this is the current interest rate in Turkey. Every different n values are chosen from Table 2. In order to avoid loss (i.e. if the NPVA value equals zero), the maximum capacities of the storage devices are:

$$\text{NPVA}_{\text{Li-ion}} = -362\text{x}5302 + 1,140,000\frac{(1+0,79)^{10} - 1}{0.79(1+0.79)^{10}} = -480.5 \text{ \$}$$

$$\text{NPVA}_{\text{Ultracapacitors}} = -66640\text{x}5302 + 1,140,000\frac{(1+0,79)^{16} - 1}{0.79(1+0.79)^{16}} = -351882237 \text{ \$}$$

The Li-ion is lower price than ultra-capacitors. This calculation declares the only device can be used is Li-ion for energy storage project of YHT 65000. However, the NPVA value is still negative. There are two ways to make the investment profitable as we cannot change calendar life of li-ion. One of them is to increase the number of trips (in a near future) and the other is to increase the unit electricity price in the country. Of course, the second situation is undesirable. However, under these conditions for this problem, it is seen that less storage causes less economic loss. Therefore, the algorithm will be redesigned and instead of storing all the energy, storing only a part of energy will save money.
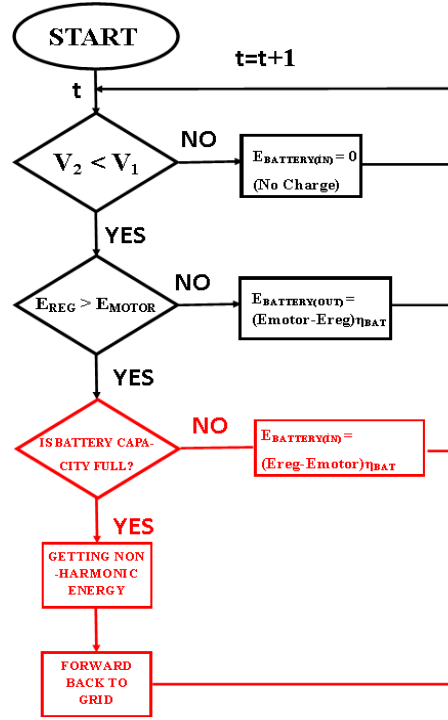
START

t

t=t+1

$V_2 < V_1$ — NO → $E_{BATTERY(IN)} = 0$ (No Charge)

YES

$E_{REG} > E_{MOTOR}$ — NO → $E_{BATTERY(OUT)} = (E_{motor} - E_{reg})\eta_{BAT}$

YES

IS BATTERY CAPACITY FULL? — NO → $E_{BATTERY(IN)} = (E_{reg} - E_{motor})\eta_{BAT}$

YES

GETTING NON-HARMONIC ENERGY

FORWARD BACK TO GRID

Fig. 5. Novelty Algorithm of Regenerative Braking Recover in Storage Devices and Forward Back to Grid

In Figure 5, an innovative algorithm has been developed that brings storage constraints due to the cost of the storage device. Because of not to lose regenerative energy gain, it is given back to the grid. The blocks marked in red are new or relocated blocks, unlike Figure 4. Thus, there will be a limit to the storage and if this limit is exceeded, the energy will be returned to the grid by making it non-harmonic. When the energy is returned to the grid, it is important to make the energy non-harmonic since it has a harmonic structure that pollutes the grid. Thus, there will be a limit to the storage and when this limit value is reached, the energy will be returned to the grid by making it non-harmonic.

5. Comparative Results

In this study, firstly a new algorithm was developed using acceleration resistance and Newton's 2nd law for to calculate the regenerative energy value of the YHT 65000 high speed train. Than two studies were searched together with this algorithm. The first one was finding the load effect in recoverable regenerative energy value according to this algorithm. The second one was finding the investment cost of two different storage devices –Li-ion batteries and ultra-capacitors with aim of NPVA. Detailed results were shown below:

Algorithm was built in that: firstly, a new mathematical equation was built for 65000 High Speed Train then the energy spent in resistors was found with the aim of this equation. An innovative algorithm was developed using calculated power requirement because of acceleration in resistors and 2nd law of motion also was used.

This algorithm was run with two load scenarios. In the first scenario; the number of passengers started as 250 in the first station increased by 50 at the second station and increased by 50 at the third station, reaching 350 passengers. In the second scenario; the number of passengers remained unchanged, at 250 for the entire journey. In both scenarios, the speeds of the trains were specified at 1-minute intervals and this process continued until the end of the journey process, in the 91st min. The speed changes were always the same in both scenarios. With the help of the developed mathematical model and algorithm, the following results were achieved:

