The techno-economic evaluation of school integrated energy system based on G1-anti-entropy weight-TOPSIS method

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Abstract. Scientific and reasonable evaluation system and method of technical economy are helpful to improve the technical economy of integrated energy system (IES). This paper analyzes the energy flow of the school integrated energy system (SIES), and constructs the techno-economic evaluation index system of the SIES from three aspects: technology, economy and environment. The evaluation index includes qualitative analysis index and quantitative analysis index. The techno-economic evaluation model of the SIES based on the G1-anti-entropy weight-TOPSIS method is constructed. The evaluation model reflects the subjectivity and objectivity of evaluation. It also overcomes the problem that the AHP method needs consistency test and high sensitivity of entropy weight method leads to the failure of index. Finally, a case study is conducted on a school in northeast China. The results of the analysis verify the feasibility of the evaluation index system and evaluation method. The evaluation system and evaluation method proposed in this paper can provide reference for the selection of SIES construction and operation plan.

1. Introduction

Energy consumption and environmental problems are two major problems and challenges facing countries with rapid economic development. The establishment of the IES is one of the key solutions to energy and environmental problems. Techno-economic evaluation is the main measure to measure the advancement of integrated energy technology (IET) research results and the extendability of engineering experience, and it is a powerful basis for the survival of the fittest in IET [1].

To improve the scientficity of the techno-economic evaluation of the IES, many researchers have proposed a variety of evaluation index systems and evaluation methods. Zhihua Wang et al proposed a new non-frost air-source heat pump (ASHP) system to evaluate its technical economy using initial investment cost and operating cost evaluation index [2]. Mario Petrollese et al established a simulation model for anaerobic digester performance analysis, and analyzed the impact of changes in anaerobic digester capacity and biogas digester capacity on main performance indicators [3]. Ana Foles et al studied the application of integrated energy storage solar PV system in residential field and the impact of energy management on the profitability of the system during battery operation, and conducted techno-economic evaluations of four different PV systems [4]. Chong Li et al conducted a techno-economic feasibility study on an autonomous hybrid wind/PV/battery power system of a household in...
Urumqi, China. The impact of different capacity PV arrays and wind power generation on economic indicators is studied [5]. Damian Shaw-Williams et al used Monte Carlo to simulate weather variables to model demand and solar power generation. The plan for the joint use of solar cells and solar cells was evaluated [6]. In the literature [7], data envelopment analysis and the fuzzy technique for order of preference by similarity to ideal solution were employed to rank the cities. Most scholars generally select economic indexes such as net present value, investment payback period, operating cost and so on to evaluate the economy of IET, which are mainly concerned by enterprises. For the government and the public, "energy efficiency, energy saving and emission reduction" is the goal of the IES. Indirect factors that affect the economy of IET, such as the energy utilization rate of the IES, the utilization rate of renewable energy, and the amount of greenhouse gas emission reduction, should also be considered. Few scholars analyze the SIES and establish the appropriate evaluation index system.

Majid Soltani et al used the gas engine cold, heat, and power cogeneration system to provide energy requirements for a commercial cold storage, and compared with the traditional system for techno-economic evaluation [8]. Tong Si et al evaluated the energy efficiency of coal-fired units based on the fuzzy AHP method [9]. Yunna Wu et al used fuzzy comprehensive evaluation method to conduct risk assessment on rooftop PV projects. Both the fuzzy comprehensive evaluation and the AHP method are highly subjective evaluation methods, without considering the objectivity of the evaluation [10]. Yan Jialun et al established a relatively comprehensive evaluation system from three aspects of energy consumption, environment, and economy for the building-type IES, and used the AHP-coefficient of variation method for comprehensive evaluation [11]. Mehdj Jahangiri et al used a fuzzy method to find the best location in Qatar for exploiting wind and solar energy to generate hydrogen and electricity [12].Sun Qiang et al constructed a comprehensive evaluation index system for smart grids, and proposed a multi-attribute network hierarchical combination evaluation method and calculation analysis model for comprehensive evaluation of smart grids, using the ANP-entropy weight method combination weight method [13]. Although the AHP and the entropy weight method are widely used in evaluation problems, the AHP has the problem of consistency checking in the determination of subjective weights. The sensitivity of the entropy weight method is too high and it is easy to cause indicator failure.

