Sustainable and Inclusive Demand-Side Resilience: A Semi-Dynamic Model for Outage Costs

Ali Safamanesh, Mohammad Sadegh Ghaziziadeh, Mahdi Habibi
Department of Electrical Engineering
Abbaspour School of Engineering
Shahid Beheshti University
Tehran, Iran
{a_safamanesh},{m_ghazizadeh},{m_habibi}@sbu.ac.ir

Vahid Vahidinasab*
Department of Engineering
School of Science and Technology
Nottingham Trent University
Nottingham, UK
vahid.vahidinasab@ntu.ac.uk

***Abstract*—The power system is primarily designed and concerned with supplying electricity to its customers at all times. Nevertheless, power outages are inevitable; therefore, one of the challenges is to accurately determine the costs and damages to consumers in a fair and inclusive manner. Outage events are regularly costed based on a parameter called the Value of Lost Load (VoLL/VOLL). Although some of the influencing factors on outage costs have been identified in the literature, the exact determination of the damage to customers is still considered a big challenge. This work is an effort toward a more sustainable and inclusive demand-side resilience that provides a semi-dynamic model for the assignment of the power outage damage costs to the customers. The results of the proposed method show how using a semi-dynamic model for outage costs leads to more sustainable and inclusive operating decisions in the power system while also leads to a fairer allocation of costs.**

***Index Terms*—Demand-side resilience, non-linear value-of-lost-load, outage cost, sustainability, affordability, security-of-supply.**

NOMENCLATURE

Indices & Sets

b	Index of buses.
g	Index of generators.
l	Index of load buses.
m	Index of transmission lines.
t	Index of time.
κ, μ	Sets of generators/loads connected to bus b.

Vatiables

$DNS_{l,t}$	Demand not supplied [MWh].
$VOLL^{*}_{DNS,l}$	Smei-Dyanamic form of VOLL [$/MWh].
$P_{g,t}$	Output power of generators [MW].
$suc_{g,t}$	Start-up cost of generators [$].
$st_{g,t}$	Binary variable of generators' start-up.
$sd_{g,t}$	Binary variable of generators' shut-down.
$I_{g,t}$	Binary online/offline status of generators.
$pf_{m,t}$	Line power flow [MW].
$\delta_{b,t}$	Angle of buses [Rad].

Constants

$VOLL$	Value of lost load [$/MWh].
K_l	Priority of load buses.
SUC_g	Start-up cost [$].
$T_{\mathrm{g}}^{\mathrm{on,min}}$	Minimum up-time of generators [h].
$T_{\mathrm{g}}^{\mathrm{off,min}}$	Minimum down-time of generators [h].
$P_{l,t}$	Hourly demand [MW].
B_b^m	Incidence matrix of connected lines to buses.
X_m	Reactance of transmission lines [p.u.].
Ru_g, Rd_g	Ramp-rate limits of generators [MW/h].
S_{base}	Base power of per-unit system [MW].
$\delta_b^{max/min}$	Maximum/minimum of bus angle [Rad].
$PF_m^{max/min}$	Maximum/minimum of power flow [MW].
α	The weighting factor for demand not supplied.
Δt	Length of each time step [h].

I. INTRODUCTION

Electricity from renewable sources is a crucial part of the worldwide effort toward decarbonization, especially for decarbonizing hard-to-decarbonize sectors (such as heating and transportation) [1]. Electricity is needed for almost every activity, and any interruption can cause significant damage to all consumers. On the other hand, supplying energy at all times may be impossible from an economic point of view. As a result of high investment costs and some unforeseen events, power system interruption and outages are inevitable, and sometimes supply outages to consumers are acceptable but expensive operative decisions. So, it is necessary to study the cost of the outage.

A. Aim and Scope

Since load shedding could be an option to restore the system after a disruption, evaluating the Demand not supplied (DNS) must be done carefully. In this regard, the concept of Value of Lost Load (VOLL) is defined as a parameter that expresses the cost of DNS. The VOLL estimates the costs of an outage in many applications of the power system.

By studying VOLL, one essentially seeks answers to the questions formulated in [2]: "*What is a consumer willing-to-pay to avoid an interruption?*", and "*What is a consumer willing-to-accept to agree for an interruption?*". Thus, the economic optimum is reached when the marginal cost of enhancing reliability is equal to the marginal benefits for consumers. While from the investments made by the system operator and their impact on system performance, it is possible

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to estimate the marginal cost of increasing reliability, estimating consumers' perceptions of benefits is more difficult, and further research on consumers' behavior is needed.