- *In the first scenario, the effect of cruise resistance on the total resistance was 72.24%, while in the second scenario this ratio was calculated as 69.29%.*
- *As a result of the proposed algorithm with 90% motor (in case of use as a generator) and 98% cable efficiency; it was found that 31.86% of the energy was consumed by the acceleration resistance in Scenario 1 and 30.57% in Scenario 2 could be recovered as regenerative energy. This amount is compatible with the experimental results of the energy rate that can be obtained from the regenerative energy studies in the literature given above. This proved that the proposed algorithm works right and can be used in another regenerative energy recovering applications.*
- *Another noteworthy point is that it was revealed that more energy which was generated in low speed braking than in braking at high speeds. Likewise, required acceleration at low speeds also required more energy. This result showed that there was an excess of energy and a deficit when approaching and moving away from the stations. Therefore, placing the energy storage devices at stations appeared reasonable for this study. The features and results of the energy storage devices were given below according to NPVA:*
- *The only Li-ion battery usage was more logical compared to ultra-capacitors. However, storing the all-regenerative energy, forwarding back to the grid is better for economic reasons. With the help of the innovative algorithm, it can be determined how much energy will be stored and how much will be sent to the network in a harmonic-free way.*

6. Conclusions

In this study, three different studies were achieved. The first one was to develop an algorithm for to find the regenerative braking value of the YHT 65000. The other one was to test the algorithm with two different load scenarios. The results showed that the values were very close to each other however, the first scenario utilized more regenerative energy with a difference of 1.29% than the second scenario. The rate of utilizing the regenerate energy was around 30% for both scenarios, in accordance with existing literature. In that way, it was verified the algorithm worked well and it was shown that the number of passengers was not a criterion that could significantly change this energy rate for high-speed trains. From the results of the algorithm, wayside energy storage was chosen as the storage type, because it was seen that more energy was needed in low speed braking and accelerations just like times at arrives and departures to the station. As the third, an investment cost calculation was made according to two different storage devices for this released energy. While making this calculation with using the different technologies, obtained them from NPVA. According to this calculation, it was observed that Li-ion storage gives better results than super-capacitor applications for the Eskişehir-Ankara and Ankara-Eskişehir journeys of the YHT 65000. The most suitable storage types are changing according to different systems. For this system, it was seen that storage should be made as station type and that Li-ion should be selected as the storage device for YHT 65000's route. Another advantage of using Li-ion's space requirement would be less because of the high energy density. The developed algorithm and the NPVA can easily be used for calculating regenerative braking energy, finding logical cost analysis of energy storage, and for choosing storage devices for different trains in different scenarios. Thanks to the innovative algorithm developed, it is possible to find out how much energy will be stored and how much will be returned to the network. These rates will depend entirely on the design. As a result; energy savings, less investment, and reduction of CO_2 emission are achieved. In future, this investment values can change with developing energy storage types and their features. However, until to that time Li-ion batteries will be the best choice for this application.

References

- AKBAYIR, Ö., & ÇAKIR, F. H. (2017). Enerji verimliliği için tren direnci formüllerinin karşılaştırılması. Mehmet Akif Ersoy Üniversitesi Fen Bilimleri Enstitüsü Dergisi, 8(Özel (Special) 1), 112-126.

- Albrecht, T. (2010). Reducing power peaks and energy consumption in rail transit systems by simultaneous train running time control. WIT Transactions on State-of-the-art in Science and Engineering, 39.

- Başeğmez, B. (2018). Türkiye şartları için uygun tren direnci formüllerinin belirlenmesi (Master's thesis, ESOGÜ, Fen Bilimleri Enstitüsü).

- Ceraolo, M., Lutzemberger, G., Frilli, A., & Pugi, L. (2016, June). Regenerative braking in high speed railway applications: Analysis by different simulation tools. In 2016 IEEE 16th International Conference on Environment and Electrical Engineering (EEEIC) (pp. 1-5). IEEE.

- Ceraolo, M., Lutzemberger, G., Meli, E., Pugi, L., Rindi, A., & Pancari, G. (2018). Energy storage systems to exploit regenerative braking in DC railway systems: Different approaches to improve efficiency of modern high-speed trains. Journal of Energy Storage, 16, 269-279.

- Ellwanger, G. (2005). Externe Kosten des Verkehrs jetzt internalisieren!. ETR. Eisenbahntechnische Rundschau, 54(1-2), 62-67.

- Falvo, M. C., Lamedica, R., Bartoni, R., & Maranzano, G. (2010, June). Energy saving in metro-transit systems: Impact of braking energy management. In SPEEDAM 2010 (pp. 1374-1380). IEEE.

- Gao, Z., Chin, C. S., Woo, W. L., & Jia, J. (2017). Integrated equivalent circuit and thermal model for simulation of temperature-dependent LiFePO4 battery in actual embedded application. Energies, 10(1), 85.

- García, P., Fernández, L. M., Torreglosa, J. P., & Jurado, F. (2013). Operation mode control of a hybrid power system based on fuel cell/battery/ultracapacitor for an electric tramway. Computers & Electrical Engineering, 39(7), 1993-2004.

- Gee, A. M., & Dunn, R. W. (2014). Analysis of trackside flywheel energy storage in light rail systems. IEEE Transactions on Vehicular Technology, 64(9), 3858-3869.

- Hentschel, F., Mueller, K., & Steiner, M. (2000, May). Energy storage on urban railway vehicles. In Proceedings of the UIC Energy Efficiency Conference, Paris.

- Irena, E. (2017). storage and renewables: costs and markets to 2030. Abu Dhabi.: Int Renew Energy Agency.

