Geographic information-driven two-stage optimization model for location decision of solar power plant: A case study of an Algerian municipality

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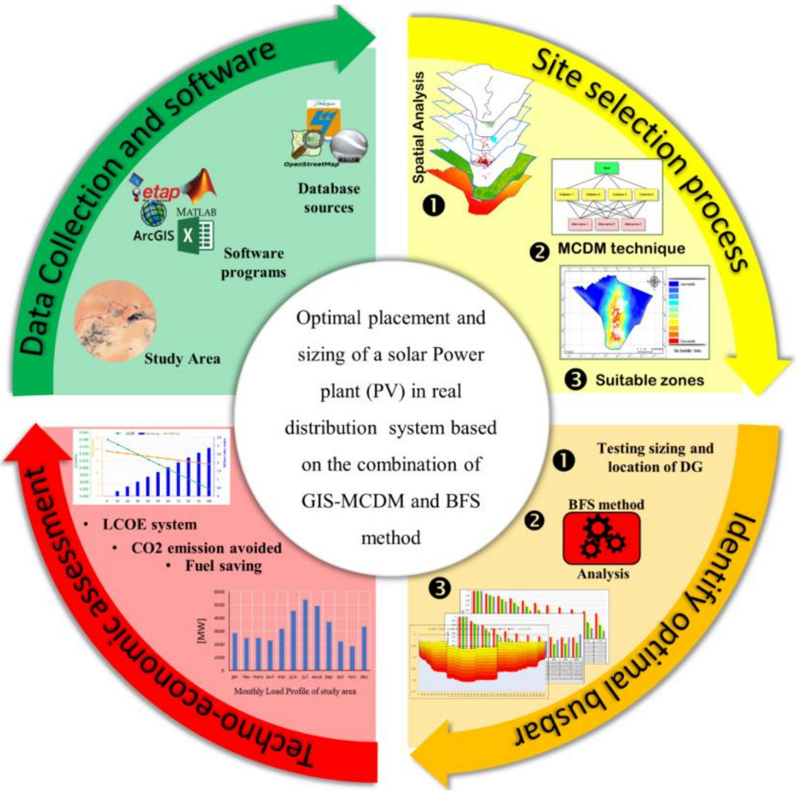
Graphical abstract



Abstract:

The integration of distributed generation (DG) units in existing power systems constitutes a promising solution for successful transition towards low carbon and sustainable energy generation systems. This paper presents an interdisciplinary framework for optimal mapping and integration of solar photovoltaic (PV) based DG systems. Contrary to previous work, the proposed framework has combined both spatial and technical economic analysis, and used efficient optimization techniques to get accurate decisions. First, a geographical information system and a multi-criteria decision method were used to identify the sites with the highest potential for hosting PV power plants. Second, Backward-Forward Sweep (BFS) load flow algorithm was used to investigate nominated sites taking into account three indices, namely, Active power losses, Voltage sensitivity Index (VSI), and voltage profile improvement. In addition, a techno-economic and environmental feasibility assessment is performed based on the characteristics of a real distribution grid (considering the 464 bus Radial Distribution System (RDS) test system with a total load of (4.4708 +

3.2332i) MVA and base voltage of 30 kV) in N'goussa region in Ouargla province, Algeria. The results show that 78 % of the studied area (which was also gradually divided into ten zones, from optimal to least suitable) is suitable for installing PV power systems. The optimal zone represents only 1.52% (45.81 km²) of the obtained suitable area. In addition, two zones were eliminated from the ten suitable zones, as they are so far from the existing grid bus bars (substation). Based on BFS method, and while taking VSI and profile voltage as the most influential factors, the bus bar 104 is the optimal point for injecting power from PV to grid. However, when taking the active power losses as the most important factor, the bus bar 63 was found to be the optimal injection point. Furthermore, the techno-economic assessment for the investigated system indicates that the levelized cost of energy is decreased by 0.4 $/kWh for each 10% increase applied to penetration rate. For the latter, for a penetration rate of 100%, the amount of fuel saved and the amount of avoided carbon dioxide (CO_2) emission will reach more than 3 million cubic meter and 500 tonnes, respectively. The outcomes of the present work are significant and could help policy makers and planers to make best decisions about implementing future solar power projects in Algeria and beyond.

Keywords:

Radial Distribution System; Geographic Information System; Multi Criteria Decision Method; Backward Forward Sweep; DG location; Optimization; Solar PV.