B. Literature Survey

Power outages occur when the electrical system supplies less electricity to electricity customers than they require [3]. Outages have different consequences for customers depending on how dependent they are on the power [4] and how long the interruption lasts. VOLL is generally used to determine the cost of power interruptions. According to the definition, the value that an average customer places on an unsupplied MWh is called the VOLL. [5]. It has been used in a variety of applications, such as load curtailment, in order to determine the optimal level of reliability in a power system [6], network investment decisions, cost-benefit analyses, quality incentive schemes of transmission and distribution networks, generation reserve procurement [7], generation capacity investment, and reliability standards [8].

Numerous studies have examined outage costs and VOLL for various regions/countries and considered a variety of factors [9], [10], [11]. There are several factors involved in this process, including interruption duration, time of interruption, type of interruption, etc. [12]. It is still common for applications to simplify the VOLL to a single, constant value despite the availability of detailed VOLL data [13]. It represents the weighted average of VOLL for different consumers.

Based on [14], blackout factors can be classified into three categories: "technical factors," "load-side factors," and "social factors.". Technical factors include the outage duration, region, frequency of outages, time of the outage (i.e., season or hour of the day), and existence of advance warning to customers [15]. Load-side factors refer to those factors that worsen the damage resulting from the structure of the electricity customer [16]. Load factors include the type and number of electricity customers and the degree of their dependence on electricity, as well as the availability of standby power. Finally, the social factors refer to regional differences in the economic and social environments, such as special social and cultural events held on some special days in some countries.

C. Research Gap and Contribution

Although previous works consider some factors which incorporate the influence of the VOLL and outage costs, it is still a challenging matter and needs more investigation to be carried out on consumers' behavior.

The costs of consumers' supply interruption were conventionally calculated by multiplying the unsupplied demand by the VOLL [17]. However, it should be noted that determining the damage to consumers is much more complicated and does not necessarily increase linearly with the increase of DNS. Different demands of consumers have different importance and priorities; therefore, this method does not reflect the costs of an outage. In this paper, we take a deeper look into the damage caused to consumers in the event of a disruption and present a new method for calculating the outage costs. The proposed model takes a semi-dynamic (non-fixed) outage cost that leads to a more sustainable and inclusive demand-side participation in resilience provision.

D. Organization

This paper is organized as follows. A semi-dynamic form is described in Section II for calculating outage costs. Section III shows the impacts of the proposed model on the operation of a power system by applying it to the unit commitment problem. A summary of the simulation results is provided in Section IV and the paper is concluded in section V.

II. Proposed Method

As mentioned earlier, the actual damage to consumers does not necessarily increase with the increase of DNS. To take a deeper dive into demand-side damage after a power outage and show the impact of demand not supplied, we can use a simple example. Assume that a residential consumer has been interrupted because of an event in the system. In the first scenario, we assume that 90 percent of this consumer's demand could be met and supplied by the power system. In this situation, this interruption does not have a major effect on the consumer's comfort and welfare, and there will not be a big damage. This situation can be resolved with some changes in the utilization of the customer's less important appliances. In the second scenario, assume that the power system can only supply 50 percent of this consumer's demand due to a bigger and more severe event in the system. In this situation, there will be much bigger damage to the consumers' comfort and welfare to the extent that the consumer may have difficulties even with his/her crucial and critical demands. according to this example, outage cost and damage after an outage does not have a linear relation to DNS. As a result, using a constant value for VOLL and then calculating outage costs as a linear function of DNS may not reflect the real damage to the consumers. So, in this paper, we propose a semi-dynamic model to calculate the outage costs, which are related to the percentage of DNS.

