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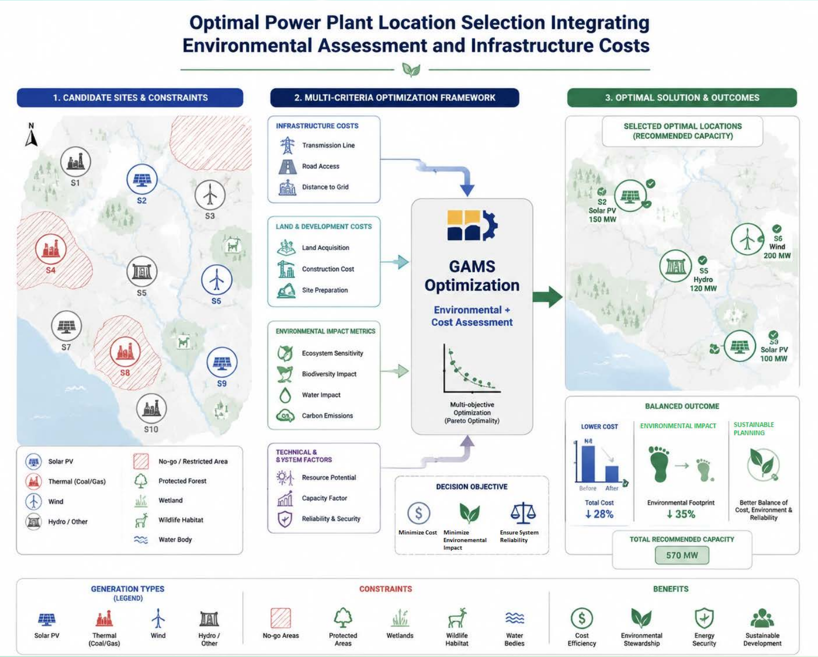
Striking the Green Balance: A Scientific Approach to Optimal Power Plant Location Selection Integrating Environmental Assessment and Infrastructure Costs

Mostafa Davoodabadi Farahani, Ali Farahani, Saeed Sharafi

Highlights

- **Incorporate environmental costs into power plant siting to reveal true fossil fuel expenses and guide engineers/governments.**
- **Broaden impact scope in future research to include post-construction factors like transmission and distribution lines.**
- **Balance environmental, political, economic, and community factors in policymaking to gain public support and sustainable growth.**
- **Engage local communities and promote renewables and energy efficiency to align economic interests with environmental goals.**
- **Adopt bi-level optimization for deeper insights into the complex environmental and**

Graphical Abstract



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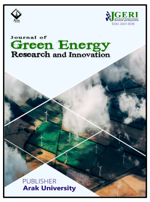

Striking the Green Balance: A Scientific Approach to Optimal Power Plant Location Selection Integrating Environmental Assessment and Infrastructure Costs

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ABSTRACT

supporting industrial and societal growth. Power generation is carried out through various sources such as solar energy, wind, and thermal systems, each with unique infrastructural demands and environmental impacts. Assessing the environmental consequences of constructing power plants is essential for minimizing harm to ecosystems and communities. This study aims to identify optimal locations for establishing electricity generation facilities by evaluating both infrastructure requirements and environmental considerations. A comprehensive site selection process is conducted, taking into account the characteristics of different types of power plants. Cost estimation for each potential site includes factors such as land acquisition and is tailored to the type and capacity of the plant. Environmental variables are also incorporated into the analysis to provide a more holistic view of each option. Using GAMS optimization software, the study identifies the most cost-effective and environmentally responsible sites for power plant installation and recommends the most suitable capacities for each selected location. The findings contribute to more sustainable energy planning and informed decision-making in the energy sector.

