Comprehensive evaluation method of micro-energy harvesters for power supply of outdoor wireless sensors

Luyang Guo¹, Shouxiang Wang²*, Haiwen Chen¹, Aichao Yang² and Bin Liang³

¹ Key Laboratory of Smart Grid of Ministry of Education, Tianjin University, Tianjin 300072, China
² State Grid Jiangxi Power Supply Service Management Centre, Nanchang, 330096, China
³ Marketing Service Center, State Grid Tianjin Electric Power Company, Tianjin, 300072, China

*Corresponding author’s e-mail: sxwang@tju.edu.cn

Abstract. There have been many solar or wind micro-energy collection technologies for outdoor wireless sensors, but it is difficult to compare them horizontally and choose the appropriate scheme. To overcome this problem, this paper proposes a comprehensive evaluation method of micro-energy harvesters which includes an evaluation matrix composed of three types of indexes and the corresponding test method. After the evaluation matrix is obtained by testing, a CRITIC-based weight calculation method is used to get a comprehensive score. Finally, ten commonly used solar or wind micro-energy harvesters in five typical regions are compared horizontally by the proposed method. The results show that the evaluation method can comprehensively consider various factors, and harvesters with higher comprehensive scores tend to have more balanced performance in all aspects. Furthermore, in regions with rich wind resources, the wind and solar harvesters have complementary time-domain characteristics.

1. Introduction

With the rapid development of 5G communication and semiconductor technology, wireless sensors, as the foundation of information transmission and the source of data flow in all walks of life, are developing rapidly towards miniaturization, scale and intelligence [1], [2]. In the power field, to meet the monitoring needs of the system, the types and numbers of sensors have grown rapidly, and more and more wireless sensors are distributed in sparsely populated or complex wind farms, substations and transmission lines. In this case, solving the power supply problem of massive wireless sensors is the key to optimizing the maintenance cost and stability of the sensor system[3].

There is a variety of environmental energy (such as solar energy, heat energy, wind energy.) available to collect and power wireless sensors [4]. Ref [5] proposed a scheme that mitigates the energy imbalance problem of solar-powered wireless sensor networks by using an efficient clustering scheme, which allows the sink node to collect more data with fewer blackouts. Ref [6] developed a low-light-level energy collection and management system, which successfully drives the wireless sensor through maximum power tracking (MPPT), supercapacitor and DC-DC transformation module. Ref [7] designed a Wireless Sensor Node (WSN) equipped with energy storage and photovoltaic power generation device. When the light intensity is weak, the energy is released through the energy storage device to meet the load demand. Ref [8] proposed an innovative solution for smart agriculture monitoring to the limited
energy availability design problem by utilizing the solar energy harvesting for battery charging of WSN nodes. Its simulation results proved that the sensor network lifetime is increased from 5.75 days to 115.75 days and higher, ideally up to infinite network lifetime.

In recent years, the micro-wind power generation technology has also received widespread attention. Ref [9] proposed a wireless wind speed sensor driven by a vibrating wind energy harvester, which vibration frequency will change with the change of wind speed, and can generate milliwatt-level energy. Ref [10] designed a WSN powered by a miniature rotating wind turbine. It optimizes energy management strategies by analyzing the overall system power consumption of all units, combining dynamic voltage regulation strategies and MPPT algorithms. The working parameters can be adjusted according to the specific tasks of the node, so that the wind energy powered WSN can obtain the maximum wind energy collection while minimizing its task power consumption. In Ref [11], a wind-driven generator named TENG working in the contact-separation mode with high output performance is designed and optimized to convert wind energy into electricity. Nine TENG units are then assembled into a 3D printed shell and installed as a power source for two environmental monitoring systems.

In summary, there have been many solar or wind micro-energy collection technologies for outdoor wireless sensors, but it is difficult to compare them horizontally and choose the appropriate scheme. Because they may collect different energy (such as solar energy or wind energy), and the performance of them is related to the environment. That makes us lack reference when selecting micro-energy harvesting schemes for WSN.

In order to solve this problem, this paper proposes a comprehensive evaluation method of micro-energy harvesters which includes an evaluation matrix composed of three types of indexes and the corresponding test method. After the evaluation matrix is obtained by testing, a CRITIC-based weight calculation method is used to get a comprehensive score. This method can quickly horizontally evaluate various micro-energy harvesters that collect solar energy or wind energy, which provides an important reference for the selection of micro-energy harvest schemes.

The rest of the paper is organized as follows. Section II introduces the evaluation matrix and test method of micro-energy harvesters. Section III introduces the weight calculation method based on the CRITIC method. Section IV analyses the experiments we have done. Finally, Section V concludes the paper.

