International Journal of Basic and Applied Sciences, 14 (SI-1) (2025) 220-227

International Journal of Basic and Applied Sciences

Website: www.sciencepubco.com/index.php/IJBAS
https://doi.org/10.14419/a1bj7r81
Research paper

Minimizing Generation Fuel Cost in Thermal Solar Power Plant Utilizing Evolutionary Programming Approach

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Received: May 15, 2025, Accepted: May 31, 2025, Published: June 7 2025

Abstract

Minimizing generation fuel costs in thermal solar power plants is crucial for enhancing their economic viability and operational efficiency. This paper addresses the problem of generating unit scheduling in a TPS with integrated solar energy systems to achieve fuel cost reduction. Load dispatch scheduling, combined with solar energy, can significantly reduce overall fuel cost while maintaining the same power output. The challenge of predicting real-time power requirements is managed by optimizing the schedule to account for uncertainties, thereby improving fuel cost reduction. This paper presents an innovative approach to optimize fuel consumption in hybrid thermal solar power systems by employing Evolutionary Programming (EP). EP, a powerful evolutionary algorithm inspired by natural evolution, is utilized to determine the optimal set of operational parameters that minimize the overall fuel cost while maintaining system performance. The approach is based on evolving a population of potential solutions through processes of mutation and selection, where the fitness function reflects the fuel cost associated with power generation and system constraints. The proposed methodology is implemented within a thermal solar power plant model framework. The results indicate the efficacy of the EP approach in attaining cost-effective solutions, underscoring substantial reductions in fuel consumption and operational expenditures. This investigation significantly contributes to the progression of sustainable energy solutions by offering a robust and efficient optimization instrument for the management of thermal solar power plants. Overall, the proposed method markedly enhances the operational efficiency of thermal power systems.

Keywords: *Fuel Cost Reduction; Solar Energy Integration; Optimization Scheduling; Evolutionary Algorithm.*

1. Introduction

The integration of unpredictable, climate-influenced electricity generation has introduced significant uncertainties that warrant consideration through the adoption of robust generation and energy storage solutions. The apprehensions expressed about fossil fuel-dependent power stations and their role in climate change have ignited a global shift in electricity research, steering it towards the embrace of eco-friendly energy practices. As renewable energy sources such as wind and solar photovoltaic power progressively integrate into the infrastructure of contemporary electrical grids, targeted research initiatives must concentrate on developing generation scheduling methodologies that accommodate the inherent variabilities and non-dispatchable features of Renewable Energy Resources [19]. The sporadic nature and extensive integration of renewables into the energy landscape present significant hurdles for system operators. This situation directly leads to complications or delays in the processes of generation scheduling. Ultimately, all these elements may impose adverse impacts on the overall equilibrium of the grid. The most promising remedies is the incorporation of energy storage systems, which helps smooth out the waves of variability in generation and supply. To date, numerous studies have been conducted to explore optimal operation scheduling strategies. These investigations approach the issue from various perspectives and under diverse conditions [20].

One of the tried-and-true methods for reducing fuel expenses or emissions from a fossil fuel power plant is optimal load dispatch, which is the distribution of load demand among various units. In a few current works, a natural cost-primarily based totally goal characteristic geared toward minimizing general expenses of a electricity plant, comprising fuel and environmental expenses of the electricity plant units, has been utilized in numerous optimization problems, consisting of the ones associated with dispatch optimization [21]. Many thermal power companies worldwide are acutely aware of the necessity for an integrated fuel management system. Integrating heterogeneous transactional and real-time systems with plant automation systems is difficult. Nonetheless, power generation firms would benefit greatly from a system that can effectively combine the operations and offer a consolidated view of the entire process [22].

In modern contexts, power generation installations function within a cycling mode distinguished by regular commencement and termination of operations, coupled with incessant variations in load to meet demand. Aside from contributing to the deterioration of equipment, such operational modalities diminish energy efficiency and exacerbate CO2 emissions [23]. The increased frequency of start-ups, particularly in the context of substantial integration of variable renewable energy sources, incurs considerable economic penalties, despite the fact that the incremental emissions remain negligible compared to the approximately 45% reduction in CO_2 emissions attributed to diminished fossil fuel consumption. The economic viability of thermal power plants may be jeopardized by the costs associated with cycling operations, in conjunction with a decline in revenue from energy sales [24].

