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Energy Management of A Smart Railway Station Considering Regenerative Braking and Stochastic Behaviour of ESS and PV Generation

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***Abstract*—The smart grid paradigm has provided great opportunities to decrease energy consumption and electricity bills of end-users. Among a wide variety of end-users, electrical railway systems (ERSs) with huge installed power should be considered as a vital option in order to avoid wasted energy provided that an energy management system is utilized. In this study, a mixed-integer linear programming (MILP) model of a railway station energy management (RSEM) system is formulated by a stochastic approach, aiming to utilize the emerged regenerative braking energy (RBE) during the braking mode in order to supply station loads. Furthermore, the proposed RSEM model is composed of an energy storage system (ESS), RBE utilization, photovoltaic (PV) generation units, and an external grid in this paper. The passengers' impact on RBE as well as the stochastic behaviour of the initial state-of-energy (SOE) of ESS along with uncertainty of PV generation by the RSEM model are also evaluated. The model is tested under a bunch of case studies formed considering several combinations of the cases that an ESS or PV are available or not and using RBE is possible or not.**

***Index Terms*—Energy storage systems, mixed integer linear programming, railway energy management system, regenerative braking energy, stochastic programming.**

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.
PV	Photovoltaic.
RSEM	Railway station energy management.
RB	Regenerative braking.
RBE	Regenerative braking energy.
SOE	State-of-energy.

Indices and Sets

s	Scenario sets of initial PV generation.
t	Period of the day index in time units [min].
w	Scenario sets of initial SOE of ESS.

Parameters

CE_{ESS}	Charging efficiency of the ESS.
CR_{ESS}	Charging rate of the ESS [kW per min].
DE_{ESS}	Discharging efficiency of the ESS.
DR_{ESS}	Discharging rate of the ESS [kW per min].
N_1	Maximum power that can be drawn from the grid [kW].
N_2	Maximum power that can be sold back to the grid [kW].
P_t^{load}	Railway station power demand during period t [kW].
$P_{t,s}^{PV}$	Power generated by PV during period t for scenario s [kW].
P_t^{RBE}	Power obtained from braking energy of train during period t [kW].
$SOE_w^{ESS,ini}$	Initial SOE of the ESS for scenario w [kWh].
$SOE^{ESS,min}$	Minimum SOE limit of the ESS [kWh].
$SOE^{ESS,max}$	Maximum SOE limit of the ESS [kWh].
ΔT	Number of time intervals in one hour.
λ_t^{buy}	Price of energy bought from the grid [€/kWh].
λ_t^{sell}	Price of energy sold to the grid [€/kWh].
π_s	Probability value of related scenario for PV generation.
π_w	Probability value of related scenario for initial SOE of ESS.

Variables

$P_{t,s,w}^{ESS,ch}$	ESS charging power during period t for scenarios s and w [kW].

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$P_{t,s,w}^{ESS,disch}$	ESS discharging power during period t for scenarios s and w [kW].
$P_{t,s,w}^{grid}$	Power supplied from the grid during period t for scenarios s and w [kW].
$P_{t,s,w}^{ESS,us}$	Power used from ESS during period t for scenarios s and w [kW].
$P_{t,s,w}^{RBE,us}$	Power used from RBE during period t for scenarios s and w [kW].
$P_{t,s,w}^{sell}$	Power sold to the grid during period t for scenarios s and w [kW].
$SOE_{t,s,w}^{ESS}$	SOE of the ESS during period t for scenarios s and w [kWh].
$u_{t,s,w}^{ESS}$	Binary variable: 1 if during charging period t for scenarios s and w, else 0.
$u_{t,s,w}^{grid}$	Binary variable: 1 if during charging period t for scenarios s and w, else 0.

I. Introduction

A. Motivation and Background

Practical evidence suggests that the energy efficiency is among the most crucial factors for decreasing carbon emissions [1]. Moreover, depletion of fossil fuel reserves and progressively increasing electricity demand have supported the rising concerns about efficient use of energy [2]. Therefore, policy makers pay particular attention to consumers with high level of energy demand due to the vast potential of energy recovery lying behind [3]. Electrical railway systems (ERSs) are one of the examples for large-scale consumers that are regarded as effective resources both in order to achieve carbon emission targets and to decrease consumption of energy. It has been stated that, the amount of greenhouse gas emissions (GHG) of transportation is presented as 14% of total emission by 2010, which is predicted to be doubled by 2050 in [4]. Yet another report revealed that 23.4% of the world's carbon emissions originated from transportation in 2013. Also, emission rate from rail transportation accounts for 3.5% of total transportation [5].

Regenerative braking (RB) is at the heart of our understanding of energy recovery depending on the huge amount of energy consumption and generation patterns in ERSs. RB is roughly defined as the process of transforming braking energy of train during the deceleration into electrical energy using traction motors and effectively use of this regenerated energy [6]. More than one option is available for using the regenerated energy such as giving back to catenary line to supply energy for other trains, or storing in an energy storage system (ESS) in order to utilize or sell in another period in the future, or directly injecting to the grid via a reversible substation [7]. It is possible that the total energy consumption of ERSs can be reduced between 10% and 45% by means of RB systems [8].

The smart grid concept presents more reliable, efficient, safe, and modernized power systems and offers a new perspective to the energy management philosophy of ERSs. Besides, using advanced computational features and bidirectional communication equipment, the smart grid paradigm provides a chance to communicate between demand side and the utility [9]. Furthermore, storing and selling energy become more possible for consumers via proliferated ESSs thanks to the smart grid concept [10]. Another beneficial aspect of smart grid concept is to integrate renewable energy sources such as photovoltaic (PV) and wind. As a consequence, aforementioned circumstances arise the smart energy management approach which can be implemented in railway transportation applications by designing a railway station energy management (RSEM) concept [11], [12].