1. Introduction

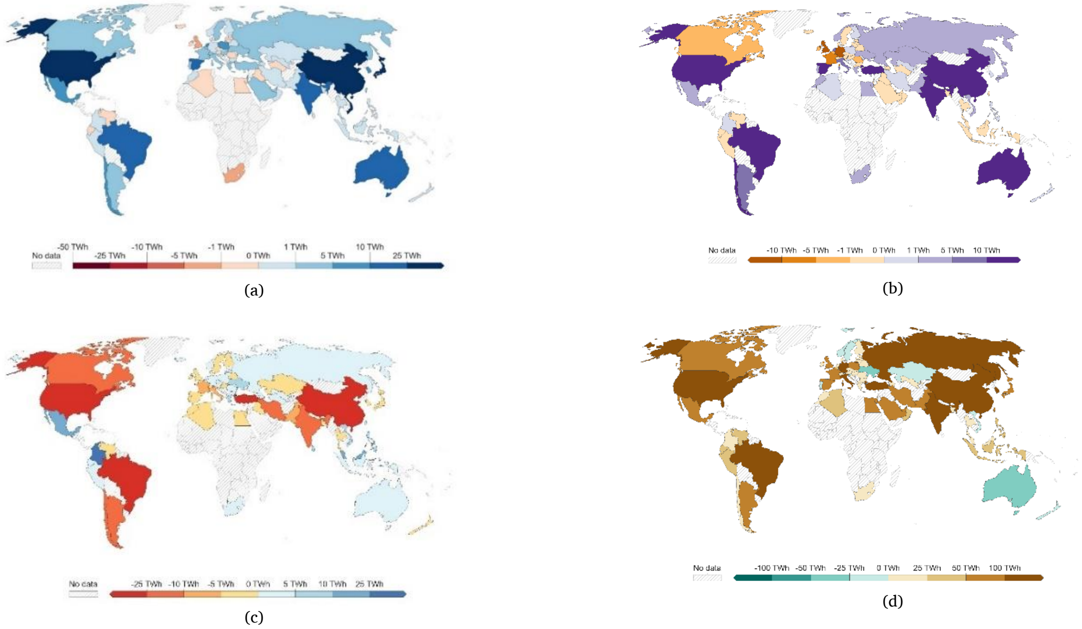
Power system planning is a multifaceted and extensive undertaking that engineers continuously explore. It encompasses various stages, including load forecasting, power plant and substation siting, transmission line placement, and ultimately, distribution network design [1]. Due to its broad scope, power system planning has been examined from numerous perspectives. The integration of increasing variable renewable energy sources into power system planning is explored in [2], while [3-5] delve into fundamental issues such as uncertainty and risk analysis. [6] proposes a comprehensive decision support model covering key factors in the design of AC electric power systems for offshore wind farms (OWFs), such as investment costs, system efficiency, and reliability. Steady-state equivalents are vital for studying the static characteristics of large power systems, particularly when computer resources are limited or solution times need to be expedited [7]. Another facet of planning, power system restoration, is presented in [8]. Generation expansion planning, a subset of power system planning, is discussed in this article. Various optimization techniques, including particle swarm optimization [9], improved genetic algorithms [10], and Lagrangian relaxation [11], have been applied to address this issue. Metaheuristic techniques are also explored in [12]. In the realm of generation expansion planning, environmental costs are often overlooked in objective functions. However, studies like [13] consider environmental impacts in power generation expansion planning for Lebanon, while [14] investigates the effects of biomass power generation and CO_2 taxation on electricity generation expansion planning and environmental emissions. Environmental impact studies on power plants, including those with carbon capture and storage [15], photovoltaic power plants [16], and renewable power plants [17], further underscore the importance of environmental assessment in power system planning.

References [18-20] focus on environmental assessments of wind turbines, solar energy systems, and hydroelectric power plant development, as well as the use of environmental assessment tools in Brazil. Additionally, [21] examines the environmental assessment of a bi-fuel thermal power plant in an isolated power system in the Brazilian Amazon region. Optimization methods are categorized into heuristic [22] and mathematical [23] approaches. Heuristic algorithms iteratively improve candidate solutions based on given quality measures, while mathematical optimization selects the best element from available alternatives. GAMS software, which employs mathematical methods for optimization, will be used to optimize power plant locations in this article. Notably, environmental effects of power plant establishment are integrated into the optimization objective function, with detailed mathematical modeling provided. The article proceeds with an introduction to environmental effects, followed by the concept and modeling of the optimization problem, solutions addressing environmental effects, and considerations of forbidden areas. Simulation results and performance analyses are presented, concluding the article in its seventh section.

2. Environmental assessment

The progression of technology and human knowledge has underscored the imperative of preserving the environment as a primary concern for future generations. Regrettably, as technology advances, so does the pace of environmental degradation. The demands of modern life and consumerism contribute to the accelerated depletion of environmental resources. Recognizing that a healthy environment is the entitlement of all living beings, both present and future, it is incumbent upon us to scrutinize our actions, identify harmful behaviors, and endeavor to rectify them to sustain our surrounding environment. Consequently, environmental impact analysis, or environmental impact assessment, serves as the foundational step toward achieving this objective. Every decision we make bears consequences for the environment, and environmental impact assessment aids in evaluating the ramifications of these decisions, identifying adverse effects, and seeking to mitigate or eliminate them. Importantly, this endeavor must be undertaken in a manner that reconciles environmental considerations with social, economic, and other associated benefits derived from our decisions. To incorporate environmental considerations into decision-making processes, it is essential to establish a clear definition of the environment. The term "environment" encompasses diverse meanings; it may evoke images of forested landscapes, pristine air, and unpolluted waters for some, while others may associate it with suburban neighborhoods or tranquil retreats. Some conceptualize the environment within the realm of ecology, contemplating interactions between flora and fauna, food chains, and conservation efforts. Indeed, the environment encompasses all these facets and more.

Electricity stands as one of humanity's most significant achievements, now deeply ingrained in our contemporary environment. While electricity exerts undeniable negative impacts on the environment, its indispensable role in human life renders its elimination unfeasible. Thus, it becomes imperative to utilize electricity in a manner that minimizes its adverse environmental effects. The environmental impacts of electricity manifest across its production, transmission, and consumption stages, though our focus here remains primarily on the production phase. Electricity production predominantly occurs through power plants, each type exerting distinct environmental effects. Notably, the adoption of renewable energy sources for power generation is steadily gaining traction. The figures below illustrate the usage rates of various power plants, each bearing its set of advantages and disadvantages. To ascertain the optimal power plant, we must address an optimization problem. Subsequently, we will delve into the concept of optimization, gradually navigating toward determining which power plant yields the least environmental impact.



