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Comprehensive Optimization Model for Sizing and Siting of DG Units, EV Charging Stations, and Energy Storage Systems

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***Abstract*—The sizing and siting of renewable resources-based distributed generation (DG) units has been a topic of growing interest, especially during the last decade due to the increasing interest in renewable energy systems and the possible impacts of their volatility on distribution system operation. This paper goes beyond the existing literature by presenting a comprehensive optimization model for the sizing and siting of different renewable resources-based DG units, electric vehicle charging stations, and energy storage systems within the distribution system. The proposed optimization model is formulated as a second order conic programming problem, considering also the time-varying nature of DG generation and load consumption, in contrast with the majority of the relevant studies that have been based on static values.**

***Index Terms*—Distributed generation, distribution system, electric vehicle charging station, energy storage system, sizing and siting.**

NOMENCLATURE

The sets, parameters and decision variables that are used in this paper are alphabetically listed below in Tables I-III. Other symbols and abbreviations are defined where they first appear.

I. INTRODUCTION

A. Motivation and Background

IN ALIGNMENT with the raising environmental concerns, the economic and political risks posed by the scarcity of fossil fuels and the technological advances during the last decades, the investments on renewable energy resources have significantly increased, promoted by the incentives offered by the governments of both developed and developing countries. Although relying on such resources presents environmental advantages and increases self-sufficiency, there are also severe drawbacks that can challenge the traditional operational and planning procedures of power systems. The most significant disadvantage is that the majority of renewable energy sources, including wind and solar power production, are highly volatile and non-dispatchable because of their dependence on meteorological conditions [1], [2]. Thus, the system operators (SOs) should carefully take into account this high variability especially in the case of power systems with significant penetration of renewable energy systems [3].

In particular, the distribution system has a more vulnerable structure compared to transmission system, and the increase in the integration of renewable energy sources in the form of distributed generation (DG) units needs proper planning actions from the SO side. In the same time, the demand side has recently shown a considerable change due to the uptake of a new generation of electric loads. For instance, electric vehicles (EVs) have significant levels of power requirements as a load (e.g., 7.4 kW for BMW i3 regular charger [4], 19.2 kW for Tesla Home Charging Station [5], 22 kW for Renault ZOE Medium Charger [6], 43 kW for Renault ZOE Fast Charger [6], 120 kW for Tesla SuperCharger [7], etc.) and a vital potential as a mobile storage unit via the Vehicle-to-Grid (V2G) operation mode with considerable battery capacities (e.g., 33 kWh for BMW i3 [4], 100 kWh for Tesla Model X [8], etc.). Moreover, the introduction of distributed energy storage systems (ESSs) within the distribution system has been also recognized by SOs as a means of enhancing the operational flexibility [9], [10].

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TABLE I
INDICES AND SETS

B^i	Set of MV buses.
B_l^{ij}	Set of lines where i is the sending and j is the receiving bus.
B_h^i	Set of LV buses and relevant MV/LV transformer units connected to MV bus i.
B_k^i	Set of sample load variations of EV charging stations.
h	Index of LV buses and relevant MV/LV transformer units.
i	Index of buses.
k	Index of sample load variations of EV charging stations.
t	Index of time periods.

TABLE II
PARAMETERS AND CONSTANTS

A, C	Binary parameters that specify the structure of the objective function
B_l	Susceptance of line l [pu].
CE^{ESS}	Charging efficiency of ESS.
DE^{ESS}	Discharging efficiency of ESS.
$M_{i,l}^F$	Coefficient that is 1 if bus i is the receiving end of line l, -1 if bus i is the sending end of line l, otherwise 0.
$M_{i,l}^L$	Coefficient that is 1 if bus i is the sending end of line l, otherwise 0.
$M_{l,i}^W$	The coefficient for bus i and line l obtained from the transpose of the matrix composed of $M_{i,l}^F$ values.
K	Ratio of allowed installed DG capacity with respect to the MV/LV transformer rated power.
k_1, k_2	Weighting coefficients.
$P_{EV\_CS,rated}$	EV charging station rated power [pu].
$P_{k,t}^{EV\_sample}$	Power demand in period t for sample load variation k of the EV charging station [pu].
$P_{h,i,t}^{L,LV\_other}$	Inelastic demand of LV bus h of MV bus i in period t [pu].
$P_{i,t}^{L,MV\_other}$	Inelastic demand of MV bus i connected directly from MV side in period t [pu].
$P_{\max @T_{ref}}$	Rated power of each reference PV panel at T_{ref} [pu].
$P_{PV\_ACT@T,h,i,t}$	Actual PV power production from each reference PV panel for LV bus h of MV bus i in period t [pu].
$P_{PV\_ACT@T,i,t}$	Actual PV power production from each reference PV panel for MV bus i in period t [pu].
$P_{wind,h,i,t}$	Actual wind power production from each reference wind turbine for LV bus h of MV bus i in period t [pu].
$P_{wind,i,t}$	Actual wind power production from each reference wind turbine for MV bus i in period t [pu].
$P_{wind,rated}$	Rated power of each reference wind turbine [pu].
$R^{ESS,ch}$	Charging rate of ESS [pu].
$R^{ESS,dis}$	Discharging rate of ESS [pu].
R_l	Resistance of line l [pu].
$Q_{i,t}^L$	Reactive power demand of MV bus i in period t [pu].
$SOE^{ESS,ini}$	Initial state-of-energy of ESS unit [pu].
$SOE^{ESS,max}$	Maximum state-of-energy of ESS unit [pu].
$SOE^{ESS,min}$	Minimum state-of-energy of ESS unit [pu].
$T_{i,t}$	Temperature variation within the region of MV bus i in period t [^{0}C].
T_{ref}	Reference temperature for PV panel (usually considered as 25^{0}C) [^{0}C].
$Temp\_coeff_{P_{max}}$	Temperature coefficient defined by manufacturer for modeling the impact of temperature change on PV power production [%/^{0}C].
$TR_{h,i}^{lim}$	Rated power of MV/LV transformer between MV bus i and LV bus h [pu].
$v_{i,t}$	Wind speed variation within the region of MV bus i in period t [m/s].
V_{max}	Maximum allowed voltage level for MV buses [pu].
V_{min}	Minimum allowed voltage level for MV buses [pu].
$\text{Ɨ}_{ACT,i,t}$	Solar radiation variation within the region of MV bus i in period t [W/m^2].
Ɨ_{REF}	Reference solar radiation for PV panel (usually considered as 1000 W/m^2) [W/m^2].
ΔT	Time granularity [h].

Considering all the aforementioned elements, the planning of investments in renewable based DG units and the integration of new technologies, such as EVs and ESSs, at the demand side is a prevalent issue and the need for distribution SO to rely on comprehensive sizing and siting methodologies is rendered evident.