B. Literature Overview

The topic of increasing energy efficiency based on storing regenerative braking energy (RBE) in ERSs has drawn the attention of various researchers around the world.

Ciceralli et al. [13] presented an energy management strategy for wayside ESS to take advantage of maximum RBE during braking periods. The model considered the actual voltage and current value of ESS, and power system losses by forecasting of train motion parameters such as inertia forces and acceleration. Nonetheless, it was stated that RBE was used for acceleration of other train at the station and changes in passengers number were not noticed while the train was operated in braking and motoring mode, additionally that paper neglected the unknown initial state-of-energy (SOE) of ESS.

Khayyam et al. [14] proposed a railway energy management system architecture considering the smart grid vision. Train loads, on-board and wayside ESS as well as distributed generation units were considered jointly for dynamic optimal energy utilization using the presented management scheme. However, it should be noted that stored energy was not used for the station loads and passengers' effect on RBE was not considered, also uncertainty of initial SOE of ESS was ignored in that study.

A hierarchical energy management strategy that has an ESS and a microgrid was suggested for unidirectionally supplied power to railway station in [15]. Furthermore, distinct scenarios were developed as whether they include microgrid or not, in order to evaluate the proposed management system from the perspective of the economic benefits. Moreover, it was claimed that the control problem of energy consumption level stated in [16], [17] was solved. On the other hand, line topology such as curves and slopes as well as availability of uncertain behaviour PV generation and stochastic characteristic of initial SOE of ESS were not considered in [15]–[17].

Lu et al. [18] suggested a power management strategy to enhance the energy saving of a diesel multiple-unit train by using dynamic programming and nonlinear programming framework. According to the presented results in that paper, fuel consumption cost was reduced by 7%. Moreover, this management strategy took into account line topology and changes in passengers number affecting energy recovery. However, the option of leveraging from RBE in order to meet the station demand was ignored. Furthermore, the uncertainty of initial SOE of ESS was neglected in the mentioned paper.

Nasr et al. [19] and Pankovits et al. [20] investigated the benefits of using RBE so as to decrease the wasted energy in ERSs. It was aimed that the stored energy from RBE was reused specifically for the station loads such as elevators, escalators, lighting etc., not for railway applications in [19]. The wind and

PV based renewables, RBE, and ESS were taken into account in order to enhance the energy efficiency in [20]. However, both [19] and [20] ignored the impact of passengers number, line topology, last but not least variable initial SOE of ESS, while only the [20] evaluated the PV, but, without stochasticity of renewables.

Hernandez and Sutil [21] proposed a DC microgrid including renewables based on PV and RBE together with ESS to charge electric vehicles next to the train station. In this paper, the strategy of power management, converter control and the impact of size of the ESS components stated as a challenging problem by the prior studies were sorted out so as to maximize the usage of renewables. Nevertheless, renewables were only used to charge electric vehicles, not for supplying station loads and passengers' changes were not taken into account in [21]. It should be noted that in this type of studies a reliable infrastructure is required to ensure that power exchange can be carried out smoothly. For this reason, the electrical protection has a critical role. The related requirements about interconnection was well-examined in [22], [23], however, this topic is not considered in this paper for the sake of the clarity.

Aguado et al. [24] developed a methodology for optimal operation of ERSs to evaluate the potential of renewable energy resources together with RBE and maximize savings in the operational costs. Even though it was declared that the uncertainties related to renewables were considered through a stochastic approach, the uncertainty due to initial SOE of ESS and passengers number were not investigated in [24].

These studies together with many other studies not referred here considered the topic from different points of view in order to enhance the efficient use of energy based on smart grid vision within ERSs.

C. Contributions

In this study, a Mixed Integer Linear Programming (MILP) model of RSEM concept covering ESS, RBE, PV, and different pricing schemes in order to evaluate the operation of a railway station is propounded. Regarding the initial SOE of ESS and PV generation as uncertain parameters, operational assessment of the railway station is carried out using stochastic programming approach.

Keeping in mind the valuable contributions made by prior studies, this paper intends to make the contributions stated below:

- The effects of uncertain initial SOE of ESS and PV generation as well as different pricing schemes on RSEM are evaluated considering several case studies.
- RBE obtained from trains is utilized in order to partially meet internal demand of railway station.
- The impact of the number of passengers varying with intensity during the day on calculated RBE is considered.

D. Organization

The rest of the paper is organized as follows: Section II provides the necessary background information for the operation of railway vehicle and presents the mathematical formulation of energy management model. Hereafter, Section III describes the evaluated case studies and related results. Section IV finalize the paper with concluding remarks and makes suggestions about possible future studies.

