

Strength Pareto Evolutionary Algorithm for the Dynamic Economic Emission Dispatch Problem incorporating Wind Farms and Energy Storage Systems

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Abstract—Intermittent and stochastic characteristics of wind energy sources cause many challenges for the existing power networks. One of these challenges is the violation of the energy balance constraint due to the high penetration of wind power. The use of Energy Storage Systems (ESSs) can facilitate the high penetration of wind power and mitigate the effect of its intermittency. Within this context, ESS incorporate the Dynamic Economic Emission Dispatch (DEED) problem. The problem is formulated as a multi-objective problem and the Strength Pareto Evolutionary Algorithm (SPEA) is used for its resolution. Simulations were carried out on a well-known ten-unit system and the results show the importance of using ESSs in reducing the total production cost of electricity and total emissions.

Keywords—dynamic dispatch; wind energy; energy storage systems; evolutionary algorithm

I. INTRODUCTION

Due to the energy shortage and the increasing pressure to protect the environment, wind energy is gaining attention. Wind is considered a clean energy source and can mitigate the dependence on fossil fuels. However, the random characteristics of the wind speed result in volatility and uncertainty of the wind power output. Consequently, high penetration of wind power may cause a negative impact on the system stability and lead to the violation of the energy balance constraint [1]. In fact, once the wind power penetration becomes more than 5% of the total energy production, the power quality will be influenced by the uncertainty of the wind power [2]. Therefore, in wind-thermal systems, it is important to allocate perfectly the generation of all units including wind power in order to alleviate wind power curtailment. This problem is referred to as the power dispatch problem. Several research works have handled the optimal dispatch for the wind-thermal systems. The resolutions of such problems have been based on quadratic programming, Genetic Algorithm (GA) [3], Particle Swarm Optimization (PSO) [4], simulated annealing [5], harmony search [6], firefly algorithm [7], chemical reaction optimization [8], etc. The uncertainty of the wind

power output is handled with different manners, such as scenario method [9], forecast error method [10], stochastic programming [11], probability theory-based model [12], fuzzy logic [13], and chance constraint model [14]. For example, a chance constraint-based formulation for the dispatch problem was described in [15]. In [16], the intermittent nature of the wind power was described by evaluating its underestimation and overestimation costs and was then incorporated in the wind-based economic emission dispatch problem.

The recent trend is directed towards the integration of ESSs into wind-thermal systems regarding the power dispatch problem. Recent studies [17, 18] have demonstrated that ESSs can decrease operational cost, improve the power system's reliability, and mitigate the impact of wind power fluctuations. Battery energy storage sizing technique has been intensively discussed in [19]. The study explored the relationship between the size of centralized battery storage and operation cost of distributed generation in a microgrid using economic power dispatch. It explained how optimal capacity storage within a specified investment cost and predefined system constraints could provide a significant reduction in operation cost. The battery storage of the study has also created opportunities for the microgrid to trade energy in the electricity market during off-peak times, which increases the benefits of the dispatchable generating units. A technique based on back-propagation neural network and multi-objective PSO was proposed in [17] for optimum siting and sizing of ESSs in hybrid wind-diesel power networks. In [18], an ESS was utilized in the DEED problem when intermittency and uncertainty of the wind power is described by a chance constraint. Authors in [20] used Markov chain to simulate PV and wind power and then applied the PSO algorithm to dispatch the thermal units and ESSs' outputs. The DEED problem aims to find the optimum schedule of power generation in order to minimize simultaneously total production cost and emission of harmful gases. The focus of this paper is to solve the DEED problem incorporating wind farms and ESSs. The main contributions of this study are:

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- The problem is represented as a multi-objective problem and the SPEA is used to provide the best solutions. Total fuel cost and total emission functions are minimized simultaneously.
- To address the uncertainty of the wind power output, the energy balance is converted into a stochastic constraint.
- The effectiveness of the proposed method is verified on a ten-unit system and through comparison with other published optimization techniques. The simulation results show that the incorporation of wind power and ESSs into the DEED problem may decrease cost and emissions.

