Mathematical model of the hybrid wind-photovoltaic plant cost calculations

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Abstract. The article is described a new approach that allows to find the optimal solution to the problem of hybrid plant cost calculations of low and medium power facilities based on renewable energy sources. The calculation is performed using a multivariate analysis of the obtained results. The need to search for the system optimal configuration with maximum capacity at minimum cost is determined by the major setback to use of renewable energy sources, such as the high cost of equipment. Initial data for math model as an example of the Hybrid Plant cost calculation was from nature conditions in Volgograd and cost equipment in the demonstration Zone of Volgograd State Agricultural University. The demo zone was created in the educational research and production center of University for conducting experiments on the self-generated power supply of the facility management.

1. Introduction

It is known that the arrival of solar radiation and the presence of wind are in antiphase (in most cases). In winter, a wind power plant accounts for the main power generation, and solar photovoltaic modules accounts in summer. Therefore, it is advisable to use a hybrid wind-photovoltaic plant to ensure uninterrupted power supply to a self-contained object, to reduce the required power of a wind turbine, solar battery and battery capacity, to improve station-operating modes.

There are many offers on the market of low- and medium-power wind-photovoltaic plants with ready-made equipment. The renewable energy market either European, American or Asian is rapidly developing towards hybrid plants [1-3]. However, it is important to learn how to calculate their cost yourself, depending on the place conditions you want to install. The developed math model simplifies the work of hybrid wind-photovoltaic plant cost calculate reducing the time required to study the place conditions and equipment corresponding to them. The plant was installed in the demonstration zone of educational research and production center in Volgograd State Agricultural University. It use conducting experiments on the self-generated power supply of the facilities management and performing cost calculations on power generation.

2. Materials and methods

The target of research is a hybrid wind-photovoltaic plant consisting of a wind turbine, a solar battery, a diesel generator, an accumulator bench and a centralized electrical network. The annualized cost of the research object components is calculated by [4]:
\[ C_{\text{ann,tot,c}} = \sum_{c=1}^{N_c} (C_{\text{acap,c}} + C_{\text{arep,c}} + C_{\text{aop,c}} + C_{\text{emissions,c}}), \]  

where \( C_{\text{acap,c}} \) – overhaul cost (Y/Y); \( C_{\text{arep,c}} \) – replacement costs (Y/Y); \( C_{\text{aop,c}} \) – direct operating costs (Y/Y); \( C_{\text{emissions,c}} \) – cost value of emission control (Y/Y). Applying the additive law of costs summation (1), a mathematical model was derived for calculating hybrid wind-photovoltaic plant cost for the year (2).

Ecologically, the disadvantage of centralized power supply is the presence of harmful emissions when conventional fuel was burning at the place of electricity generation. Integration with the network is not considered by modeling a decentralized green hybrid equipment with generating energy from renewable sources. Hence, all parameters related to it are reset.

\[ C_{\text{com}} = \sum_{w=1}^{N_w} (C_{1,w} + C_{2,w} + C_{3,w}) + \sum_{s=1}^{N_s} (C_{1,s} + C_{2,s} + C_{3,s}) + \sum_{g=1}^{N_g} (C_{1,g} + C_{2,g} + C_{3,g} + C_{4,g}) + \]

\[ \sum_{b=1}^{N_b} (C_{1,b} + C_{2,b} + C_{3,b}) + ((C_f + C_{st}) + C_d) + C_n + (C_{1,gr} + C_{2,gr} + C_{3,gr} + C_{4,gr}) - C_{5,gr}, \]

where \( N_w \) – wind turbine imbalance, pcs; \( C_{1,w} \) – capital investments in the purchase of wind turbines, \$/Y; \( C_{2,w} \) – replacement costs of wind turbines, \$/Y; \( C_{3,w} \) – direct operating costs of wind turbines, \$/Y; \( N_s \) – solar battery imbalance, pcs; \( C_{1,s} \) – capital investments in the purchase of solar panels, \$/Y; \( C_{2,s} \) – replacement costs of solar panels, \$/Y; \( C_{3,s} \) – direct operating costs of solar panels, \$/Y; \( N_g \) – diesel generator imbalance, pcs; \( C_{1,g} \) – capital investments in the purchase of diesel generators, \$/Y; \( C_{2,g} \) – replacement costs of diesel generators, \$/Y; \( C_{3,g} \) – direct operating costs of diesel generators, \$/Y; \( C_{4,g} \) – cost of fuel for a diesel generator, \$/Y; \( N_b \) – accumulator bench imbalance, pcs; \( C_{1,b} \) – capital investments in the purchase of accumulator benches, \$/Y; \( C_{2,b} \) – replacement costs of accumulator benches, \$/Y; \( C_{3,b} \) – direct operating costs of accumulator benches, \$/Y; \( C_f \) – fuel delivery cost, \$/Y; \( C_d \) – cost of fuel storage, \$/Y; \( C_s \) – cost of equipment delivery, \$/Y; \( C_n \) – total tax on emissions of harmful substances, \$/Y; \( C_{1,gr} \) – investments in the construction of power lines for the kilometer, \$/Y; \( C_{2,gr} \) – cost of power line operation for the kilometer, \$/Y; \( C_{3,gr} \) – cost of connecting to the power network (in the case of a power line), \$/Y; \( C_{4,gr} \) – cost of power consumption from the power line, \$/kWh/Y; \( C_{5,gr} \) – cost of selling electricity generated from renewable energy sources to the power network, \$/kWh/Y.

It should be noted that the parameter \( C_d \) should meet following circumstances:

- available equipment must be delivered to remote areas of the country;
- missing equipment must be brought from other regions (countries).