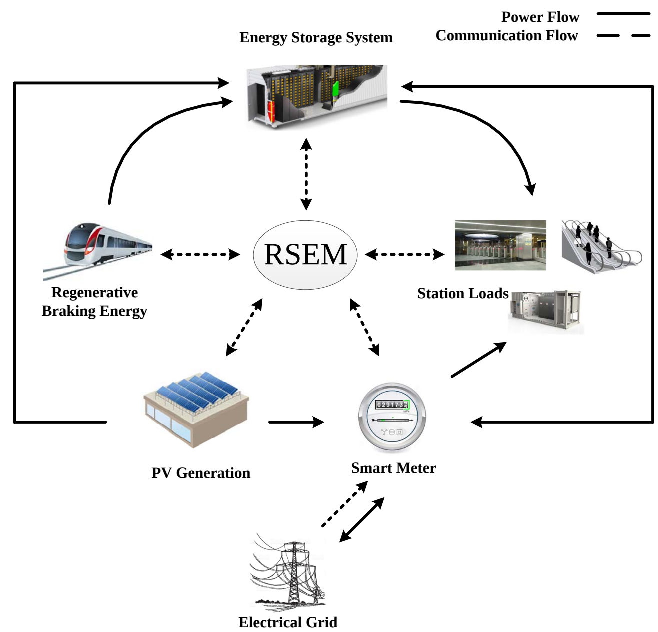

Fig. 1. The block diagram of RSEM.

II. Methodology

The block diagram of RSEM strategy is demonstrated in Fig. 1. The RSEM system manages the operation of a smart railway station in a subway line taking into account RBE, pricing signal received from the utility, and ESS. The term used as smart railway station in this paper implies the station infrastructure is able for bidirectional power and information flow which is compatible with well-known smart grid concept. In RSEM system, only the internal demand of a station is considered and energy consumption of the train is assumed to be supplied via traction transformers. The rest of this section gives information about the 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:

$$\sum_{i=1}^{n} F_i = m_t.a \tag{1}$$

In (1), F_i represents the total forces that affect the train motion, m_t is the rotating train mass, and a is the acceleration of the train. The forces affecting the train motion are divided

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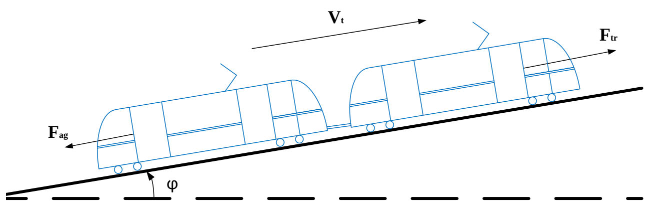

Fig. 2. The forces acting on train motion.

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.
- F_{ag}: Total forces that play negative role against train motion. It consists of line gradient, line curve, and resistance caused by own train motion.

$$F_{tr} - F_{ag} = m_t.a \quad (2)$$

Equation (1) can be rearranged by substitution of total forces that act on train motion with F_{tr} and F_{ag} (2).

$$F_{ag} = F_r + F_{gr} + F_c \quad (3)$$

The total forces that have a negative effect on train motion are obtained by sum of F_r, F_{gr}, and F_c which symbolize resistance caused by own train motion, gradient of line, and curve of line, respectively, in (3). Herein, F_r is modelled by using well-known Davis formula [25].

$$P_t = \frac{(m_t.a + F_{ag}).\ v_t}{\eta_g.\ \eta_m.\ \eta_i.\ 3,6} + P_a \quad (4)$$

$$I_t = \frac{P_t}{V_l} \quad (5)$$

In (4), P_t indicates the instantaneous power of train and it is assumed as positive while train accelerates. Conversely, when train brakes, P_t is considered as negative due to the generated power in traction motors on train. Also, P_a represents auxiliary loads of train while η_g, η_m, and η_i are efficiency of gear, traction motors, and inverters respectively. Lastly, v_t symbolizes train speed at time t. It should also be noted that I_t represents the instantaneous current and V_l indicates the line voltage in (5).

B. Energy Management Model

In this paper, minimizing the total daily cost of railway station electricity consumption is determined as the objective of the energy management model. The objective function is composed of the probability value of related PV generation and initial SOE of ESS scenarios (π_s) and (π_w), power bought from the grid ($P^{grid}_{t,s,w}$) and power sold to the grid ($P^{sell}_{t,s,w}$) which are considered as variables during the period t for scenarios s and w. In addition, the time dependent pricing signals (λ^{buy}_t) and (λ^{sell}_t) are used in energy management model.

$$min \sum_s \sum_w \sum_t \pi_w\ \pi_s \left(\frac{P^{grid}_{t,s,w}\ \lambda^{buy}_t - P^{sell}_{t,s,w}\ \lambda^{sell}_t}{\Delta T} \right) \quad (6)$$

The main focus of this study is merely minimizing the daily operational cost of the railway station. Therefore, the other possible costs apart from the operational costs such as the investment costs of the necessary communication system infrastructure, investment of ESS, along with the wear and tear cost of ESS or any other system components are not taken into account. Moreover, decision options for time granularity ΔT is not limited as considered in this paper and can be extended according to preferences of the related designer of the model, such as 1h, 30 min, 15 min, etc.

1) Power Balance: The most crucial equation that forms the basis of the model is given in (7). This equation states that grid ($P^{grid}_{t,s,w}$), PV ($P^{PV}_{t,s}$) and ESS ($P^{ESS,us}_{t,s,w}$) can be used together in a combined form or independently to supply internal power demand of railway station loads (P^{load}_t) and ESS ($P^{ESS,ch}_{t,s}$) or to sell available power to the grid ($P^{sell}_{t,s,w}$). It is worthy to note that inherent constraints due to the nature of power exchange of grid and ESS will be explained in further subsections [26].

$$P^{grid}_{t,s,w} + P^{PV}_{t,s} + P^{ESS,us}_{t,s,w} = P^{load}_t + P^{ESS,ch}_{t,s,w} + P^{sell}_{t,s,w}, \qquad \forall t,s,w \quad (7)$$