(a) (b)

(c) (d)

Figure 1. The amount of use of all types of power plants in the world in 2020: (a) solar power plant, (b) wind power plant, (c) hydroelectric power plant and (d) thermal power plant with fossil fuels.

3. Optimization

Every day, we are faced with numerous decisions, each prompting us to seek the optimal outcome. For instance, when purchasing a product, we aim to secure the best quality at the lowest price, a quintessential act of optimization. The fundamental goal of optimization problems is to identify solutions that either minimize or maximize a variable. In this article, we primarily focus on minimization.

3.1. Problem Definition

Defining the problem marks the initial step in optimization. In any optimization endeavor, the decision-maker must delineate the decision variables, constraint functions, and objective function. Understanding these components is pivotal in optimization.

3.1.1. Decision and Dependent Variables

Decision variables serve as the independent entities, the values of which are optimized by the decision-maker. Dependent variables, in turn, are determined based on the optimized values of the decision variables. In our context, optimizing power plant location with regard to environmental costs entails decision variables encompassing location, type, and capacity of power plants. Dependent variables may include total fuel, equipment, land, and line costs, along with costs associated with land and air pollution.

3.1.2. Constraint Functions

Optimization problems often entail constraints that delineate the solution space. These constraints can be technical, economic, environmental, or similar in nature, effectively partitioning the solution space into acceptable and unacceptable regions. In our scenario, optimizing power plant location mandates adherence to constraints such as total power plant production meeting the load and reserve requirements, suitability of locations for wind and solar power plants based on environmental factors, and considerations regarding land availability and cost.

Fossil fuel power plants, while prevalent, are recognized for their environmental drawbacks, prompting global efforts to phase them out. Gas turbine power plants offer advantages such as smaller size, lighter weight, and lower initial costs compared to steam power plants. However, they may face fuel shortages in winter. Hydroelectric power emerges as a competitive and environmentally friendly option, offering low production costs and minimal water consumption. Additionally, hydroelectric plants afford flexibility in power generation and produce minimal waste and greenhouse gas emissions.

3.1.3. Objective Functions

Objective functions encapsulate the overarching goals of the optimization endeavor. For instance, in our case, the suitability of thermal power plants with fossil fuels hinges on meeting the required power capacity, whereas hydro and wind power plants are preferable if minimizing fossil fuel usage is paramount.

3.2. Problem Modeling

Once decision variables, constraints, and objective functions are defined, the decision-maker must model the problem in a suitable format for resolution. Modeling considerations include available tools, algorithms for problem-solving, required accuracy, and potential simplifications. A generic optimization problem model typically assumes the following form (Equation (1)):

$$\begin{aligned} &Minimize\ C(x) \\ &Subject\ to\ g(x) <= b \end{aligned} \tag{1}$$

Where x is the decision variable, C(x) is the objective function and g(x) < = b is the inequality constraint. The decision variables may be either real or integer or binary.

3.2.1. Mathematical Techniques

Mathematical optimization techniques entail formulating the problem within a mathematical framework, typically represented as Equation (1). If the objective function and/or constraints are nonlinear, the problem is termed a Nonlinear Optimization Problem (NLP). Quadratic programming represents a special case of NLP, where the objective function is quadratic in x. When both the objective function and constraints are linear functions of x, the problem is categorized as a Linear Programming (LP) problem. Additional categories arise based on the nature of variables; for instance, if x is of integer type, it denotes an Integer Programming (IP) problem. Mixed types like Mixed Integer Linear Programming (MILP) may feature both real and integer variables, with the problem still being of LP type.

In this study, the CPLEX solver was employed within the GAMS environment to solve the proposed mixed-integer programming (MIP) model. CPLEX is known for its efficiency and robustness in handling large-scale optimization problems involving discrete and continuous variables. To manage the complexity and scalability of the problem, the number of candidate sites and power plant types was limited during preprocessing. Additionally, certain parameters were grouped or discretized to reduce computational burden without significantly affecting model accuracy.

This approach ensures a balance between solution precision and computational feasibility, allowing the optimization process to converge efficiently while preserving the integrity of decision-making in power plant location planning.

3.2.2. Versus Heuristic Techniques

While most mathematical-based algorithms can ensure reaching an optimal solution, they may not guarantee a global optimum. Global optimality is attainable, checkable, or guaranteed only for simple cases. Conversely, many practical optimization problems deviate from the strict forms and assumptions of mathematical algorithms. Complex problems may pose challenges for mathematical algorithms, and achieving a global optimum remains elusive. Heuristic algorithms address these issues by handling combinatorial problems, even in highly complex scenarios, within a reasonable timeframe. However, they prioritize finding good solutions without guaranteeing optimality or proximity to the optimal point.

