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Research on the Modes of Joint Use of Generating and Storage Capacities to Minimize the Weighted Average Cost of Electricity While Covering the Load Schedule

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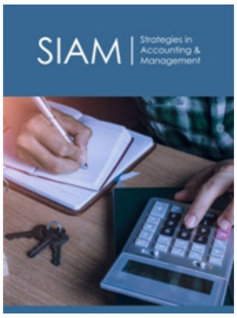

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Abstract

Paper discusses the optimization of generation and storage technologies within power systems, focusing on minimizing electricity costs while ensuring reliable load coverage-an ongoing challenge for global power grids. Through test calculations, the study provides numerical estimates, maps the optimal distribution of generating and storage capacities, and evaluates the required hourly costs for electricity supply across different load schedules. The research explores the integration of various energy sources, including traditional generation and energy storage systems, to minimize overall electricity costs while meeting demand. The importance of calculating the weighted average cost of electricity, considering various discount rates and the relative costs of generation technologies, is emphasized. Additionally, the study highlights the strategic use of storage systems for both charging and discharging based on demand conditions, further reducing costs. A detailed analysis of the optimal distribution of generating and storage capacities is presented, underlining the role of storage systems in balancing load variations. The dual role of storage-acting as both a consumer and a supplier of electricity-enables more efficient use of available capacity, especially in combination with other generation technologies like nuclear and thermal power plants. The findings offer practical approaches for energy system operators and policymakers to design more economically efficient and sustainable power generation systems. Given the growing importance of renewable energy integration and energy storage, this research lays the foundation for future advancements in optimizing the energy balance and addressing challenges related to fluctuating energy demand.

Keywords: Generation and storage technologies; Integration of various energy sources; Analysis of the optimal distribution of generating and storage capacities

Abbreviations: CHP: Combined Heat and Power; **HPP:** Hydropower Plant; **IPS:** Integrated Power System; **NPP:** Nuclear Power Plant; **PSPP:** Pumped Storage Power Plant; **RES:** Renewable Energy Sources; **SS:** Battery Electric Storage System; **TPP:** Thermal Power Plant

Introduction

The study of the development and improvement of energy systems is an urgent scientific problem, which is given considerable attention [1-13]. In case of a disruption in the continuous balance of supply and demand for electricity through operational and planned coverage of the load schedule by means of an appropriate amount of electricity generation and guaranteed delivery to consumption nodes, the network frequency and voltage levels in the power system change. This, in turn, may lead to mass consumer outages or damage to generating, transmission, and distribution equipment, as well as consumer electrical installations. All this underscores the relevance of solving the problem of calculating optimal operating modes for the generating and storage capacities within the power system, which ensure the minimization of the weighted average cost of generated electricity while covering the specified load. A comparative analysis of the weighted average cost of generated electricity, when the power system components operate in modes different from the base load mode, can serve as a justification for selecting the best option to solve this problem.

The weighted average cost depends on:

A. The amount of capital investments, including the cost of any loans required to finance construction, which may prove to be one of the main components of the final cost of electricity.

B. Operating costs throughout the entire life cycle.

C. Fuel costs.

Typically, the weighted average cost is determined using one of the versions of a widely used formula (1) [14], which depends on technological, regional, and economic parameters.

$$C_k^{-f} = \frac{\sum_\tau^T \frac{\{c_k^{cap} + c_k^{fix} + c_k^{\mathrm{var}(f)}\}}{(1+i)^\tau}}{\sum_\tau^T \frac{E_k^f}{(1+i)^\tau}} \qquad (1)$$

Where f is a mode from the list of allowable operating modes for the power unit. For each of the considered modes f, the capacity factor of the installed capacity of the k-th technology, $CF_k(f)$, takes one of the following values: Nom, 0.7* Nom; 0.5* Nom; 0.3* Nom. The value $CF_k(Nom)$ is the value in the base load mode.