Aiming at the problems in the above-mentioned research, this paper constructs 10 quantitative and qualitative index systems including technology, economy and environment by analyzing the energy flow of the SIES. The indicator system not only considers indicators such as investment cost, operating cost, and investment recovery period, but also considers the technical index and environmental index which indirectly affect the technical economy of the SIES. The techno-economic evaluation model of the SIES based on the G1-anti-entropy weight-TOPSIS method is constructed. This evaluation model overcomes the problem of the AHP method requiring consistency testing and the high sensitivity of the entropy weight method leading to indicator failure, and also reflects the subjectivity and objectivity of the evaluation method. Finally, a case analysis of SIES is carried out, the economics of four IETs are analyzed, and the accuracy and reliability of the evaluation index system and evaluation methods are verified.

2. School integrated energy system
In the traditional SIES, the supply of energy mainly comes from the power grid and the centralized heating network, which cannot realize the gradient utilization and complementary coupling of energy. Schools generally cover a large area and are rich in renewable energy sources such as wind energy and solar energy. The transformed SIES mainly utilizes renewable resources. The electricity consumption of the SIES mainly comes from wind energy and solar energy. When the electricity load is greater than wind and PV power generation, the insufficient electricity is provided by the large grid. When wind and PV power generation is greater than the electricity load, batteries and SEHS devices are used for energy storage. Heating system consists of solid electric heat storage (SEHS), ASHP and solar collector (SC). The SC can convert the solar energy into heat energy; SEHS device can convert the excess electric energy in the system into heat energy and store it. The heat energy released can meet
the needs of some heat load; ASHP can make full use of the position heat energy in the environment and convert it into high heat energy to realize the step utilization of energy in the system. In order to provide a quiet and comfortable learning environment, the SIES generally uses air-conditioning equipment for cooling. The energy flow diagram is shown in Figure 1.

![Energy flow diagram of SIES](image1)

**Figure 1.** Energy flow diagram of SIES.

In Figure 1, $Q_h$, $Q_c$, $E_e$ are respectively the heat, cooling and electricity load of the SIES; $Q_s$, $Q_r$, $Q_i$ are the heating capacity of ASHP, SC and (SEHS) respectively; $E_{in}$, $E_f$, $E_g$, $E_{c,sh}$ are respectively grid injected power, wind power, PV power, and electric energy storage equipment discharge; $E_t$, $E_{c,sh}$, $E_{c,sh}$ are electricity consumption for electric refrigeration, electric energy storage equipment, and SEHS, respectively.

3. Evaluation index system

Establishing a reasonable evaluation index system is the key to the techno-economic evaluation of the SIES. The index system must include indicators that directly affect technical economy, as well as indicators that indirectly affect technical economy; It should include both objective and scientific quantitative indicators and qualitative indicators determined by experience.

![Evaluation system of the SIES](image2)

**Figure 2.** Evaluation system of the SIES.
Generally speaking, schools have a large building area and are rich in renewable energy such as solar and wind energy. Renewable energy utilization, comprehensive energy utilization, and greenhouse gas emission reduction have become important reference indicators for evaluating the energy saving and emission reduction effects of the SIES; Investment cost, operating cost, and investment payback period are indicators that directly reflect the technical economy of the SIES; the construction of the IES will introduce a large number of equipment, such as PV arrays, wind generators, ASHP, etc. Maintainability and the impact of noise on the environment have also become the focus of the SIES construction. Therefore, this paper constructs the techno-economic evaluation index system shown in Figure 2.

3.1. Technical indicators

3.1.1. Comprehensive energy utilization rate. Comprehensive energy utilization rate is an important indicator for evaluating the energy efficiency of an IES and is widely used. Its definition is the ratio of the heat, cold, and electricity output by the system to the total energy input by the system. The calculation formula [14] of the comprehensive energy utilization rate is:

$$\eta = \frac{Q_{s} + E_{c} + \frac{Q_{e}}{\eta_{a}}}{\eta_{i} + \left(1 - \varphi\right) \eta_{a}}$$

Where: $Q_{s}$, $Q_{c}$, $E_{c}$ are the heat, cold, and power generation of the system, respectively, unit kW; $\eta_{h}$, $\eta_{c}$, $\eta_{e}$ is the heating, cooling and power generation efficiency; $\nu$ is the proportion of the power transmission of the power grid; $\varphi$ is the power grid transmission line loss rate, take 7%.