4. Solving the problem of power plant location according to environmental costs

4.1. Case Study

Table 1 illustrates the geographical distribution of load nodes, each assumed to have a value of 0.9 p.u Table 2 presents candidate locations for power plants (the data in this table have been extracted from Reference [1].), while Table 3 outlines the costs associated with solar, gas, thermal, hydro, and wind power plants. The type and capacity of each power plant have been selected by the authors based on the predefined scenarios considered in the study, which take into account different infrastructural and environmental conditions. In addition to fuel prices, the table includes data on land area requirements, equipment costs, and other essential factors. The construction and maintenance costs for each power plant type have been extracted from Source [24], which offers standardized and widely accepted economic estimates for energy systems.

Power plants must supply the loads listed in Table 1 (the data in this table have been extracted from Reference [1].), with their location and type determined based on Tables 2 and 3, along with specific scenario conditions to be addressed later.

4.2. Defining the problem of power plant location according to environmental costs

The primary objective is to minimize the cost of establishing power plants to meet desired loads while adhering to various constraints. The solution must determine the allocation, type, and size of power plants, along with associated investment and operating costs. Mathematically, the problem may be expressed as Equation (2):

$$\begin{gathered} \textit{Minimize } C_{total} = C_{\text{inv}} + C_{opt} \\ \text{Subject to constraintinvs} \end{gathered} \tag{2}$$

where C_{inv} refers to all investment costs and Copt denotes the operational costs. A typical investment cost is the cost of constructing a new power plant, where as the cost of providing the fuel is a typical operational cost. Various constraints should also be observed during the optimization process. For instance, the capacity of a power plant should not violate a specified limit, or any type of power plants cannot be established in all candidate locations.

4.3. Problem formulation

In this section, we try to formulate the problem of previous section as a mathematical optimization problem.

4.3.1. Objective function

The objective function, C_{total}, consists of the following three terms; C_{fix} (Fixed costs), C_{var} (Variable costs) and C_{env} (Environmental costs) (Equation (3)):

$$C_{Total} = C_{Fix} + C_{Var} + C_{\text{Env}} \tag{3}$$

4.3.2. Fixed costs

Fixed costs are further categorized into three components: transmission line costs, land costs, and infrastructure costs. The assumption is made that loads are directly linked to the power plant, with the cost of transmission lines denoted as gL(i) (for the ith load). This cost is defined as the cost per unit length (e.g., 1 km) for one unit of power transfer capability (e.g., 1 MVA). If Np represents the number of power plant points and NL represents the number of load nodes, and H(i, j) denotes the distance between the load node and the power plant, then we have (Equations (4)-(5)):

$$C_{Line} = \sum_{i=1}^{Nl} \sum_{j=1}^{Np} g_L(i) X(i,j) H(i,j) S_L(i) \tag{4}$$

Where;

$$H(i,j) = \sqrt{(Xi - Xj)^2 + (Yi - Yj)^2} \tag{5}$$

In the context provided, X(i,j) denotes the decision variable. For example, X(4,1) equals 1 if load node 4 is supplied through power plant 1; otherwise, it is zero. It is important to note that the value of X(i,j) is determined through the solution of the optimization problem. Consequently, at the conclusion of the process, the supply point for each load node is established. Additionally, SL(i) represents the load value of i in MVA (Equation (6)):

$$C_{Land} = \sum_{i=1}^{Np}\sum_{t=1}^{Nt} L_p(j)Space(t)u(j,t) \tag{6}$$

In this context, u(j, t) represents the decision variable for the type of power plant. For instance, referencing Tables 1 and 3, u(4, 8) equals 1 if there exists a power plant at location 4 as per Table 1, and the type of power plant corresponds to a hydro-power plant as specified in Table 3. The term Space(t) denotes the area of land required for a power plant of the type outlined in Table 3. Additionally, LP(j) signifies the value of each square meter of land at the jth point, as per Table 1. Throughout this article, the term "cost of infrastructure" refers to expenses associated with road construction and similar factors, computed as Equation (7):

$$Cinfrastructure = \sum_{i=1}^{Np}\sum_{t=1}^{Nt} Cinf(t)u(j,t) \tag{7}$$

Where $C_{inf(t)}$ is the cost of infrastructure depends on the type of power plant. Finally, fixed costs are calculated from the following Equation (8):

$$C_{Fix} = C_{Line} + C_{Land} + C_{infrastructure} \tag{8}$$

4.3.3. Variable costs

In this study, fuel costs and operator costs are classified as variable costs. Among these, fuel cost stands out as one of the most crucial objective functions, representing a substantial portion of expenses. The cost of fuel is treated as a continuous expense, computed annually for each power plant unit based on its capacity (UC) and fuel consumption. Ultimately, it is calculated over the entire useful lifespan of the power plant unit (UL).