2. The Evaluation matrix and test method of micro-energy harvesters

2.1 The Evaluation matrix

A self-powered WSN is usually composed of energy harvester, energy management circuit, energy storage device, and sensor body. In order to evaluate micro-energy harvesters more comprehensively, we considered the power requirements of WSN and constructed an evaluation matrix for micro-energy harvesters, as shown in figure 1. The following is the calculation method for each indicator.

Figure 1. Evaluation index system of micro-energy harvester.
2.1.1 Operating index. In WSN, due to the existence of DC-DC or AC-DC circuits, the voltage mismatch between harvester and back-end circuits will affect the energy conversion efficiency. Therefore, the harvesters are expected to have an output voltage within the appropriate range while performing MPPT. We use 10v as the voltage reference, the calculation of operating voltage indexes is as follows, where ov represents the I1 or I3 in figure 1.

\[
\text{voltage} = |ov - 10|
\]

Because micro-energy harvesters cannot be at the optimal environmental energy levels most of the time, it is necessary to test their performance at weak energy levels. The environmental energy levels in different geographical environments are quite different. For example, in the Tibet region, China, the radiation amount is \(670 \sim 837 \times 10^4\) kJ/cm\(^2\)·a. In southern China, the radiation is \(419 \sim 502 \times 10^4\) kJ/cm\(^2\)·a. It is difficult to define a weak energy level standard that applies to all regions. Therefore, this paper sets the weak energy level as 40% of the energy level when the harvester is at maximum power output.

2.1.2 Energy index. Different micro-energy harvesters tend to operate at different energy levels when they reach maximum power output. Moreover, we cannot unify the energy of light and wind. To compare different types of micro-energy harvesters horizontally, we propose a kind of energy index. This index is the average amount of energy collected by micro-energy harvesters in a specified region and period. It puts micro-energy harvesters into a unified environment and reflects the actual performance of each micro-energy harvester in the real environment. In application, it needs to be calculated separately according to the region where the micro-energy harvester is installed. Since it is difficult to test the micro-energy harvester in every region, a discrete integral method is proposed in this paper to calculate the energy index quickly. Steps are as follows.

1) Test the operating indexes of micro-energy harvesters at different energy levels by artificial simulated wind energy and light environment.

2) According to the install region of micro-energy harvesters, obtain the daily average wind speed and solar radiation curve of the four seasons.

3) Match the test result of step one with the curve obtained in step two, and then use the following formula to calculate the energy collected by the micro-energy harvester in one day. Where \(d\) represents the energy collected, \(p_n\) represents the average energy collected at \(n\)-th hour of the day.

\[
d = \sum_{n=1}^{24} p_n
\]

4) Use the energy matching coefficient to limit the unlimited growth of energy collected, because collecting too much energy will cause waste. In this way, the energy harvester can pursue better performance in other aspects while meeting the energy demand. In this paper, the threshold is set at 37,000 mWh, which is equal to the capacity of four typical 18650 lithium batteries [12].

2.1.3 Economic index. The economy is also an essential factor affecting the selection of micro-energy harvest schemes. Generally, the cheaper and lighter harvester is a better choice, so we need to consider its economic indexes when evaluating harvesters. The operating volume index is not the net volume of micro-energy harvesters, but the volume occupied by them during operation.

2.2 Test method

The equipment and connection method used for the test are shown in figure 2. Since there are many energy managements chips, energy storage solutions and MPPT methods, to avoid these factors from affecting the evaluation of micro-energy harvesters, we replace the actual load with DC adjustable load. During the test, we adjust the adjustable load to obtain the maximum power output and then use a high-precision power meter to measure the various parameters of micro-energy harvesters. Since energy management chips are usually designed for direct current, for micro-energy harvesters that output alternating current, a high efficiency Schottky rectifier bridge is used to convert the alternating current into direct current.
Figure 2. The connection relationship of equipment during test process.

The test process of micro-energy harvesters is shown in figure 3. This process is generally divided into three steps, each step will get a kind indexes, and these indexes are weighted and integrated to obtain the comprehensive score of the micro-energy harvester.

Figure 3. The test process of micro-energy harvesters.

3. CRITIC-based weight calculation method
The CRITIC method is an objective weighting method proposed by Diakoulaki [13], [14], which the basic idea is to determine an index's weight based on the contrast and conflict between indexes. The contrast uses the mean square error (MSE) to characterize the difference of indexes. The larger the MSE, the greater the amount of information contained in the index. Conflict represents the correlation between different indexes. If the correlation coefficient between the two indexes is larger, the correlation is stronger, and the conflict is lower. Compared with subjective weighting methods such as the entropy weight method and standard deviation method, the CRITIC method is more reasonable. Its evaluation process is as follows.