TABLE III
DECISION VARIABLES

$E_i^{ESS\_cap}$	Total capacity of ESS unit of MV bus i.
$n_{EV\_CS,k,h,i}$	Number of EV charging stations installed within LV bus h of MV bus i for sample EV load k.
$n_{LV\_ESS,h,i}$	Number of reference ESS units installed within LV bus h of MV bus i.
$n_{LV\_PV,h,i}$	Number of reference PV panels installed within LV bus h of MV bus i.
$n_{LV\_wind,h,i}$	Number of reference wind turbines installed within LV bus h of MV bus i.
$n_{MV\_PV,i}$	Number of reference PV panels installed directly connected to MV bus i.
$n_{MV\_wind,i}$	Number of reference wind turbines installed directly connected to MV bus i.
$P_i^{DG\_cap}$	Total DG capacity for MV bus i.
$P_{h,i}^{DG\_cap\_LV}$	DG capacity for LV bus h of MV bus i.
$P_i^{DG\_cap\_MV}$	DG capacity directly connected to MV bus i.
$P_{h,i,t}^{ESS,ch}$	Charging power of ESS unit connected to LV bus h of MV bus i in period t [pu].
$P_{h,i,t}^{ESS,dis}$	Discharging power of ESS unit connected to LV bus h of MV bus i in period t [pu].
$P_i^{EV\_CS\_cap}$	Total EV charging station capacity for MV bus i.
$P_{i,t}^G$	Power available at MV bus i in period t [pu].
$P_{i,t}^L$	Total load of MV bus i in period t [pu].
$P_{h,i,t}^{L,EV}$	Total EV charging based power consumption for LV bus h of MV bus i in period t [pu].
$P_{l,t}^{loss}$	Active power loss of line l in period t [pu].
$\hat{P}_{l,t}^{loss}$	Model variable to represent the active power loss of line l in period t [pu].
$P_{h,i,t}^{LV-}$	Total power drawn by LV bus h from MV bus i in period t [pu].
$P_{h,i,t}^{LV+}$	Total power injected by LV bus h to MV bus i in period t [pu].
$P_{h,i,t}^{LV\_DG}$	Total DG power production for LV bus h of MV bus i in period t [pu].
$P_{h,i,t}^{LV\_PV}$	Total PV power production for LV bus h of MV bus i in period t [pu].
$P_{h,i,t}^{LV\_wind}$	Total wind power production for LV bus h of MV bus i in period t [pu].
$P_{i,t}^{MV\_DG}$	Total DG power production directly injected to MV bus i in period t [pu].
$P_{i,t}^{MV\_PV}$	Total PV power production directly injected to MV bus i in period t [pu].
$P_{i,t}^{MV\_wind}$	Total wind power production directly injected to MV bus i in period t [pu].
$P_{l,t}^r$	Active power flow at receiving end of line l in period t [pu].
$P_{i,t}^S$	Substation supply at bus i in period t [pu].
$Q_{l,t}^{loss}$	Reactive power loss of line l in period t [pu].
$Q_{i,t}^G$	Reactive power generated/consumed at bus i in period t[pu].
$Q_{l,t}^r$	Reactive power flow at receiving end of line l in period t [pu].
$SOE_{h,i,t}^{ESS}$	State-of-energy of ESS unit connected to LV bus h of MV bus i in period t [pu].
$V_{i,t}$	Voltage magnitude at bus i in period t [pu].
$W_{i,t}$	Square of the voltage magnitude at bus i in period t [pu].
$W_{r,t}$	Square of the voltage magnitude at receiving bus r ($r \in i$) in period t [pu].
$u_{h,i,t}^1$	Binary variable of logical constraints for the power decomposition of LV bus h.
$u_{h,i,t}^2$	Binary variable for ESS model. 1 if ESS unit connected to LV bus h of MV bus i is charging in period t, otherwise 0.

B. Literature Overview

There are several studies that dealt with the sizing and siting of DG units. Among them, Moradi and Abedini [11] solved the power loss minimization and voltage stability maximization oriented multi-objective DG sizing-siting problem in distribution system using a combined genetic algorithm and particle swarm optimization based approach.

Kefayat *et al.* [12] proposed a multi-objective DG sizing-siting problem simultaneously considering the minimization of losses, cost and emissions, as well as the maximization of the voltage stability index. The contribution of [12] was the consideration of the uncertainty pertaining wind production and load consumption. Kaur *et al.* [13], proposed a sequential siting and capacity planning model using a Mixed Integer Nonlinear Programming (MINLP) context aiming to minimize distribution system losses. Rueda-Medina *et al.* [14] developed an investment and operational cost minimization oriented Mixed Integer Linear Programming (MILP) model for the DG sizing and siting problem in radial distribution systems. Foster *et al.* [15] compared MILP and genetic algorithm (GA) methods for the DG sizing and siting problem in terms of computational performance. Sheng *et al.* [16] proposed an improved solution technique for multi-objective DG sizing and siting problem, targeting at minimum line losses and voltage deviation, as well as maximum stability. Pereira *et al.* [17] considered the sizing and siting of both DG units and capacitor banks within a distribution system and adopted a Tabu search and GA based hybrid solution technique, considering also the stochasticity in power production of DG units. Ameli *et al.* [18] combined the DG owner's with the distribution company's point of view in a multi-objective optimization context solved by particle swarm optimization (PSO). Kroposki *et al.* [19] proposed a feeder ranking based approach for renewable DG sizing and siting in distribution systems.

Two different studies considering the sizing and siting of EV charging stations and ESS units within the distribution system without taking DG units into account can be found in [20] and [21]. Lastly, a comprehensive literature study considering the sizing and siting of both DG units and EV charging stations was provided in [22]. More detailed reviews dedicated to this topic can be found in [23]–[26].

It should be noted that, in general, distribution system planning problems consider investment, replacement, maintenance and other operational costs. However, sizing and siting oriented distribution system problems are generally different than the regular distribution system planning problems. The main idea behind sizing and siting approaches is to determine the optimal capacity of DG and other technologies that can be installed in the distribution system without hampering its tight operational limits. Thus, in such studies the perspective of the SO is adopted in order to determine limits to a possible additional production/consumption units based private investment in terms of DG units, EV charging stations, etc. at a particular connection point within the distribution system, such that operational limits are not violated. Besides, SO based investments such as common ESS units to increase the operational flexibility from SO point of view can also be analyzed together with the impacts of aforementioned possible private investments within such conceptual analyses.

C. Content and Contributions

In this study, an optimal sizing and siting approach formulated as a second order conic programming problem, simultaneously considering wind and solar energy based DG units, EV charging stations and ESS units is proposed.

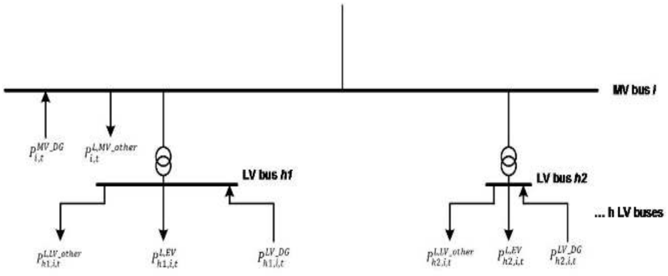

Fig. 1. Schematic of a MV bus considered in this study.

The novel points of the proposed study compared to the existing literature can be listed as follows:

- To the best knowledge of the authors, this is the first literature study that co-optimizes the size and location of different renewable-based DG units, EV charging stations and ESS units.
- Unlike several studies that consider only static values for generation and consumption, this study simultaneously considers time-varying profiles of load demand, DG production and EV based charging demand in order to address temporal mismatches between the production of DG units and load consumption.

D. Organization of the Paper

The remainder of the paper is organized as follows: in Section II the proposed methodology is described in detail. Results are presented and discussed in Section III. Finally, conclusions are drawn and directions for future studies are provided in Section IV.

II. METHODOLOGY

The proposed methodology aims to determine the optimum size of DG (photovoltaics - PV, wind), EV charging station and ESS penetration within the distribution system. Figure 1 presents a MV bus that connects directly DG units and loads, as well as LV buses where relatively smaller loads, DG and ESS units are connected.