E_k^f – the amount of annual generation of the power unit when used in f mode.

i – discount (%).

c_k^{cap} – investment.

c_k^{fix} – fixed operating costs.

$c_k^{\mathrm{var}(f)}$ – variable operating costs, which according to manufacturers include the cost of fuel and depend on the mode f.

T – power unit life cycle duration.

The aim of this work is research of optimal operating modes for the generating and storage capacities within the power system, which ensure the minimization of the weighted average cost of generated electricity while covering the specified load.

Methods and Materials

In the first of the two stages of modeling and determining the set of optimal modes for the use of generating and storage capacities on a subset of available technological solutions, a matrix c_k^{-f} was calculated. The elements of this matrix represent the weighted average cost of electricity generated for each technology and for each of the *f* allowable operating modes of the power unit. Four generating technologies and one energy storage technology were selected for test calculations. Specifically, the following were considered.

1. Nuclear power unit NPP NuScale-in base load mode and several maneuvering modes to cover the specified load using the Turbine bypass technology.

2. Nuclear power unit NPP Holtec SMR-160-in base load mode and several maneuvering modes to cover the specified load using the Load Following technology.

3. Installation of the combined cycle.

4. Installation of the coal cycle.

5. Accumulator (SS-Storage System), with an installed storage capacity of 30MW.

Modeling, calculation, and comparative assessment of the weighted average cost for each of the listed generating and storage technologies and installations were performed for each of the permissible maneuvering modes used in covering the model load schedule. The weighted average cost was calculated for the following discount values: 3%; 3.5% (which is a control value according to the manufacturer's data); 5%; 7%; 7.5% (which is a control value according to the manufacturer's data); and 10%. A comparison of the weighted average cost for all these technologies was carried out for discount values of 3.5% and 10% per year. The basis for selecting these discount values for comparing the weighted average cost is the availability of control values provided by the manufacturer for certain installations. The input data for calculating the weighted average cost of electricity for traditional technologies in base load modes and several maneuvering modes for covering the given load were obtained from [15-17]. The calculations of the weighted average cost values C_k^{-f} for the listed generating and storage technologies and the results obtained are presented below. A comparison of the results of the modeling with the control values provided by the equipment manufacturers allowed confirming the adequacy of the model. In the second stage of modeling, using the obtained values of the weighted average cost C_k^{-f} for the listed generating and storage technologies, a model was developed and tested to solve the problem of selecting optimal modes for utilizing the generating and storage capacities of the energy system. These modes are designed to minimize the cost of generated electricity at each time segment in the mode of covering the given load. The following steps were taken to implement the model. Using statistical information on the hourly power balance of the IPS of Ukraine for one of the critical days [18-19], Table 1 was created. Based on Table 1, Table 2 was calculated, showing the hourly absolute and relative power changes of the generating technologies NPP and TPP, as well as the absolute and relative changes in consumption power. Based on Tables 1 & 2, a model hourly schedule of the specified load was calculated for test calculations, and an assessment of the relative distribution of the installed capacity balance in the IPS of Ukraine was performed. This ratio was used in forming the set of generating and storage technologies for a separate model power supply node (Table 3).

Table 1: Hourly power balance (MW) of the IPS of Ukraine for a critical day, used for test calculations.