Nomenclature

AHP	Analytic Hierarchy Process
BFS	Backward/Forward Sweep
DG	Distributed Generation
GIS	Geographic Information System
LCOE	Levelized Cost of Energy
MCDM	Multi-Criteria Decision Making
RDS	Radial Distribution System
RES	Renewable Energy System
VSI	Voltage Sensitivity Index

1 Introduction

Energy is an important factor needed for a society's sustainable development and prosperity. By the end of 2018, fossil fuels accounted for more than 84% of the world's primary energy consumption (coal, oil and natural gas). Oil, natural gas and coal dominate the consumed energy resources by 33.62%, 23.86% and 27.2% respectively [1,2]. According to outlook reports of British Petroleum (BP) and the International Energy Agency (IEA) [3,4], the projection of global energy demands indicates an increase by 26% by 2040. Clearly, fossil fuel resources are dwindling and will run out in the future. The insufficient amount of fossil fuels might result in increased long-term costs.

The dramatic growth in energy consumption especially electricity (due to urbanization, economic growth and industrialization), as a result of global energy tension and environmental concerns of fossil fuel based electrical generation, means that the use of alternative renewable energy sources in electric networks is becoming increasingly unavoidable. In other words, there is a need to use Renewable Energy System (RES) in electrical grids to achieve higher levels of energy efficiency, renewable energy resource integration, system reliability, increased economic growth, and new employment opportunities [5].

Within this context, there are many technological factors for the growth of Distributed Generation (DG) that offer the electricity networks its many benefits. In fact, to reduce power losses, there are several techniques that have helped in this way, such as DG unit placement [Ref?], feeder reconfiguration [Ref?], and capacitor placement [Ref?]. Although the term Distributed Generation is often used to depict a small-scale electricity generation, in literature there are actually other definitions of a distributed generation including decentralization, dispersed, district and local generation. Other definitions of Distributed Generation exist from different agencies or organizations such as International Energy Agency (IEA), International Council on Large Electric Systems (CIGRE) and Electric Power Research Institute (EPRI). They all agree that the DG is a power plant with a capacity smaller than 50-100 MW, which is considered as a decentralized generation and is usually installed nearby customers in remote areas. Another essential point is how to integrate DG in distribution systems. The IEEE 1547, VDE-AR-N4105 and IEC 61727 are major standards for Solar PV power plant integration as a DG in voltage distribution systems. These standards are described and detailed in many papers (e.g. [6–10]).

1.1 Optimization of the placement and sizing of Distributed Generation (DG) an overview

For most studies on optimization of Distributed Generation Allocation (DGA), the objectives are divided into three main groups [11]: technical, financial and multi objectives. In the first one, there are two kinds of objectives: the minimization of the power / energy losses [12–14] or voltage profile improvement (or other objective improvement) [15–17]. For the second group which focuses on financial objectives, the main goals are DG efficiency, energy harvest maximization [18–20], as well as cost minimization and profit maximization [21–23]. For the multi objective optimization, generally, it provides competing goals and allows planners to choose the best solution from the options available, based on their experience and points of view. This group is divided into real value multi-objective (MO) function [24–26] or index based MO function [27–29]. The most common combinations are summarized in **Fig. 1**.

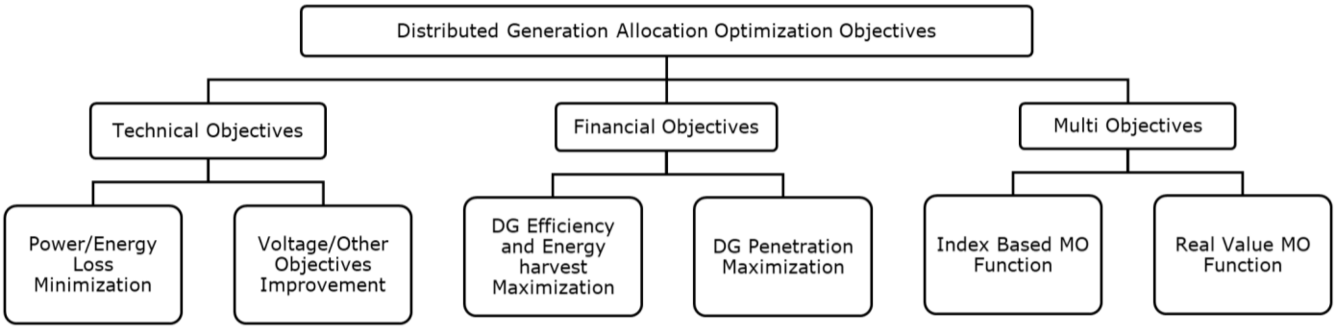


Fig.1. Overview of the objectives function in Distributed Generation Allocation [11].