The objective function of the optimization problem is represented by (1). As described by (1), the objective can either be minimizing the total losses ($A = 1, C = 0$), maximizing the total DG, EV charging station and ESS penetration within the distribution system ($A = 0, C = 0$) or a multi-objective combination of both ($A = 0, C = 1$).

$$\begin{aligned} \mathit{Minimize}\ L = {} & A \cdot \left(\sum_t \sum_l \hat{P}_{l,t}^{loss} \right) \\ & - (1 - A) \cdot \sum_i \left(P_i^{DG_{cap}} + P_i^{EV_{CS_{cap}}} + E_i^{ESS_{cap}} \right) \\ & + C \cdot \left(\sum_t \sum_l k_1 \cdot \hat{P}_{l,t}^{loss} - k_2 \right. \\ & \left. \times \left[P_i^{DG_{cap}} + P_i^{EV_{CS_{cap}}} + E_i^{ESS_{cap}} \right] \right) \end{aligned} \tag{1}$$

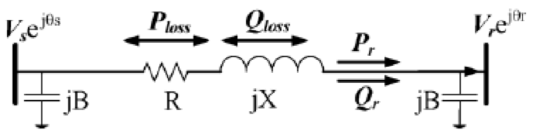

Fig. 2. Line model [27].

The constraints of the problem are expressed by (2)-(34).

$$P^G_{i,t} - P^L_{i,t} = \sum_{l \in B^{ij}_l} \left(M^F_{i,l} \cdot P^r_{l,t} + M^L_{i,l} \cdot P^{loss}_{l,t} \right) \quad \forall i, t \tag{2}$$

$$Q^G_{i,t} - Q^L_{i,t} = \sum_{l \in B^{ij}_l} \left(M^F_{i,l} \cdot Q^r_{l,t} + M^L_{i,l} \cdot Q^{loss}_{l,t} - B_l \cdot M^W_{l,i} \cdot W_{i,t} \right) \quad \forall i, t \tag{3}$$

$$P^G_{i,t} = P^S_{i,t} + P^{MV\_DG}_{i,t} + \sum_{h \in B^i_h} P^{LV+}_{h,i,t} \quad \forall i, t \tag{4}$$

$$P^L_{i,t} = P^{L,MV\_other}_{i,t} + \sum_{h \in B^i_h} P^{LV-}_{h,i,t} \quad \forall i, t \tag{5}$$

$$W_{i,t} = V^2_{i,t} \quad \forall i, t \tag{6}$$

$$P^{loss}_{l,t} = 2 \cdot R_l \cdot \hat{P}^{loss}_{l,t} \quad \forall l, t \tag{7}$$

$$X_l \cdot P^{loss}_{l,t} - R_l \cdot Q^{loss}_{l,t} = 0 \quad \forall l, t \tag{8}$$

$$\sum_i \left(M^W_{l,i} \cdot W_{i,t} \right) = 2 \cdot R_l \cdot P^r_{l,t} + 2 \cdot X_l \cdot Q^r_{l,t} + R_l \cdot P^{loss}_{l,t} + X_l \cdot Q^{loss}_{l,t} \forall l, t \tag{9}$$

$$2 \cdot \hat{P}^{loss}_{l,t} \cdot W_{r,t} \geq {P^r_{l,t}}^2 + {Q^r_{l,t}}^2 \quad \forall l, t \tag{10}$$

$$V^2_{min} \leq W_{i,t} \leq V^2_{max} \quad \forall i, t \tag{11}$$

Constraints (2) and (3) stand for the active and reactive power balance at each MV bus. Equation (4) decomposes the power that is available at each MV bus to the contribution of the DG units directly connected to MV bus, the injection at substation buses, and the power injected by the excess power of LV buses. Similarly, (5) enforces the fact that the system load comprises inelastic demand, and the power deficit of LV buses. The equality constraints (6)-(10) enforce relationships between substitute variables in order to obtain a simpler AC power flow representation as derived directly from [27] with relevant adjustments. It should be noted that a power flow representation in conic format is adopted in this study due to its capabilities of achieving high-accuracy modeling compared to DC power flow model, and of obtaining a relatively simpler power flow representation compared to full AC power flow model. Furthermore, the iteration numbers in these models are generally very low and do not change considerably with the increasing size of the network, which enables these models to be used effectively for practical implementations. The relevant representation for the power flow concept can also be followed from Fig. 2. Besides, (11) constrains the voltage at each bus to be between allowable lower and upper limits.

The power decomposition and the logical constraints regarding the power balance at each LV bus are represented by (12)-(14).

$$P^{LV\_DG}_{h,i,t} + P^{ESS,dis}_{h,i,t} - P^{L,LV_{other}}_{h,i,t} - P^{L,EV}_{h,i,t} - P^{ESS,ch}_{h,i,t} = P^{LV+}_{h,i,t} - P^{LV-}_{h,i,t} \tag{12}$$

$$P^{LV+}_{h,i,t} \leq TR^{lim}_{h,i} \cdot u^1_{h,i,t} \tag{13}$$

$$P^{LV-}_{h,i,t} \leq TR^{lim}_{h,i} \cdot \left(1 - u^1_{h,i,t} \right) \tag{14}$$

The decomposition of the total DG power injected directly to MV bus consists of possible PV and wind turbine (WT) installations as in (15).

$$P^{MV\_DG}_{i,t} = P^{MV\_PV}_{i,t} + P^{MV\_wind}_{i,t} \tag{15}$$

The PV power for each reference PV panel is calculated considering the temperature variation and solar irradiation as in (16).

$$\begin{aligned} P_{PV\_ACT@T,i,t} &= \frac{\text{Ɨ}_{ACT,i,t}}{\text{Ɨ}_{REF}} \\ &= \frac{\left(T_{i,t} - T_{ref} \right) \cdot Temp\_coeff_{P_{max}} + 100}{100} \cdot P_{\max @T_{ref}} \end{aligned} \tag{16}$$

where the reference solar irradiation and temperature values are 1000 W/m^2 and 25°C, respectively. Thus, the PV power injected directly to each MV bus is calculated by (17).

$$P^{MV\_PV}_{i,t} = n_{MV\_PV,i} \cdot P_{PV\_ACT@T,i,t} \tag{17}$$

The wind power of each WT with rated power $P_{wind,rated}$ is obtained as a function of the wind speed as in (18), where the power curves of specific WT types can be employed in this regard.

$$P_{wind,i,t} = f\left(v_{i,t} \right) \tag{18}$$

Thus, the wind power injected directly to each MV bus is calculated by (19).

$$P^{MV\_wind}_{i,t} = n_{MV\_wind,i} \cdot P_{wind,i,t} \tag{19}$$

Similar expressions can be derived for LV bus DG installations as in (20)-(22), assuming that the same PV panel and WT is used in the installation and the meteorological conditions — and as a result the power variations of reference PV panels and WTs — in different regions of the same bus are identical, i.e., $P_{PV\_ACT@T,i,t} = P_{PV\_ACT@T,h,i,t}, P_{wind,i,t} = P_{wind,h,i,t}$.

$$P^{LV\_DG}_{h,i,t} = P^{LV\_PV}_{h,i,t} + P^{LV\_wind}_{h,i,t} \tag{20}$$

$$P^{LV\_PV}_{h,i,t} = n_{LV\_PV,h,i} \cdot P_{PV\_ACT@T,h,i,t} \tag{21}$$

$$P^{LV\_wind}_{h,i,t} = n_{LV\_wind,h,i} \cdot P_{wind,i,t} \tag{22}$$

The total installed DG capacity connected at each LV bus h is calculated by (23).

$$P^{DG\_cap\_LV}_{h,i} = n_{LV\_PV,h,i} \cdot P_{\max @T_{ref}} + n_{LV\_wind,h,i} \cdot P_{wind,rated} \tag{23}$$

In some countries, regulations limit the total installed DG capacity at the LV side to be below a ratio of the rated MV/LV transformer capacity. For instance, in Turkey, the relevant regulation states that the total installed DG capacity should not exceed 30% of the relevant MV/LV transformer's rated power. This is enforced by (24).

$$P^{DG\_cap\_LV}_{h,i} \leq K \cdot TR^{lim}_{h,i} \tag{24}$$

Similar to (23), the total installed DG capacity directly connected at each MV bus i is calculated by (25). Thus, the total DG capacity from both the MV and LV side for each MV bus i can be obtained by (26).