2) ESS Modelling: In order to evaluate the uncertain characteristic of the initial SOE of ESS along with the PV generation, the ESS model in [26] is revised and made compatible for stochastic programming approach. Equation (8) enforces that the discharging efficiency of ESS (DE_{ESS}) affects the amount of available power ($P^{ESS,us}_{t,s,w}$) to supply the internal loads of the railway station, which is obtained from discharging power of ESS ($P^{ESS,disch}_{t,s,w}$). Furthermore, in inequalities (9) and (10), a binary variable is used to model the physical nature of ESS depending on the fact that an ESS cannot be charged and discharged at the same time. Total charging power of the ESS composed of the effective usable power from RBE ($P^{RBE,us}_{t,s,w}$) and the power taken from grid in order to charge the ESS ($P^{ESS,ch}_{t,s,w}$), is limited by ESS charging rate (CR_{ESS}) in (9) due to modelling purpose of the limited charging nature of the ESS. Correspondingly, in (10), discharging rate of ESS (DR_{ESS}) draws an upper limit for the utilizable power provided from ESS ($P^{ESS,disch}_{t,s,w}$).

Equation (11) demonstrates the mathematical relationship between the remaining SOE of ESS from the previous time interval ($SOE^{ESS}_{t-1,s,w}$), charging energy supplied from RB and/or electrical grid, and discharging energy used for meeting internal railway station loads in order to obtain the SOE of ESS ($SOE^{ESS}_{t,s,w}$) for every time internal. As far as the SOE value of ESS at the beginning is concerned, the initial SOE of ESS ($SOE^{ESS,ini}_{s,w}$) is assigned as SOE of ESS using (12). It is worthy to note that the initial SOE of ESS is assumed to change in a stochastic manner according to the related scenarios. Last but not least, SOE of ESS is restricted in the range of allowed maximum ($SOE^{ESS,max}$) and minimum

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($SOE^{ESS,min}$) values by using the constraints (13) and (14).

$$P_{t,s,w}^{ESS,us} = P_{t,s,w}^{ESS,disch} . DE_{ESS} \quad , \qquad \forall t,s,w \quad (8)$$

$$P_{t,s,w}^{RBE,us} + P_{t,s,w}^{ESS,ch} \leq CR_{ESS} \ . \ u_{t,s,w}^{ESS} \ , \qquad \forall t,s,w \quad (9)$$

$$P_{t,s,w}^{ESS,disch} \leq DR_{ESS} \ . \ (1 - u_{t,s,w}^{ESS}), \qquad \forall t,s,w \quad (10)$$

$$SOE_{t,s,w}^{ESS} = SOE_{t-1,s,w}^{ESS} + CE_{ESS} \cdot \left(\frac{P_{t,s,w}^{ESS,ch} + P_{t,s,w}^{RBE,us}}{\Delta T} \right) - \frac{P_{t,s,w}^{ESS,disch}}{\Delta T} \ , \qquad \forall t \geq 1 \ \forall s,w \quad (11)$$

$$SOE_{t,s,w}^{ESS} = SOE_{w}^{ESS,ini}, \qquad if \ t = 1 \ \forall s,w \quad (12)$$

$$SOE_{t,s,w}^{ESS} \leq SOE^{ESS,max}, \qquad \forall t,s,w \quad (13)$$

$$SOE_{t,s,w}^{ESS} \geq SOE^{ESS,min}, \qquad \forall t,s,w \quad (14)$$

3) RBE Modelling: The total amount of available RB power that can be used for charging of the ESS is indicated as P_t^{RBE}. Although the main target is to use this energy as much as possible, some amount of P_t^{RBE} can inevitably be wasted due to the the maximum allowed charging capacity of ESS. Regarding this variable nature of the utilized energy from RB over the time, a variable called $P_{t,s,w}^{RBE,us}$ is defined in order to model the energy used for charging purposes of ESS. Equation (15) helps to avoid this variable to take higher values than RBE obtained from train braking.

$$P_t^{RBE} \geq P_{t,s,w}^{RBE,us} \qquad \forall t,s,w \qquad (15)$$

4) Power Exchange Constraints: It is worthy to note that power cannot be bought from the grid and sold to the grid during the same time interval. In order to model aforementioned constraint a binary variable ($u_{t,s,w}^{grid}$) is used. As can be seen from (16) and (17), the station is able to draw power from the grid when $u_{t,s,w}^{grid}$ is 1, and sell back power to the grid when $u_{t,s,w}^{grid}$ is 0.

$$P_{t,s,w}^{grid} \leq N_1 . u_{t,s,w}^{grid} \qquad \forall t,s,w \qquad (16)$$

$$P_{t,s,w}^{sell} \leq N_2 . (1 - u_{t,s,w}^{grid}) \qquad \forall t,s,w \qquad (17)$$

III. Test and Results

With the aim of evaluating the RBE and ESS effect along with the stochastic behaviour of the initial SOE of the ESS and PV generation on the daily cost of a railway station, the proposed MILP model is tested in GAMS v.24.1.3 software with CPLEX v.12 solver [27]. It should be noted that RBE calculation is performed by modelling the M1A light metro line in RAILSIM 8 software [28].

The M1A light metro line with a length of 19.7 kilometer and 18 stations, is one of the busiest metro line in Istanbul. The route map of M1 light metro line can be seen from Fig. 3. Concerning to obtain closer results to real case, the actual data related to traction motor sizes together with the topological features of line such as gradient and curve, which are supplied from Metro Istanbul Co, are used.