2. Proposed solution methodology

In [1], an evaluation of the efficacy and economic viability of centralized versus decentralized solar thermal electricity generation in India is conducted, wherein a comparative analysis of the levelized electricity costs for solar thermal energy (STE) against the prevailing levelized electricity costs associated with current electricity generation methods reveals that STE emerges as a financially feasible technology under conducive circumstances [29]. The integration of solar energy with pre-existing power generation facilities represents a well-established strategy to address the challenges posed by escalating fuel costs and environmental pollution [25]. In this domain, a comprehensive examination of the extensive body of research and literature pertaining to the intersection of solar thermal energy and both conventional and innovative power generation paradigms [2] was undertaken. A pivotal element of this inquiry encompasses a thorough examination of the operational traits of hybrid solar steam cycle power generation facilities, innovations in solar combined-cycle technology, and hybrid solar–gas turbine energy frameworks, with a focal point on the synthesis of solar thermal energy with conventional power generation techniques. The research will further explore a pivotal inquiry concerning whether the amalgamation of solar thermal energy with more economically viable photovoltaic technologies [3], in conjunction with a form of solar thermal energy storage, can yield reduced levelized electricity costs and enhanced dispatchability in comparison to the independent performance of photovoltaic or solar thermal systems in isolation [26].

A novel framework addressing the optimal scheduling dilemma, which incorporates the ramifications of forecast uncertainty [4] pertaining to wind, solar photovoltaic, and load demand, is proposed. The efficacy of the proposed optimal scheduling methodologies has been validated through simulation results derived from the IEEE 30 and 300 bus test systems utilizing GA and 2PEM. Solar energy is captured preceding the boiler and directly following the initial high-pressure feed water heater through the utilization of a solar preheater, thereby enabling the facility to function in a dedicated fuel-conserving mode as there is no displacement of the feed water heater. The analysis of a 330 MW Solar Aided Coal Power Plant located in northern Niger [5] serves as a pertinent illustration of the successful integration of solar thermal energy into a coal-based electricity generation framework [27]. The data indicates an annual generation of 208 GWh of solar energy, with solar contributions potentially constituting up to 15% of the total electricity produced [11].

Employing a well-established optimization framework [6] that is specifically designed to enhance revenue within a temporal scope of one year, the examination is carried out utilizing a traditional 48-hour look-ahead approach with an hourly resolution on a concentrated solar power (CSP) facility that is presently under construction in California. This facility, utilizing the molten salt power tower technology with a net output capacity of 150 MWe, including thermal energy storage for extending peak operational load for eight hours, and a solar field sized 1.75 times the rated thermal energy output of the turbine [28]. In [7] authors examines a dynamic economic dispatch model that takes into account both thermal and solar sources, as well as the impact of a thermal plant's gas emissions and a realistic scenario of sun irradiation, and that satisfies the hourly load demand over a 24-hour time horizon. Additionally, a novel heuristic and an effective evolutionary framework based on a genetic algorithm are suggested. The optimal day-ahead scheduling of thermal and renewable power generation problem [8] employs multi-objective optimization and incorporates the inherent unpredictability associated with load demands, thermal generators, and renewable energy sources.

The α-constrained simplex technique, developed through the integration of the α-constrained method [9] within the nonlinear simplex approach alongside mutations, is utilized to enhance the solar-thermal power scheduling problem of an integrated system, which is proposed to be both economically and environmentally sustainable. The validity of the proposed methodology has been assessed using five distinct test systems. To address the thermal and electrical demands, an alternative stochastic scheduling problem [10] for a virtual power plant is formulated, accounting for uncertainties related to wind velocity, solar irradiance, market pricing fluctuations, and network security constraints. The platform consists of a net output of 150 MWe molten salt power tower with a seven and a half hour thermal energy storage for extended peak operational load and a solar field that is 1.75 times the rated thermal energy output of the turbine. The algorithm further takes into consideration the precise locations of each distributed energy resource (DER) within the public network and their specific capabilities. The establishment of a coal-fired power facility that utilizes solar energy to elevate the temperature of the feed water [12] prior to its entry into the boiler results in a reduction in fuel consumption. Consequently, a diminished quantity of fuel is requisite for heating the feed water of the boiler and for the generation of steam.