Hour	NPP	CHP	RES	TPP	HPP	PSPP (Generation)	Consumption	PSPP(Pumping)
1	10946	1219	227	5329	617	0	16872	-494
2	10939	1213	227	5265	422	0	16336	-902
3	10920	1229	218	5179	396	0	16131	-893
4	10936	1230	218	5461	483	0	16103	-1323
5	10938	1231	216	5491	631	0	16418	-1310
6	10916	1231	217	5633	398	0	17036	-404
7	10934	1229	209	6252	939	0	18662	0
8	10955	1238	204	6636	1558	0	19627	0
9	10950	1199	199	6885	2004	319	20863	0
10	10947	1200	213	7317	2320	319	21476	0
11	10935	1199	210	7472	2156	644	21872	0
12	10942	1204	178	7588	2170	319	21539	0
13	10961	1202	152	7643	2282	0	21484	0
14	10952	1208	137	7874	2106	0	21476	0
15	10976	1209	123	7913	1985	0	21481	0
16	10931	1193	90	7892	2033	0	21383	0
17	10951	1213	78	8137	1472	322	21119	0
18	10946	1256	89	7721	1405	1159	21808	0
19	10925	1264	74	7680	1278	1158	21570	0
20	10936	1260	46	7715	1631	324	21027	0
21	10942	1254	39	7598	1828	0	20861	0
22	10940	1263	40	7359	1593	0	20233	0
23	10943	1262	32	6990	949	0	19240	0
24	10959	1270	34	7218	681	0	18447	-897

Table 2: Hourly absolute and relative power changes of the generating technologies NPP and TPP, as well as the absolute and relative changes in consumption power.

Hour	NPP real	TPP	ΔTPP	Consumption	ΔConsumption	ΔConsumption relative
1	10946	5329	150	16872	769	0,73
2	10939	5265	86	16336	233	0,71
3	10920	5179	0	16131	28	0,70
4	10936	5461	282	16103	0	0,70
5	10938	5491	312	16418	315	0,71
6	10916	5633	454	17036	933	0,74
7	10934	6252	1073	18662	2559	0,81
8	10955	6636	1457	19627	3524	0,85
9	10950	6885	1706	20863	4760	0,91
10	10947	7317	2138	21476	5373	0,93
11	10935	7472	2293	21872	5769	0,95
12	10942	7588	2409	21539	5436	0,94
13	10961	7643	2464	21484	5381	0,93
14	10952	7874	2695	21476	5373	0,93
15	10976	7913	2734	21481	5378	0,93
16	10931	7892	2713	21383	5280	0,93
17	10951	8137	2958	21119	5016	0,92
18	10946	7721	2542	21808	5705	0,95
19	10925	7680	2501	21570	5467	0,94

20	10936	7715	2536	21027	4924	0,91
21	10942	7598	2419	20861	4758	0,91
22	10940	7359	2180	20233	4130	0,88
23	10943	6990	1811	19240	3137	0,84
24	10959	7218	2039	18447	2344	0,80
Δ		2 958	2 958	5 769	5 769	

Table 3: Set of generating and storage technologies for a separate model power supply node.

Technology	Installed Power, MW	Relative Installed Power, %	CF (*Nom*)	Maximum Available Power, MW
NPP Holtec SMR-160*2	320	23	0,95	304
Adv CC Gas/Oil Comb/ CCS	340	24	0,93	316
Coal with 30% CCS	650	46	0,93	605
SS Li-On 30*3	90	6	0,86	77
Total	1400	100		1302

The maximum available power is calculated according to the formula (2):

$$P_k^{MAX} = P_k^{INST} * CF_k(Nom) \quad (2)$$

where k– technology number of a separate model power supply node.

P_k^{MAX} – the maximum available power of the *k*-th technology.

P_k^{INST} – the installed power of the *k*-th technology.

$CF_k(Nom)$ – capacity factor of the *k*-th technology in base load mode.

The ratio of installed powers, considering the data from Table 2, is specified by expert assessment. The values of $CF_k(Nom)$ for each technology were obtained based on reference data from manufacturers [15-17, 19-22] and are provided in Table 3. Based on the parameters of Table 3, the following matrices were constructed.

1. The matrix $E_k^{Annual(f)}$ of the maximum available annual generation volumes for each technology in each of the *f* modes, according to formula (3), is presented in Table 4.

$$E_k^{Annual(f)} = P_k^{MAX} * CF_k(f) * YH, \quad (3)$$

where – mode from the list of possible modes of technology use.

$CF_k(f)$ – capacity factor of the *k*-th technology in mode *f*, which takes the values *Nom*, *0.7*Nom*; *0.5*Nom*; *0.3*Nom;*

YH – number of hours per year – 8 760.