II. MATHEMATICAL MODELING OF THE PROBLEM

A. Modeling of the Wind Power for the Dispatch Problem

The uncertainty of the wind power is modeled by a chance constraint and a Probability Distribution Function (PDF) is used to describe the stochastic nature of the wind speed. The Weibull PDF given in (1) is proposed to describe the wind speed distribution. The corresponding Cumulative Distribution Function (CDF) is given in (2).

$$f_V(v) = \frac{k}{c} \left(\frac{v}{c}\right)^{k-1} \exp\left[-\left(\frac{v}{c}\right)^k\right] \quad (1)$$

$$F_V(v) = \int_0^v f_V(\tau) d\tau = 1 - \exp\left[-\left(\frac{v}{c}\right)^k\right], \quad v \geq 0 \quad (2)$$

where, v is the wind speed. Parameters k and c are the shape and scale factors. These parameters depend on the geographical location of the wind source. Several techniques such as least squares fit method and method of moments have been suggested to estimate the values of k and c [15].

The probability to have wind power equal to or less than w is given in (3) [18], where, v_{in} , v_{out} and v_r are cut-in, cut-out, and rated wind speeds respectively.

$$F_W(w) = \Pr(W \leq w) = \begin{cases} 0, & (w < 0) \\ 1 - \exp\left[-\left(\frac{\left(\frac{v_r - v_{in} w}{1 + \frac{v_{in}}{w_r}}\right) v_{in}}{c}\right)^k\right], & 0 \leq w < v_r \\ + \exp\left[-\left(\frac{v_{out}}{c}\right)^k\right], & 0 \leq w < w_r \\ 1, & (w \geq w_r) \end{cases} \quad (3)$$

B. Objective Functions and Constraints

The DEED problem is formulated as an optimization problem, where the objective functions to be minimized are the

total fuel cost FT and the total emission ET. These functions are [21]:

$$F_T = \sum_{h=1}^H \sum_{i=1}^N a_i + b_i P_{i,h} + c_i (P_{i,h})^2 + \left| d_i \sin\{e_i (P_i - P_{i,h})\} \right| \quad (4)$$

$$E_T = \sum_{h=1}^H \sum_{i=1}^N \alpha_i + \beta_i P_{i,h} + \gamma_i (P_{i,h})^2 + \eta_i \exp(\lambda_i P_{i,h}) \quad (5)$$

where $a_i, b_i, c_i, d_i,$ and e_i are cost coefficients and $\alpha_i, \beta_i, \gamma_i, \eta_i,$ and λ_i are emission coefficients.

The previous objective functions are optimized under the following constraints:

1) Generation Limits

$$\underline{P}_i \leq P_{i,h} \leq \bar{P}_i, \quad i = 1, \dots, N \quad (6)$$

$$0 \leq W_h \leq w_r \quad (7)$$

2) Ramp Rate Limits

$$P_{i,h-1} - P_{i,h} \leq U_i^{down} \quad (8)$$

$$P_{i,h} - P_{i,h-1} \leq U_i^{up} \quad (9)$$

where U_i^{down} and U_i^{up} are the prohibited operating zones of unit i .

3) Constraints Related to the ESS

The Constraints of the ESS are described below. Equation (10) states the energy conversion. Equations (11), (12) and correspond to the limits of charging and discharging powers of the ESS and its storage capacity respectively.

$$E_{s,h} = E_{s,h-1} + \eta_c P_{sc,h} CH_{s,h} \Delta t - P_{sd,h} DC_{s,h} \frac{\Delta t}{\eta_{sd}} \quad (10)$$

$$0 \leq P_{sc,h} \leq k_{sc} \times E^{cap} \quad (11)$$

$$0 \leq P_{sd,h} \leq k_{sd} \times E^{cap} \quad (12)$$

$$0 \leq E_{s,h} \leq E^{cap} \quad (13)$$

$$CH_{s,h} \times DC_{s,h} = 0 \quad (14)$$

where $k_{sc} \in [0,1]$ and $k_{sd} \in [0,1]$.