To begin, let's introduce the relevant indicators:

- Load Peak (LP): This refers to the maximum load experienced during a specific time period.
- Load Factor (LF): The ratio of the total energy produced over a defined period (typically a year) to the product of the load peak and the duration of that period (usually 8,760 hours). The average load factor, in this case, is 0.65.
- Efficiency (EF): The ratio of net output to gross input, indicating the effectiveness of the power generation process (Equations (9)-(10))

$$p.f.plant = price * LF * 8760 * EF * UC * UL \tag{9}$$

$$Cfuel = \sum_{i=1}^{Np}\sum_{t=1}^{Nt} p.f.plant(t)u(j,t) \tag{10}$$

Operator costs are calculated as follows (Equation (11)):

$$Coperator = \sum_{i=1}^{Np}\sum_{t=1}^{Nt} p\_operato\_plant(t)u(j,t) \tag{11}$$

Where p-operator plant(t) is the costs related to the power plant operator (Equation (12)).

$$C_{Var} = C_{fuel} + C_{operator} \tag{12}$$

4.3.4. Environmental costs

Environmental costs in this article, only the costs caused by air pollution and land pollution are considered, which are calculated as follows (Equation (13)):

$$Cair = \sum_{i=1}^{Np}\sum_{t=1}^{Nt} p.air.plant(t)u(j,t) \tag{13}$$

where p.air.plant(t) is the costs related to the power plant air pollution cost (Equation (14)):

$$Cland = \sum_{i=1}^{Np}\sum_{t=1}^{Nt} p.land.plant(t)u(j,t) \tag{14}$$

where p.land.plant(t) is the costs related to the power plant land pollution cost, and finally, the environmental costs are calculated from the following formula (Equation (15)):

$$C_{Env} = C_{air} + C_{land} \tag{15}$$

In fact, incorporating environmental costs stemming from air and land pollution caused by the establishment of power plants is a complex and multifaceted issue. These costs can be broadly categorized into impacts on ecosystems, wildlife, and human health. Notably, damage to human health, especially life-threatening effects, cannot be compensated by any financial value and often involves significant uncertainty in quantification.

Since a comprehensive and precise evaluation of environmental costs is beyond the scope of this study, and due to the lack of standardized methods or accessible data to economically quantify such effects (especially in the context of the target region), this paper adopts a hypothetical and comparative approach. Specifically, environmental damages are reflected in the model through estimated coefficients incorporated into the objective function. These coefficients are calibrated to strike a balance between environmental impacts and conventional infrastructure-related costs, such as land acquisition, equipment, and fuel. The primary aim of this study is to introduce a novel methodology that integrates environmental considerations into optimal power plant site selection rather than attempting an exact economic valuation of environmental consequences.

4.4. Constraints

In practice, power plants are linked to substations via high-voltage transmission lines, and subsequently, the substations are linked to loads through additional transmission lines. However, for the purposes of this article, it is assumed that loads are directly linked to power plants via transmission lines, with no limitations on the placement of these lines. Given this assumption, the primary constraint of the problem is connecting each load to only one power plant, which is defined as follows (Equation (16)):

$$\sum_{j=1}^{Np} X(i, j) = 1.0, \forall i = 1, \ldots, Nl \tag{16}$$

where the Σ term represents the burden on power plant j. we use constraint below Determining the value of Xs(j) to be either zero or one (Equation (17)):

$$\sum_{i=1}^{Nl} X(i, j) \le X_s(j) Nl, \forall j = 1, \ldots, Np \tag{17}$$

A next constraint to be met is the power plant capacity as follows (Equation (18)):

$$\sum_{i=1}^{Nl} X(i, j) S_L(i) \le \overline{Sj}, \forall j = 1, \ldots, Np \tag{18}$$

Overline Sj represents the maximum capacity of the jth power plant. also X(i, j), Xs(j) are binary variable (zero or 1).

5. Prohibited area (definition and mathematical modeling)

As previously mentioned, one of the key innovations of this article is the incorporation of prohibited areas into the power plant location selection process, with consideration of associated environmental costs. In this context, prohibited areas refer to locations where the construction of power plants is either unfeasible or inadvisable due to environmental constraints. For example, hydropower plants cannot be installed in every location, as they require the presence of running water and suitable conditions for dam construction. Similarly, wind power plants demand areas with sufficient wind coverage and minimal physical obstructions. Solar power plants need regions with high solar radiation and favorable temperature conditions. Moreover, establishing thermal power plants in areas prone to air pollution is impractical. Biologists also advise against constructing power plants in ecologically sensitive regions with minimal human presence, as such developments could disrupt natural landscapes and biodiversity. Therefore, it is essential to incorporate prohibited area constraints into the power plant location optimization process. The modeling and treatment of these prohibited zones will be further illustrated through examples in the simulation section. In Reference [25], the authors aimed to determine optimal locations for wind power plants by evaluating the commercial viability of various wind speeds.

Their study identifies wind speed thresholds that are economically feasible for wind power generation and, in doing so, effectively defines prohibited zones for wind plant establishment based on insufficient wind potential.

6. Simulation

For the simulations, we utilized the system illustrated in Figure 1, as described by Seifi and Sepasian [1]. This system consists of 37 load nodes, each with a consumption of 30 MVA (0.3 p.u.). The geographical distributions of these loads are detailed in Table 1, while Table 2 presents the geographical distributions of the power plants in terms of longitude (X) and latitude (Y). Also, the cost per square meter of land for each candidate location is presented in dollars.