3.1.2. Renewable energy utilization rate. The important reason why the government supports the construction of an IES is that the IES can increase the consumption of renewable energy and save the consumption of traditional fossil energy. Generally speaking, the school covers a large area and is rich in renewable energy. The utilization rate of renewable energy has become an indispensable indicator in the techno-economic evaluation of SIES. The formula [15] for calculating the utilization rate of renewable energy is as follows:

$$RER = \frac{P_{r}}{P_{s}}$$

Where: $P_{r}$ is the utilization of renewable energy in the IES, in kWh; $P_{s}$ is the total energy consumption in the IES, including heat, cold and electric energy, in kWh.

3.1.3. Equipment maintainability. The degree of equipment maintainability affects the operation and maintenance costs of the IES. After the equipment fails, it can be repaired quickly, which can reduce maintenance costs and reduce economic losses caused by downtime. This indicator is a qualitative indicator, which is quantified by a score. For example, a score of 95 represents "unmanned operation and low maintenance costs."

3.2. Economic indicators

3.2.1. Initial investment cost. Different IET use different equipment, and the purchase and installation costs of project equipment are different. The initial investment cost is an important indicator that affects which IET a company chooses. The formula [16] for calculating the initial investment cost is as follows:

$$C_{a} = \sum I_{s}C_{a} + C_{s}$$

Where: $C_{a}$ is the unit price of equipment, in ten thousand yuan; $I_{s}$ represents the number of equipment; $C_{r}$ represents the installation cost of the equipment, in ten thousand yuan.
3.2.2. **Operating cost.** IET solutions with high operating costs will increase the debt pressure of enterprises, and the level of operating costs will affect the choice of IET solutions. This article mainly considers the total annual electricity and maintenance costs, the formula [16] is as follows:

$$C_s = F_u + A_e$$  \hspace{1cm} (4)

Where: $F_u$ is the annual maintenance cost, 10,000 yuan; $A_e$ is the total annual electricity cost, 10,000 yuan.

3.2.3. **System life cycle.** The system life cycle refers to the time from when the system equipment is put into operation until the core equipment cannot operate. The inability of the core equipment of the IES to work will directly affect the economic benefits of the system.

3.2.4. **Investment payback period.** The payback period [8] is an index used to calculate the profit time of the system and evaluate whether a project has economic significance. This article selects the static payback period, which is defined as follows:

$$T = \frac{C_x}{C_x - C_a}$$  \hspace{1cm} (5)

Where: $C_x$ represents the initial investment cost, 10,000 yuan; $C_a$ represents the annual income of the IES, 10,000 yuan.

3.3. **Environmental indicators**

"Energy saving and emission reduction" is an important goal of the SIES. CO$_2$ emission reduction and SO$_2$ emission reduction are used to evaluate the emission reduction effect of the SIES. The construction of the SIES will introduce a large number of equipment. If the equipment is noisy, it will affect the quiet learning environment of students. Therefore, this paper adopts CO$_2$ emission reduction, SO$_2$ emission reduction [17] and noise impact as environmental assessment indicators.

3.3.1. **Annual CO$_2$ , SO$_2$ emission reduction.** In this paper, the product of the supply of renewable energy in the system and the emission factor is used as the emission reduction, and the formula [17] is as follows:

$$\Delta E_{CO_2} = (E_r + E_s + \frac{Q_s + Q_o}{3.6 \times 10^7}) \alpha_{CO_2}$$  \hspace{1cm} (6)

$$\Delta E_{SO_2} = (E_r + E_s + \frac{Q_s + Q_o}{3.6 \times 10^7}) \beta_{SO_2}$$  \hspace{1cm} (7)

Where: $E_r$, $E_s$ are wind power generation and PV power generation, respectively, kWh; $Q_s$, $Q_o$ are ASHP heat supply and SC heat supply, kJ; $\alpha_{CO_2}$, $\beta_{SO_2}$ are respectively the CO$_2$, SO$_2$ emission factors of coal-fired power generation which are 1000g/kWh and 9.14g/kWh.