Table 4: Maximum available annual generation volumes for each technology in each of the f modes.

	Annual Generation, TWh, for CF_k(Nom) (8760 Hours/Year)			
Technology	Nom	0,7*Nom*	0,5*Nom*	0,3*Nom*
NPP Holtec SMR-160*2	1,33	0,98	0,70	0,42
Adv CC Gas/Oil Comb/ CCS	2,77	2,08	1,49	0,89
Coal with 30% CCS	5,29	3,99	2,85	1,71
SS Li-On 30*3	0,23	0,18	0,13	0,08

2. The matrix $P_k^{Available(f)}$ of available loads, calculated using formula (4), is presented in Table 5.

$$P_k^{Available(f)} = P_k^{INCT} * CF_k(f) \quad (4)$$

where P_k^{INCT} – the installed power of the *k*-th technology.

Table 5: The matrix of available loads.

	Available Loads, MW, For CF_k(f)			
Technology	*Nom*	0,7*Nom*	0,5*Nom*	0,3*Nom*
NPP Holtec SMR-160*2	304	213	106	32
Adv CC Gas/Oil Comb/ CCS	316	221	111	33
Coal with 30% CCS	605	423	212	63
SS Li-On 30*3	77	54	27	8
Total	1302	911	456	137

3. The matrix of electricity supply cost values per hour in mode *f*, calculated using formula (5), is presented in Table 6.

$$C_k^f = P_k^{Available(f)} * C_k^{-f} . \quad (5)$$

Table 6: Matrix of electricity supply cost values per hour in mode f.

	The Cost of Electricity Supply Per Hour, in USD. for CF_k(f)			
Technology	Nom	0,7*Nom	0,5*Nom	0,3*Nom
NPP Holtec SMR-160*2	16720	14045	8938	3990
Adv CC Gas/Oil Comb/ CCS	9170	7968	5312	2490
Coal with 30% CCS	34457	31313	21369	10346
SS Li-On 30*3	2786	2330	1544	731
Total cost	63133	55656	37163	17558

Using the obtained results, the problem of calculating the binary matrix B_k^f of optimal sets of generating and storage technology modes for each possible load coverage mode was formulated and solved, with the aim of minimizing the total cost of the generated electricity.

$$C_{\sum}^{PLoad} = \sum_k C_k^f * B_k^f \Rightarrow \min, \quad (6)$$

when applying the constraints (7), (8), (9):

$$\sum P_k^{Available(f)} * B_k^f > P^{Load}, \quad (7)$$

$$\sum B_k^f \le 1, \quad (8)$$

$$P_{SS}^{P_k^{Available(f)}} = \begin{cases} P_{SS}^{P_k^{Available(f)}}, \forall PLoad < P_{mean}^{Load} \\ -P_{SS}^{P_k^{Available(f)}}, \forall PLoad > P_{mean}^{Load} \end{cases} \quad (9)$$

As follows from Table 2, takes values from 0.7 to 0.95, with an average value of P_{mean}^{Load} = 0.86. Constraint (9) ensures the charging mode of the accumulator when $PLoad < P_{mean}^{Load}$, meaning the accumulator is a consumer of electricity, and the discharging mode of the accumulator when $PLoad > P_{mean}^{Load}$, meaning the accumulator is an additional power source. Table 7 presents the results of the test optimization calculations and the resulting optimal distribution map of generating and storage capacities, along with the specific hourly electricity supply costs for each of the possible values (from 0.7 to 0.95) of the model load schedule.

Table 7: Map of generating and storage capacities, along with the specific hourly electricity supply costs for each of the possible values (from 0.7 to 0.95) of the model load schedule.