This specific plant configuration incorporates a series of solar Fresnel collectors that facilitate the direct heating of the boiler feed water. The proposed alteration to the plant model results in a significant reduction [13] in the consumption of fossil fuels. An exhaustive evaluation of land resources and solar irradiance across 591 districts nationwide is undertaken to determine the viability of Concentrated Solar Power (CSP) systems. Essential factors for assessing potential have been recognized as the appropriateness of land, advantageous solar resource conditions, and the wind power density present in the surrounding area. To augment the comprehension of the cost/performance dynamics of Solar Thermal Energy (STE) plants, a detailed analytical examination [14] of interrelations is conducted. Considering that the power block embodies a well-established and commercially feasible technology characterized by clearly defined efficiencies and specific costs, it has been utilized as the benchmark component in the modeling of the plant. A series of high-level parameters has been utilized to characterize the remaining components of the plant, including energy storage and the solar field, in terms of cost and energy management. The temporal coordination of thermal energy dispatch necessitates meticulous selection to synchronize with periods of elevated pricing or significant value, thereby enhancing the economic benefits associated with concentrating solar power systems. Two unique approaches that have traditionally been employed to gauge the efficacy and worth of CSP systems include the implementation of PCMs, which enhance the commitment and dispatch schedules for a diverse range of generators aimed at reducing the expenses associated with meeting electricity demand, and PT models [15], which fine-tune the dispatch of the CSP system based on historical or anticipated electricity prices to amplify the revenue accrued for the CSP operator. An analysis of the performance enhancement and cost reduction associated with energy generation for a 50 MWe PT facility [16] situated in Abu Dhabi, UAE, was presented. The simulations were executed utilizing the System Advisor Model software. Initially, a comprehensive analysis was conducted of seven scenarios pertaining to a PT facility incorporating various technologies and specifications.

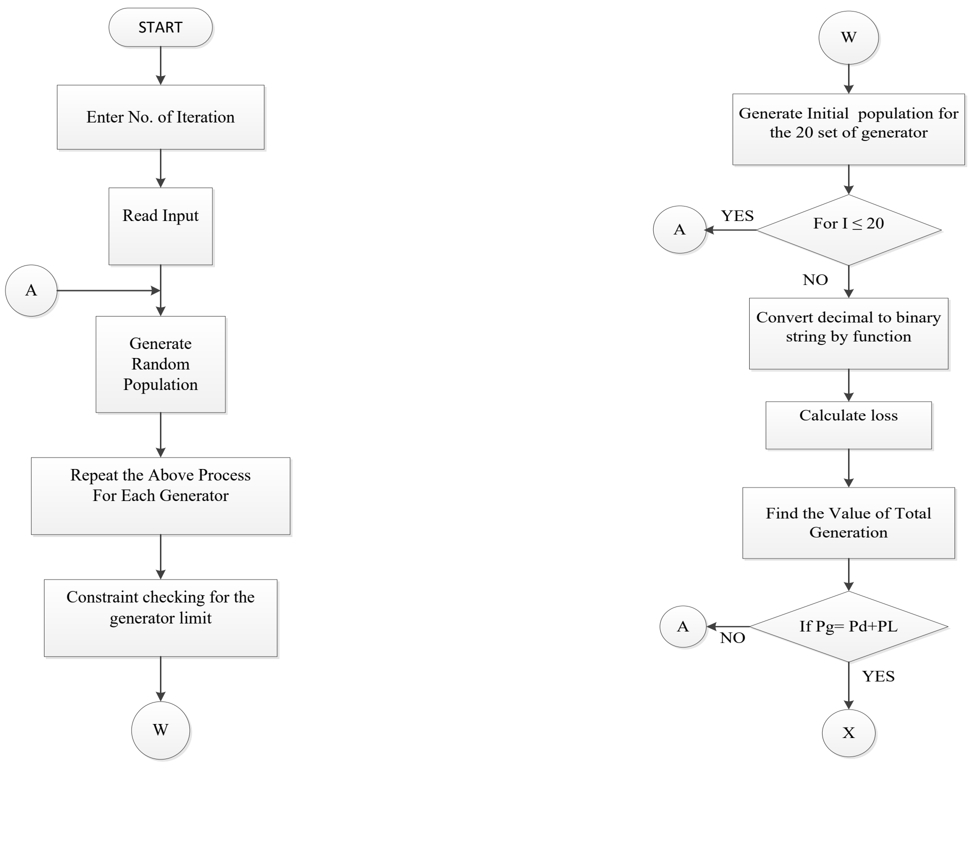
In order to evaluate the economic and technical viability of a cost-effective gravel and water pit storage system [17], which is intentionally positioned beneath the greenhouse to maximize surface area utilization. This investigation offers a unique analysis of the charging and discharging processes across a full year of operation, based on empirical hourly heating requirements and climatic data. The levelized cost of heat is evaluated with the utmost care in regard to storage pit dimension and expanse of the solar collector. In addition to this, as a means to construct a self sustaining and eco friendly scheduling optimization framework for solar thermal power facility, this research establishes the blueprint of a solar thermal power plant with the incorporation of a thermal storage system and investigates it key energy flow dynamics [18]. The findings from the simulation of the case study revealed that the integration of a thermal storage system could remarkably boost the power output capability of the photovoltaic power facility and elevate profits for the self-sustaining model, which is centered on power generation tactics and the strategy of peak-valley energy pricing.