4) Energy Balance Constraint

When wind power and ESSs are integrated into the DEED problem, the energy balance constraint can be described by a chance constraint in order to take into account the wind power intermittency. This constraint can be written as:

$$F_W \left(P_{D,h} + loss_h - \sum_{i=1}^N P_{i,h} - W_h - P_{sc,h} CH_{s,h} + P_{sd,h} DC_{s,h} \right) \leq \zeta \quad (15)$$

where $loss_h$ is the total losses at hour h . It may be calculated using B-loss formula as given in (16):

$$loss_h = \sum_{i=1}^N \sum_{j=1}^N P_{i,h} B_{ij} P_{j,h} + \sum_{i=1}^N B_{oi} P_{i,h} + B_{oo} \quad (16)$$

where B_{ij} , B_{oi} and B_{oo} are the loss-coefficient matrices.

III. PROPOSED ALGORITHM: SPEA APPROACH

SPEA [21] is an elitist multi-objective evolutionary algorithm. A brief description of the SPEA is given in this section. For more detailed explanation, the interested reader can be referred to [21]. The main steps of an iteration of SPEA are:

- Step 1: Generate the initial population P_0 with N_{pop} individuals, set the external archive $P'_0 = \emptyset$ and $t=0$.
- Step 2: Extract the Pareto solutions from P_t referred as $PARETO(P_t)$.
- Step 3: Set $P'_t = P'_t \cup PARETO(P_t)$.
- Step 4: Set $P'_t = PARETO(P'_t)$.
- Step 5: If $size(P'_t) > N'$, reduce P'_t with the clustering method.
- Step 6: Assign the strength Pareto of each individual i from P'_t defined as given in (17), where n_i is the number of solutions from P_t that are dominated by or are equal to the individual i .

$$S_i = \frac{n_i}{N_{pop} + 1} \quad (17)$$

- Step 7: Assign the fitness f_j of each solution X_j from the current population P_t as given in the following equation:

$$f_j = 1 + \sum_{i < j} S_i \quad (18)$$

- Step 8: Combine the current population P_t and the external archive P'_t . Then, use selection, crossover, and mutation operations to generate the new population P_{t+1} .

- Step 9: Set $t=t+1$.
- Step 10: If $t < t_{max}$ return to step 2. Else the archived members are the Pareto optimal solutions.

IV. SIMULATION RESULTS

A. Presentation of the Ten-unit System

In this section, the ten-unit system is used to prove the feasibility of the proposed optimization method for solving the DEED problem. All cited operating constraints are considered. The B-loss matrix of the ten-unit system is given in (19). Both cost and emissions are optimized individually and simultaneously according to the variation of the power demand $P_{D,h}$ in MW over a time period of one day, subdivided into 24 time intervals of one hour. Unit data are

taken from [18]. Wind source and ESS parameters are as given in [18].

$$B = 10^{-4} \begin{bmatrix} 0.49 & 0.14 & 0.15 & 0.15 & 0.16 & 0.17 & 0.17 & 0.18 & 0.19 & 0.20 \\ 0.14 & 0.45 & 0.16 & 0.16 & 0.17 & 0.15 & 0.15 & 0.16 & 0.18 & 0.18 \\ 0.15 & 0.16 & 0.39 & 0.10 & 0.12 & 0.12 & 0.14 & 0.14 & 0.16 & 0.16 \\ 0.15 & 0.16 & 0.10 & 0.40 & 0.14 & 0.10 & 0.11 & 0.12 & 0.14 & 0.15 \\ 0.16 & 0.17 & 0.12 & 0.14 & 0.35 & 0.11 & 0.13 & 0.13 & 0.15 & 0.16 \\ 0.17 & 0.15 & 0.12 & 0.10 & 0.11 & 0.36 & 0.12 & 0.12 & 0.14 & 0.15 \\ 0.17 & 0.15 & 0.14 & 0.11 & 0.13 & 0.12 & 0.38 & 0.16 & 0.16 & 0.18 \\ 0.18 & 0.16 & 0.14 & 0.12 & 0.13 & 0.12 & 0.16 & 0.40 & 0.15 & 0.16 \\ 0.19 & 0.18 & 0.16 & 0.14 & 0.15 & 0.14 & 0.16 & 0.15 & 0.42 & 0.19 \\ 0.20 & 0.18 & 0.16 & 0.15 & 0.16 & 0.15 & 0.18 & 0.16 & 0.19 & 0.44 \end{bmatrix} \quad (19)$$

B. Implementation of the Proposed Method

Two cases for the ten-unit system are considered in this sub-section. Case 1: only thermal units are considered and case 2: with WP and ESSs. Figure 1 shows the convergence of total cost and emissions for case 1, by using the proposed algorithm and the Non-dominated Sorting Genetic Algorithm (NSGA). Convergence is obtained after 100 iterations. Figure 2 shows the Pareto solutions of the static EED problem where the power demand equals to 1700MW. From Figures 1 and 2 it is clear that the proposed method provides better solutions when compared to the NSGA.