- Kebede, A. A., Kalogiannis, T., Van Mierlo, J., & Berecibar, M. (2022). A comprehensive review of stationary energy storage devices for large scale renewable energy sources grid integration. Renewable and Sustainable Energy Reviews, 159, 112213.

- Khodaparastan, M., & Mohamed, A. (2018, June). Modeling and simulation of regenerative braking energy in DC electric rail systems. In 2018 IEEE Transportation Electrification Conference and Expo (ITEC) (pp. 1-6). IEEE.

- Killer, A., Armstorfer, A., Diez, A. E., & Biechl, H. (2012, August). Ultracapacitor assisted regenerative braking in metropolitan railway systems. In 2012 IEEE Colombian Intelligent Transportation Systems Symposium (CITSS) (pp. 1-6). IEEE.

- Killer, A., Armstorfer, A., Diez, A. E., & Biechl, H. (2012, August). Ultracapacitor assisted regenerative braking in metropolitan railway systems. In 2012 IEEE Colombian Intelligent Transportation Systems Symposium (CITSS) (pp. 1-6). IEEE.

- Kulworawanichpong, T. (2015). Multi-train modeling and simulation integrated with traction power supply solver using simplified Newton–Raphson method. Journal of Modern Transportation, 23(4), 241-251.

- Lin, F., Li, X., Zhao, Y., & Yang, Z. (2016). Control strategies with dynamic threshold adjustment for supercapacitor energy storage system considering the train and substation characteristics in urban rail transit. Energies, 9(4), 257.

- Møller, K. T., Jensen, T. R., Akiba, E., & Li, H. W. (2017). Hydrogen-A sustainable energy carrier. Progress in Natural Science: Materials International, 27(1), 34-40.

- Moskowitz, J. P., & Cohuau, J. L. (2010, September). STEEM: ALSTOM and RATP experience of supercapacitors in tramway operation. In 2010 IEEE Vehicle Power and Propulsion Conference (pp. 1-5). IEEE.

- Najafi, S. E., Nozari, H., & Edalatpanah, S. A. (2022). Artificial Intelligence of Things (AIoT) and Industry 4.0–Based Supply Chain (FMCG Industry). A Roadmap for Enabling Industry 4.0 by Artificial Intelligence, 31-41.

- Nozari, H., Ghahremani-Nahr, J., Fallah, M., & Szmelter-Jarosz, A. (2022). Assessment of cyber risks in an IoT-based supply chain using a fuzzy decision-making method. International Journal of Innovation in Management, Economics and Social Sciences, 2(1).

- PORTUGAL, P. (2016). Relatório de sustentabilidade. Obtido a, 10.

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

- Pugi, L., Malvezzi, M., & Conti, R. (2014). Optimization of traction and braking subsystems with respect to mission profile. Civil-Comp Proceedings, 104.

- Ratniyomchai, T., Hillmansen, S., & Tricoli, P. (2014). Recent developments and applications of energy storage devices in electrified railways. IET Electrical Systems in Transportation, 4(1), 9-20.

- Sabihuddin, S., Kiprakis, A. E., & Mueller, M. (2014). A numerical and graphical review of energy storage technologies. Energies, 8(1), 172-216.

- Sertsöz, M. (2021). A Novelty Energy Storage Algorithm for High Speed Trains: Economical and Energy Saving Evaluation.

- SERTSÖZ, M., & FİDAN, M. (2020). A critical approach to the particle swarm optimization method for finding maximum points. Journal of Scientific Perspectives, 4(2), 111-122.

- Shan, R., Reagan, J., Castellanos, S., Kurtz, S., & Kittner, N. (2022). Evaluating emerging long-duration energy storage technologies. Renewable and Sustainable Energy Reviews, 159, 112240.

- Sheikholeslami, M. (2022). Numerical analysis of solar energy storage within a double pipe utilizing nanoparticles for expedition of melting. Solar Energy Materials and Solar Cells, 245, 111856.

- Spiryagin, M., Wolfs, P., Szanto, F., Sun, Y. Q., Cole, C., & Nielsen, D. (2015). Application of flywheel energy storage for heavy haul locomotives. Applied energy, 157, 607-618.

- Steiner, M., Klohr, M., & Pagiela, S. (2007, September). Energy storage system with ultracaps on board of railway vehicles. In 2007 European conference on power electronics and applications (pp. 1-10). IEEE.

- Steiner, M., Scholten, J., Steinegger, H., & Jenewein, T. (2001). Energy Storage Systems for Improved Efficiency of Railway Vehicles. WCRR, Köln.

- Transportation, B. (2009). MITRAC Energy Saver. EcoActive Technology, Propulsion & Controls, 1-4.

- Wang, X., Luo, Y., Qin, B., & Guo, L. (2022). Power dynamic allocation strategy for urban rail hybrid energy storage system based on iterative learning control. Energy, 245, 123263.

- Whitman, D. L., & Terry, R. E. (2012). Fundamentals of engineering economics and decision analysis. Synthesis Lectures on Engineering, 7(1), 1-219.