Smart Railway Station Energy Management Considering Regenerative Braking and ESS

Ibrahim Sengor, Hasan Can Kılıçkıran, Huseyin Akdemir, Bedri Kekezoglu, and Ozan Erdinç
Yildiz Technical University
TURKEY
isengor@yildiz.edu.tr, hckiran@yildiz.edu.tr, hakdemir@yildiz.edu.tr, bkekey@yildiz.edu.tr
and oerdinc@yildiz.edu.tr

João P. S. Catalão
INESC TEC and FEUP, Porto,
C-MAST/UBI, Covilhã, and
INESC-ID/IST-UL, Lisbon,
Portugal
catalao@ubi.pt

Abstract—Optimum operation of the energy consumption of end-users gains more importance to reduce total electricity bills and in order to more efficiently use energy resources thanks to smart grid concept. Electrical railway stations are one of the best places to take into account for in this manner. This study proposes a railway station energy management (RSEM) model. As the main contribution to the literature, regenerative braking energy (RBE) recovered during the operation of a metro line is assumed to meet the station load demand in daily operation. The RSEM model composed of RBE usage, energy storage system (ESS), and grid support is formulated as a mixed-integer linear programming (MILP) framework. RSEM model is tested by introducing the impact of passengers change on RBE for such cases that whether RBE and ESS are considered or neglected.

Index Terms—Energy storage, mixed integer linear programming, railway energy management, regenerative breaking energy.

NOMENCLATURE

The main nomenclature used in this paper is expressed below. Other symbols and abbreviations are defined where they first appear.

Abbreviations

ERS Electrical Railway System.
ESS Energy Storage System.
MILP Mixed Integer Linear Programming.
RSEM Railway Station Energy Management.
RB Regenerative Braking.
RBE Regenerative Braking Energy.
SOE State-of-energy.

Indices

$t$ Period of the day index in time units [min].

Parameters

$C_{E_{SS}}$ Charging efficiency of the ESS.
$CR_{E_{SS}}$ Charging rate of the ESS [kW per min].
$DE_{E_{SS}}$ Discharging efficiency of the ESS.
$DR_{E_{SS}}$ Discharging rate of the ESS [kW per min].
$P_{load}$ Railway station power demand [kW].

Variables

$P_{RBE}^{t}$ Power generated from braking energy of train [kW].
$SOE_{ESS,ini}^{t}$ Initial SOE of the ESS [kWh].
$SOE_{ESS,min}^{t}$ Minimum SOE limit of the ESS [kWh].
$SOE_{ESS,max}^{t}$ Maximum SOE limit of the ESS [kWh].
$\Delta T$ Number of time intervals in one hour.
$\lambda_{buy}^{t}$ Price of energy bought from the grid [€/kWh].
$P_{ESS,ch}^{t}$ ESS charging power [kW].
$P_{ESS,disch}^{t}$ ESS discharging power [kW].
$P_{grid}^{t}$ Power supplied from the grid [kW].
$P_{ESS,used}^{t}$ Power used from ESS [kW].
$P_{RBE,used}^{t}$ Power used from RBE [kW].
$SOE_{ESS}^{t}$ State-of-energy of the ESS [kWh].
$u_{ESS}^{t}$ Binary variable: if 1 during charging period $t$, else 0.

I. INTRODUCTION

A. Motivation and Background

Due to the several reasons such as rising fossil fuel prices, necessity of reducing $CO_2$ emissions, depletion of fossil fuel reserves and, most significantly, increasing electricity demand, the efficient use of energy plays a pivotal role to cope with the aforementioned problems. Recent developments in the field of efficient use of energy have led to a renewed interest in electrical railway systems (ERSs) in terms of transportation [1]. Besides, progressive expansion of ERSs network have undeniable pressure on the electrical grid due to the huge amount of energy consumption and energy recovery derived from regenerative braking (RB) [2]. RB means regenerated energy during braking mode by traction motors and re-using this energy in the form of electricity. Moreover, this energy may supply a great energy potential for energy efficiency via giving back to the catenary line, energy storage system (ESS), and reversible substation [3].

