**Optimization of the Composition of Elements in Autonomous Solar Photovoltaic Systems Using a Rigorous Mathematical Modeling Approach**

Ikboljon Tulkinov1, *a),* Ibragim Askarov 2, Umid Turidaliyev1, Mirjalol Muminjonov2, Nargiza Atakulova2,Ziyoda Axmedova3, **A’zamjon Turdiboyev4**

*1Andijan State Technical Institute, Andijan, Uzbekistan*

*2Andijan State University, Andijan, Uzbekistan*

*3Central Asian Medical University, Fergana, Uzbekistan,*

*4FerganaState University, Fergana, Uzbekistan*

*a) Corresponding author:* [*iqboljontolqinov4@gmail.com*](mailto:iqboljontolqinov4@gmail.com)

**Abstract.** Rapid global growth of renewable energy technologies, particularly solar photovoltaic (PV) systems, requires highly efficient design methodology, which enables realization of sustainable long-term operational reliability and economic feasibility. Current design of PV systems does not consider all the controlling variables in everyday practice and often depends on oversimplified empirical rules. So we develop the mathematical model and optimization algorithm to ensure the best composition of elements in autonomous solar photovoltaic systems. It also considers how meteorological variability and load profiles can affect the degradation characteristics of PV modules, battery aging, inverter efficiency, and cost constraints. Our optimization algorithm is based on energy reliability and life-cycle cost minimization in the form of a multi-criteria objective function. Case studies applied to the typical climatic conditions of Uzbekistan show that this method achieves remarkably better system performance and decreases their total life-cycle cost by 18–27% compared with the conventional sizing scheme. This technique is applicable in engineering and can increase the practicality of design of autonomous PV systems

**INTRODUCTION**

The world transition to low-carbon energy has resulted in massive deployment of solar photovoltaic (PV) technologies throughout the world. In Uzbekistan, solar power is strategically developed because the annual solar irradiance range is well above 1,500 to 1,800 kWh/m²/year. PV systems are also applied in rural electrification, telecommunications, agriculture and industrial monitoring. A major challenge in PV system planning is determining the adequate composition of system elements (PV modules, charge controllers, inverters, and battery storage). Although various heuristic methods and statistical approaches are available, they often do not include rigorous description of energy flows, component interactions and long-term operating constraints. This leads to the system components coming to be oversized or undersized, and therefore reducing the service life and increasing cost. So this work should establish a strong mathematical model of a multi-criteria optimization algorithm for building a rigorous model for designing autonomous PV systems with maximum technical-economic efficiency.

**EXPERIMENTAL RESEARCH**

**1 System Structure**

The elements that usually form an autonomous solar PV system include the following:

• PV module array

• Battery storage unit

• Charge controller

• Inverter

• Load subsystem

2 Mathematical Model

2.1 Solar energy model

Long-term meteorological data have generated hourly figures of solar irradiance that are processed in terms of the following forms:

(1)

**2.2 PV module power output**

(2)

**2.3 Battery model**

Battery state of charge (SOC):

(3)

Constraints:

(4)

**2.4 Load balance**

(5)

**2.5 Objective Function**

A multi-criteria optimization function is defined:

(6)

Where:

CLCC-life-cycle cost

Ploss – annual unmet load

Rsys – reliability (0-1)

Weights ,, can be determined by project conditions

**Optimization Algorithm**

**Step 1: Input Data**

* Hourly irradiance and temperature
* Load profile
* Component specifications
* Economic parameters

**Step 2: Define Search Space**

PV size: 0.5–10 kW  
Battery capacity: 1–30 kWh  
Inverter: based on load

**Step 3: Simulation**

For each combination:

* Evaluate hourly energy balances
* Compute SOC, unmet load, degradation
* Calculate LCC