Additionally, Table 3 outlines the capacities and costs associated with each type of power plant. To enhance comprehension of the various costs involved, three scenarios have been devised, which will be elaborated upon shortly. Notably, the study area is segmented into four parts based on land prices; the two dark-colored regions exhibit lower prices compared to the two white-colored areas.

6.1. Scenario 1

In Scenario 1, we solely factor in the cost of land for power plant construction and the cost of transmission lines. Initially, we consider only one type of power plant candidate (Code. 6 of Table 3 - thermal power plant) for establishment, optimizing solely for power plant locations. Costs due to land and transmission lines are the most basic type of cost in the problem of power plant location. It is usually used in simulations where the type and power of the power plant are the same and only the location of the power plant is unknown. According to the type of selection costs, we expect the candidate locations for power plant deployment to be selected using simulation, which first have lower land cost than other candidate location. Secondly, they are also chosen in such a way that the least number of transmission lines are required.

Table 1. Geographical distributions of load nodes.

Code	X	Y	Code	X	Y	Code	X	Y
1	2	40	14	52	40	27	95	73
2	20	40	15	44	32	28	95	44
3	2	28	16	46	15	29	90	40
4	5	21	17	44	76	30	94	33
5	20	28	18	52	76	31	91	32
6	10	50	19	58	74	32	92	28
7	25	50	20	54	66	33	93	19
8	30	57	21	60	53	34	98	12
9	40	61	22	58	19	35	75	32
10	37	55	23	64	17	36	85	17
11	43	45	24	60	6	37	85	10
12	35	35	25	67	40			
13	46	42	26	85	57			

Table 2. Geographical distributions of power nodes.

Code	X	Y	Land Cost	Code	X	Y	Land Cost
1	15	33	3.5	14	55	58	5
2	35	50	65	15	75	55	3
3	85	33	85	16	33	33	1
4	55	33	80	17	70	33	80
5	48	70	65	18	12	19	7
6	60	14	89	19	28	19	9
7	65	55	2	20	44	21	7
8	92	15	80	21	60	22	6
9	12	70	50	22	12	10	5
10	32	70	45	23	28	10	8
11	65	70	4	24	44	10	5
12	88	70	5	25	70	10	99
13	15	50	75				

Table 3. Establishment and running costs of power plants ($/1pu).

Code	Type	Capacity (p.u)	Space (p.u m-2)	Area cost	Land cost	Fuel cost	Operator cost	Under cost
1	pv	1	15000	0	500	0	200	500
2	pv	2	30000	0	10000	0	250	500
3	pv	3	45000	0	15000	0	300	500
4	Gas	3	1000	5000	3000	4000	9000	15000
5	Gas	5	2000	10000	6000	8000	10000	15000
6	Thermal	5	1500	150000	4000	2000	8000	10000
7	Thermal	8	5000	300000	9000	3500	15000	10000
8	Hydro	2	7000	0	6000	0	1000	10000
9	Hydro	3	8000	0	7000	0	1500	10000
10	Wind	1	700	0	1000	0	200	500

The graphical representation of the simulation results is depicted in Figure 2, while Table 4 provides a breakdown of the costs. It is worth noting that according to Table 2, candidate locations 16, 7, and 15 have the lowest, respectively the amount of cost per square meter of land among the candidate places for the establishment of the power plant. To investigate the impact of line costs, the simulations were repeated with a 20% reduction in land costs. The results are presented in Figure 3 and Table 5. With the decrease in land expenses, the most optimal strategy involves expanding the power plant coverage to include locations 7, 16, and 21. In the previous simulation, the selected power plant locations were situated in areas with lower land costs (colored areas). However, with the reduced land expenses, the significance of line costs increases, leading to the optimization of transmission line expenditures. As shown in Table 5, the costs associated with the green items have decreased compared to the previous iteration.

6.2. Scenario 2

In this scenario, three different types of power plants are considered: a solar power plant, a gas power plant, and a thermal power plant fueled by mazut. The capacity of each power plant is considered to be 1, 2, and 3 units respectively. The cost of equipment for each power plant is considered equal to 10,000$, 15,000$, and 700,000$, respectively. Also, the cost of land pollution (land pollution means changing the face of nature and interference in the environment of the region and pollution caused by waste and waste water) is considered to be approximately 9,000$, 30,000$ and 400,000$ respectively for all three power plants.

Table 4. Costs related to the geographical distribution of power plants based on the cost of land and cost of lines.

Total cost	Land cost	Line cost
1571698	750000	821698

Table 5. Costs related to the geographical distribution of power plants based on the cost of lines and reducing the cost of land by 20%.

Total cost	Land cost	Line cost
963984	225000	738984

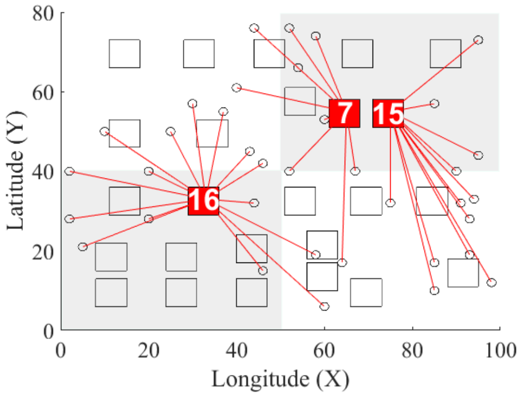


Figure 2. Geographical distribution of power plants according to the cost of land and cost of lines.