1) Normalization of indexes. Suppose there are \( m \) evaluation objects and \( n \) evaluation indexes. Taking into account that different indexes have different effects on the final evaluation result, different normalization methods are adopted for positive and reverse indexes.

Positive indexes:

\[
b_y = \frac{a_y - \min\{a_{ij}, \cdots, a_{im}\}}{\max\{a_{ij}, \cdots, a_{im}\} - \min\{a_{ij}, \cdots, a_{im}\}}
\]  

(3)

Negative indexes:

\[
b_y = \frac{\max\{a_{ij}, \cdots, a_{im}\} - a_y}{\max\{a_{ij}, \cdots, a_{im}\} - \min\{a_{ij}, \cdots, a_{im}\}}
\]  

(4)

Where \( i = 1, 2, \cdots, m \), \( j = 1, 2, \cdots, n \), \( a_y \) represent the j-th index value of i-th harvester, \( b_y \) represent the j-th index value of i-th harvester after normalization.

2) Calculate index matrix correlation coefficient. The correlation coefficient represents the degree of linear correlation between indexes. In the CRITIC method, it is also used to represent the conflict between the indexes. If the positive correlation between the two indexes is stronger, the conflict will be smaller, and the weight will be lower. The calculation method of the correlation coefficient is as follows.

\[
r_y = \frac{\sum_{i=1}^{n}(x_i - \bar{x})(y_i - \bar{y})}{\sqrt{\sum_{i=1}^{n}(x_i - \bar{x})^2} \sqrt{\sum_{i=1}^{n}(y_i - \bar{y})^2}} = \frac{\sum_{i=1}^{n}x_i y_i - n\bar{x}\bar{y}}{\left(\sum_{i=1}^{n}x_i^2 - n(\bar{x})^2\right)\left(\sum_{i=1}^{n}y_i^2 - n(\bar{y})^2\right)}
\]  

(5)

Where \( i = 1, 2, \cdots, n \), \( j = 1, 2, \cdots, n \) and \( r_y \) represents the correlation coefficient between the i-th index and the j-th index.
3) Calculate weight. The calculated index correlation coefficient matrix is used to calculate each index's contrast and conflict. The formula is as follows.

\[
\begin{align*}
    CI_j &= \sigma_j \\
    CT_j &= \sum_{i=1}^{n} (1 - r_{ij})
\end{align*}
\]

Where \( j = 1, 2, \cdots, n \), \( \sigma_j \) represents the MSE of \( j \)-th index, \( CI_j \) represents the contrast of \( j \)-th index, \( CT_j \) represents the conflict of \( j \)-th index between other indexes.

Based on the contrast and conflict of the index, use the following formula to calculate the amount of information in the index.

\[
G_j = \sigma_j \sum_{i=1}^{n} (1 - r_{ij})
\]

Where \( j = 1, 2, \cdots, n \), the larger the \( G_j \), the higher the \( j \)-th index's information, and the higher the \( j \)-th index's weight.

The final weight of the \( j \)-th index is:

\[
W_j = \frac{G_j}{\sum_{j=1}^{n} G_j}
\]

4) Calculate the comprehensive performance. Use the following formula to combine all second-level indexes with the corresponding weights to obtain comprehensive score.

\[
y = \sum_{j=1}^{n} W_j x_j
\]

Where \( y \) represents the comprehensive score, \( n \) represents the number of second-level indexes, \( x_j \) and \( W_j \) respectively represent the value of \( j \)-th index after normalization and the corresponding weight.

### 4. Experiment analysis

#### 4.1 Experimental setup

A total of ten commonly used micro photovoltaic generators or micro wind-driven generators solutions for analysis in this section. For wind-driven generators, the blade wing design and the generators' internal structure will affect its performance. The unique shape and structure will weaken the reference value of the experiment. Therefore, the wind-driven generators analyzed in this section adopt the universal rotating horizontal blade and H-shaped vertical blade. The internal structure also adopts the commonly used permanent magnet or disc type ironless core generators.