For an excellent resource on the future deployment of distributed generation, Ehsan and Yang [30] present a comprehensive review about the analytical techniques used in the planning and optimization of the integration of DG into power distribution systems. Sadeghian and Wang [31] presented a detailed impact-assessment framework to assess the impacts of renewables distributed generations “PV” connected to a realistic distribution network, based on the multi-objective optimization as a tool in problem formulation. Some papers used the IEEEs i-bus distribution system to solve the DGs’ optimal siting and sizing problems by using different algorithms. For example, Luo et al. [32] used weighted voltage support ability index (WVSAI) analysis which was applied in IEEE-33 bus by using PV-STATCOM. Singh et al. [33] used Monarch butterfly optimization method which is a Multi-Criteria Decision Making (MCDM) method to select the optimal integration of Distributed Energy Resources (DER) mix which is also applied in IEEE 33 bus. Reddy et al. [34] also tested the flower pollination algorithm in 15-bus, 34-bus, and 69-bus Radial Distribution Systems (RDSs) as application for optimal siting and sizing of DG in those distribution systems. Aman et al. [35] used Particle Swarm Optimization (PSO) as multi objective algorithm to solve placement and sizing problems of DG in 12, 30, 33 and 69-bus RDSs, then compared their objective function (voltage stability maximization and minimization of power losses) with other methods such as Analytical and Grid search methods. In another study presented by Bouhouras et al. [36], they used PSO method to find optimal penetration (sizing), placement and number of DGs; the proposed method was applied in 30 and 33-bus as

RDS which takes into account losses minimization as objective function. Pesaran et al. [37] used a hybrid genetic-PSO method in their analysis taking into account the improvement of three objectives functions which were power losses (active /reactive) and the deviation of bus voltages; this later method was applied in IEEE 33 and 69 bus. In a similar approach, Bayat and Bagheri [38] used a novel heuristic method to identify the best location of DGs and applied it to 33, 69, and 119-bus distribution grids based on power losses minimization (active/reactive), and the results were compared with serval algorithms. A study presented by Singh and Gyanish [39] tested DG penetration levels, based on the minimization of power loss (active/ reactive), and improvement of voltage profile. The analysis was tested in IEEE-14 bus RDS by using the optimal power flow method.

In the power flow studies of radial distribution systems, the Backward/Forward Sweep (BFS) method has become one of the most popular methodologies. In comparison with other methods such as three-phase current injection method (TCIM) [40], Newton-Raphson and fast decoupled methods [41], the BFS method is superior when applied with distribution system due to high x/r ratio of feeders [42]. Another essential point regarding the advantages of BFS method is its simplicity, easy to understand mathematical execution of the basic algorithm, and generally its excellent results for this kind of system [40].

1.2 Combination of GIS-MCDM for site selection application

The combination of Geographic Information System (GIS) tools and Multi-Criteria Decision Making (MCDM) methods has become a successful assessment approach to solve complex problems such as site selection of renewable power plants, including taking into account several criteria in order to estimate the potential of a territory to host PV power plants. The literature contains various MCDM approaches, such as the Analytic Hierarchy process (AHP) [43–48]. Shao et al. [49] presented a review study of MCDM application for renewable energy site selection, which covered five RES options published in 85 paper over a period of 17 years (2001-2018) in high-impact journals. Prăvălie et al. [50] also presented a review study of solar radiation distribution globally, continentally and nationally. In their study, they investigated both types of solar radiation: direct normal irradiation and global horizontal irradiation. Their results showed that for GHI hotspots there were 6 major regions, including Northern Africa and the Arabian Peninsula, with annual values of more than 2200 kWh/m². For the Middle East and North Africa (MENA) region, there are many studies in the field of GIS based MCDM for site selection. In Qatar, Martín-Pomares et al. [51] used GIS as tools to present and analyze the solar resource (GHI and DNI) to assess the power generation potential by using satellite-derived data and kriging method as interpolation technique. In the United Arab Emirates, Gherboudj and Ghedira [52] combined GIS tools, remote sensing and weather forecast models to develop a solar map (with the effects of the land constraints) and weather conditions to assess implementation of solar power plants (PV and CSP). In Saudi Arabia, Al Garni and Awasthi [53] used GIS based MCDM application to find the optimal sites for solar PV power plant, in which the solar map was developed based on a tool in ArcGIS (a solar analyst which requires, as input, the digital elevation model (DEM)). In Turkey, Uyan [54] used AHP and GIS to select optimal sites for solar farms, although the solar potential was not evaluated with the study's criterion due to its small intervals of 50 kWh.m².year between maximum and minimum values. In Algeria, a study by Messaoudi et al. [55] presented a methodology for site selection of solar hydrogen based on combination of GIS-AHP. Another study by [56] and [57] applied to Algerian territory focused on determining suitable land sites of PV and CSP power plant connected to grid, respectively. In addition, other research works were carried out in different countries and regions, e.g., Spain [58,59], Morocco [45,60], Turkey [47,54,61,62], and Iran [63–65].