3.3.2. **Noise impact.** The SIES includes various equipment, which may include gas turbine noise, water pump noise, fan noise, etc. According to relevant national standards, it should not exceed 60dB during the day and 55dB at night. The noise impact index is a qualitative index, and it is also quantified by scoring. For example, a score of 95 represents "higher noise impact".

4. **Techno-economic evaluation model**

The selection of SIES construction and operation schemes requires evaluation of multiple IET schemes, and only technical solutions with high technical economy will be adopted. This paper uses the TOPSIS method that introduces weights to evaluate the technical economy of the SIES, and uses the G1 method and the anti-entropy weight method to determine the combination weights. The G1 method can omit the step of consistency checking of the AHP method and simplify the calculation process; the anti-entropy weight method can overcome the problem that the sensitivity of the entropy method is too high and the index is invalid.
4.1. Numerical specification of evaluation indicators

The SIES evaluation index is a multi-attribute mixed index. The units of different indexes are different. The same index may have different magnitudes in different schemes. The comprehensive evaluation indexes include positive and negative indicators. It is necessary to carry out dimensionless and normalization processing for each index. See reference [17] for specific methods.

4.2. Determining the index weight

4.2.1. The G1 method. The G1 method is a popular subjective weighting method [18] in recent years. Compared with the AHP, the advantage is that no consistency test is required, and in the case of a large number of indicators, it can overcome the accuracy caused by the hesitation of experts in judgment. The subjective weight can be determined quickly and accurately, providing an effective basis for state evaluation. See reference [18] for specific methods.

4.2.2. Anti-entropy method. The anti-entropy method is an objective weighting method, which overcomes the problem of excessive sensitivity of the entropy method [19]. In the anti-entropy method, the greater the difference of the indicators, the smaller the entropy value obtained, but the larger the weight coefficient. See reference [19] for specific methods.

4.2.3. Revision of the anti-entropy method to the G1 method. In order to consider the objectivity and subjectivity of index weights, an anti-entropy variable is introduced, and formula (8) is used to combine the G1 method and the anti-entropy weight method to calculate the weight [18].

$$w_j = w_j^1 h_j + w_j^2 (1 - h_j), j = 1, 2, ..., n$$  \(8\)

Where \(w_j\) is the unnormalized weight value, \(w_j^1\) is the weight value determined by the G1 method, \(w_j^2\) is the weight value determined by the anti-entropy weight method, and \(h_j\) is the evaluation index anti-entropy value.

4.3. TOPSIS comprehensive evaluation method.

The TOPSIS method is a commonly used comprehensive evaluation method, which can make full use of the information of the original data. It is more suitable for the techno-economic evaluation of multiple IET solutions, assuming there are \(m\) evaluation objects and \(n\) evaluation indicators. The evaluation steps of TOPSIS method [20] are as follows:

1) Determine the maximum and minimum values of each column of the standardized matrix. Use formula (9) to define the maximum value matrix \(P^+\) and formula (10) to define the minimum value matrix \(P^-\).

$$P^+ = (\max\{p_{11}, p_{21}, ..., p_{m1}\}, \max\{p_{12}, p_{22}, ..., p_{m2}\}, ..., \max\{p_{1n}, p_{2n}, ..., p_{mn}\})$$  \(9\)

$$P^- = (\min\{p_{11}, p_{21}, ..., p_{m1}\}, \min\{p_{12}, p_{22}, ..., p_{m2}\}, ..., \min\{p_{1n}, p_{2n}, ..., p_{mn}\})$$  \(10\)

Where \(D^+\) is the distance between the evaluation object and the maximum value, \(D^-\) is the distance between the evaluation object and the minimum value, and \(w_j\) is the combined weight value.

2) Using the weights determined by the combined weighting method, use formulas (11) and (12) to calculate the distance between each evaluation object and the maximum and minimum values.

$$D^+ = \sqrt{\frac{\sum_{j=1}^{n} w_j (P^+_j - p_j)^2}{\sum_{j=1}^{n} w_j^2}}$$  \(11\)

$$D^- = \sqrt{\frac{\sum_{j=1}^{n} w_j (P^-_j - p_j)^2}{\sum_{j=1}^{n} w_j^2}}$$  \(12\)

3) The degree of closeness between the calculation scheme \(ii (i = 1, 2, ..., m)\) and the ideal scheme is \(S_i = \frac{D^-}{D^+ - D^-}\), the larger the value of \(S_i\) is, the closer the IET scheme is to the ideal value, and the higher the integrated energy technology and economy is.
5. Case study