$$P_i^{DG\_cap\_MV} = n_{MV\_PV,i} \cdot P_{\max @T_{ref}} + n_{MV\_wind,i} \cdot P_{wind,rated} \tag{25}$$

$$P_i^{DG\_cap} = P_i^{DG\_cap\_MV} + \sum_{h \in B_h^i} P_{h,i}^{DG\_cap\_LV} \tag{26}$$

The EV charging load at each LV bus h should be also derived. Considering only a single type of charging station type for the sake of simplicity, k types of sample load variations can be defined considering the physical usage of the EV charging station which can differ regarding the actual area the charging station is placed (in a household, in a working place, etc.) and the charging habits of the EV owners. Thus, the EV charging load at each LV bus h is obtained by defining the number of identical charging stations of sample load variation k that can be placed at each LV bus h in (27).

$$P_{h,i,t}^{L,EV} = \sum_{k \in B_k^i} n_{EV\_CS,k,h,i} \cdot P_{k,t}^{EV\_sample} \tag{27}$$

Thus, the total EV charging station capacity for each MV bus i is calculated by (28).

$$P_i^{EV\_CS\_cap} = P_{EV\_CS,rated} \cdot \sum_{h \in B_h^i} \sum_{k \in B_k^i} n_{EV\_CS,k,h,i} \tag{28}$$

Finally, the ESS model considered in this study is represented by (29)-(33) [28]. Eqs. (29) and (30) limit the ESS charging and discharging rate together with logical constraints on charging and discharging power. State-of-energy (SOE) of ESS is considered by (31) and (32) while it is bounded by lower and upper limits using (33). Finally, the total capacity of ESS unit of MV bus i is calculated by (34).

$$0 \le P_{h,i,t}^{ESS,ch} \le R^{ESS,ch} \cdot u_{h,i,t}^2, \quad \forall t \tag{29}$$

$$0 \le P_{h,i,t}^{ESS,dis} \le R^{ESS,dis} \cdot \left(1 - u_{h,i,t}^2\right), \quad \forall t \tag{30}$$

$$SOE_{h,i,t}^{ESS} = SOE_{h,i,t-1}^{ESS} + CE^{ESS} \cdot P_{h,i,t}^{ESS,ch} \cdot \Delta T - \frac{P_{h,i,t}^{ESS,dis}}{DE^{ESS}} \times \Delta T, \ \forall t \ge 1 \tag{31}$$

$$SOE_{h,i,t}^{ESS} = n_{LV\_ESS,h,i} \cdot SOE^{ESS,ini}, \ if \ t = 1 \tag{32}$$

$$n_{LV\_ESS,h,i} \cdot SOE^{ESS,min} \le SOE_{h,i,t}^{ESS} \le n_{LV\_ESS,h,i} \cdot SOE^{ESS,max}, \ \forall t \tag{33}$$

$$E_i^{ESS\_cap} = \sum_{h \in B_h^i} n_{LV\_ESS,h,i} \cdot SOE^{ESS,max} \tag{34}$$

It should be also noted that this problem can be discretized into sub-problems of either sizing or siting respectively considering the sites or sizes for implementation as known parameters. The proposed formulation can therefore be manipulated in this manner either considering the size or site information as an input data instead of a decision variable.

TABLE IV
ALIBEYKOY FEEDER LINE PARAMETERS

	From	To	R [pu]	X [pu]	B [pu]
L1	n1	n0	0.00015	0.000244	0.080639
L2	n2	n1	6.47E-05	0.000106	0.034815
L3	n3	n2	6.47E-05	0.000106	0.034937
L4	n3	n4	5.71E-05	9.33E-05	0.030783
L5	n4	n5	2.86E-05	5.46E-05	0.017975
L6	n5	n6	2.44E-05	4.7E-05	0.01542
L7	n7	n6	2.44E-05	4.62E-05	0.015374
L8	n7	n8	3.28E-05	5.38E-05	0.017657
L9	n9	n8	2.52E-05	4.03E-05	0.013406
L10	n9	n10	4.79E-05	7.81E-05	0.025921
L11	n11	n10	4.2E-05	6.89E-05	0.022762

TABLE V
MV/LV TRANSFORMER CAPACITIES OF ALIBEYKOY FEEDER

	Transformer Power [kVA]		Transformer Power [kVA]
n11	630	**n5**	1250x2 (2 LV buses exist)
n10	1600	**n4**	1000
n9	1000	**n3**	1000
n8	1000	**n2**	1250
n7	1600	**n1**	630
n6	630		

TABLE VI
HADIMKOY FEEDER LINE PARAMETERS

	From	To	R [pu]	X [pu]	B [pu]
L1	100	0	5.88E-05	0.00015	0.061173
L2	100	103	0.000121	0.000294	0.03076
L3	100	132	0.000477	0.001111	0.034754
L4	100	144	0.00048	0.001152	0.461362
L5	143	144	3.53E-05	3.78E-05	0.009826
L6	142	143	6.3E-05	6.89E-05	0.017663
L7	141	142	4.7E-05	5.12E-05	0.013294
L8	140	141	0.000133	0.000145	0.037351
L9	100	147	0.000501	0.001214	0.485938
L10	137	138	8.65E-05	9.41E-05	0.024293
L11	138	139	3.11E-05	3.36E-05	0.008657
L12	139	140	7.23E-05	7.81E-05	0.020214
L13	147	149	4.2E-06	4.2E-06	0.001102
L14	147	148	6.72E-06	7.56E-06	0.001857

TABLE VII
MV/LV TRANSFORMER CAPACITIES OF HADIMKOY FEEDER

	Transformer Power [kVA]		Transformer Power [kVA]
n140	1250	**n137**	1250
n141	1000	**n149**	1600
n142	1250	**n148**	1600
n143	1250	**n147**	1600
n144	630	**n103**	400
n139	1600	**n132**	1000
n138	1600	**n100**	1000

III. TESTS AND RESULTS

A. Input Data

The proposed approach is tested on two real distribution system feeders in Istanbul, namely Alibeykoy and Hadimkoy feeders, which are located within the operation zone of Boğaziçi Elektrik Dağıtım A.Ş. (BEDAŞ), which is the electricity distributer serving to the European side of Istanbul. The line parameters and transformer data of the Alibeykoy feeder are presented in Tables IV and V, while the relevant data for the Hadimkoy feeder are given in Tables VI and VII.

For the mentioned feeders, the yearly inflexible consumption data of the buses with the lowest and highest peak

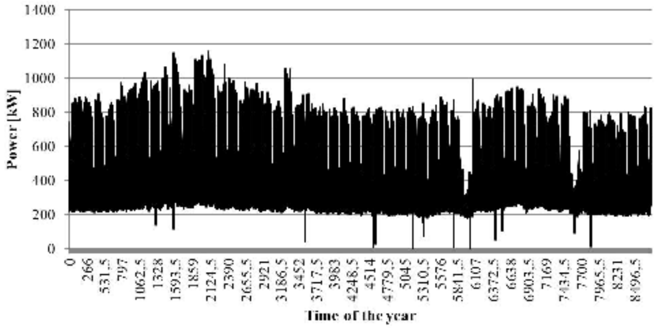

Fig. 3. The yearly power consumption profile of the bus with the highest peak demand (n2) for Alibeykoy feeder.

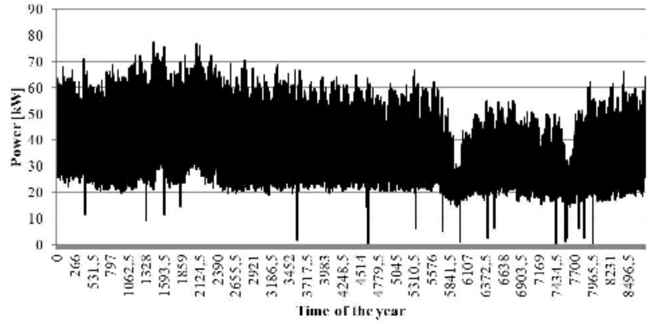

Fig. 4. The yearly power consumption profile of the bus with the lowest peak demand (n4) – Alibeykoy feeder.