Their detailed information is shown in table 1. The SC represents Solar Cell, and the MS, TF, PS represent different SC types, where the MS represents Monocrystal Silicon, the TF represents Thin-Film, the PS represents Polycrystalline Silicon. The WG represents Wind-driven Generator, and H, V represents different WG types. The H represents Horizontal Axis, the V represents Vertical Axis, and the IC represents Iron Core.

| Harvester | HV1 | HV2 | HV3 | HV4 | HV5 | HV6 | HV7 | HV8 | HV9 | HV10 |
|-----------|-----|-----|-----|-----|-----|-----|-----|-----|-----|------|
| Kind      | SC  | SC  | SC  | SC  | WG  | WG  | WG  | WG  | WG  | WG   |
| Structure | MS  | TF  | MS  | PS  | H & IC | V & IC | H & Disc | V & Disc | H & IC | V & IC |
| Weight (g) | 262 | 242 | 1523 | 2331 | 92  | 88  | 683 | 450 | 402 | 635  |
4.2 Experimental results and analysis

Based on wind and photovoltaic resources, we selected five representative regions in China and evaluated these micro-energy harvesters in these regions. They are the Inner Mongolia area (region 1) and the Southwest Tibet area (region 2) with rich wind and photovoltaic resources, the Chongqing area (region 3) with poor wind and photovoltaic resources, the Yunnan area (region 4) with poor wind and rich photovoltaics resources, the South-East coastal area (region 5) with rich wind and resources. Data for these areas are derived from two publicly available meteorological datasets[15], [16].

The method proposed in this paper is used to test these harvesters, and the results are shown in table 2. The operating and economic indexes are independent of the region, and the energy indexes are region related.

Table 2. The summary table of test result

| Index type | HV1   | HV2   | HV3   | HV4   | HV5   | HV6   | HV7   | HV8   | HV9   | HV10  |
|------------|-------|-------|-------|-------|-------|-------|-------|-------|-------|-------|
| Operating  |       |       |       |       |       |       |       |       |       |       |
| index      |       |       |       |       |       |       |       |       |       |       |
| Index 1    | 4.97  | 3.82  | 19.73 | 30.43 | 1.95  | 0.20  | 6.45  | 2.29  | 6.07  | 0.69  |
| Index 2    | 5.40  | 6.35  | 7.82  | 7.06  | 5.65  | 5.58  | 44.14 | 4.57  | 35.06 | 0.04  |
| Index 3    | 3.28  | 2.06  | 6.71  | 16.91 | 0.22  | 0     | 0.65  | 0.13  | 0.49  | 0.05  |
| Index 4    | 5.55  | 5.99  | 8.04  | 7.07  | 4.73  | 10.08 | 8.22  | 6.75  | 6.34  | 6.97  |
| Energy     |       |       |       |       |       |       |       |       |       |       |
| index (Region 1) |   |       |       |       |       |       |       |       |       |       |
| Index 5    | 24947 | 14542 | 37000 | 37000 | 6327  | 423   | 21861 | 5279  | 14514 | 1766  |
| Index 6    | 35710 | 21934 | 37000 | 37000 | 4921  | 293   | 16120 | 3675  | 10836 | 1231  |
| Index 7    | 24444 | 14061 | 37000 | 37000 | 3379  | 150   | 10457 | 2170  | 7021  | 754   |
| Index 8    | 10110 | 4809  | 37000 | 37000 | 827   | 8201  | 9662  | 25543 | 3152  |       |
| Energy     |       |       |       |       |       |       |       |       |       |       |
| index (Region 2) |   |       |       |       |       |       |       |       |       |       |
| Index 5    | 27420 | 17264 | 37000 | 37000 | 10805 | 846   | 37000 | 10156 | 26520 | 3309  |
| Index 6    | 37000 | 28406 | 37000 | 37000 | 6162  | 397   | 21203 | 4995  | 13697 | 1675  |
| Index 7    | 29783 | 18725 | 37000 | 37000 | 3927  | 210   | 12390 | 2632  | 8202  | 898   |
| Index 8    | 16450 | 8868  | 37000 | 37000 | 7866  | 592   | 28165 | 7200  | 18852 | 2357  |
| Energy     |       |       |       |       |       |       |       |       |       |       |
| index (Region 3) |   |       |       |       |       |       |       |       |       |       |
| Index 5    | 18422 | 9725  | 37000 | 37000 | 1210  | 32    | 2713  | 494   | 1780  | 175   |
| Index 6    | 28245 | 16612 | 37000 | 37000 | 472   | 13    | 1853  | 294   | 1246  | 111   |
| Index 7    | 19508 | 10307 | 37000 | 37000 | 103   | 7     | 1381  | 167   | 920   | 67    |
| Index 8    | 10956 | 4969  | 19032 | 37000 | 276   | 9     | 1448  | 206   | 957   | 78    |
| Energy     |       |       |       |       |       |       |       |       |       |       |
| index (Region 4) |   |       |       |       |       |       |       |       |       |       |
| Index 5    | 31160 | 20333 | 37000 | 37000 | 1210  | 9.1   | 3191  | 524   | 2290  | 210   |
| Index 6    | 34850 | 21998 | 37000 | 37000 | 472   | 2.2   | 1160  | 151   | 810   | 65    |
| Index 7    | 26476 | 15826 | 37000 | 37000 | 103   | 1.7   | 243   | 22    | 148   | 7     |
| Index 8    | 18459 | 10297 | 37000 | 37000 | 276   | 11.3  | 638   | 58    | 422   | 26    |
| Energy     |       |       |       |       |       |       |       |       |       |       |
| index (Region 5) |   |       |       |       |       |       |       |       |       |       |
| Index 5    | 23372 | 13636 | 37000 | 37000 | 10906 | 908   | 37000 | 10852 | 26856 | 3502  |
| Index 6    | 34253 | 21647 | 37000 | 37000 | 6338  | 395   | 21098 | 5213  | 14883 | 1738  |
| Index 7    | 29067 | 17992 | 37000 | 37000 | 8100  | 623   | 29825 | 7548  | 19453 | 2470  |
| Index 8    | 16372 | 8577  | 37000 | 37000 | 17238 | 1534  | 37000 | 18083 | 37000 | 5830  |
| Economic   |       |       |       |       |       |       |       |       |       |       |
| index      |       |       |       |       |       |       |       |       |       |       |
| Index 9    | 262   | 242   | 1523  | 2331  | 92    | 88    | 683   | 450   | 402   | 635   |
| Index 10   | 2268  | 2268  | 12556 | 25168 | 1156  | 768   | 3240  | 12100 | 5832  | 12100 |