This method is the basis for calculating the cost of hybrid plants.

3. Results

The basis is the concept of building a house complex, consisting of 10 houses, which is based on the principles of economy, environmental friendliness and energy efficiency [5]. Of course, the electrical load has a significant impact on the cost and size of the units (table 1).

| Name of electric load consumer | Power, Whe | On-time, h | Energy, Whe h/daily |
|-------------------------------|-----------|------------|---------------------|
| 1 Lamps (10 pcs x 10 Whe)    | 100       | 5          | 500                 |
| 2 TV                          | 100       | 1          | 100                 |
| 3 PC                          | 400       | 1          | 400                 |
| 4 Electric deep pump          | 1500      | 2          | 3000                |
| 5 Refrigerator                | 150       | 24         | 3600                |
| **Total**                     |           |            | **7600**            |
Undoubtedly, the nature of renewable energy sources directly affects the regime and economy of energy systems, since resources determine the volumes and synchronization of energy production. Therefore, the paper is provided a detailed description of the renewable resources modeling such as the sun and the wind.

It should be noted that analysis of technical and economic parameters of the combination utility is carried out the software product "HOMER 2". It is the world standard in the field of micro power networks optimization.

Using the Graham algorithm, "HOMER 2" generates solar radiation data (hourly) based on the input data on monthly solar resources. Hypothetically, the geographic location of the house complex is Kuznetsk. It is city in the Penza region. The sums of monthly solar radiation on a horizontal surface are taken from the database SSE NASA (figure 1).

![Figure 1. Monthly averaged solar radiation.](image1)

Yearly average value is 3.56 kWhe h/m²/day. The output data is an 8760-hour database of solar radiation with statistical characteristics similar to the results of real measurements, taking into account variability and autocorrelation.

For the convenience of calculations, the hub height is taken equal to 10 m. In addition, the average monthly velocity was taken from the characteristics of the natural conditions of the research area. The wind energy cadaster is used to describe the wind resource as an energy source [6]. The wind energy cadaster is a set of aero logical and energy characteristics of the wind. Among the main cadastral characteristics, attention is paid to the average annual wind speed. Data on average annual wind speeds serve as the initial characteristic of the overall level of wind intensity. Results are shown in figure 2.

If the wind speed measurement was not made at the correct height (the height of the air turbine hub), then it is necessary to establish the dependence of the wind speed on the hub height. This can be done using a logarithmic or power law.

![Figure 2. Average monthly wind speed.](image2)
Yearly average value is 3.51 m/sec. To provide power supply, it is proposed to use a hybrid power plant, components of which are tabulated in table 2.

Simulating the load variability for the uniqueness of the daily schedule it is added randomness in the form of 10% daily and hourly load variability. "HOMER 2" generates a daily load profile based on hourly energy consumption per day.

### Table 2. Combined power plant components.

| Name of combination utility components | Model                  | Power, kWe | Cost, k₽ | Note                      |
|----------------------------------------|-------------------------|------------|----------|---------------------------|
| Solar battery                          | Silicon                 | 5-20       | 275      |                           |
| Wind turbine                           | Windelectric-Europe 5000| 5          | 285      | Starting wind speed – 2 m/sec |
| Invertor                               | Hyundai                 | 15         | 95       | Efficiency coefficient – 0.9 |
| Accumulator benches group              | Surrette 6CS25P         | 7          | 57       |                           |
| Diesel generator                       | "Azimut" AD 15-T400    | 15         | 315      |                           |

Circuit of modelled hybrid utility is shown in figure 3.

It is possible to exclude a reserve diesel generator from the system, since for the third category of reliability the permissible number of hours of shutdown per year is 72 hours. In a system with generation from renewable energy sources, a reserve diesel generator is intended to use no more than 20 h/y.

![Figure 3. Utility circuit.](image-url)
model for solving similar tasks.

Table 3. Possible device unit combinations.

| Generation from renewable energy sources, % | Wind turbine, kWhe | Solar battery, kWhe | Diesel generator, kWhe | Accumulator bench, pcs | Diesel generator operating time, h/y | Diesel fuel consumption, l/y | Initial investment, M ₽ | Cost of equipment delivery, k ₽ | Cost of fuel delivery, k ₽/y | Total investment*, M ₽ | Total price, ₽/kWhe h |
|-------------------------------------------|-------------------|--------------------|-----------------------|------------------------|-------------------------------------|----------------------------|--------------------------|----------------------------|----------------------------|--------------------------|--------------------------|
| 52                                        | 5                 | 5                  | 15                    | 7                      | 15                                  | 2.5                        | 31                       | 5.4                       | 10.5                      | 15                      | 2.5                      |
| 90                                        | 2x5               | 10                 | 15                    | 30                     | 15                                  | 5.5                        | 62                       | 1.2                       | 9.2                       | 25                      | 1547                     |
|                                           |                   |                    |                       |                        |                                     |                             |                          |                           |                           |                         | 451                      |

* – the payback period of investments is 25 years including the replacement and maintenance of equipment, a slight increase in the cost of fuel.

4. Conclusion

The model, in contrast to (1), is more accurate. Since it takes into account a number of new coefficients of the total cost. The cost estimate of a hybrid plant, consisting of solar batteries and wind turbine, has shown a potential for the use of renewable energy sources for electricity generation in comparison with traditional power consumption. A software based on the developed mathematical model have written to calculate the total cost of the hybrid plant. Among its components are placed renewable energy sources. The developed math model helps to choose the components of a hybrid wind-photovoltaic plant testing various control options for place conditions, simplifies the work of calculating the plant cost and reduce the time required to study this issue.

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