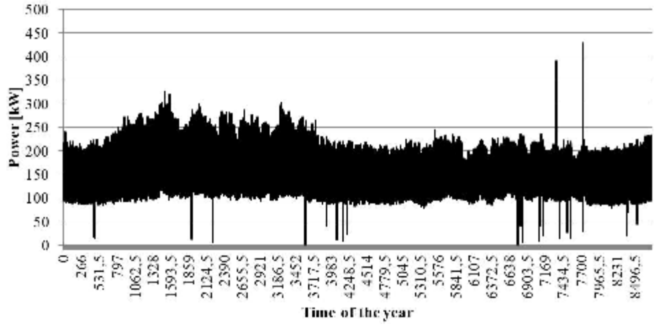

Fig. 5. The yearly power consumption profile of the bus with the highest peak demand (n140) – Hadimkoy feeder.

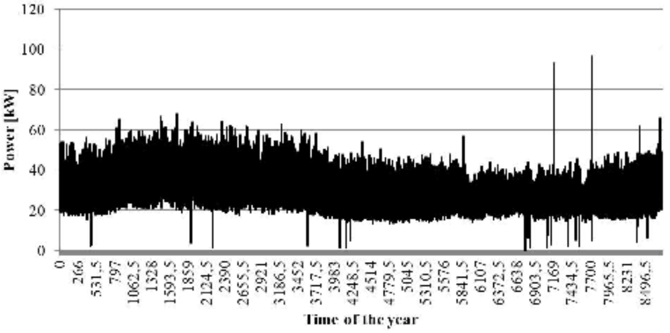

Fig. 6. The yearly power consumption profile of the bus with the lowest peak demand (n144) – Hadimkoy feeder.

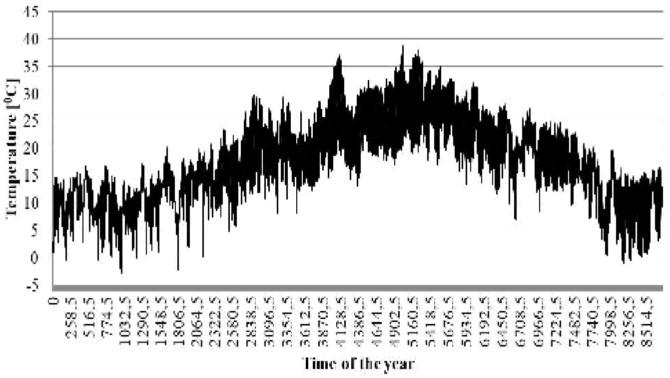

Fig. 7. Yearly temperature variation.

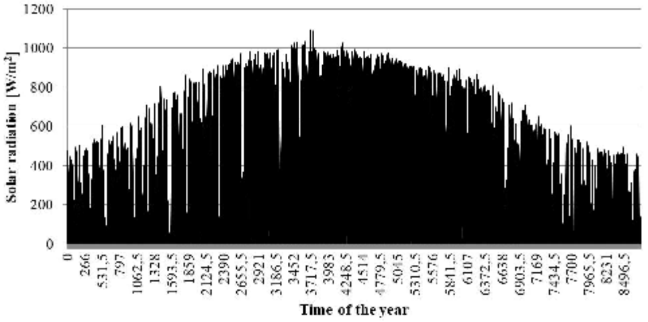

Fig. 8. Yearly solar radiation variation.

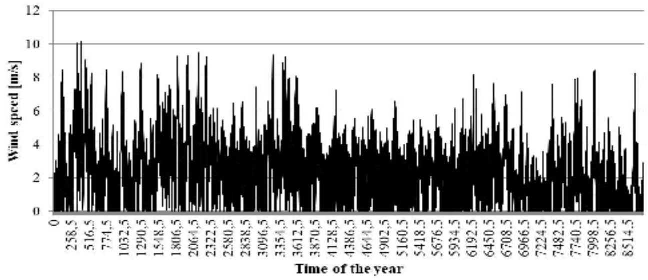

Fig. 9. Yearly wind speed variation.

power demand are given in Figs. 3-6 due to space limitations. It should be noted that the time granularity of the available data and also the simulation studies is 0.5h (30mins). Besides, the relevant meteorological data including temperature, solar radiation and wind speed variations are presented in Figs. 7-9 respectively. Here it should be also stated that for the relevant parameters of PV panel, the specifications of the 250 W industrial PV panel given in [29] are utilized.

The EV consumption profiles are obtained experimentally using charging data of a BMW i3 as shown in Fig. 10 for a normal charging station.

Three different profiles are provided for normal and fast charging stations as follows: 1) Type-1/K1, normal charging station – workplace load, 2) Type-1/K2, normal charging station – residential neighborhood load, 3) Type-2/K1, fast charging station (obtained via normalization of time and power values for normal charging station data) – a common place (such as a gas station) load profile. The relevant profiles are presented in Figs. 11-13.

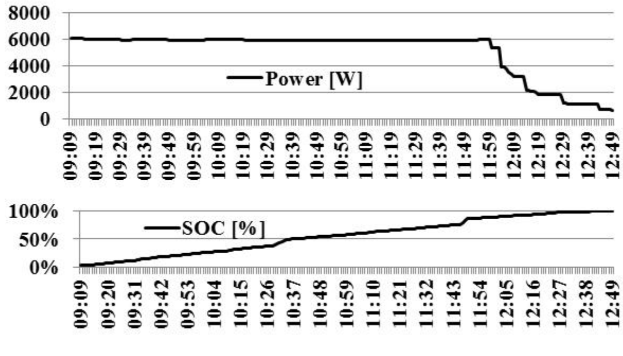

Fig. 10. The experimental charging data for BMW i3.

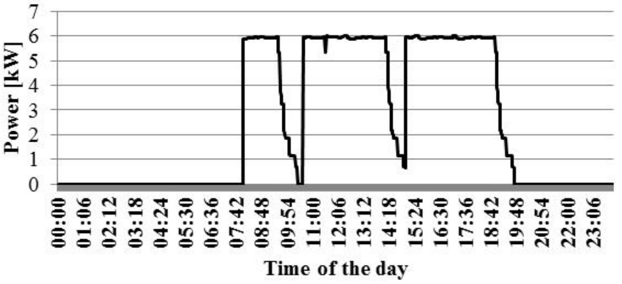

Fig. 11. The power demand curve of EV charging for Type-1/K1.

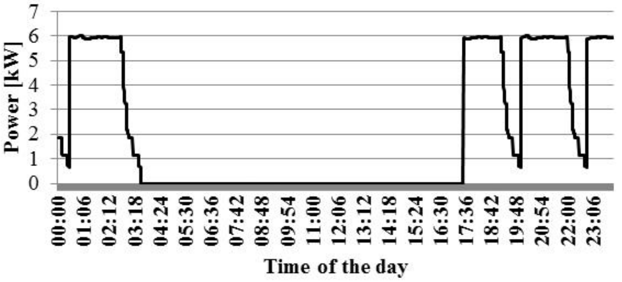

Fig. 12. The power demand curve of EV charging for Type-1/K2.