3. Evolutionary programming method

The economic burden of integrating solar energy into power systems involves complex equity and inequality constraints, particularly when balancing costs between thermal and solar energy sources. Evolutionary algorithms (EAs) can address these challenges by optimizing solutions that consider both economic impacts and fairness in distribution. EAs are well-suited to handle these constraints due to their ability to explore diverse solutions and evolve optimal strategies. They can balance the initial investment required for solar infrastructure with ongoing operational costs, ensuring that financial impacts are equitably distributed. Since solar power produces no air pollution, EAs can prioritize solutions that maximize environmental benefits while minimizing economic disparities, aligning with the goal of reducing overall emissions effectively.

3.1. Evolutionary algorithm

Evolutionary optimization techniques are advanced optimization. Evolutionary optimization methods are based on the theory of population. Use mutation and recombination to improve individual results which already discuss in [15].
After the exhibition, we delved into the evolution of evolutionary programming within the realms of design research and optimization. Initially, Lawrence Fogel pioneered the use of evolutionary programming primarily for the development of end-user machines. Over time, this approach has been refined with the introduction of self-adaptive parameters and various mutation strategies.
Research has demonstrated the effectiveness of classical evolutionary programming in designing economic distributors. The appeal of classical evolutionary programming lies in its simplicity compared to Genetic Algorithms (GA), as it does not require specialized encoding. Instead, it operates directly with real-valued parameters, simplifying the process. Additionally, evolutionary programming does not impose restrictions or modifications on the objective function, which further simplifies its application to various problems. This ease of integration makes it particularly useful in algorithm development for economic load balancing.
Differential evolution, a related technique, has been successfully applied across several domains. Beyond energy engineering, differential evolution has also found applications in filter design, neural network training, fuzzy logic applications, and optimal control problems. It plays a crucial role in achieving economical load balancing and optimal solutions.
Evolutionary Programming is an optimization technique inspired by the process of natural evolution. It's part of the broader family of evolutionary algorithms, including genetic algorithms and genetic programming. EP primarily focuses on evolving a population of potential solutions to a problem over successive generations, using processes that mimic natural selection, mutation, and survival of the fittest. Evolutionary Programming is adaptable to various problem types, from numerical optimization tasks to more complex problems like machine learning model training or robotic path planning. The algorithm's ability to search for solutions globally means it's less likely to get trapped in local optima compared to other optimization methods. It can handle problems with complex, noisy, and discontinuous objective functions, making it versatile for a wide range of optimization tasks.
Here's Fig. 1. detailed flow chart description for the Evolutionary Programming process:
evolutionary programming is an iterative process where a population evolves through random mutations, selection of the best solutions, and the survival of the fittest until an optimal or near-optimal solution is found.