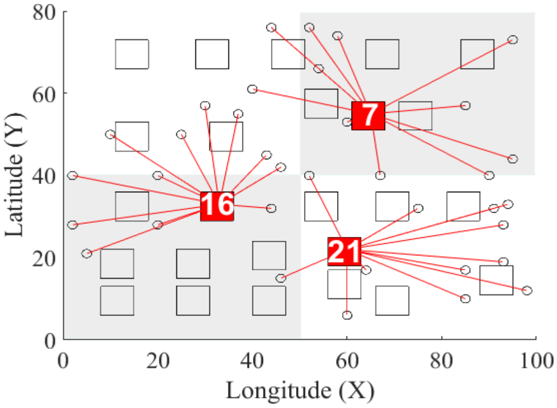


Figure 3. Geographical distribution of power plants based on the cost of lines and reducing the cost of land by 20%.

This cost is considered more for the solar power plant that needs to occupy a wider area of land than others. Of course, determining the amount of cost due to land pollution for each type of power plant is a very complex task and is not in the scope of this article, and in this article, approximate numbers are used to show the huge effect of this cost in the location of power plants. The optimization process takes into account land costs, line costs, the type of power plant, fuel costs, equipment costs, and expenses related to land pollution. The simulation results are presented in Figure 4 and Table 6. According to the simulation results, candidate locations 1, 7, 11, 14, 15, and 21 have been chosen for the establishment of gas plants, while candidate location 16 has been selected for the establishment of a solar plant. The most type of power plant selected by simulation is gas power plant, the reason for this can be considered the lower cost of this power plant in terms of land pollution. On the other hand, only one solar power plant with a capacity of 1 megawatt has been selected to supply the requested amount of electricity, and as you can see, the simulation of the thermal power plant has not been selected. The reason for this is the higher cost of the equipment compared to the other two types of power plants and the higher cost of soil pollution compared to the gas power plant.

In this revised simulation, the costs stemming from air pollution caused by power plants are taken into account. The considered cost for air pollution is 0, 25 and 40 $/MW for solar, gas and thermal power plants, respectively. Considering the cost of air pollution for solar power plants is zero, it is expected that the number of solar power plants will increase.

The results are summarized in Table 7 and Figure 5. Candidate locations 7 and 16 have been identified as suitable for establishing solar power plants. Consequently, land costs have increased while fuel costs have decreased. Candidate locations 1, 11, 14, and 15 have been designated for gas power plant construction, and candidate location 21 is chosen for a thermal power plant using mazut fuel. Overall, the total costs have escalated. In Table 7, the costs associated with green items have decreased compared to the previous iteration, while the costs attributed to orange items have increased in comparison. In general, in this scenario, it was found that considering the cost of land and air pollution has significant changes in the simulation results.

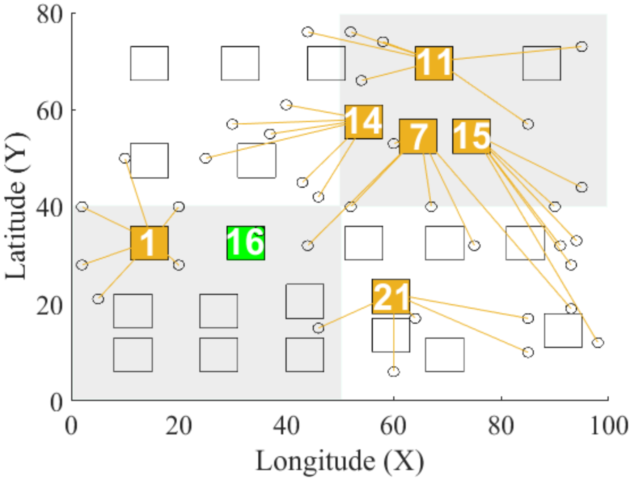


Figure 4. Geographical distribution of power plants based on the cost of land, cost of lines, cost of fuel, cost of equipment, and cost of land pollution, three types of power plants (solar, gas and thermal) are considered.

Table 6. costs related to the geographical distribution of power plants based on the varios costs of the three types of power plants (solar, gas and thermal.

Total cost	Land cost	Line cost
31360650	1337500	667214
Fuel Cost	Equipment Cost	Land Pollution Cost
19985940	19985940	19985940

Table 7. costs related to the geographical distribution of power plants based on the varios costs of the three types of power plants (solar, gas and thermal.