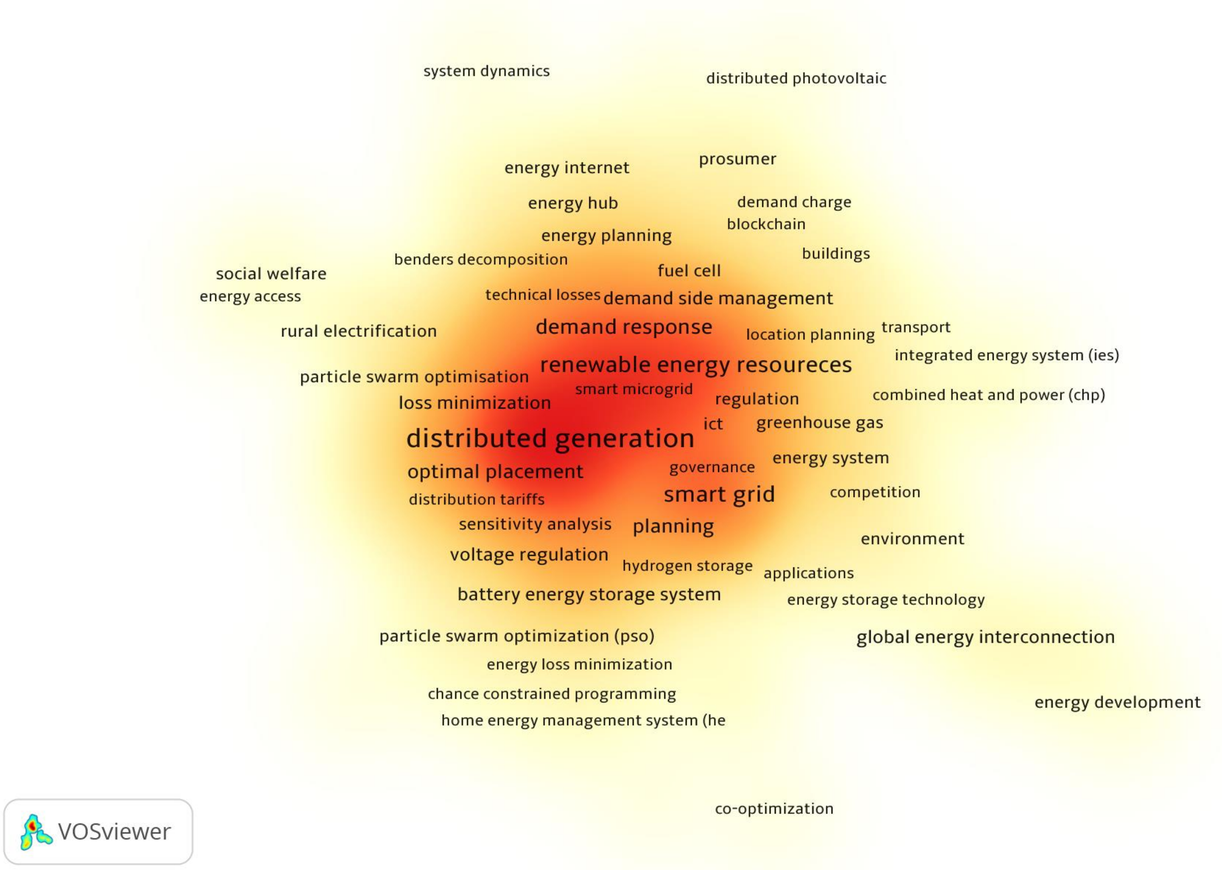


Fig.2: Schematic view of the bibliometric study of the optimal placement in the distribution system of photovoltaic distributed generation, depending on the VOSviewer display. Notice that the keywords that are in red and written in bold letters are widely reported and used in those papers; on the other hand, the other keywords that are less utilized are shown in light orange color with a transparent letter.