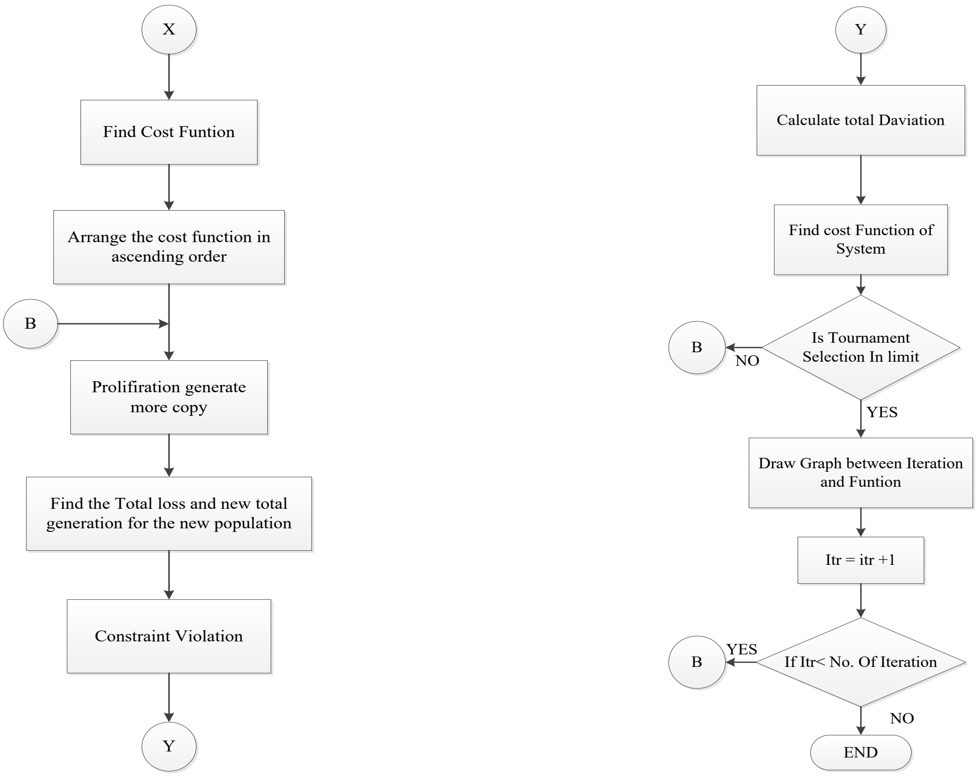


Fig. 1: Detail Flow Chart for Evolutionary Programming.

The algorithm for differential evolution in economic load balancing typically follows these main steps:

- Initialization: Set up initial parameters and population.
- Evaluation: Assess the fitness of each individual.
- Repeat: Continuously refine solutions through iterative processes.
- Mutation: Introduce variations to enhance diversity.
- Crossover: Combine features from different solutions to create new candidates.
- Evaluation: Reassess the fitness of the newly created solutions.
- Selection: Choose the best solutions to move forward.

A flowchart illustrating the optimization process using evolutionary programming is provided for a clearer understanding of these steps. For the current study, the objective function is defined as follows:

3.2. Minimizing fuel cost

Where a_i, b_i, and c_i are cost coefficients and NG is the number of generators. The Equation (1) is shown as,

$$F_1 = \sum_{i=1}^{NG}(a_i Pg_i^2 + b_i Pg_i + c_i) \text{ kg/h} \tag{1}$$

3.3. Primary Constraint

The generator output is the primary constraint or equality constrain and the equation (2) is in accordance with it is given

$$\sum_{i=1}^{N} Pg_i = P_D$$

$$\sum_{i=1}^{N} Pg_i = P_D + P_{LOSS} \tag{2}$$

P_D = total load connected to the grid and
P_{LOSS} = total loss in the over system.

3.4. Secondary constraint

Secondary constraints or Inequality constraints is defined as maximum and minimum range of sole power station. The Equation (3) is shown as,

$$P_{MIN} \le Pgi \le P_{MAX} \tag{3}$$

The boiler, turbine or generator capacity determines how much power the generating unit can output at its highest level.