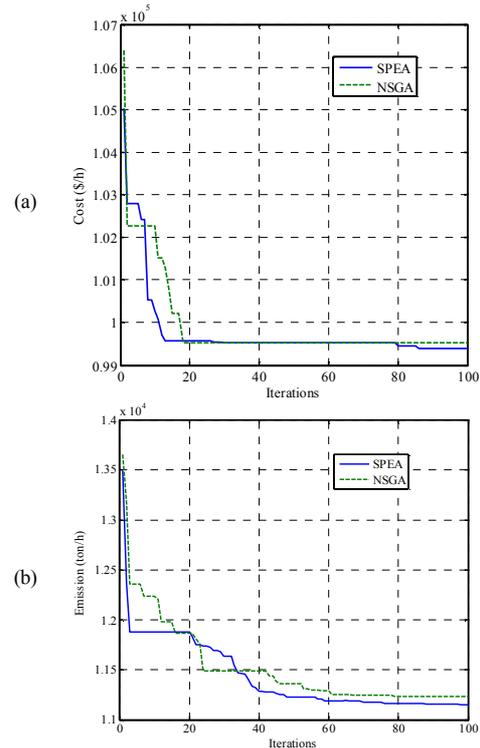


Fig. 1. Convergence of the objective functions: (a) cost, (b) emissions

Optimum compromise solutions under these two cases are shown in Tables II and III respectively. In this study, compromise solutions were obtained using fuzzy theory [23]. It is clear from these two Tables that all constraints were taken into account. In addition, the total production cost and the total emission are decreased when the wind energy source and the

ESS are incorporated in the problem. The total production cost and the total emissions are 2530173.68\$ and 315022.47ton respectively for the first case and 2357551.22\$ and 266882.90ton respectively for the second case. The effect of the use of wind source and ESS is shown in Figure 3. It is clear that minimum production cost and minimum emissions are clearly reduced when wind power and ESSs are used.

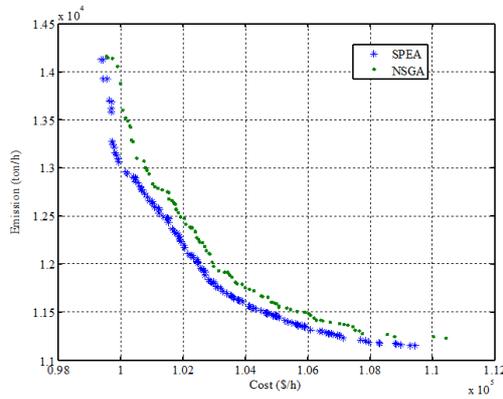


Fig. 2. Pareto solutions for $P_D=1700MW$

TABLE I. COMPARISON WITH OTHER TECHNIQUES FOR CASE 1

Method	Minimum Cost	Minimum emissions
SPEA	2474311.14	295120.82
NSGAII	2.5168x10 ⁶	3.1740x10 ⁵
IBFA	2481733.3	295833.0

It is clear from Table I that SPEA outperforms NSGAII [24] and IBFA [25] for both minimum cost and minimum emissions.