To solve mentioned issues in the power system of ERSs, smart grid concept should also be implemented to ERSs in all aspects. Smart grid is a novel concept to deal with complexity
of electrical grid and efficient usage of electricity from the production to end-user points considering all generation and storage options, as well as providing communication between sides in a power system. This paradigm provides achieving convenient energy management solutions including different type of producers and consumers [4], [5]. There are many studies to evolve electrical infrastructure of ERSs for smart grid framework; where numerous R&D projects exist considering this topic from different points of view [6].

B. Literature Overview

There are several studies dealing with increase energy efficiency based on storing of RBE in ERSs.

Ciceralli et al. [7] suggested an energy management control strategy for wayside ESS to obtain maximum RBE during braking mode. The proposed model considered the actual voltage and current value of ESS together with power system losses, and based on forecasting of train motion parameters such as inertia forces and acceleration. Nevertheless, RBE was used for acceleration of other train at the station and passengers’ impacts were not evaluated while train is operated in braking and motoring mode.

Khayyam et al. [8] developed a railway energy management system architecture based on the smart grid concept. In this architecture, dynamic optimal energy usage was aimed whilst taking into account train loads, on-board and wayside ESS as well as distributed generation units. However, the station loads and passenger effect on RBE were not considered.

Novak et al. [9] considered a hierarchical energy management strategy that has an energy storage system and a microgrid, for single power fed railway station. The economic benefits of aforementioned management system was investigated in terms of different scenarios whether microgrid was included or not. Also, the control problem of energy consumption level stated in [10] and [11] was solved. Nonetheless, line topology such as curves and slopes was not considered in [9].

Lu et al. [12] suggested a power management strategy to enhance the energy saving of a diesel multiple-unit train based on dynamic programming and nonlinear programming. It was stated that the proposed strategy reduced the cost of fuel consumption by 7%. Although line topology and passenger numbers were considered to obtain energy consumption and generation by the train, RBE was not reused for the station loads.

Nasr et al. [13] performed a smart DC microgrid system to prevent waste of RBE based on energy storing. This study was aimed that RBE was reused for the station loads such as elevators, escalators, lighting etc., not railway operations so as to increase benefit from energy recovery. However, the impact of varying price and passenger number were not evaluated in [13].

Pankovits et al. [14] analyzed the feasibility of implementing smart grid to the railway application taking into account wind and PV based generation units, RBE, and ESS by using fuzzy logic and genetic algorithm. However, line topology and passenger effects were not considered as well as utilization of energy for a station loads.

There are also several other studies not referred here considering the topic from different points of view.

C. Contributions

This paper propounds a Mixed Integer Linear Programming (MILP) model of Railway Station Energy Management (RSEM) concept including ESS, RBE, and different price schemes such as dynamic price, time-of-use, flat price, for the purpose of an overall operational assessment of a railway station. Keeping in mind the valuable contributions made by prior studies, this paper intends to make contributions stated below:

- RBE is used with the purpose of feeding internal demand of a railway station.
- The number of passengers that change depending on the intensity during the day, is taken into account while computing RBE.
- The effects caused by different price schemes on RSEM are investigated by carrying out case studies.

D. Organization

The rest of the paper is organized as follows: The operation of railway vehicle and mathematical formulation of problem are expressed in Section II. Thereafter, the case studies and related results are presented and discussed in Section III. Finally, concluding remarks and recommendations for future studies are summarized in Section IV.

II. METHODOLOGY

The block diagram of RSEM strategy is demonstrated in Fig. 1. The RSEM system rules the operation of a smart railway station in a subway line taking into account RBE, price signal received from the utility, and ESS. In RSEM system, only the internal demand of station is considered and energy consumption of train is assumed to be fed via traction transformers. The rest of this section gives information about mathematical model of train motion and the proposed energy management model.

A. Mathematical Model of Train Motion

In order to determine the potential of RBE, the mathematical model of train motion is used. This subsection presents the model of train motion.

The train motion is based on Newton’s one dimensional motion laws and directly affected by not only the line topology but also the characteristics of traction devices:

\[ \sum_{i=1}^{n} F_i = m^*a \]  

(1)

In (1), \( F_i \) represents the total forces that affects on train motion, \( m^* \) is the rotating train mass, and \( a \) is the acceleration of the train. The forces affecting the train motion are divided into two main categories as \( F_{tr} \) and \( F_{ag} \), and are illustrated in Fig. 2.