Generator limit (inequality constraint). The Equation (4) is shown as,

$$PgiMIN \leq Pgi \leq PgiMAX \quad (4)$$

Where PgiMIN and PgiMAX are the Minimum and Maximum capacity of generation
Power balance (equality constraint). The Equation (5) is shown as,

$$\sum_{i=1}^{NG} Pg_i - (P_D + P_L) = 0 \quad (5)$$

Where PD is the load demand, PL is the transmission losses.
Where, equality constraint representing power balance and inequality constraint representing unit generating capacity.

4. Hybrid thermal solar power plant

The data generated represents the performance metrics of a thermal power station. Sampling was conducted exclusively at power outputs of 240 MW, 240 MW, and 150 MW. The recorded data pertains to the generator's operational parameters and efficiency at these specific output levels. Table 1 provides detailed generation data for the power plant, including various metrics such as output levels, fuel consumption, and operational efficiency at different points in time.

Table 1: Generation Data

Unit No.	Generator (MW)	Maximum (MW)	Minimum (MW)
1	240	260	100
2	240	260	100
3	150	130	40

Table 2: Generation Constant

Unit No.	Ai	Bi	Ci
1	0.00684	7.456	254.75
2	0.00487	10.54	154.25
3	0.00245	8.56	53.42

Table 3: Loss Coefficient for the Given Station

Unit No.	Ai	Bi	Ci
1	0.00548	7.624	228.46
2	0.00625	10.25	145.25
3	0.00547	8.25	58.32

Meanwhile, Table 2 presents the generator constants, which are crucial for understanding the machine's performance characteristics, such as its efficiency and power factor. Table 3 outlines the loss coefficients associated with the plant, which represent the losses incurred in the system due to factors like friction, heat dissipation, and electrical inefficiencies. These tables collectively offer a comprehensive view of the plant's operational and performance parameters.

5. Result and discussion

5.1. Optimizing fuel cost with only thermal plant

In with a total load of 350 MW distributed equally among three power plants, calculate the coal needed for each plant's power generation.

Table 4: Result for 10 ITR without Solar Plant

Sr. no	PG1 (MW)	PG2 (MW)	PG3 (MW)	Total Generation (MW)	Total Coal Consumption (Kg\h)
1	182.0726	119.7154	50.49856	352.28656	188737.5245
2	181.6932	119.8082	49.87105	351.37245	187820.2869
3	181.6918	119.8087	49.8707	351.3712	187813.7626
4	181.6935	119.8867	49.71498	351.29518	187773.1286
5	181.6739	119.7099	49.47943	350.86323	187542.2442
6	181.6738	119.7037	49.4751	350.8526	187536.5622
7	181.6664	119.7063	49.47774	350.85044	187535.4077
8	181.6741	119.7012	49.47531	350.85061	187535.4986
9	181.6741	119.7012	49.47531	350.85061	187535.4986
10	181.6741	119.7012	49.47531	350.85061	187535.4986

Table 4 provides fuel cost data for a 350 MW coal-fired power plant, detailing fuel cost reduction using the evolutionary method. To evaluate cost impact, we compare these data with those from a renewable energy source, such as wind or solar, which typically have negligible fuel cost. By analyzing and contrasting these values, we aim to determine the optimal energy solution, favouring the renewable source due to its significantly lower fuel cost compared to coal-fired plants.
Fig. 2 illustrates the variation in fuel cost over multiple iterations. The figure provides a detailed view of fuel cost concentration and its fluctuations throughout the testing iterations. Notably, the data across all figures indicate that the reduction in fuel cost values tends to stabilize after approximately seven iterations. This observation suggests that a consistent pattern in fuel cost reductions is achieved beyond this point, reflecting the effectiveness of the solar power integration in achieving steady improvements in fuel cost control.