This paper takes a school in Northeast China as a practical case to evaluate the technical economy of the SIES. The usable roof area is 15238.64 square meters. The location of the school is long in winter, short in summer and vacation, so the system is mainly considered for electricity and heating. The average electricity price is 0.697 yuan/kWh. It is 48W/m² for buildings without insulation and 30W/m² for buildings with insulation. The annual peak hours of sunshine are 1569.5 hours, and the annual available wind volume is about 1,200 hours. The local solar and wind energy are sufficient, suitable for the development of wind and solar storage distributed power generation systems. At the same time, SEHS devices, ASHPs and solar collectors are used for distributed heating. The total price of ASHP equipment with capacity of 1488 P is 2.6 million yuan, The total price of SEHS devices with power of 78540kW is 2.98 million yuan, The total price of solar collector equipment with area of 203 m² is 0.2 million yuan, The total price of the 1390 kW PV equipment is 5.56 million yuan, The total price of wind power equipment with power of 40 kW is 0.6 million yuan. This paper mainly conducts economic evaluation on the following 4 types of IETs:

Plan 1: Install PV arrays on the roof of an available building, install two 20kW wind turbines in an open area of the campus, and install energy storage batteries to form a wind-solar distributed power generation system. The campus heating uses ASHP and SCs. The ASHP investment is 70 yuan/m², the operating cost is 20 yuan/m², the SC investment is 1,000 yuan/m².

Plan 2: On the basis of Plan 1, consider the impact of controlling energy conservation on integrated energy technology and economy, and implement time-sharing control on the heating system of the building.

| Table 1. Data of each index. |
|-----------------------------|
| index                      | Indicator type | plan 1 | plan 2 | plan 3 | plan 4 |
| Comprehensive energy efficiency | Positive index | 78     | 84     | 88     | 90     |
| Renewable energy utilization | Positive index | 79     | 83     | 90     | 86     |
| Equipment maintainability    | Positive index | 84     | 79     | 90     | 87     |
| Initial investment cost      | Negative index | 1406   | 1427   | 1444   | 1458   |
| Operating costs              | Negative index | 122.9  | 102.9  | 145    | 134    |
| System life cycle            | Positive index | 25     | 24     | 20     | 19     |
| Payback period              | Negative index | 7.5    | 7      | 8      | 7.8    |
| AnnualCO₂ emission reduction| Positive index | 1871065| 1881165| 1781035| 1792540|
| AnnualSO₂ emission reduction| Positive index | 17101  | 17710  | 16547  | 16950  |
| Noise influence              | Negative index | 65     | 60     | 55     | 52     |

Plan 3: Power supply using the methodology provided in Plan 1. The heating of the campus uses SEHS devices and SCs. The SEHS investment is 80 yuan/m², and the operating cost is 26 yuan/m².

Plan 4: On the basis of Plan 3, consider the impact of controlling energy conservation on the technology and economy of comprehensive energy, and implement time-sharing control of building heating.

Calculate the index data of the four schemes respectively as shown in Table 1. Compared with Plan 1, the initial investment cost and operating cost of Plan 3 are increased by 380,000 yuan and 221,000 yuan, respectively. The investment cost and operating cost of the SEHS device are higher than the investment cost and operating cost of the ASHP. In the SIES, the electric energy used by SEHS devices mainly comes from wind turbines and PV arrays, so the comprehensive energy utilization rate and renewable energy utilization rate of Plan 3 and Plan 4 are about 10% higher. System maintainability of scheme 1 and scheme 2 is low. The equipment maintainability scores of Plan 1 and Plan 2 are 84 points and 79 points respectively, about 10 points lower than the scores of Plan 3 and
Plan 4. The energy of the SIES mainly comes from wind and solar energy, which greatly reduces the emissions of carbon dioxide and sulfur dioxide. Affected by the rotating noise of wind turbines and ASHPs, the noise of Plan 1 and Plan 2 is higher. Plan 2 and Plan 4 are to add energy-saving control on the basis of Plan 1 and Plan 3 respectively, which can improve the system's comprehensive energy utilization rate and renewable energy utilization rate, reduce operating costs, and reduce system noise, but the introduction of the control system increases the investment cost of the system and reduces the maintainability of the system.