- \( F_{tr} \): Force generated by traction motors. It is considered as positive in traction mode, while negative in braking mode.
The main aim of energy management model is to minimize the total daily cost of railway station electricity consumption. Therefore, the objective function comprises only power bought from grid \( P_{buy}^{grid} \) as a variable at time \( t \). Beside, the price signals \( \lambda_{buy}^{grid} \) are time dependent.

\[
\min \sum \frac{P_{buy}^{grid}}{\Delta T} \lambda_{buy}^{grid} \tag{6}
\]

It is worth to note that this study focuses on operational cost of the railway station. Hence, investment costs of communication system and any other power system components are not considered. In addition, there are more than one option to decide time granularity \( \Delta T \) such as 1h, 30 min, 15 min, etc.

1) Power Balance:

\[
P_{t}^{grid} + P_{t}^{ESS,used} = P_{t}^{load} + P_{t}^{ESS,chg}, \forall t \tag{7}
\]

Equation (7) enforces that power demand of railway station loads \( (P_{t}^{load}) \) and ESS \( (P_{t}^{ESS,chg}) \) can be met from either grid \( (P_{t}^{grid}) \) or ESS \( (P_{t}^{ESS,used}) \), or combination of them. Additionally, details of ESS model are presented in the next subsection [5].

2) ESS Modelling:

\[
P_{t}^{ESS,used} = P_{t}^{ESS,disch} \cdot DE_{ESS}, \forall t \tag{8}
\]

\[
P_{t}^{RBE,used} + P_{t}^{ESS,chg} \leq CR_{ESS} \cdot u_{t}^{ESS}, \forall t \tag{9}
\]

\[
P_{t}^{ESS,disch} \leq DR_{ESS} \cdot (1 - u_{t}^{ESS}), \forall t \tag{10}
\]

\[
SOE_{t}^{ESS} = SOE_{t-1}^{ESS} + CE_{ESS} \cdot \frac{P_{t}^{ESS,chg} + P_{t}^{ESS,used}}{\Delta T} - \frac{P_{t}^{ESS,disch}}{\Delta T}, \forall t \geq 1 \tag{11}
\]

\[
SOE_{t}^{ESS} = SOE_{t}^{ESS,ini}, \text{ if } t = 1 \tag{12}
\]

\[
SOE_{t}^{ESS} \leq SOE_{t}^{ESS,max}, \forall t \tag{13}
\]

\[
SOE_{t}^{ESS} \geq SOE_{t}^{ESS,min}, \forall t \tag{14}
\]

Equation (8) states that used ESS power \( (P_{t}^{ESS,used}) \) so as to meet railway station loads is a function of discharged efficiency and discharged power capacity of ESS \( (P_{t}^{ESS,disch}, DE_{ESS}) \). Additionally, considering ESS cannot be charged and discharged at the same time, (9) and (10) regulate ESS charging and discharging operation by using a logical constraint. ESS charging rate \( (CR_{ESS}) \) restricts power provided from RBE \( (P_{t}^{RBE,used}) \) and charging power of ESS \( (P_{t}^{ESS,chg}) \) in (9). Similarly, maximum power taken from ESS \( (P_{t}^{ESS,disch}) \) is constrained by discharged rate of ESS \( (DR_{ESS}) \) in (10). For any time interval, the SOE of ESS \( (SOE_{t}^{ESS}) \) comprises charging energy taken from RB and electrical grid, discharging energy used for railway station loads, and SOE of ESS in the previous time interval \( (SOE_{t-1}^{ESS}) \). In the beginning of operation, SOE of ESS is equalled to initial SOE of ESS \( (SOE_{t}^{ESS,ini}) \) thanks to (12). Last but not least, constraints (13)
and (14) ensure that keeping SOE of ESS between maximum \((\text{SOE}_{\text{ESS,max}})\) and minimum \((\text{SOE}_{\text{ESS,min}})\) value.