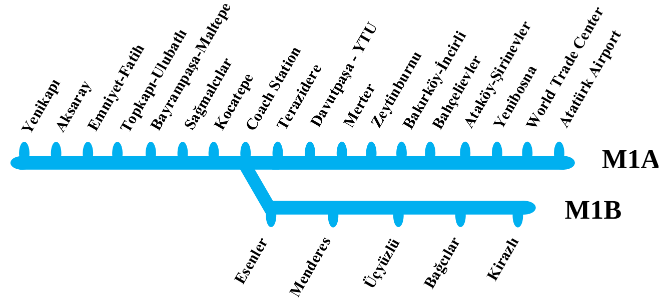

Fig. 3. The route of Istanbul M1 light metro line.

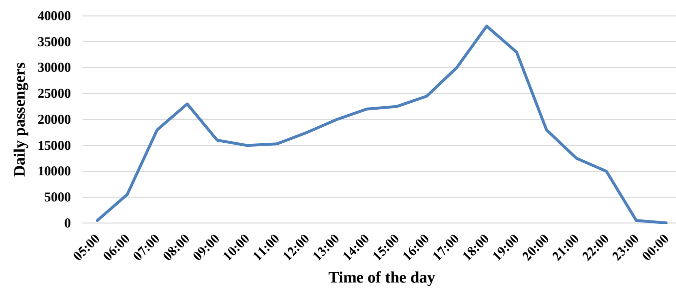

Fig. 4. The daily passenger profile of M1 light metro line.

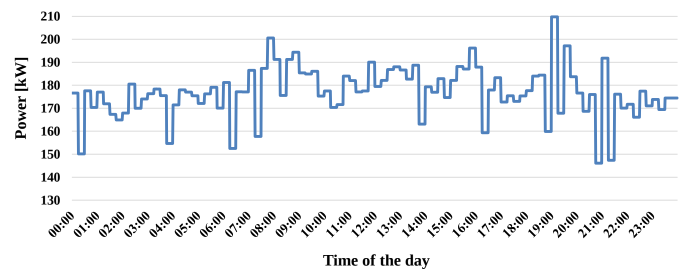

Fig. 5. The daily load demand profile of Bahcelievler railway station.

It is also considered in this study that passengers number in the evaluated station dynamically changes. The dynamic number of passengers indirectly affects the RBE amount by leading to an alteration in the total mass of the train. To obtain more accurate results, the actual passenger profile of the station taken from Istanbul Metro Co. is considered, which is given in Fig. 4.

Another important parameter used in this study is the station load demand. Assessments are carried out for only Bahcelievler Station. Figure 5 pictures the power demand profile of Bahcelievler Station which is recalculated based on the actual energy measurements of the station. The load spectrum of station is assumed as consisting of escalators, elevators, lighting, heating, ventilation and air conditioning. Moreover, the sampling time of the recorded data is reorganized to be 1 minute due to very short RB time.

In the RSEM structure, it is assumed that railway station loads can be supplied by grid, PV or ESS while ESS can be charged by either utilizing RBE, PV or grid. Figure 6 illustrates RB power profile of the related station. It is worthy to underline

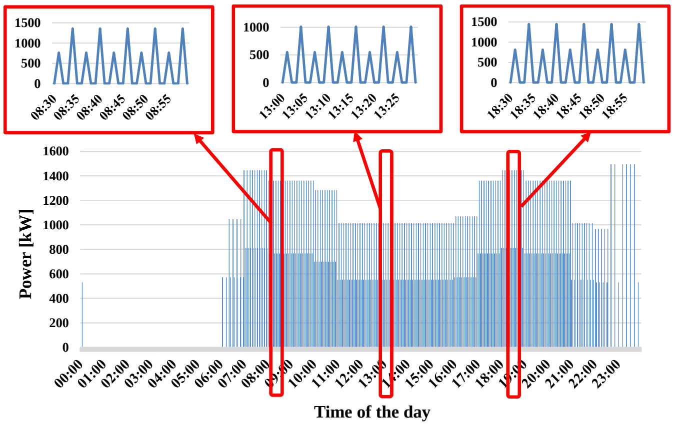

Fig. 6. The daily RB power profile for Bahcelievler Station.

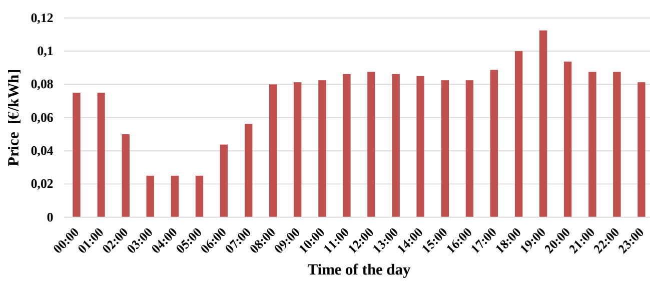

Fig. 7. Dynamic pricing signal.

that the whole RBE is consumed with the purpose of meeting internal station demand via ESS. Also, the option that the power supplied by ESS and PV to the grid in a reverse way, is evaluated in this paper. Last but not least, RBE is considered as it is indirectly sold to the grid over ESS.