Load, Relative	0,69	0,71	0,73	0,75	0,77	0,79	0,81	0,83	0,85	0,87	0,89	0,91	0,93	0,95
Load Absolute, MW	898	924	951	977	1 003	1 029	1 055	1 081	1 107	1 133	1 159	1 185	1 211	1 237
Coverage, MW														
NPP Holtec SMR-160*2	106	106	106	213	213	213	213	213	213	213	304	304	304	304
Adv CC Gas/Oil Comb/CCS	316	316	316	221	221	316	316	316	316	316	316	316	316	316
Coal with 30% CCS	605	605	605	605	605	605	605	605	605	605	605	605	605	605
SS Li-On 30*3	-77	-71	-61	-56	-27	-35	-22	-16	-2	5	15	25	38	46
Total Coverage, MW	950	956	966	983	1 012	1 099	1 112	1 118	1 132	1 139	1 240	1 249	1 263	1 271
Cost Per Hour, $														
NPP Holtec SMR-160*2	8 938	8 938	8 938	14 045	14 045	14 045	14 045	14 045	14 045	14 045	16 720	16 720	16 720	16 720
Adv CC Gas/Oil Comb/ CCS	9 170	9 170	9 170	7 968	7 968	9 170	9 170	9 170	9 170	9 170	9 170	9 170	9 170	9 170
Coal with 30% CCS	34 457	34 457	34 457	34 457	34 457	34 457	34 457	34 457	34 457	34 457	34 457	34 457	34 457	34 457
Storage System	2 786	2 786	2 623	2 408	1 539	948	1 254	912	162	450	855	1 409	1 628	1 993
Total Cost per hour, $	55 350	55 350	55 187	58 878	58 009	58 619	58 925	58 583	57 833	58 121	61 201	61 755	61 974	62 340
Weighted Average Total Cost, $/MWh	58,3	57,9	57,1	59,9	57,3	53,4	53,0	52,4	51,1	51,1	49,4	49,4	49,1	49,0

Results and Discussion

The paper discusses the optimization of generation and storage technologies in the power system. This optimization is crucial to reduce the cost of electricity while ensuring reliable load coverage, which is a constant challenge for power systems worldwide. The results obtained during the test calculations allowed us to obtain numerical estimates, a map of the optimal distribution of generating and storage capacities, and the required weather costs of supplying electricity for each of the possible values of the load schedule. The influence of integrating various energy sources, including traditional generation and energy storage systems, is considered. Models to simulate different operating modes are developed, addressing the problem of minimizing the total cost of electricity while meeting the required load schedule. It emphasizes how the combination of generating and storage capacities can help ensure a more cost-effective energy supply. An important aspect of the research is the calculation of the weighted average cost of electricity, taking into account various discount rates and the relative costs of different electricity generation technologies. The article not only emphasizes the importance of optimizing generation costs but also highlights how storage systems can be strategically used for charging and discharging based on demand and supply conditions, leading to further cost reductions.

Conclusion

A detailed analysis of the optimal distribution of generating and storage capacities is presented, which is crucial for minimizing the weighted average cost of electricity. The concept of using energy storage systems for both charging and discharging, depending on load conditions, is a key part of the optimization. For example, when the load is below the average demand, storage systems act as consumers, absorbing excess energy, while when the load exceeds the average demand, these systems discharge energy, supporting the grid and reducing the need for expensive peaking power plants. The dual role of storage systems-acting both as a consumer and as a supplier of electricity-allows for more efficient use of available capacity. The ability to optimize the use of storage in combination with other generation technologies, such as nuclear and thermal power plants, can lead to a significant reduction in electricity costs. Presented research makes a significant contribution to the understanding of how generation and storage technologies can be jointly utilized to minimize the cost of electricity while maintaining reliable supply. The application of optimization models, along with the evaluation of cost factors, provides a practical approach for energy system operators and policymakers to design more economically efficient and sustainable power generation systems. Given the growing importance of integrating renewable energy sources and energy storage, this research lays the foundation for future advancements in optimizing the energy balance and addressing the challenges associated with the fluctuating nature of energy demand.

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