As mentioned earlier, the outage cost in the power system can be calculated by multiplying DNS by VOLL:

$$OutageCost = \sum_{l \in L} VOLL_l \times DNS_l \times \Delta t \tag{1}$$

According to the equation above, a fixed value is used to indicate the VOLL in each bus. This equation shows the calculation of the outage cost in a linear way, where the VOLL is a constant value and has no dependence on the DNS. As mentioned, if the disruption is small, and therefore the percentage of DNS is small, it may not seriously harm the consumer's comfort. But as the percentage of DNS increases, the harm to consumers' comfort increases even to the point that they even can not meet their crucial needs. Therefore, the equation above cannot show the real damage to the consumers in case of a disruption. It can be noted that the damage to consumers does not increase linearly with the increase in the

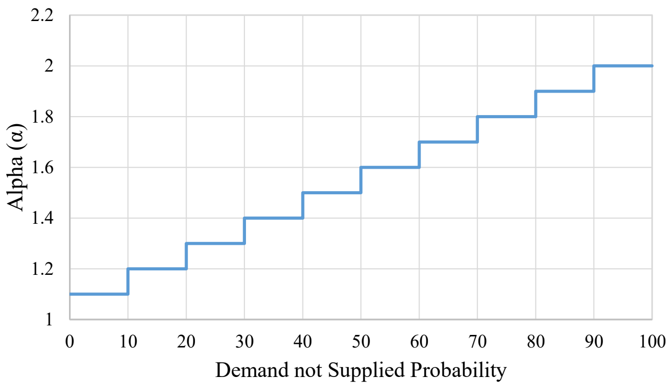

Fig. 1. A representation of α with 10 steps.

demand not supplied probability. This section presents a semi-dynamic model to calculate the outage cost, in which the VOLL is proportional to the DNS. In the following, the idea of considering VOLL in a stepped form proportional to the percentage of DNS is proposed.

If $VOLL_l$ is the fixed value of lost load for load bus l, then the semi-dynamic (stepped) form of outage cost can be calculated using the equations below:

$$\texttt{if} \quad 0 \leq DNS_l \leq 10\% \qquad \texttt{then} \quad \alpha = 1.1 \tag{2}$$

$$\texttt{if} \quad 10\% < DNS_l \leq 20\% \qquad \texttt{then} \quad \alpha = 1.2 \tag{3}$$

$$\vdots$$

$$\texttt{if} \quad 90\% < DNS_l \leq 100\% \qquad \texttt{then} \quad \alpha = 2.0 \tag{4}$$

$$VOLL^*_{DNS,l} = \alpha \times VOLL_l \tag{5}$$

$$OutageCost = \sum_{l \in L} k_l \times VOLL^*_{DNS,l} \times DNS_l \times \Delta t \tag{6}$$

where $VOLL^*_{DNS,l}$ is the semi-dynamic form of VOLL, and α is a weighting factor. According to (2)-(4), with the increase in the percentage of DNS, the weighting factor α increases. Finally, $VOLL^*_{DNS,l}$ is calculated by multiplying α by $VOLL_l$. Sometimes there are some buses in the power system which are more critical and have a higher priority due to the types of consumers on that bus. In (6), K_l is a coefficient that reflects the priority of each bus of the system. Higher k_l for a bus means that the desired bus has a higher priority from the operator's perspective.

The α coefficient with ten steps is shown in Fig.1. Here, it should be noted that the accurate determination of α and the number of steps requires extensive studies. This paper only intended to present the conceptual idea; hence, estimating α values in different situations requires more studies, designing a questionnaire for consumers, etc., which is outside of the scope of this paper.

III. Model Applied to Unit Commitment Problem

In this section, we use the unit commitment (UC) problem to show the effects of using the proposed semi-dynamic model for outage costs. Minimizing the outage costs can be used in the operation of the power system after a disturbance [18]. Here it is assumed that the power system has faced some limitations in generation units and load shedding is one of the solutions that can be used. The UC problem shows how the utilization of the semi-dynamic model for outage costs leads to different operating decisions.

The objective function of the UC problem is to minimize the operating cost, which contains the penalty associated with reducing damages to consumers due to load shedding. The UC problem is widely used in operational planning, and the corresponding formulation is described in the literature [19], [20]. Accordingly, the proposed UC model is presented in (7) to (19).

$$\begin{aligned} Min \ \ Cost = & \sum_{t \in T} \sum_{g \in G} c_g(P_{g,t}) + SUC_{g,t} + \\ & \sum_{t \in T} \sum_{l \in L} VOLL^*_{DNS,l} \times DNS_{l,t} \times \Delta t \end{aligned} \tag{7}$$

$$suc_{g,t} = SUC_g \times st_{g,t} \tag{8}$$

$$st_{g,t} + sd_{g,t} \leq 1 \tag{9}$$

$$I_{g,t} - I_{g,(t-1)} = st_{g,t} - sd_{g,t} \tag{10}$$

$$\sum_{t'=t+1-T_{\text{g}}^{\text{on,min}}}^{t} st_{g,t'} \leq I_{g,t}, \qquad \forall g, t \in \left[T_{\text{g}}^{\text{on,min}}, NT\right] \tag{11}$$