3) RBE Modelling: Herein, \(P_{t}^{\text{RBE}}\) symbolizes RB power that is available for charging of ESS. Regarding the maximum allowed charging capacity of ESS some amount of \(P_{t}^{\text{RBE}}\) might be curtailed. Keeping in mind all possible cases, RBE model is built by defining a variable which is called as \(P_{t}^{\text{RBE,used}}\). Equation (15) draws an upper limit for RBE obtained from train braking.

\[
P_{t}^{\text{RBE}} \geq P_{t}^{\text{RBE,used}}, \quad \forall t
\]

### III. Test and Results

The calculation of potential RBE regarding the metro line is carried out using RAILSIM 8 software [16]. Afterwards, a MILP model constructed so as to decrease daily electricity cost of a railway station using RBE is assessed in GAMS v.24.1.3 software with CPLEX v.12 solver [17].

In this study, M1A light metro line as one of the busiest metro lines in Istanbul is simulated. Fig. 3 pictures the overall look of the M1 metro line. In this study, only 19.7 kilometres of M1A line which has 18 stations, is simulated in RAILSIM. To make the simulation as realistic as possible, real data including traction motor sizes, topological features of line such as gradient and curve, taken from Metro Istanbul Co. is considered.

It is regarded in this paper that the number of passengers dynamically changes per hour. Therefore, it is allowed that dynamic variations in passengers affect RBE. Daily passenger profile obtained from the records of Metro Istanbul Co. is given Fig. 4.

The proposed RSEM is implemented just for one railway station, namely Bahcelievler. The energy demand of this station was recorded and the computed power values depending on actual data is illustrated in Fig. 5. Herein, railway station loads are composed of escalator, elevators, lightning, heating, ventilation, and air conditioning. Because of the fact that duration of RB process is very short, it is assumed in this study as 1 minute; therefore, the sampling time of recorded data is rearranged according to this.

In this study, it is considered that railway station loads are fed by grid and ESS. Also, ESS is assumed to be charged via RBE or grid. RB power profile of the related station is given in Fig. 6. It is worthy to note that one-way power flow is assumed to be from grid to the station loads. In other words, there is no energy-selling back to grid.

The proposed ESS model is supposed to have 100 kWh capacity. Besides, charging and discharging rate of ESS is considered as 100 kW per minute. It is regarded that ESS has 50 kWh initial SOE and charging/discharging efficiencies are 0.95. Additionally, deep discharging limit is taken as 20 kWh. Last but not least, it is considered that total electricity cost of RSEM operation is independent from investment cost of ESS.

Assuming that the station has a smart meter infrastructure, it is accepted that RSEM can dynamically adjust the electricity consumption demand related to the price signal coming from the utility with its own internal instruments. In this study, three pricing schemes are considered as dynamic price signal, time of use, and single price. Time varying price signal used in this study is shown in Fig. 7, that is a normalized version of the scheme given in [18]. Moreover, single price is counted as 0.084 €/kWh and details of time of use signal are given in Table I.

### TABLE I

<table>
<thead>
<tr>
<th>Time Interval</th>
<th>Price Signal [€/kWh]</th>
</tr>
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<tbody>
<tr>
<td>23:00-07:00</td>
<td>0.05</td>
</tr>
<tr>
<td>07:00-18:00</td>
<td>0.081</td>
</tr>
<tr>
<td>18:00-23:00</td>
<td>0.127</td>
</tr>
</tbody>
</table>

Fig. 8 pictures the power flows and the change in SOE of ESS in the Bahcelievler railway station between the hours 5:00 and 6:30 for case study with the dynamic prices. Since the RSEM model is analyzed in minutes, it is given only for a specific time interval of Fig. 8, for the sake of the clarity. The reason for choosing this range is that all the load flow possibilities for ESS that can be observed are within this range. Figure 8(a) shows the instantaneous power flow of ESS located...
Fig. 6. The daily RB power profile for Bahcelievler Station

Fig. 7. Dynamic Price Signal

Fig. 8. The variation of: (a) Power decomposition of ESS, (b) Power bought from grid, (c) SOE of ESS in Bahcelievler railway station. Instantaneous drawn power from grid by ESS is shown in red, the power transferred from RBE to ESS is shown in green, and blue graph illustrates the instantaneous power that ESS gives so as to feed internal load demand of station. Figure 8(b) shows the instantaneous power that the station draws from the grid to meet its internal load demand. In addition, Fig. 8(c) depicts the variations in SOE of ESS.