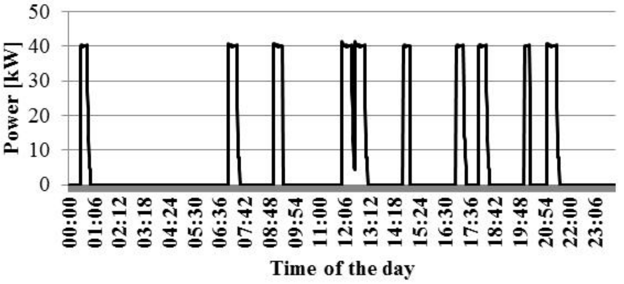

Fig. 13. The power demand curve of EV charging for Type-2/K1.

B. Simulation and Results

The model was coded in GAMS 24.0.2 and has been solved by the commercial solver MOSEK. Six different cases are evaluated for both Alibeykoy and Hadimkoy feeders:

- *Case-1:* ESS available, objective function is to minimize losses;
- *Case-2:* ESS available, objective function is to maximize DG, EV charging station and ESS capacity;
- *Case-3:* ESS available, objective function is both to minimize losses and maximize DG, EV charging station and ESS capacity;
- *Case-4:* ESS unavailable, objective function is to minimize losses;
- *Case-5:* ESS unavailable, objective function is to maximize DG and EV charging station capacity;
- *Case-6:* ESS unavailable, objective function is both to minimize losses and maximize DG and EV charging station capacity.

It should be noted that for Cases 3 and 6, the weighting coefficients in Eq. (1) are both considered equal to one. The obtained sizing and siting results are given in detail in Tables VIII and IX respectively for Alibeykoy and Hadimkoy feeders. It should be noted that Type-1 for the considered WT corresponds to 200 kW rated power, while Type-2 corresponds to 50 kW. The minimum voltage among all buses and total active power losses for both feeders are also summarized in Table X. Note that the minimum voltage value of each bus at each time step does not decrease below the predefined minimum voltage, which is 0.9 pu, for all the cases considered. In Table X, the percentage of active power losses is calculated by the division of total load energy consumption via EV charging, inflexible loads and ESS charging by the total energy drawn through the distribution lines from the connection point of the relevant feeder to the main distribution system.

As seen from the obtained results, the approach maximizes the ESS capacity during the availability of ESS as the capital cost required for ESS investment, etc. is not considered. The availability of ESS generally results in lower active power losses and increased DG and EV charging station capacities. Here, the change of the objective function especially affects the obtained results during the ESS unavailability conditions. The choice of a multi-objective concept instead of solely considering loss minimization results in a slightly increase in total losses in turn of increasing DG and EV charging station capacities. It should be stated here that the mentioned percentage of losses does not consider many other factors and therefore presented just for comparison purposes. In reality, the transformer losses, the LV line losses, etc. factors are non-negligible and the percentage of losses therefore will be greater together with these impacts.

In order to clearly observe the benefits of the ESS and DG units to the operation of the distribution system, various analyses are also presented on a higher-resolution scale for Alibeykoy feeder. With this objective, two different typical days that reflect the frequently encountered generation and consumption profiles in the considered area are chosen. It should be noted that only the buses with the highest renewable generation and power consumption are considered first and among them the ones having the data with the maximum standard deviation, namely buses n10, n5, n3 and n2, are shown in the related figures in order to avoid data redundancy.

The power generation values of PV panels and wind turbines that have the maximum capacities for the predetermined buses given in Table VIII for case 1 are shown in

TABLE VIII
THE RESULTS OF DIFFERENT CASES FOR ALIBEYKOY FEEDER

Bus	PV power [kW]	WT power [kW]	N. of WT		N. of EV charging stat.			ESS cap. [kWh]	PV power [kW]	WT power [kW]	N. of WT		N. of EV charging stat.			ESS cap. [kWh]
			Type-1 [50 kW]	Type-2 [200 kW]	Type-1		Type-2				Type-1 [50 kW]	Type-2 [200 kW]	Type-1		Type-2	
					K1 [7.4 kW]	K2 [7.4 kW]	K1 [50 kW]						K1 [7.4 kW]	K2 [7.4 kW]	K1 [50 kW]	
	Case-1								**Case-2**							
n11	25	150	0	3	0	0	0	100	0	0	0	0	39	25	1	100
n10	25	450	2	1	0	0	0	100	50	400	2	0	78	48	6	100
n9	0	100	0	2	0	0	0	100	125	0	0	0	58	64	5	100
n8	0	250	0	5	0	0	0	100	25	0	0	0	40	55	2	100
n7	25	450	0	9	0	0	0	100	25	400	2	0	77	95	2	100
n6	125	0	0	0	1	0	0	100	0	0	0	0	40	41	1	100
n5	100	1350	5	7	87	0	0	200	575	800	4	0	119	130	41	200
n4	0	50	0	1	0	0	0	100	25	0	0	0	21	93	1	100
n3	50	300	0	6	0	0	0	100	25	200	0	4	86	0	0	100
n2	25	350	1	3	0	0	0	100	100	50	0	1	49	38	0	100
n1	25	150	0	3	0	0	0	100	0	100	0	2	31	34	2	100
	Case-3								**Case-4**							
n11	25	150	0	3	0	0	0	100	0	150	0	3	0	0	0	-
n10	25	450	2	1	0	0	0	100	0	250	1	1	0	0	0	-
n9	0	100	0	2	0	0	0	100	0	100	0	2	0	4	0	-
n8	0	250	0	5	0	0	0	100	0	300	1	2	0	2	0	-
n7	25	450	2	1	0	0	0	100	25	450	2	1	0	0	0	-
n6	0	50	0	1	0	0	0	100	50	50	0	1	0	0	0	-
n5	0	1400	5	8	87	0	0	200	0	1300	6	2	25	0	0	-
n4	0	50	0	1	0	0	0	100	0	50	0	1	0	0	0	-
n3	0	300	0	6	0	0	0	100	0	300	0	6	0	0	0	-
n2	25	350	1	3	0	0	0	100	0	350	1	3	1	0	0	-
n1	25	150	0	3	0	0	0	100	25	150	0	3	0	0	0	-
	Case-5								**Case-6**							
n11	25	50	0	1	18	32	2	-	0	150	0	3	0	0	0	-
n10	200	250	0	5	59	69	0	-	0	250	1	1	0	0	0	-
n9	50	50	0	1	68	28	4	-	0	100	0	2	4	4	0	-
n8	0	0	0	0	46	44	5	-	0	300	1	2	0	2	0	-
n7	150	200	1	0	95	16	0	-	25	450	2	1	0	0	0	-
n6	25	0	0	0	26	16	1	-	50	50	0	1	0	0	0	-
n5	25	1300	4	10	134	50	71	-	0	1300	6	2	25	0	0	-
n4	0	100	0	2	93	66	2	-	0	50	0	1	0	0	0	-
n3	150	50	0	1	53	32	3	-	0	300	0	6	0	0	0	-
n2	75	250	0	5	32	25	5	-	0	350	1	3	1	0	0	-
n1	25	50	0	1	27	6	6	-	25	150	0	3	0	0	0	-

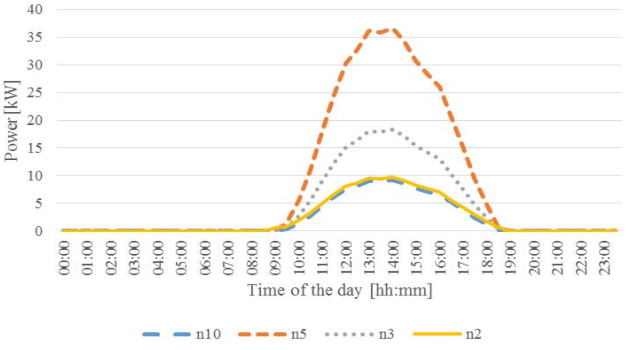

Fig. 14. Daily power curve of PV panels connected to different buses for the first day considered.