Normalize and normalize the data in Table 1 to obtain standardized index data. Then calculate the weight value shown in Table 2.

|                | $A_1$ | $A_2$ | $A_3$ | $B_1$ | $B_2$ | $B_3$ | $B_4$ | $C_1$ | $C_2$ | $C_3$ |
|----------------|------|------|------|------|------|------|------|------|------|------|
| **Anti-entropy method** | 0.1203 | 0.1204 | 0.1204 | 0.0749 | 0.0703 | 0.1196 | 0.0611 | 0.1205 | 0.105 | 0.0875 |
| **Entropy method** | 0.0008 | 0.0006 | 0.0006 | 0.2218 | 0.2285 | 0.0037 | 0.2513 | 0.0002 | 0.0998 | 0.1928 |
| **Order relation method** | 0.0502 | 0.1002 | 0.013 | 0.123 | 0.1402 | 0.0704 | 0.206 | 0.124 | 0.082 | 0.091 |
| **Combination weight** | 0.0924 | 0.1058 | 0.0826 | 0.0939 | 0.1027 | 0.0971 | 0.1419 | 0.1122 | 0.0889 | 0.0825 |

From the analysis in Table 2, it can be seen that the weight value of the combination weight is between the weight values determined by the G1 method and the anti-entropy weight method, so that the combination weight takes into account the subjectivity and objectivity of the evaluation. Comparing the anti-entropy weight and entropy weight in Table 2, it can be seen that the sensitivity of the entropy weight method to the degree of index difference is much greater than that of the anti-entropy weight method, resulting in some extreme cases where the weight of the index is less than 0.001 when the weight is assigned. The data loses its meaning, and the anti-entropy law avoids this extreme situation. The G1 method omits the consistency check step in the calculation process and simplifies the calculation process. To sum up, the G1 method and the anti-entropy method to determine the combination weight have obvious advantages compared with the previous methods.

This paper uses the TOPSIS method considering the weight to evaluate the economic efficiency of the four IET, and the evaluation results are shown in Table 3 by using formulas (9)-(12).

|                | plan 1 | plan 2 | plan 3 | plan 4 |
|----------------|-------|-------|-------|-------|
| **Combination weight-TOPSIS** | 0.2804 | 0.3781 | 0.1370 | 0.2046 |

It can be seen from Table 3 that the scores of the four IET: Option 2> Option 1> Option 4> Option 3. By analyzing the data in Table 2, the most ideal set of index data can be obtained (90, 90, 90, 1406, 102.9, 25, 7, 1881165, 17710, 52). Option 2 has the highest score, indicating that the data of each indicator of Option 2 is close to the ideal solution, and its techno-economic performance is good. Option 3 has the lowest score, mainly because the investment cost and operating cost of the SEHS device are higher. For this project, although adding energy-saving control to the SIES can increase the technical economy of the system, it cannot compensate for the high investment and operating costs. Therefore, Plan 2 is more suitable for this project.
6. Conclusions

Based on the analysis of the energy flow of the SIES, this paper constructs an evaluation system with a total of 10 indicators from the three criterion levels of technology, economy, and environment, and establishes the G1-anti-entropy weight-TOPSIS comprehensive evaluation model suitable for the SIES. The following conclusions are obtained through the analysis of actual calculation examples:

(1) Through the evaluation system proposed in this paper, the more comprehensive index data that affects the technical economy of the SIES can be obtained. The combination of G1-anti-entropy weight method can weaken the influence of the subjective weight of the G1 method, omit the consistency check step, simplify the calculation process, and overcome the shortcoming that the entropy weight method is too sensitive to cause the index failure, at the same time, subjective and objective weights are taken into consideration, which not only adopts the expert's analysis of the importance of each index, but also uses the information contained in the data itself, which can make the evaluation result more scientific and accurate.

(2) This paper evaluates and analyzes the technical economy of the SIES. The results show that the SIES composed of wind-solar power generation system and air source heat pump-solar collector heating system is more suitable for this case. After the introduction of energy-saving control, the technical economy of the system will further increase; the techno-economic evaluation index system and evaluation method proposed in this article are relatively reasonable, which can provide a reference for the selection of the SIES construction plan, and has strong practical value.

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