Considering the evaluation of daily operation cost of the station, it is more likely that pricing signal plays an important role. The communication infrastructure between utility and station required for the RSEM to take dynamic actions is assumed to be provided owing to a smart meter at the station. In this study, three different pricing schemes are considered, namely dynamic pricing signal, time of use, and fixed price. The flat price is taken as 0.084 €/kWh and it is assumed that it does not change during the whole day. Apart from the flat price, energy price in time of use scheme is considered as 0.05 €/kWh, 0.081 €/kWh, and 0.127 €/kWh for the time period of 23:00-07:00, 07:00-18:00, and 18:00-23:00, respectively. Last but not least, Fig. 7 illustrates the time varying pricing signal used in this study. It is worthy to underline that the average value of the scheme given in [29] is manipulated to obtain a value approximate to the fixed price signal in order to create opportunity for a more realistic comparison. It should be noted that the selling price is assumed as equal to the buying price for every single scheme.

One of the specifications of the proposed ESS model is that ESS has a total capacity of 100 kWh. Additionally, it is assumed that charging and discharging rates of the ESS are limited to 100 kW per minute together with the charging and

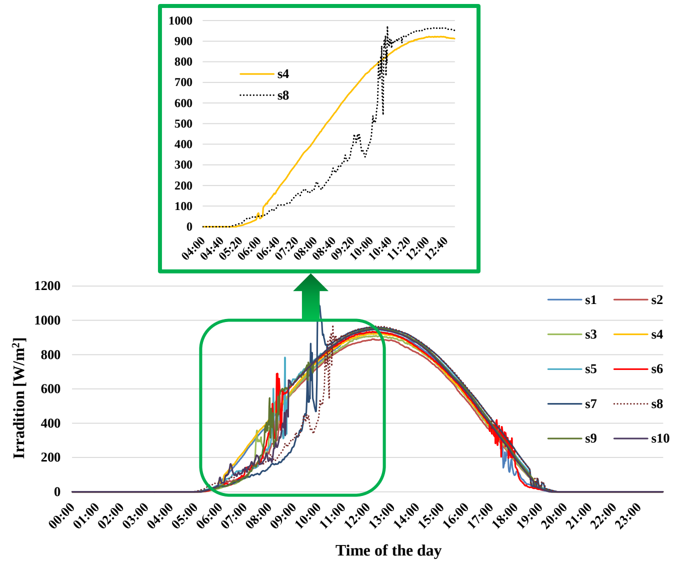

Fig. 8. The examined scenarios for PV generation

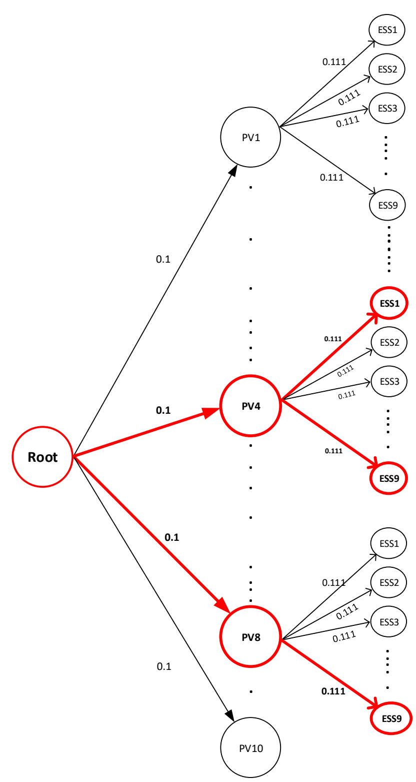

Fig. 9. Scenario tree composed of PV generation and initial SOE of ESS scenarios

discharging efficiencies of 0.95. Lastly, it is not allowed for ESS to be discharged below 20 kWh. It should be reminded that the daily operational cost of station is regarded as independent from investment cost of the ESS. Although assessment of initial SOE of the ESS can be realized assigning an exact value to the initial SOE of the ESS, it cannot be precisely known under some conditions due to the various reasons, which means the problem needs to be stochastically programmed and evaluated. Therefore, in this study initial SOE of the ESS is examined not

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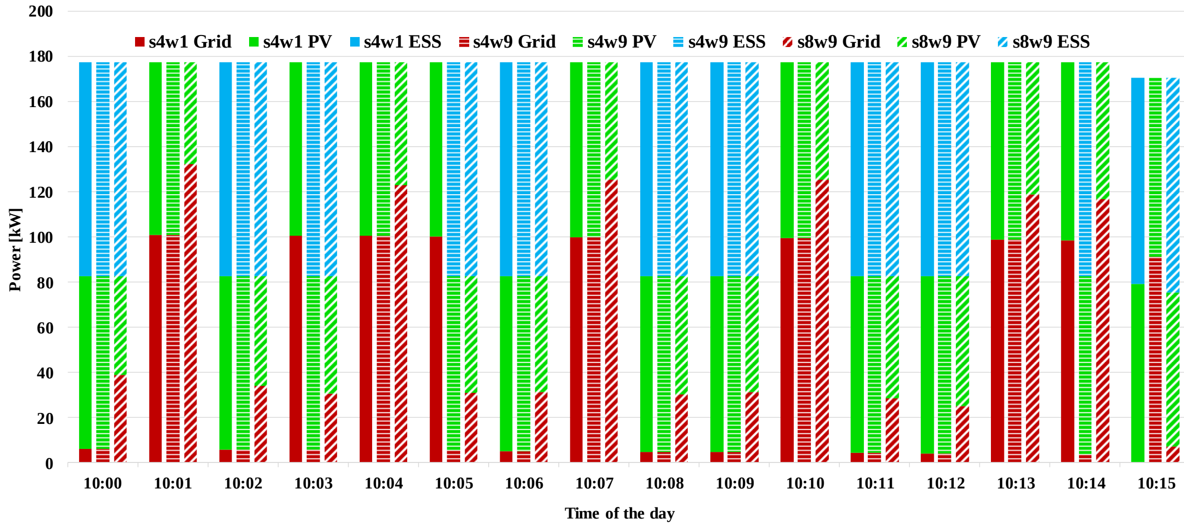

Fig. 10. Decomposition of used power in order to meet the load demand.