$$\sum_{t'=t+1-T_{\text{g}}^{\text{off,min}}}^{t} sd_{g,t'} \leq 1 - I_{g,t}, \ \forall g, t \in \left[T_{\text{g}}^{\text{off,min}}, NT\right] \tag{12}$$

$$P_g^{\text{min}} I_g^t \leq p_{g,t} \leq P_g^{\text{max}} I_g^t \tag{13}$$

$$p_{g,t} - p_{g,(t-1)} \leq Ru_g I_{g,(t-1)} + RS_g st_{g,t} \tag{14}$$

$$p_{g,(t-1)} - p_{g,t} \leq Rd_g I_{g,(t-1)} + RD_g sd_{g,t} \tag{15}$$

$$pf_{m,t} = S_{\text{base}} \sum_b \left(B_b^m \delta_{b,t}\right) / X_m \tag{16}$$

$$-\delta_b^{\text{max}} \leq \delta_{b,t} \leq \delta_b^{\text{max}} \tag{17}$$

$$-PF_m^{\text{max}} \leq pf_{m,t} \leq PF_m^{\text{max}} \tag{18}$$

$$\sum_{g \in \kappa} p_{g,t} = \sum_{l \in \mu} (P_{l,t} - DNS_{l,t}) + \sum_m B_b^m pf_{m,t}^s \tag{19}$$

As (7) represents, the objective function consists of three parts. In the first part, c_g is the cost function of generation units. The second part includes generators' start-up costs, and the third shows the damage caused by load shedding. The constraints considered in the problem consist of binary start-up/shut-down constraints, generation limits, and ramp rate limits, which are presented in equations (9) to (15). It should be noted this paper uses DC power flow constraints to solve the problem, while generation and Line flow limits refer to the output power limits of generators and line power-flow limits, respectively (equations (16)-(19)).

IV. Results

The simulation is performed on an IEEE 24-bus test system. It is assumed that several generation units are out of service,

TABLE I
PRIORITIES OF DIFFERENT BUSES IN THE SYSTEM

	buses
Priority-1	4, 8, 16, 20
Priority-2	3, 7, 15, 19
Priority-3	2, 6, 10, 14, 18
Priority-4	1, 5, 9, 13

TABLE II
FEATURES OF THE TEST-CASES

	Specifications	
	Priority of Demands	VOLL Type
Case-1	NO	Fixed
Case-2	Yes	Fixed
Case-3	Yes	DNSP

and therefore the power system is facing a generation limitation.

Since load shedding is often considered the last solution of operation, the values of VOLL for each bus are considered much higher than the costs associated with generation units. Here, system buses are divided into four different groups and priorities. Priority-1 buses have the highest VOLL value. In contrast, buses categorized in Priority-4 have the lowest VOLL value and are more suitable options for load shedding. Table I shows the priority of different buses.

To show the effect of using the proposed method on load-shedding decisions, the problem is solved in three different cases presented in Table II. In Case-1, a fixed VOLL is used for each bus, and all buses are assumed to have the same priority. In Case-2, a fixed VOLL is used, but each bus has different priorities based on TABLE I. In Case-3, the VOLL proportional to the DNS is used according to the proposed method.

The optimization problem is solved for all cases for 24 hours, and the amount of load shedding is calculated for different buses of the system. It is assumed that all loads are flexible and can change within certain ranges. This flexibility is performed by demand response. After solving the problem, the amount of load shedding in different buses of the system at 18:00 (peak load hour) for three cases is shown in Fig.2, Fig.3, and Fig.4.

According to Fig.2, in Case-1, where the linear outage cost is used, all buses have the same priority, and there is no difference between the system buses. In this case, load shedding occurs randomly in some buses, and the load in other buses is fully supplied. This is not a desirable situation because there are different types of consumers. Therefore, the priority of each bus should be different. In addition, some buses in the system may have very important and critical loads, such as medical centers. In this case, any disruption in the electricity supply in these buses can cause irreparable damage. Therefore, it is necessary to consider a different priority for each bus according to its loads.