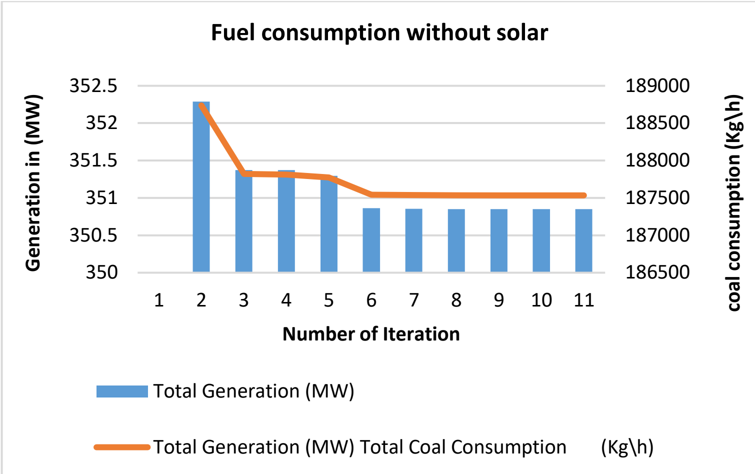


Fig. 2: Fuel Consumption without Solar Plant.

5.2. Optimizing fuel cost with thermal plant and solar

Specifically, an evaluation of a solar power installation is being performed as a viable alternative to conventional coal-based electricity production. The application of solar energy is projected to considerably diminish fuel costs.

In this context, the efficacy of the solar power facility will be enhanced to guarantee its successful substitution of coal-fired generation, with careful consideration of variables such as energy output and operational efficiency.

This optimization procedure will encompass a thorough evaluation of the system's capability to achieve the intended reduction in emissions while ensuring dependable electricity generation.

Moreover, a notable benefit of integrating a solar energy system is its considerably diminished operational costs in comparison to conventional fossil fuel-based power plants. Solar power plants have minimal maintenance needs and do not incur fuel costs, resulting in lower long-term operational expenses.

Table 5 provides a comprehensive overview of the solar power plant's performance and economic benefits. This table includes data on the plant's emission reductions, operational efficiency, and cost analysis, offering a clear comparison with the coal-fired plant. It highlights the benefits of transitioning to solar energy, both in terms of environmental impact and cost-effectiveness.

Table 5: Generation Data with Solar Plant

Unit No	Generator rating in MW	Maximum value in MW	Minimum value in MW
1	240	260	100
2	240	260	100
3	150	130	40
4(solar)	100	100	20

Table 6: Loss Coefficient for the given Plant

Unit No.	Ai	Bi	Ci
1	0.0000168	0.0000163	0.0000168
2	0.0000157	0.0000145	0.0000245
3	0.0000164	0.0000235	0.000136
4(solar)	0.0000016	0.0000024	0.0000026

In the above Table 6, the loss coefficient for each plant has been considered because losses are inherent in power generation processes. This means that the actual energy output of the plants is reduced by these losses, impacting overall efficiency.

In contrast, the solar power plant is represented with a zero-fuel cost and zero emission coefficient. This is due to the fact that solar power generation does not produce any direct emissions during operation, highlighting a significant environmental advantage of using solar energy. The absence of emissions from solar power plants underscores their role as a cleaner and more sustainable energy source compared to traditional fossil fuel-based plants.

Table 7 provides data on fuel cost for a 350 MW solar power plant. This data is crucial for comparing the environmental impact of solar energy with that of a coal-fired power plant. For reference, Table 4 presents the fuel cost data for a 350 MW coal-fired power plant. It also presents fuel cost data across ten iterations, revealing varying values for each. The minimum emissions were observed after the 8th iteration. This suggests that adjustments in the generating units, both thermal and solar, positively impact the reduction fuel cost. Fuel Consumption with Solar Plant shown in Fig. 3.