Total Cost	Land Cost	Line Cost
70662290	2787500	631614
Fuel Cost	Equipment Cost	Land Pollution Cost
1611180	13200000	340000
Area pollution Cost		
36792000		

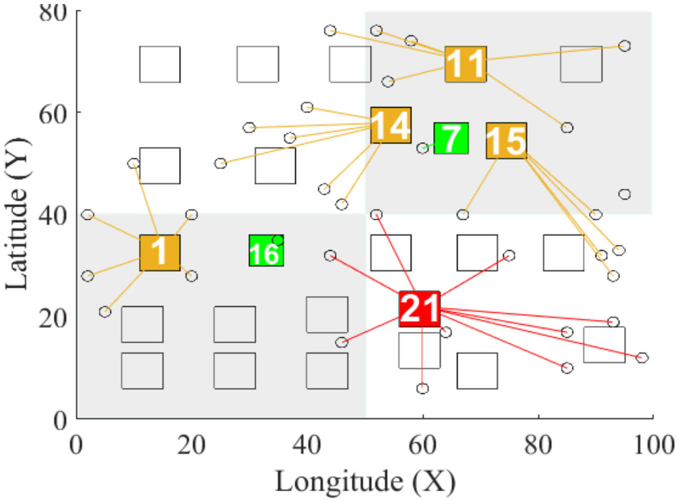


Figure 5. Geographical distribution of power plants based on the cost of land, cost of lines, cost of fuel, cost of equipment, cost of land pollution and air pollution, three types of power plants (solar, gas and thermal) are considered.

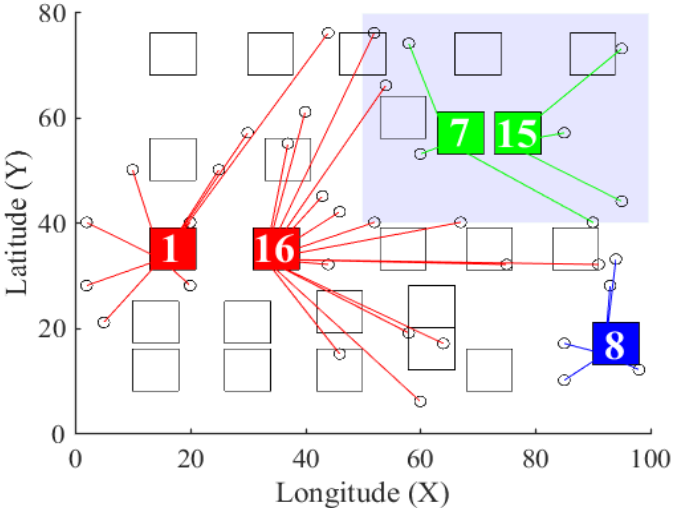


Figure 6. Geographical distribution of power plants based on the prohibited areas.

6.3. Scenario 3

In the previous scenario, three types of solar, gas and thermal power plants were considered. However, there are different types of power plants, such as wind and hydro power plants. Now, as stated in the previous section, I have to consider this point, each type of power plant has different limitations for operation, and the possibility of establishing each type of power plant in Not every place is a candidate. Some of these restrictions are restrictions on sunlight and wind, land size restrictions, air pollution restrictions, and environmental restrictions.

The primary objective of this scenario is to investigate the impact of prohibited areas on the optimal location of power plant establishments. All 10 types of power plants outlined in Table 3 are taken into consideration. To delineate the prohibited areas, we initially assume that in candidate locations 7, 11, 12, 14, and 15, situated in the upper right area (highlighted in pale blue), only solar power plants of varying capacities (power plants 1 to 3 according to Table 3) and wind farms are permitted for establishment. To enforce this restriction, the following constraint has been incorporated into the problem formulation (Equation (19)):

$$\sum_{t\in A} u(j,t) = 0,\ A = \{t > 3\ and\ t < 10\},\ \forall j = 7,11,12,14,15 \tag{19}$$

We have also assumed that the candidate location for the establishment of power plant No. 8 only has the ability to establish a hydro power plant, which is formulated as follows (Equation (20)):

$$\sum_{t\in B} u(j,t) = 1, B = \{t = 8\}, \forall j = 8 \tag{20}$$

The simulation results are shown in Figure 6. As expected, only the solar power plant has been allowed to be established in the mentioned area, and only the hydro power plant has been allowed to be established in candidate 8.

7. Conclusions

Considering environmental costs in power plant location decisions reveals the hidden expenses associated with fossil fuel power plants. This consideration assists engineers and governments in making informed decisions regarding the optimal type and location of power plants while minimizing environmental impacts. Although this article focuses on some of the most prominent environmental effects of power plant establishment, it proposes various formulations to accommodate additional potential impacts. This approach aims to support future research efforts that consider a broader range of environmental effects.

For future work, we suggest incorporating transmission line and distribution costs incurred after plant establishment into the decision-making process. Moreover, addressing the problem using a bi-level optimization approach could provide deeper insights and more comprehensive solutions to the complex challenges involved in power plant location selection.

Beyond environmental factors, policymakers should also consider political and economic aspects when deciding on power plant locations. Collaboration with local communities and leveraging economic development opportunities in selected areas can promote sustainable growth and enhance public support for energy projects. Additionally, providing incentives for investment in renewable energy infrastructure and encouraging energy efficiency initiatives can align economic interests with environmental goals, contributing to a more sustainable energy future

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Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper. The ethical issues, including plagiarism, informed consent, misconduct, data fabrication and/or falsification, double publication and/or submission, redundancy, have been completely observed by the authors.

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