According to Fig.3, in Case-2, where the linear outage cost is used, all the load shedding occurs in the buses with lower priorities, and the load in other buses is fully supplied. Since the objective function is to reduce costs and damages, the obtained result seems reasonable. In Case-3 (Fig.4), where the semi-dynamic outage cost is used, it can be seen that load shedding is divided between different buses. In this case, the amount of load shedding is also according to the priority of

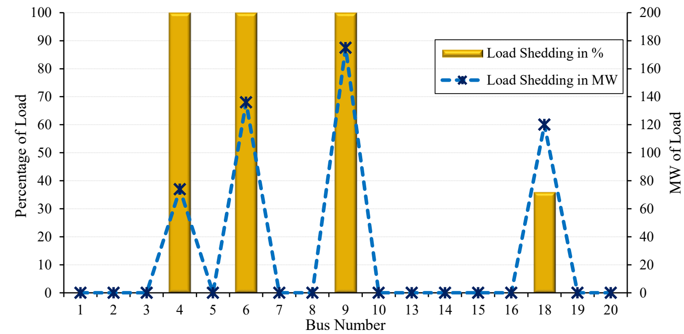

Fig. 2. The percentage of DNS in the load buses during the peak load hour-linear outage costs without bus priorities (Case-1)

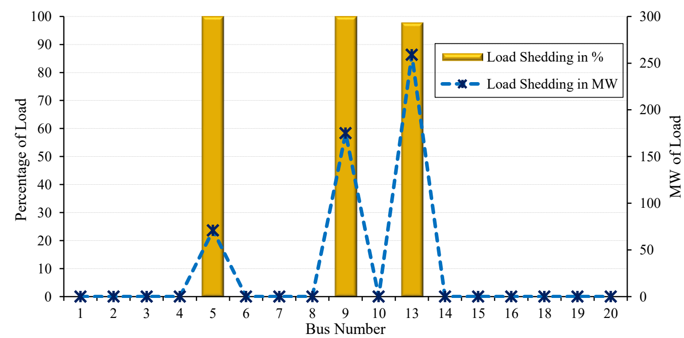

Fig. 3. The percentage of DNS in the load buses during the peak load hour-linear outage costs with bus priorities (Case-2)

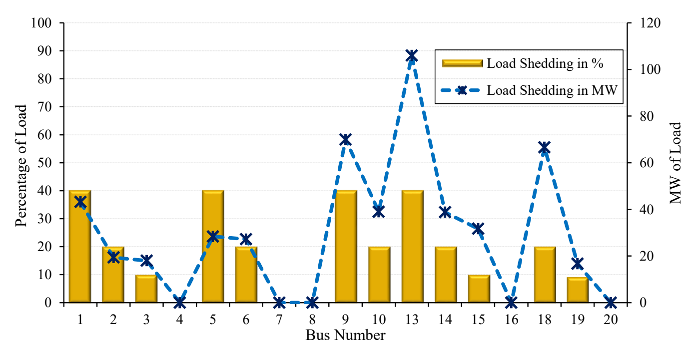

Fig. 4. The percentage of DNS in the load buses during the peak load hour-Proposed Method (Case-3)

the buses, and the maximum of it occurs in the low-priority buses, but other buses have also faced some limitations. As mentioned earlier, the decision regarding the load shedding is made to reduce the damages to consumers; so in this case, instead of increasing the percentage of DNS in low-priority buses, some of the load in the buses with higher priorities have also been shed. A small amount of load shedding in these buses does not cause major damage to the consumers, and with proper load management on the consumer's side, this limitation can be controlled with minimal damage.

The obtained results for load shedding happen due to the application of the proposed semi-dynamic outage cost and non-fixed VOLL. In this case, the damage to consumers does not increase linearly with the increase of DNS, and a small amount of load shedding in the buses with higher priorities is more economical and does not cause much damage compared to more load shedding in low-priority buses.

V. Conclusion

The value of the lost load parameter indicates the damage caused to consumers in case of a power outage. Determining the amount of this damage is complicated and depends on various parameters and factors. Previous studies have identified a few related factors on the value of lost load and outage costs. However, the amount of damage in the case of a disturbance does not increase linearly with demand not supplied, and it has not been addressed so far. This paper presented a semi-dynamic model of outage cost, which used the value of lost load changes with the amount of demand not supplied to reflect a better consideration of consumers' damage during an outage. The unit commitment problem has been solved to investigate the behavior of the power system using the proposed method and determine the amount of load shedding in different buses during a generation limitation. The results showed how utilizing the proposed model leads to varied decisions regarding load shedding. As for future directions, this field still needs more detailed research on the behavior of consumers to model the actual damage to consumers in case of an outage. Whilst the focus of this work was on one of the influencing factors, there is a need to consider other factors, such as duration, time, frequency of events, etc., in a single model.