Based on these literary works and others, a detailed bibliometric analysis of Elsevier database papers over the last 15 years was performed (more than 1000 published papers), using distributed generation, optimization, distribution system, and allocation as keywords used in the studies to relate to the optimum allocation of DG in the radial distribution system; the results using VOSviewer tool are shown in **Fig. 2.** The following observations can be made from Fig.2:

i) The majority of papers on the optimal placement of distributed generation in distribution systems have focused on technical indices such as the power loss reduction and voltage profile improvement.
ii) The particle swarm optimization, genetic algorithm, multi-objective optimization and optimal power flow are the most used optimization techniques;
iii) Most papers used the distributed generation and smart grid which considered a promising alternative (DG) in the transition toward smart grids;
iv) Most of the studies are focused on solar photovoltaic, virtual power plant and distributed generation planning to ensure adequate response to energy demands.

In contrast, very few papers have been published on optimal placement and sizing of DGs in a realistic distribution system, as well as the spatial consideration to install the photovoltaic solar power plant as DG. To do so, an interdisciplinary framework should be adopted to access the optimal placement of PV-DG in real distribution networks, taking into account the spatial feasibility of installation and optimization and considering technical factors such as minimization of power losses, voltage improvement and stabilities of voltage profile. Based on the literature review, the multi-objective optimization methods have become widely used in these fields of research, in which many authors have suggested that future works should be focused on the utilization of multi-objective optimization methods and their combination with spatial analysis techniques.

In order to overcome the limitations highlighted above, in this paper, the authors propose a novel approach to determine the optimal placement and sizing of solar PV based DG integration into a real Radial Distribution System (RDS) contrary to what has been mentioned previously by combining spatial analysis based on GIS-MCDM and optimization of bus bar based on Backward Forward method. To do so, this paper proposes a new framework that works in two stages. In the first stage, a geographic information system based multi on criteria decision method (AHP) is used to identify sites with the highest solar potential based on several criteria including environmental, economic and orography aspects. In the second stage, Backward-Forward Sweep (BFS) load flow algorithm is used to investigate nominated sites based on the viewpoint of three technical indices: active power losses, voltage sensitivity index, and voltage profile improvement.

2 Methodological framework

The methodological framework which is proposed in this paper is structured following different steps that are summarized and illustrated in **Fig.3.** As described in **Section 3.1,** the study area was initially identified after preliminary consideration of the geographical location, availability of renewable energy sources and indications of increasing demand for electricity in the region. **Section 3.2** shows that the key steps of the framework are to determine the buffer zone as well as the classified area and, finally, to determine the appropriate area. After that, a conclusion to this section is outlined by describing MCDM using AHP in a GIS environment. In **Section 3.3,** by using the suitable zones given by spatial analysis in the preceding section to identify the exact location of Distribution Generator (DG), BFS method is then used on existing Distribution Network (DN) (N’goussa region in our case), and the Voltage Sensitivity Index (VSI), power active losses and voltage profile improvement are used as technical indices. Finally, in **Section 3.4** a techno-economic and environmental approach of different DG penetration is applied to determine LCOE, CO_2 emission avoided and fuel saved for each penetration rate.