TABLE I
COMPARISON OF DIFFERENT CASE STUDIES

Description of Cases	Dynamic Pricing Signal		Time of Use Signal		Flat Pricing Signal	
	Total Operational Cost [€]	Cost Reduction [%]	Total Operational Cost [€]	Cost Reduction [%]	Total Operational Cost [€]	Cost Reduction [%]
Base Case (None of RBE, ESS, or PV)	316.132	Base Case	337.152	Base Case	356.837	Base Case
Case 2 (Considering only ESS)	306.412	3.07%	329.523	2.26%	353.159	1.03%
Case 3 (Considering only PV)	255.211	19.27%	277.859	17.58%	295.346	17.23%
Case 4 (Considering both ESS and RBE)	265.394	16.05%	285.374	15.36%	312.136	12.52%
Case 5 (Considering both ESS and PV)	255.198	19.27%	277.859	17.58%	295.331	17.23%
Case 6 (Considering all of ESS, RBE, and PV)	204.909	35.18%	226.502	32.82%	251.134	29.62%

TABLE II
COMPARISON OF CASE STUDIES FOR DIFFERENT PV SIZES

Description of Cases	Dynamic Pricing Signal		Time of Use Signal		Flat Pricing Signal	
	Total Operational Cost [€]	Cost Reduction [%]	Total Operational Cost [€]	Cost Reduction [%]	Total Operational Cost [€]	Cost Reduction [%]
Base Case (None of RBE, ESS, or PV)	316.132	Base Case	337.152	Base Case	356.837	Base Case
Case 2 (Considering all of ESS, RBE, and 100 kW-PV)	204.909	35.18%	226.502	32.82%	251.134	29.62%
Case 3 (Considering all of ESS, RBE, and 90 kW-PV)	211.084	33.23%	232.505	31.04%	257.359	27.87%
Case 4 (Considering all of ESS, RBE, and 80 kW-PV)	217.253	31.28%	238.521	29.25%	263.584	26.13%
Case 5 (Considering all of ESS, RBE, and 70 kW-PV)	222.806	29.52%	243.921	27.65%	269.186	24.56%

only deterministically but also stochastically for the scenarios of having 20, 30, 40, 50, 60, 70, 80, 90 and 100 kWh initial SOE of the ESS. Furthermore, probability of each scenario of initial SOE of ESS is chosen as equal.

In this study, it is assumed that the railway station is able to be supplied by PV generation unit. Regarding the uncertain behaviour of PV power generation unit, the problem is modelled as it reflects the stochastic nature of PV. Therefore, 10 different scenarios are considered so as to properly model the problem in a stochastic manner. Included irradiation and temperature data taken from [30] for 10 different days is used to calculate generation power profiles which are assumed as 10 different scenarios for PV generation. It should be noted that the specifications of PV panels given in [31] are used while computing power generation profiles by using irradiation and temperature data. Figure 8 illustrates the evaluated scenarios for PV generation. Upper of this figure also explains the pattern difference between cloudy and sunny day scenarios using two

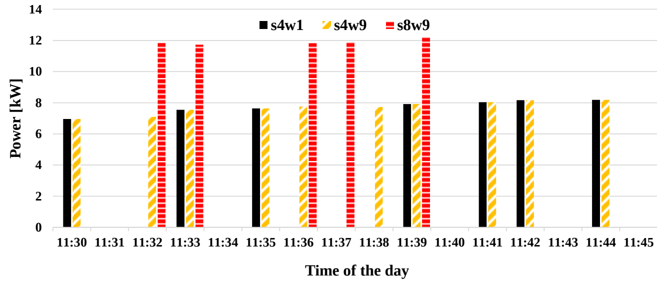

Fig. 11. Power sold back to the grid in selected scenarios.

scenarios as an example, the PV generation scenarios roughly follow the same pattern at the rest of the day. Assessments are also carried out about effect of the PV generation unit size on daily operational cost creating 4 cases such as PV sizes are 70, 80, 90 and 100 kW.

Combining 10 scenarios for PV generation with 9 scenarios for initial SOE of ESS, a scenario tree is constructed, which includes 90 different scenarios. Graphical demonstration of scenario tree is given in Fig. 9. For the sake of clarity, the evaluations of the graphical results are investigated based on results of selected 3 scenarios while the results in Table I and II cover the whole 90 scenarios. While selecting the scenarios used in graphical results, it was considered that the results provide opportunity for comparing sunny and cloudy days as well as different SOE levels.

The decomposition of used power so as to supply the station loads for 3 selected scenarios is given in Fig. 10 for a very short time interval. Each column represents the instantaneous power drawn both from the grid and the ESS together with power used from PV generation for 3 selected scenarios, namely scenario s4w1, s4w9, and s8w9. As can be seen in Fig. 10, the power drawn from the grid is severely affected by the initial SOE of the ESS and PV generation, even in the late hours of the day.

Owing to the two way power exchange infrastructure of the smart railway station, the power sold back to the grid is shown for a short time interval in Fig. 11. Sold power is observed as more stable for the sunny day scenario compared to cloudy one. It should be underlined that when uncertain behaviour of initial SOE of ESS is introduced, the results of ESS scenarios are similar except for minor irregularity, which are observed at ESS scenario with full SOE level.