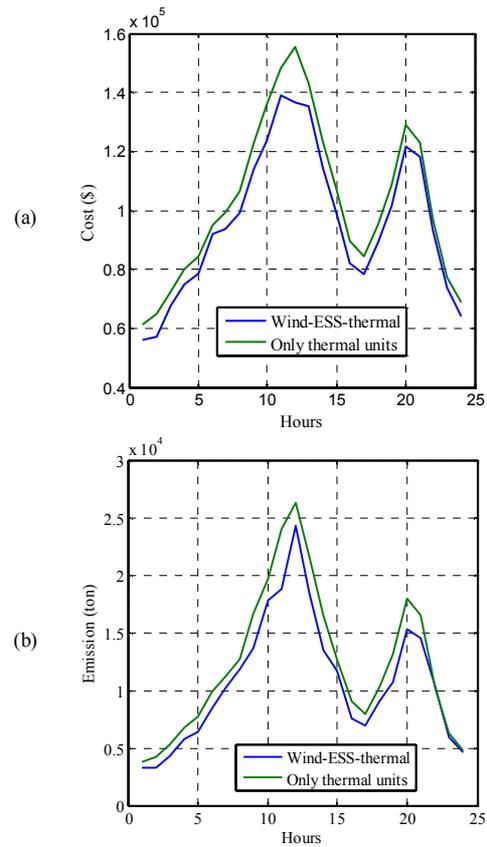


Fig. 3. Variation of minimum cost and emission over a single day

TABLE II. BEST COMPROMISE SOLUTION FOR CASE 1

Hour	$P_{D,h}$	P_1	P_2	P_3	P_4	P_5	P_6	P_7	P_8	P_9	P_{10}
1	1036	151.87	135.00	93.95	68.72	126.84	132.97	102.84	120.00	80.00	43.58
2	1110	150.81	135.00	80.55	118.72	170.82	144.07	116.73	90.00	71.01	54.74
3	1258	154.10	135.00	141.16	138.64	181.96	151.59	130.00	120.00	79.10	55.00
4	1406	159.01	215.00	174.99	122.99	231.96	160.00	130.00	113.47	80.00	55.00
5	1480	171.29	221.75	188.90	172.99	231.97	157.95	128.43	115.54	78.32	53.17
6	1628	217.44	223.49	262.22	192.82	243.00	160.00	123.34	120.00	80.00	55.00
7	1702	249.44	244.87	271.04	226.46	225.95	160.00	130.00	120.00	80.00	48.65
8	1776	229.28	265.74	281.88	276.46	243.00	159.17	128.73	118.25	79.37	53.30
9	1924	248.81	345.74	312.37	300.00	243.00	160.00	130.00	120.00	80.00	55.00
10	2022	303.44	404.20	340.00	300.00	237.47	153.90	130.00	116.79	75.22	41.20
11	2106	371.77	415.27	340.00	300.00	243.00	139.45	130.00	120.00	80.00	55.00
12	2150	344.53	470.00	340.00	300.00	243.00	160.00	130.00	120.00	80.00	55.00
13	2072	368.93	390.00	340.00	300.00	243.00	160.00	130.00	120.00	80.00	25.00
14	1924	298.98	312.96	299.65	300.00	242.05	159.68	128.90	117.93	80.00	55.00
15	1776	224.60	241.71	295.30	300.00	243.00	159.28	130.00	109.59	78.67	52.78
16	1554	161.81	161.71	265.52	250.00	238.72	160.00	130.00	120.00	55.00	55.00
17	1480	161.2867	165.25	190.72	242.21	242.21	160.00	128.15	120.00	55.00	54.83
18	1628	198.24	155.05	270.72	292.21	243.00	160.00	130.00	120.00	55.00	52.24
19	1776	272.35	235.05	283.41	299.61	235.61	160.00	130.00	116.50	53.27	49.63
20	1972	346.63	315.05	307.59	300.00	243.00	160.00	130.00	120.00	70.28	55.00
21	1924	305.13	308.83	327.88	300.00	230.08	159.72	109.96	119.88	78.89	55.00
22	1628	227.10	228.83	247.88	250.00	243.00	160.00	96.77	120.00	48.89	55.00
23	1332	153.70	148.83	171.15	200.00	193.00	119.83	126.77	120.00	78.89	51.95
24	1184	154.35	135.00	106.67	118.72	163.66	152.62	130.00	119.97	75.46	52.98
Total cost (\$)	2530173.68										
Total emission (ton)	315022.47										
Total losses (MW)	1302.82										