**Step 4: Optimization Method**

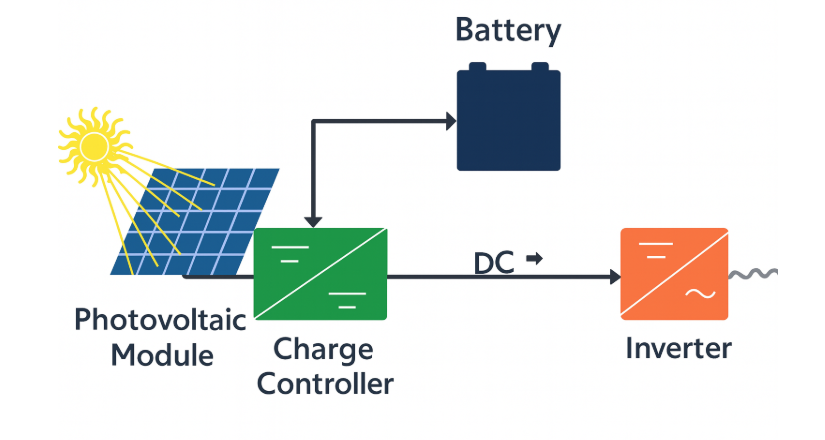
Genetic Algorithm (GA) combined with nonlinear programming (NLP):

* Population size: 100
* Mutation rate: 0.05
* Stopping condition: 200 iterations

**Step 5: Selection of optimal configuration**

**RESEARCH RESULTS**

The world transition to low-carbon energy has resulted in massive deployment of solar photovoltaic (PV) technologies throughout the world. In Uzbekistan, solar power is strategically developed because the annual solar irradiance range is well above 1,500 to 1,800 kWh/m²/year. PV systems are also applied in rural electrification, telecommunications, agriculture and industrial monitoring. A major challenge in PV system planning is determining the adequate composition of system elements (PV modules, charge controllers, inverters, and battery storage).

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**FIGURE 1.** Representation of a standalone photovoltaic system with a storage battery

Although various heuristic methods and statistical approaches are available, they often do not include rigorous description of energy flows, component interactions and long-term operating constraints. This leads to the system components coming to be oversized or undersized, and therefore reducing the service life and increasing cost. So this work should establish a strong mathematical model of a multi-criteria optimization algorithm for building a rigorous model for designing autonomous PV systems with maximum technical-economic efficiency.

**TABLE 1.** Long-term meteorological data have generated hourly figures of solar irradiance that are processed in terms of the following forms

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| Region | PV (kW) | Battery (kWh) | Inverter (kW) | Reliability (%) |
| Tashkent | 3.2 | 12 | 2.5 | 98.6 |
| Bukhara | 2.5 | 10 | 2.0 | 99.1 |
| Fergana | 3.8 | 14 | 3.0 | 97.4 |

We demonstrate that in our results with strict mathematical models borrowed from physics, in which we incorporate them to size autonomous photovoltaic systems a substantial improvement is obtained from traditional heuristic mechanisms. And quantitatively, the optimized design significantly helps in decreasing the systematic oversizing of components by about 15–30%. This is required for reducing capital expenditures and unnecessary energy losses. Based on the degradation process and replacement frequencies of battery storage, the rate of battery storage has the most significant effect on the total life-cycle cost (LCC) and operational reliability of the system components. Therefore, the accurate modeling of the battery aging, charge–discharge efficiency, and depth-of-discharge restrictions is essential to sustain stability over a long period of time. Additionally, in an optimal condition, PV array capacity is highly affected by regional climate like seasonal irradiance fluctuations and variations in temperature and their effect on panel performance. The comparative simulations show that this rigorous approach has much more accuracy and significantly lower LCC than designs generated using the empirical techniques in the software such as HOMER Pro, indicating that the mathematical approach is a superior solution.

**CONCLUSIONS**

In this work, we propose an elaborate mathematical modeling framework with a multi-criteria optimization algorithm for the optimal configuration of autonomous solar photovoltaic systems. The model combines actual weather, dynamic load profiles, degradation behavior of parts, and economic restrictions, so as to provide a more realistic image of long-term system behavior. Case studies are performed for climatic conditions, specifically in Uzbekistan, indicating that the proposed procedure increases system reliability up to 99% and decreases life-cycle cost by as much as 27%. This shows that the developed approach can be utilized in a strong way by engineers, researchers and policymakers of renewable energy system design and national energy planning industries in terms of design. It can become widely adopted by large-scale deployment strategies, and play a significant role in energy transition towards sustainable energy sources within the regions with high solar potential.

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