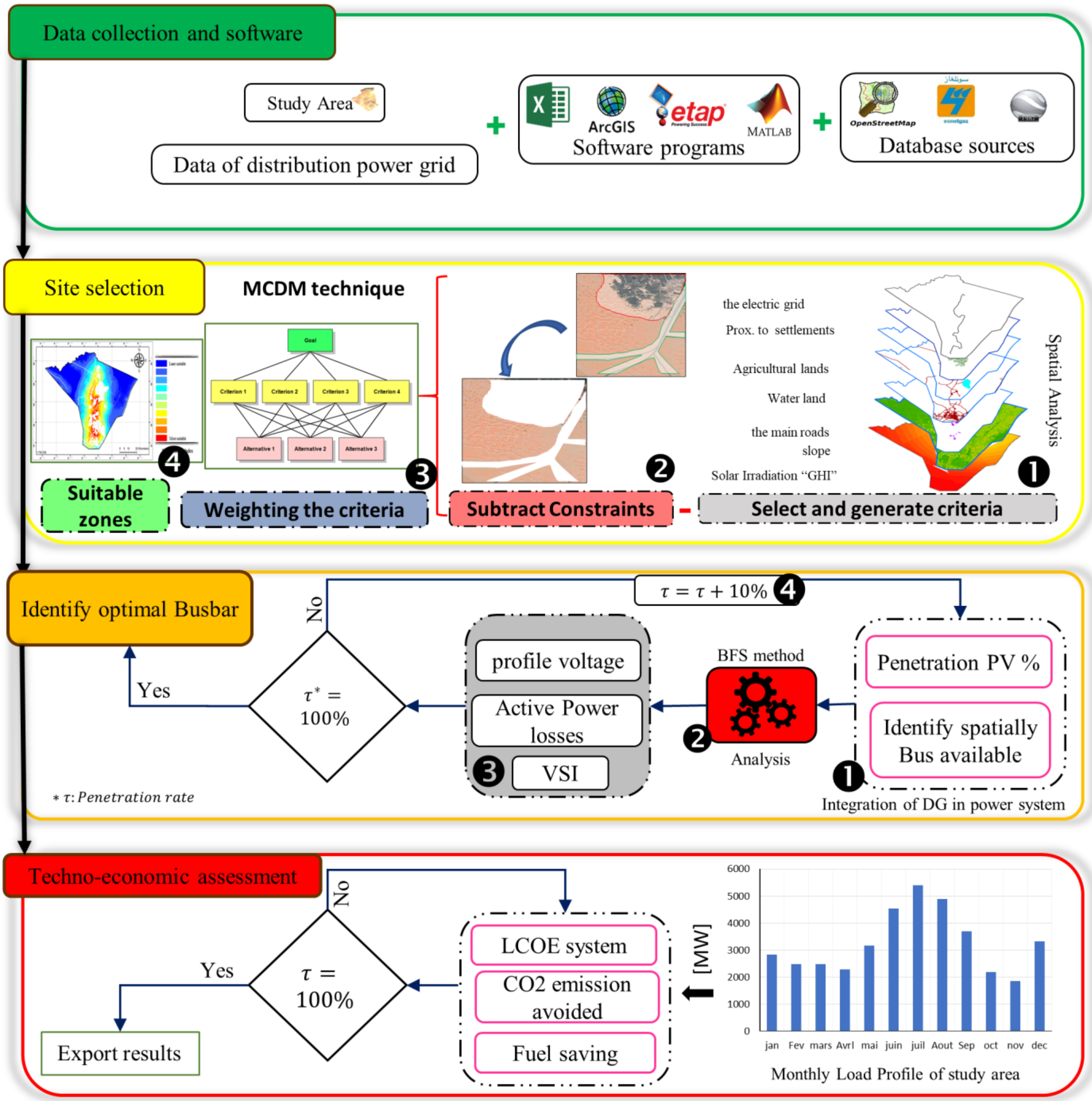
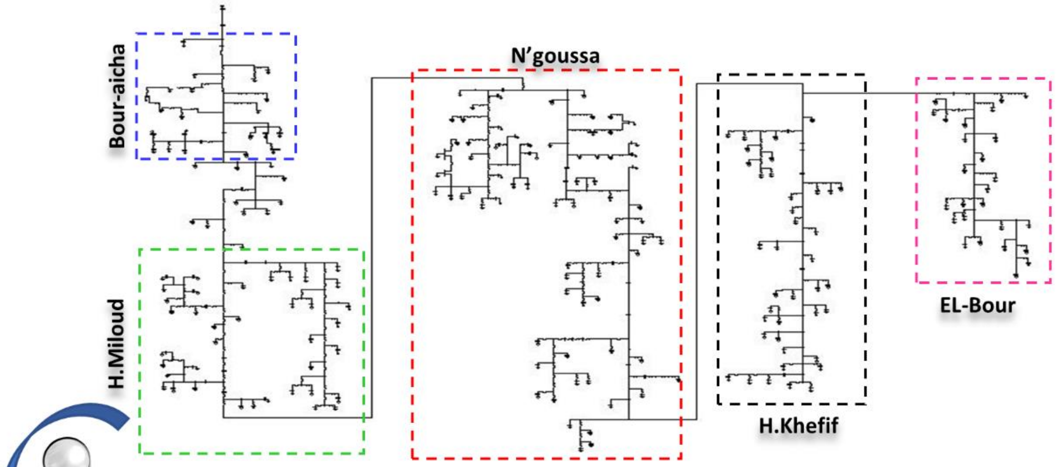