As can be seen from Fig. 8, ESS stores energy between 05:00 and 05:20 hours because of the low energy cost of the respective time interval due to dynamic pricing. Because of RBE of train that comes to station at 06:05, RSEM model prefers to use stored energy in ESS instead of buying from grid just before that time. The reduction in power drawn from grid for the related time interval can be seen from Fig. 8(b).

Figure 9 pictures the corresponding results of ESS SOE where it is obvious that the charging and discharging states of ESS are directly affected by RBE usage. It is noteworthy that dashed line indicates the case includes only ESS while the other one, straight line, shows the case that RBE and ESS instruments take place at the same time. In the mentioned figure, although the both cases are examined under dynamic price signal, the case without RBE leads to less variation in SOE of ESS. However, it can be also seen from the same figure that when RBE is introduced, SOE of ESS alters more frequently related to prior case.

Table II encapsulates the case studies assessed in this paper. It can be stated that utilization of whether only ESS or ESS together with RBE positively affects the total electricity cost of railway station. The worst case scenario is assumed as railway station has no ESS while its smart meter of railway station is operated under single price signal, and RBE is wasted through resistances placed over the trains.

Although most of the actual railway stations are not managed by using dynamic price signal, evaluations marked that the biggest cost advantages in cases with dynamic price signal. In RSEM application, one option for decreasing the total electricity cost of railway station is to equip the station with ESS, which provides nearly 2.75% drop in cost. Yet another and more effective one is to reuse the RBE, which can provide a significant reduction in cost as 15.74% compared to the previous case.

IV. CONCLUSION

Depletion of fossil fuel reserves together with increasing public knowledge and sensitivity against climate change made energy efficiency a more important issue to deal with decreasing
TABLE II
COMPARISON OF DIFFERENT CASE STUDIES

<table>
<thead>
<tr>
<th>Case Study</th>
<th>Dynamic Price</th>
<th>TOU Price</th>
<th>Single Price</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Total Cost [€]</td>
<td>Cost Reduction [%]</td>
<td>Total Cost [€]</td>
</tr>
<tr>
<td>Without ESS</td>
<td>316,132</td>
<td>Base Case</td>
<td>337,152</td>
</tr>
<tr>
<td>Without RBE</td>
<td>307,432</td>
<td>2.75</td>
<td>330,379</td>
</tr>
<tr>
<td>With RBE + ESS</td>
<td>266,372</td>
<td>15.74</td>
<td>286,168</td>
</tr>
</tbody>
</table>

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carbon emission levels due to the energy usage. ERSs are one of the best candidate for using energy in a more effective way with their promising potential of RBE.

This study aimed to model a RSEM structure consisting of RBE, ESS, and smart meter capable of being operated by various pricing schemes, so as to regain the RBE occurring during decelerating periods of trains. During minimizing the electricity cost of a railway station, the passenger effect and different pricing schemes were taken into account, which can be listed as the main contributions of this study. In addition, three different pricing schemes were evaluated by constructing a MILP model of RSEM. Moreover, RBE occurring in Bahcelievler railway station was computed with RAILSIM software. It is noteworthy that this paper assumed power can only flow from grid to railway station. Therefore, any selling price or directional power flow between grid and station were not considered in this paper.

In this paper, several cases created according to the variations of ESS and RBE were examined under different pricing schemes. The case that railway station neither includes ESS or has the ability to utilize RBE, was selected as the base case for each kind of price signal. From the electricity consumption point of view, a more economical operation of railway station was obtained when the station has access to ESS. Furthermore, the economic operation could be improved with the introducing the RBE compared to the prior cases. The results also showed that the most significant reduction as 15.74% can be achieved by using ESS and RBE at the same time under dynamic price signal.

It is worth to underline that all analysis made in this study are based on only deterministic approach. Considering this, the authors would like to state that an comprehensive evaluation of a RSEM model including demand response strategies and distributed generation units with a stochastic approach is planned as a future study.

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