Then we use the CRITIC-based method to calculate each index's weight coefficients in these regions, and the results are shown in figure 4. It can be seen that compared with other indexes, index 2, 9, and 10 have a higher weight. Because there is no apparent correlation between the voltage and power of harvesters, and the weight and volume of harvesters usually conflict with the power of them.
Integrate each index according to the weight and get each harvester's comprehensive score in different regions, as shown in figure 5. The comprehensive score of solar cells in each region is significantly better than that of wind-driven generators. Because the difference in solar resources in these regions is significantly smaller than that of wind resources, and solar cells have excellent power generation efficiency. Since the HV3 and HV4 are larger, more weight, and have higher voltages, a separate step-down circuit needs to be designed, and the energy collected has reached the upper limit, causing waste, so their comprehensive score is not as good as HV1.

For wind-driven generators, it can be seen that the score of vertical-axis wind generators is significantly lower than that of horizontal-axis wind generators. The reason may be that the H-shaped airfoil has a smaller force range, but its advantage is the full wind direction. For horizontal axis wind generators, compared with HV5, although HV7 and HV8 have higher power output, their weight is much higher than HV5, so the comprehensive score is lower than HV5. The above analysis shows that the evaluation method proposed in this paper comprehensively considers various vital factors in actual engineering. Harvesters with higher comprehensive scores tend to have more balanced performance in all aspects, proving the proposed method's effectiveness.

The average daily energy collection in each month of several harvesters with similar comprehensive score, power, and volume are shown in figure 6. The wind-driven generators only consider regions 1, 2, and 5 with rich wind resources. It can be seen that wind and solar harvesters collect not only complementary energies but also have complementary time-domain characteristics. Wind-driven generators can collect more energy in spring and winter, while solar cells can collect more energy in
summer and autumn. The results show that in areas with rich wind resources, it may be a better solution to use solar and wind harvesters to power sensors simultaneously.

5. Conclusion
This paper proposed a comprehensive evaluation method of micro solar or wind energy harvesters for power supply of wireless sensors which includes an evaluation matrix composed of three types of indexes and the corresponding test method. Ten commonly used solar or wind harvesters were analyzed in the experimental section. The results show that the evaluation method comprehensively considers various vital factors in actual engineering, and harvesters with higher comprehensive scores tend to have more balanced performance in all aspects. Furthermore, in regions with rich wind resources, the wind and solar harvesters have complementary time-domain characteristics. The proposed method provides an important reference for the selection of micro-energy harvest schemes and the development of mixed micro-energy harvest schemes.

Acknowledgments
This work was supported in part by the State Grid Technology Project (Project name: Research and application of self-powered wireless sensor based on micro-energy collection, Project number: 5700-202025165A-0-0-00).

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