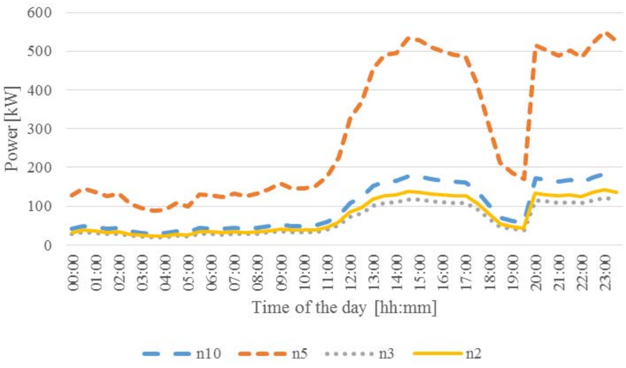

Fig. 15. Daily power curve of wind turbines connected to different buses for the first day considered.

Figs. 14 and 15 for the first day considered. It should be noted that the same characteristics with different power levels are obtained for different buses as the same types of PV panel and wind turbine are considered in the test cases. As seen from Figs. 14 and 15, a considerable amount of renewable energy, which is 801.3 kWh and 18332.1 kWh for solar power and wind power from all the buses respectively, is supplied to the distribution system, which prevents the active power losses that are likely to be faced on both transmission and distribution lines. More importantly, these DG units connected to the optimum buses with the appropriate power rating values

TABLE IX
THE RESULTS OF DIFFERENT CASES FOR HADIMKOY FEEDER

Bus	PV power [kW]	WT power [kW]	N. of WT		N. of EV charging stat.			ESS cap. [kWh]	PV power [kW]	WT power [kW]	N. of WT		N. of EV charging stat.			ESS cap. [kWh]
			Type-1 [50 kW]	Type-2 [200 kW]	Type-1		Type-2				Type-1 [50 kW]	Type-2 [200 kW]	Type-1		Type-2	
					K1 [7.4 kW]	K2 [7.4 kW]	K1 [50 kW]						K1 [7.4 kW]	K2 [7.4 kW]	K1 [50 kW]	
	Case-1								Case-2							
n140	0	100	0	2	0	0	0	100	250	100	0	2	76	33	6	92
n141	0	200	1	0	8	0	0	100	100	200	1	0	69	63	2	92
n142	0	100	0	2	0	0	0	100	25	100	0	2	13	79	3	91
n143	0	200	1	0	6	0	0	93	25	0	0	0	71	69	6	92
n144	0	50	0	1	3	0	0	91	0	50	0	1	44	28	4	91
n139	0	200	1	0	35	0	0	95	175	0	0	0	50	30	1	93
n138	0	150	0	3	1	0	0	100	25	0	0	0	24	28	0	93
n137	0	200	1	0	17	0	0	100	25	50	0	1	94	13	0	93
n149	0	200	1	0	40	0	0	94	100	0	0	0	13	57	0	93
n148	25	200	1	0	5	4	0	97	250	100	0	2	68	22	15	100
n147	0	200	1	0	43	0	0	100	50	0	0	0	51	17	16	91
n103	0	100	0	2	0	0	0	94	100	0	0	0	0	12	1	100
n132	0	300	1	2	0	0	0	92	0	300	0	6	1	43	0	100
n100	0	200	1	0	1	0	0	90	25	150	0	3	1	6	15	100
	Case-3								Case-4							
n140	0	300	1	2	1	0	0	100	0	250	1	1	0	0	0	-
n141	0	200	1	0	7	0	0	100	0	100	0	2	0	0	0	-
n142	0	100	0	2	0	0	0	99	25	100	0	2	1	0	0	-
n143	0	200	1	0	5	0	0	100	0	200	1	0	21	0	0	-
n144	0	50	0	1	5	0	0	99	75	0	0	0	8	2	0	-
n139	0	200	1	0	35	0	0	100	0	100	0	2	3	0	0	-
n138	0	150	0	3	1	0	0	100	0	150	0	3	1	3	1	-
n137	0	200	1	0	17	0	0	100	125	0	0	0	8	1	0	-
n149	0	200	1	0	44	0	0	100	0	100	0	2	0	0	0	-
n148	25	200	1	0	5	4	0	100	25	200	1	0	23	7	0	-
n147	0	200	1	0	38	0	0	100	0	100	0	2	8	0	0	-
n103	0	100	0	2	0	0	0	100	0	0	0	0	2	1	0	-
n132	0	300	1	2	0	0	0	100	0	300	1	2	3	0	0	-
n100	0	200	1	0	1	0	0	100	0	200	1	0	2	0	1	-
	Case-5								Case-6							
n140	25	0	0	0	53	37	1	-	0	250	1	1	0	0	0	-
n141	0	250	0	5	78	29	1	-	0	100	0	2	0	0	0	-
n142	200	100	0	2	89	36	7	-	25	100	0	2	1	0	0	-
n143	100	150	0	3	85	31	8	-	0	200	1	0	21	0	0	-
n144	25	0	0	0	53	0	1	-	75	0	0	0	8	2	0	-
n139	0	50	0	1	16	63	0	-	0	100	0	2	3	0	0	-
n138	0	100	0	2	97	38	9	-	0	150	0	3	1	3	1	-
n137	75	150	0	3	84	29	3	-	125	0	0	0	8	1	0	-
n149	25	150	0	3	55	72	12	-	0	100	0	2	0	0	0	-
n148	0	250	1	1	44	99	14	-	25	200	1	0	23	7	0	-
n147	50	50	0	1	23	41	28	-	0	100	0	2	8	0	0	-
n103	0	0	0	0	24	15	1	-	0	0	0	0	2	1	0	-
n132	0	100	0	2	100	13	1	-	0	300	1	2	3	0	0	-
n100	275	0	0	0	60	26	7	-	0	200	1	0	2	0	1	-

enable power-intensity loads such as EVs to be connected to the distribution systems with the minimum power losses and without being affected by the LV transformer power capacity limits. A high number of EVs can thus be connected to the distribution system and even charged at the same time, as seen from Fig. 16 that shows the load demand of LV buses including the EV charging loads.

During various time periods, the renewable power generation can be low when the total load demand is very high. For such cases, the ESS units have the capability of providing a portion of these demands, which both decreases the resulting power losses caused by the delivery of the required energy from grid to the loads and helps the voltage level remain in the allowable limits. As seen from Figs. 14, 15 and 16, such a case is encountered between 18:00 and 19:00 and during this peak demand period, the ESS units connected to different buses support the distribution system as much as possible as shown in Fig. 16 while limiting the power drawn from the grid through the LV transformer. The buses to which the power from the available ESS units will be injected are determined based on the load demand of the buses, voltage levels of the buses and also the factors influencing

TABLE X
MINIMUM VOLTAGE AND ACTIVE POWER LOSSES
VALUES OBTAINED FOR BOTH FEEDERS

Case	Alibeykoy		Hadimkoy	
	Min. voltage [pu]	Percentage of power losses [%]	Min. voltage [pu]	Percentage of power losses [%]
Case-1	0.998	0.086	0.999	0.054
Case-2	0.936	6.278	0.925	3.404
Case-3	0.998	0.085	0.999	0.054
Case-4	0.998	0.085	0.999	0.059
Case-5	0.930	6.524	0.921	3.482
Case-6	0.998	0.085	0.999	0.059

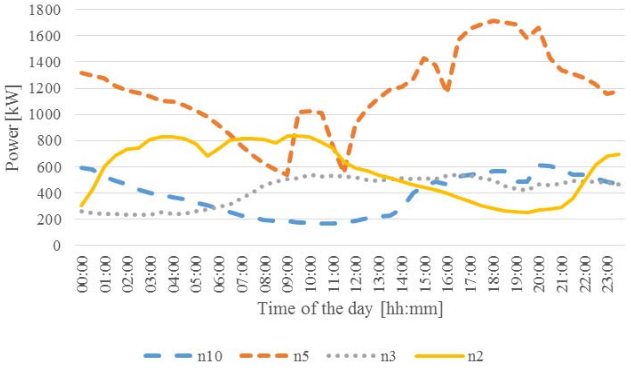

Fig. 16. Daily LV load demand curve connected to different buses for the first day considered.