Table 7: Result for 10 ITR with Solar Power Plant

Sr. no	PG1 (MW)	PG2 (MW)	PG 3 (MW)	PS 1(MW)	Total Gen (MW)	Total Coal Consumption (Kg\h)
1	141.073	102.713	41.498	65	351.284	154199.079
2	141.122	102.835	41.871	65	351.828	153212.428
3	139.897	102.843	41.871	65	350.668	153713.911
4	139.646	102.835	41.715	65	350.196	153887.788
5	139.688	102.877	41.479	65	350.444	153589.800
6	139.986	102.735	41.475	65	350.596	153518.560
7	139.761	102.706	41.478	65	350.445	153583.763
8	139.671	102.701	41.475	65	350.34	153629.868
9	139.579	102.701	41.475	65	350.248	153670.222
10	139.576	102.701	41.475	65	350.245	153671.538

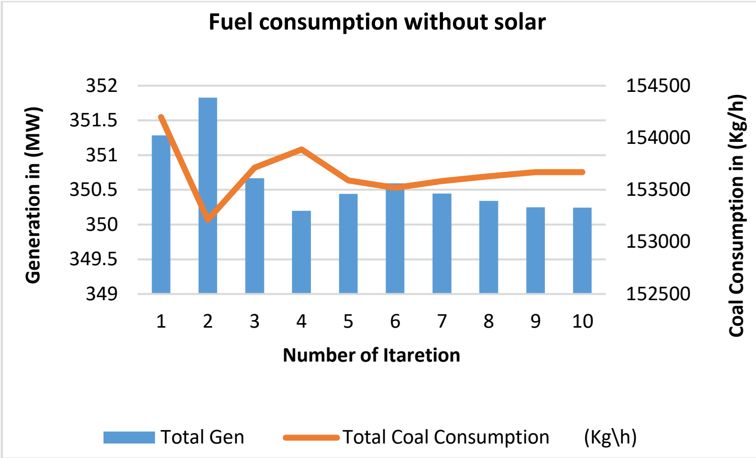


Fig. 3: Fuel Consumption with Solar Plant.

In comparing the 350 MW generation scenario with and without the solar power plant, we focus on how the emissions differ between the two setups. Specifically, Table 7 shows that the solar power plant has zero fuel cost due to less cost energy generation.
To assess the impact of integrating solar power, one optimal value from 10 iterations of performance and emission analysis will be used. This optimal value will provide insight into the best-case scenario for emissions reduction when coal-fired generation is replaced with solar power.

The integration of thermal and solar power plants for generating 350.34 MW of electricity has yielded notable reductions in fuel cost. This section discusses the impact on key fuel cost effective respective tables.

Table 8: Fuel Consumption Comparison

Total Generation MW	Fuel Consumption (kg/h) Only Thermal	Thermal+ Solar	Reduction in %
350.34	187535.4986	153629.868	18.0796

Table 8 reveals a significant decrease in fuel cost with the implementation of solar power. Specifically, the implementation of solar power reduced fuel cost from 187535.4986 kg/hr to 153629.868 kg/hr, signifying a 18.0796% reduction. This reduction highlights the effectiveness of incorporating solar energy in lowering fuel cost, which are critical for improving efficiency of overall plant.
Overall, the adoption of solar power in thermal power generation has demonstrated a substantial economic benefit by reducing fuel cost of thermal power plant. The results of this study underscore the efficacy of incorporating solar energy within traditional power generation frameworks, leading to enhanced air quality and a decrease in greenhouse gas emissions.
The aforementioned reductions highlight the significant environmental and economic advantages associated with the integration of solar energy into power generation infrastructures, illustrating a distinct enhancement in air quality and a reduction in greenhouse gas emissions relative to conventional fossil fuel-dependent power facilities.

6. Conclusions

In this academic study, we evaluated the dilemma of establishing unit scheduling in thermal power generation facilities aimed at decreasing fuel expenditures, alongside the incorporation of a solar energy system. The key findings can be encapsulated as follows:

- Optimization of Unit Scheduling: Optimizing the scheduling in thermal power stations effectively manages uncertainties in real-time power demand, leading to significant fuel cost reductions.
- Effectiveness of Evolutionary Programming: The evolutionary programming method proves to be an efficient approach for reducing fuel costs in thermal power stations.
- Integration of Solar Energy: The integration of solar energy yields better emission reductions compared to a standalone thermal power station system.
- Cost Reduction: A slight increase in the generation schedule leads to a notable 18.0796% reduction in fuel costs.
- Overall Efficiency Improvement: The proposed approach enhances the overall efficiency of thermal power stations, contributing to a more sustainable and cost-effective energy generation system.

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