It is obvious that charging and discharging states of the ESS are directly affected by either RBE usage, PV generation or initial SOE of the ESS, as seen in Fig. 12. It is worthy to underline that 3 selected scenarios related to the initial SOE of the ESS PV generation are presented in Fig. 12 for the case that includes RBE and PV generation with 100 kW under the dynamic price scheme. Nevertheless, it can be also seen from the mentioned figure that after RBE is introduced about at 06:00, the first train arrives to the station, SOE of the ESS alteration increases for all scenarios.

Table I encapsulates the base case together with five different cases assessed in this study considering the different pricing schemes. It can be deduced from the table that utilization of only ESS, only PV, or combinations of the ESS, PV and RBE

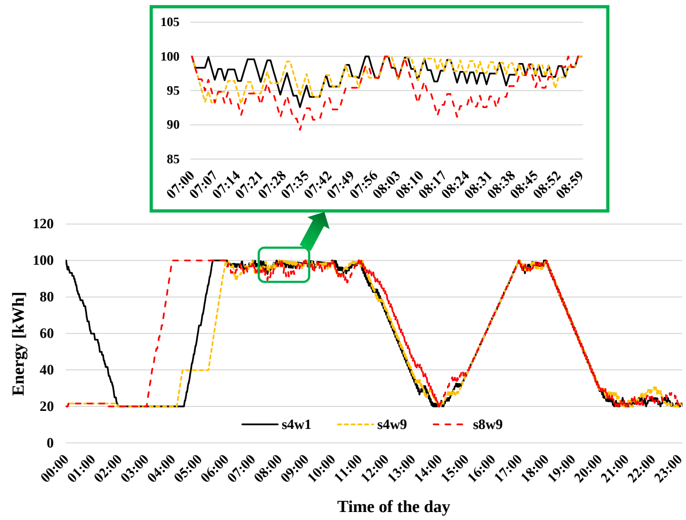

Fig. 12. The variations in SOE of ESS during a day for each scenario in case RSEM includes RBE and ESS and is operated under dynamic price scheme.

have significant impact on reducing total daily operational cost of the smart railway station for the stochastic approach. The case including none of RBE, ESS, or PV is assumed as the base case, while it is the worst case evaluated considering the flat pricing signal. Dynamic pricing and time-of-use signals are also considered so as to highlight the impact of smart grid applications by using smart metering features even though not in most of actual railway stations. It can be seen that different pricing schemes provide a great opportunity for minimizing total daily operational cost of the railway station. Using RSEM, nearly 2-3% drop in cost is ensured for the stochastic approach even if the railway station is equipped with only ESS. Furthermore, reusing of RBE together with the ESS and PV is another and the most efficient option, which provides more than 35% cost reduction for the stochastic approach. It is worthy to state that the aforementioned evaluations are conducted in case of RSEM operated under dynamic pricing signal.

The results belong to the cases that is created for evaluating the PV size impact on daily operational cost of smart railway station, are given in Table II. It can be said that the increase in PV size results in a significant decrease in daily operational cost of the smart railway station. Similar to the results given in Table I, the most severe decrease in operational cost is obtained under the cases with dynamic price scheme, which emphasize the importance of smart grid concept. Nevertheless, the installation cost should be considered while deciding the required PV size, which is assumed as out of scope for this paper.

IV. Conclusion

Aiming to reduce dependence on fossil fuels and to relieve the public anxieties on global climate change by decreasing the GHGs, efficient use of energy has become an important topic. Due to the high reusable energy potential lying behind the ERSs, railway operation can be considered as a key factor for reaching the goals in energy efficiency.

This study presented a MILP model of RSEM for evaluating dynamic variations of passengers, different pricing schemes, and stochastic nature of the initial SOE of the ESS along with the uncertainties in PV generation while aiming to minimize daily operational cost of a railway station by using its own instruments such as ESS, PV, RBE and external one i.e. grid. It was assumed that ESS, PV, RBE and a smart meter allowing to operate Bahcelievler railway station under different pricing signals, form the RSEM structure. The calculation of RBE was carried out using RAILSIM software. In addition, ninety different scenarios were evaluated in order to explore the impact of initial SOE of the ESS and PV generation, which were considered as a parameter that cannot be precisely known by RSEM. It should be noted that two-way power flow between grid and station was considered in this paper. Therefore, RSEM system managed the power flow in station regarding the options that buying from and selling to the utility.

In order to evaluate the impact of RBE, different pricing schemes and stochastic nature of the ESS along with the uncertainties in PV generation on daily cost of railway station, six different cases were created in this study. The case that railway station has no ESS and PV or is not able to utilize RBE was selected as base case for all kind of pricing signals. The results showed that the reduction in cost of daily electricity consumption of railway station is possible using the ESS, nevertheless, using ESS together with RBE had a tremendous effect on the daily cost and decreased it by nearly 16% in stochastic approach. One unanticipated finding was that, the cases that utilizes only the PV, and ESS along with PV, resulted in same decrease rate as 19% in the cost of daily operational. The most significant reduction was observed when the station was able to use all of RBE, ESS, and PV, which was calculated as 35%. It should be emphasized that due to the stochastic behaviour of initial SOE of the ESS and PV generation, RSEM response in terms of station power flows during the day changed according to the related scenario.

In this paper, all the examinations were carried out through a MILP model of RSEM considering it is comprised of ESS, PV, RBE and smart meter. Regarding this, authors would like to indicate that this research can be extended to integrate demand response strategies to RSEM, which is considered as a future study.

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