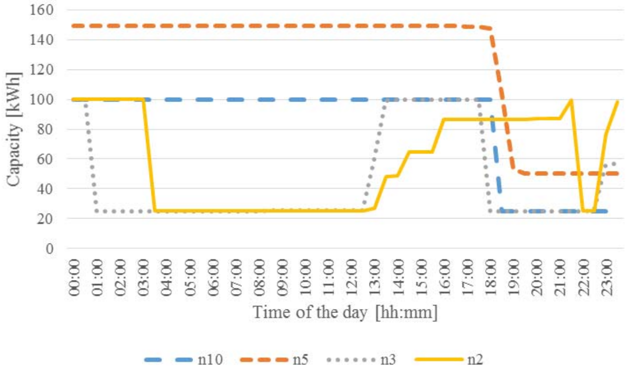

Fig. 17. Daily capacity curve of storage systems connected to different buses for the first day considered.

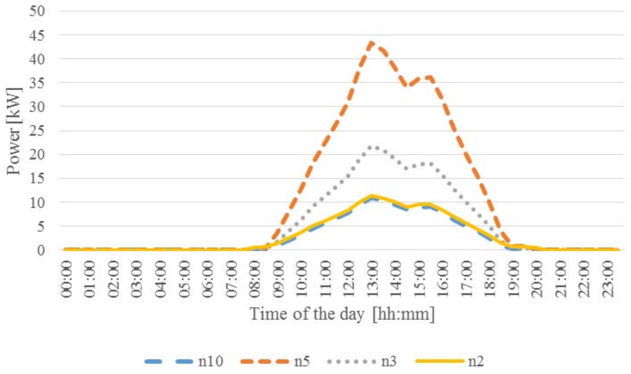

Fig. 18. Daily power curve of PV panels connected to different buses for the second day considered.

the total power losses such as the impedance between the buses.

Regarding the latter representative day, similar generation and consumption profiles can be observed from Figs. 18-21. As a difference from the first day, the generation from the DG units is much higher in this case for almost the same consumption values. Therefore, the ESS units are charged with the excess power frequently compared to the case for the first day. The lower initial capacities of these units are also the other reason for these more frequent charging-discharging interactions.

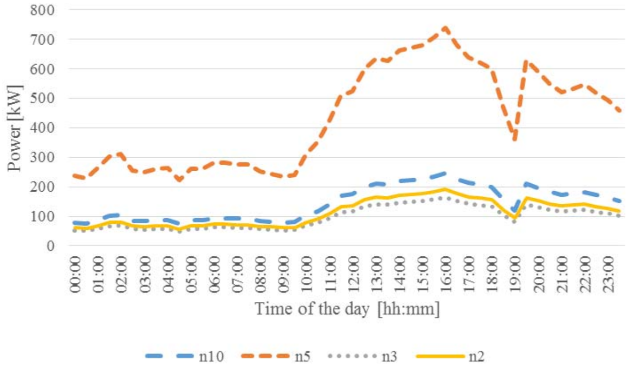

Fig. 19. Daily power curve of wind turbines connected to different buses for the second day considered.

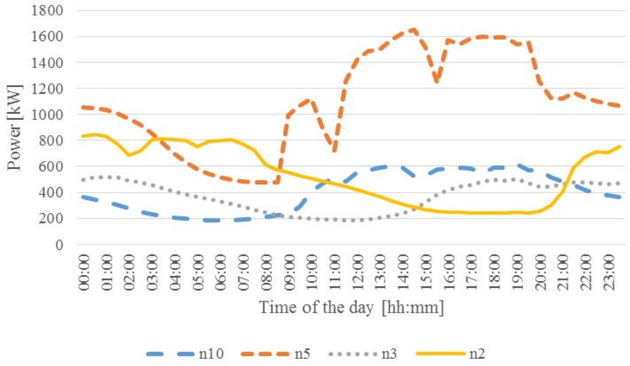

Fig. 20. Daily LV load demand curve connected to different buses for the second day considered.

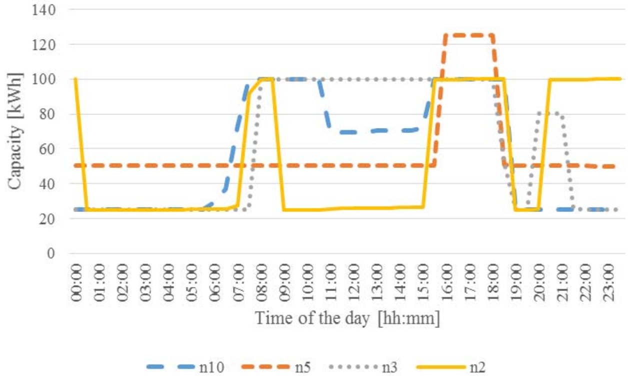

Fig. 21. Daily capacity curve of storage systems connected to different buses for the second day considered.

C. The User Interface

The aforementioned concept normally needs deep understanding of the given formulation in Section II and the understanding of the code written in GAMS. The technical staff of a SO might not be expert in understanding the optimization model that was developed in Section II and manipulate GAMS code. Nevertheless, the results of the procedure might be interpreted on the basis of their technical knowledge. For this reason, an easy-to-use user interface to be used by SO was developed in Java. After the installation of the program the user simply selects the MS Excel file that

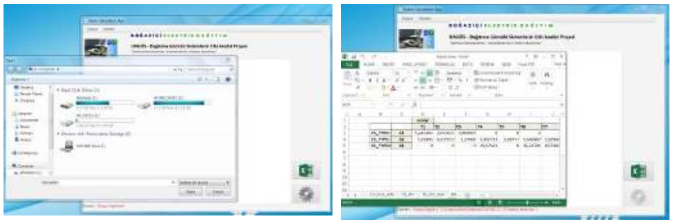

Fig. 22. The input file selection and revision stage for the user interface.

Fig. 23. The pop-up screens presenting the progress of the running code behind and then the results obtained.

contains the optimization model input parameters in an easily understood manner and documented in the User's Guide, as it is shown in Fig. 22. Then, the user simply needs to click the Run button and the GAMS code in the back-end is executed, while the solution progress and finally the output of the simulation results can be followed by the pop-up screens as shown in Fig. 23. The main screen also shows a brief and useful summary of the obtained results where the pop-up Excel folder shows further results in a more detailed version. The graphical user interface has a modular structure where the written GAMS code and all other details can be changed, revised and upgraded easily by following the available User's Guide.

IV. CONCLUSION

In this study, a new concept simultaneously considering the sizing and siting of wind and solar based renewable DG units, EV charging stations of different types serving multiple types of end-users and ESS units for distribution systems was proposed. The proposed approach considered the time dependency of DG based power production and EV and other loads based consumption, on the contrary to the majority of the literature that neglected the time-varying nature of the mentioned factors. Comprehensive simulations were conducted with the real distribution system and load data of BEDAS for two different real distribution system parts of Istanbul, Turkey. Besides, an SO interface for non-expert users of the proposed algorithmic structure was developed.

The future studies on this topic can consider the possible flexibility of loads with demand response strategies. Besides, the stochasticity regarding several parameters such as DG based production, EV (regarding plug-in times, arrival SoE values and desired departure SoE values) and other loads based consumption can also be taken into account by transforming the proposed formulation into a stochastic programming concept. Moreover, the investment, replacement and maintenance costs of SO owned assets such as ESS units rather than private investment related costs can also be considered in the planning problem in upcoming studies.

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