TABLE III. BEST COMPROMISE SOLUTION FOR CASE 2

Hour	$P_{D,h}$	P_1	P_2	P_3	P_4	P_5	P_6	P_7	P_8	P_9	P_{10}
1	1036	150.00	135.00	73.00	146.30	128.40	71.58	20.00	47.00	80.00	55.00
2	1110	151.76	135.00	73.00	106.41	114.04	118.85	50.00	77.00	80.00	55.00
3	1258	150.00	135.00	153.00	151.77	127.58	151.19	74.11	102.39	50.00	54.29
4	1406	153.20	135.00	181.5	160.99	177.58	160.00	104.11	120.00	80.00	55.00
5	1480	150.00	165.28	170.80	158.21	225.60	136.77	126.35	119.39	78.24	53.41
6	1628	170.39	245.28	250.80	208.21	175.60	160.00	130.00	89.39	80.00	55.00
7	1702	231.92	165.28	284.85	224.68	205.50	160.00	130.00	119.39	60.97	42.45
8	1776	205.52	210.35	299.50	234.68	241.21	159.58	118.97	110.94	80.00	54.01
9	1924	248.74	290.35	278.77	284.68	243.00	160.00	130.00	120.00	80.00	34.62
10	2022	269.46	308.25	340.00	300.00	218.83	152.63	130.00	120.00	80.00	55.00
11	2106	327.73	388.25	340.00	253.67	239.77	156.49	130.00	114.17	71.40	50.83
12	2150	354.75	436.84	340.00	283.32	189.77	160.00	128.74	104.06	73.25	46.40
13	2072	428.66	356.84	313.83	233.32	239.77	146.08	113.72	115.90	45.15	37.55
14	1924	361.14	276.84	233.83	283.32	243.00	124.18	130.00	119.65	75.15	55.00
15	1776	283.53	220.45	154.90	260.62	242.65	159.91	129.79	119.25	79.76	54.80
16	1554	212.65	155.59	158.25	218.29	243.00	160.00	130.00	96.80	49.76	55.00
17	1480	150.00	185.98	172.47	168.29	243.00	133.65	117.49	120.00	55.00	55.00
18	1628	230.00	215.08	246.21	218.29	243.00	160.00	105.13	90.00	25.00	26.69
19	1776	206.54	295.08	294.86	168.29	243.00	144.32	130.00	120.00	55.00	55.00
20	1972	277.98	365.02	336.86	209.69	242.92	156.01	130.00	119.48	51.09	52.15
21	1924	239.14	314.48	301.78	225.77	239.65	155.98	129.80	120.00	79.85	53.83
22	1628	163.96	235.28	221.78	181.93	218.23	160.00	129.13	107.88	78.15	52.49
23	1332	150.00	155.28	144.70	131.93	178.00	126.78	130.00	120.00	80.00	27.41
24	1184	150.00	135.00	156.48	81.93	176.16	76.78	100.00	118.95	58.37	55.00
Total cost (\$)	2357551.22										
Total emission (ton)	266882.90										
Total wind energy (MWh)	1190.94										
Total ESS energy (MWh)	185.05										
Total losses (MW)	1133.02										

V. CONCLUSION

During the last decades, the high penetration of wind energy has created difficulties in energy dispatching due to the stochastic availability of wind power. Thus it is required to handle these random characteristics of energy sources. In this study, a method based on the SPEA technique is proposed for solving the DEED problem incorporating wind power. In order to avoid the overestimation penalty and underestimation costs, the wind power output is described by a chance constraint. Moreover, ESSs are added to the power network to increase the penetration of the wind energy. The effectiveness of the proposed method is verified on a ten-unit system. Simulation results show that the incorporation of ESS into the DEED problem can decrease clearly cost and emissions.

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NOMENCLATURE

$f_V(\bullet)$	Probability density function (PDF)
$F_V(\bullet)$	Cumulative distribution function (CDF)
v	Wind speed in m/s
ζ	Threshold tolerance
F_T	Total fuel cost in \$.
E_T	Total emission in tons
$P_{i,h}$	Output power of unit i at hour h

$\bar{P}_i, \underline{P}_i$	Lower and upper generation limits of unit i
N	Number of thermal units
W_h	Wind power output at hour h in MW
$E_{s,h}$	Stored energy of the ESS at hour h
$P_{sc,h}$	Charging power at hour h in MW
$P_{sd,h}$	Discharging power at hour h in MW
η_c and η_{sd}	ESS charging and discharging efficiency, respectively
$CH_{s,h}$ and $DC_{s,h}$	Charging and discharging status at hour h
E^{cap}	ESS capacity in MWh
$loss_h$	Total losses at hour h
$P_{D,h}$	Demand power at hour h

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