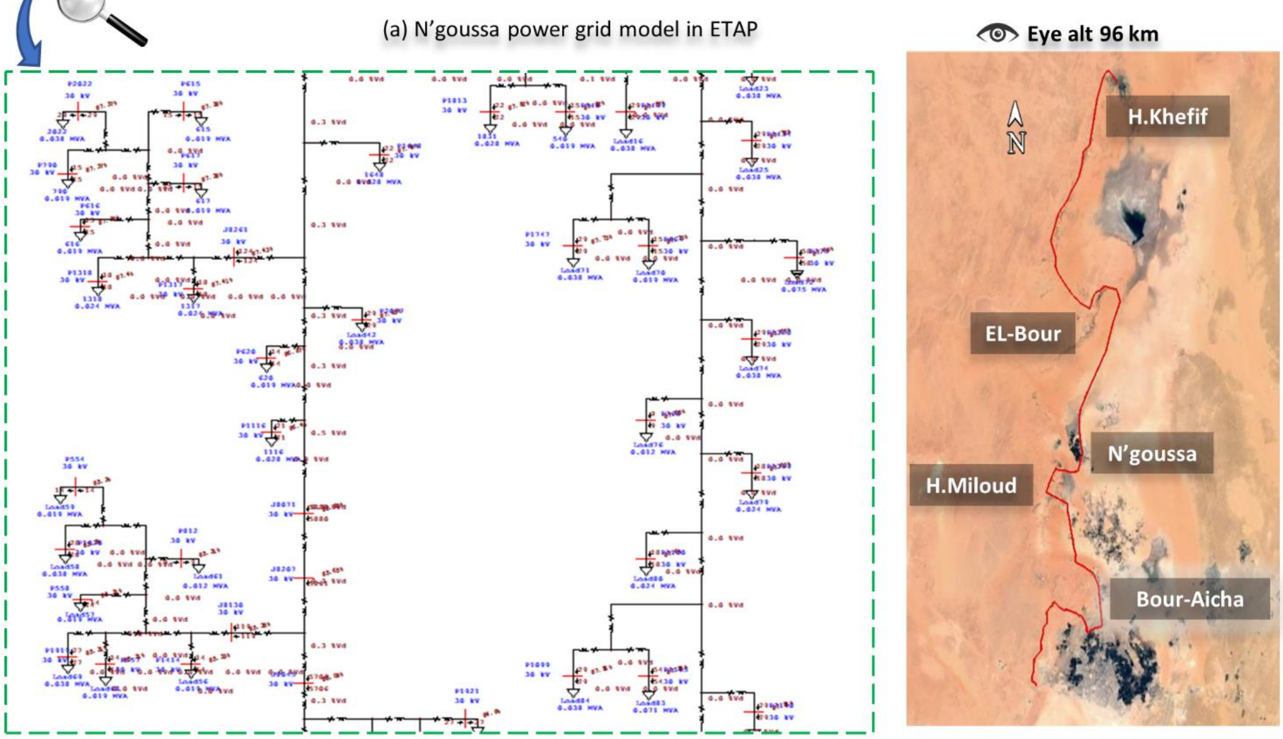
Fig. 3: Architecture of the proposed methodology.

2.1 Presentation of study area

The region of the study includes N'goussa region, with a total land area of 3,866 km², making it one of the largest communities of Ouargla province in the southeast region of Algeria. The area is generally characterized by arid climate. As shown in Fig. 6, the solar map developed by [56] indicates that Ouargla province has one of the highest solar irradiation values in Algeria. In our case study (N'goussa region), the mean annual solar irradiation was within 2164 kWh/m²/year and 2192 kWh/m²/year, clearly showing encouraging investment potential in solar energy. The case study of N'goussa region contains one of the largest distribution system operators in Ouargla. The region is characterized by the following technical parameters; 464 bus Radial Distribution System (RDS) with a total load of (4.4708 + 3.2332i) MVA and base voltage of 30 kV. The single line diagram of 464 bus systems is shown in Fig. 4.



(a) N'goussa power grid model in ETAP



(b) Zoomed of Hassi-Miloud power grid model in ETAP

(c) N'goussa power Line

Fig.4: Presentation of study area (the picture on the left is very unclear; is it essential to have it?)