References

[1] V. Vahidinasab and B. Mohammadi-Ivatloo, *Whole Energy Systems: Bridging the Gap Via Vector-Coupling Technologies*. Springer Nature, 2022.

[2] K. Kariuki and R. N. Allan, "Evaluation of reliability worth and value of lost load," *IEE proceedings-Generation, transmission and distribution*, vol. 143, no. 2, pp. 171–180, 1996.

[3] V. S. Ajodhia, "Regulation beyond price: integrated price-quality regulation for electricity distribution networks," 2006.

[4] A. P. Sanghvi, "Economic costs of electricity supply interruptions: Us and foreign experience," *Energy Economics*, vol. 4, no. 3, pp. 180–198, 1982.

[5] P. Cramton and J. Lien, "Value of lost load," *University of Maryland (February)*, 2000.

[6] P. Joskow and J. Tirole, "Reliability and competitive electricity markets," *The RAND Journal of Economics*, vol. 38, no. 1, pp. 60–84, 2007.

[7] F. M. Baldursson, E. Lazarczyk, M. Ovaere, and S. Proost, "Cross-border exchange and sharing of generation reserve capacity," *The Energy Journal*, vol. 39, no. 4, 2018.

[8] M. Munasinghe and M. Gellerson, "Economic criteria for optimizing power system reliability levels," *The Bell Journal of Economics*, pp. 353–365, 1979.

[9] B. E. Baarsma and J. P. Hop, "Pricing power outages in the netherlands," *Energy*, vol. 34, no. 9, pp. 1378–1386, 2009.

[10] A. Chowdhury, T. Mielnik, L. Lawion, M. Sullivan, and A. Katz, "Reliability worth assessment in electric power delivery systems," in *IEEE Power Engineering Society General Meeting, 2004.* IEEE, 2004, pp. 654–660.

[11] E. Wojczynski, R. Billinton, and G. Wacker, "Interruption cost methodology and results-a canadian commercial and small industry survey," *IEEE Transactions on power Apparatus and Systems*, no. 2, pp. 437–444, 1984.

[12] M. De Nooij, R. Lieshout, and C. Koopmans, "Optimal blackouts: Empirical results on reducing the social cost of electricity outages through efficient regional rationing," *Energy Economics*, vol. 31, no. 3, pp. 342–347, 2009.

[13] M. Ovaere, E. Heylen, S. Proost, G. Deconinck, and D. Van Hertem, "How detailed value of lost load data impact power system reliability decisions," *Energy Policy*, vol. 132, pp. 1064–1075, 2019.

[14] A. Ratha, E. Iggland, and G. Andersson, "Value of lost load: How much is supply security worth?" in *2013 IEEE Power & Energy Society General Meeting*. IEEE, 2013, pp. 1–5.

[15] T. Schröder and W. Kuckshinrichs, "Value of lost load: An efficient economic indicator for power supply security? a literature review," *Frontiers in energy research*, vol. 3, p. 55, 2015.

[16] D. W. Caves, J. A. Herriges, and R. J. Windle, "Customer demand for service reliability in the electric power industry: A synthesis of the outage cost literature 1," *Bulletin of Economic research*, vol. 42, no. 2, pp. 79–121, 1990.

[17] D. S. Kirschen, "Power system security," *Power Engineering Journal*, vol. 16, no. 5, pp. 241–248, 2002.

[18] A. Safamanesh, "Enhancement of distribution system resiliency, considering demand quota for consumers," Master's thesis, Shahid Beheshti University, August 2022.

[19] M. Habibi, V. Vahidinasab, B. Mohammadi-Ivatloo, J. Aghaei, and P. Taylor, "Exploring potential gains of mobile sector-coupling energy systems in heavily constrained networks," *IEEE Transactions on Sustainable Energy*, vol. 13, no. 4, pp. 2092–2105, 2022.

[20] M. Habibi, V. Vahidinasab, and M. S. Sepasian, "A privacy-preserving approach to day-ahead tso-dso coordinated stochastic scheduling for energy and reserve," *IET Generation, Transmission & Distribution*, vol. 16, no. 1, pp. 163–180, 2022.