2.2 Hierarchy model development

Based on several published papers in literature, case studies are found that are concerned with methods of solar PV power plant site selection, including experts' opinion in the field of energy policy. The methodology followed in this paper is presented in **Fig.3**. Initially, data collection from different sources (e.g. governmental organizations, open sources database) was performed using in development and digitalization of database, with high raster resolution (29x29 m which is more than 4 million pixels for each map). Afterwards, eight layers were developed as presented in **Table 3,** which add up to DEM and solar map. A buffer zone around the roads, lakes, power lines, urban areas, vegetation areas and the areas with a slope greater than 5% have been imposed as constraints. Six criteria were chosen along with the weighting process by using the AHP method. Then, a raster calculator (a tool in GIS) was used to build the suitability map. This map was clustered into ten groups: from "least suitable to "most suitable.".

2.2.1 The analytical hierarchy processes (AHPs)

The AHP approach is a decision support tool for solving complex problems using a multi-level hierarchical structure of criteria, parameters and sub-criteria. The AHP method is a mathematical approach for MCDM problems, developed by mathematician Thomas L. Saaty [66,67] and can be used to evaluate various problems. As **Fig.5** shows, the AHP has a number of steps. The criteria and alternatives should be defined at the beginning of each AHP step. Practical judgement should then be required for selection of criteria [68].

- **Step (1):** a matrix $M\ (n \times n)$ of n elements (number of criteria used) is used in establishing $(n \times n)$ comparison of multiple criteria. Let P_{ij} = extent to which we prefer factor i to factor j. Then, assume $P_{ij} = 1/P_{ij}$. The relative importance of pairwise comparison is measured according to a numerical scale from 1 to 9 as shown in **Table .1**.

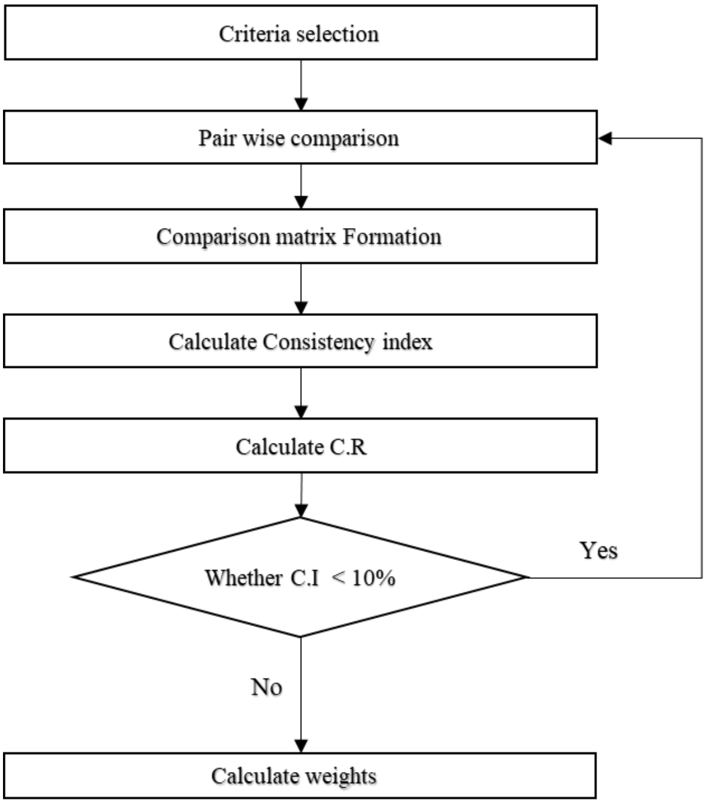


Fig.5. Flowchart of AHP.

- **Step (2)**, to establish a normalized pairwise comparison matrix *M*:
  - (i) The sum of each column must equal to 1. (is this true according to Eq.1?)
  - (ii) To find a standardized matrix, split each element in the array by its total column sum.
  - (iii) For each criterion, the average of each row of the last matrix gives the relative weight.

$$M = \begin{bmatrix} 1 & a & b \\ 1/a & 1 & c \\ 1/b & 1/c & 1 \end{bmatrix} \qquad \text{(Eq.1)}$$

Table .1: AHP evaluation scale.

Score of criteria $\boldsymbol{i}$ to criteria $\boldsymbol{j}$ $\boldsymbol{P(ij)}$	Definition
1	factor$s$ $\boldsymbol{i}$ and $\boldsymbol{j}$ are of **Equal** importance.
3	factor $\boldsymbol{i}$ is **Slightly** more important than $\boldsymbol{j}$
5	factor $\boldsymbol{i}$ is **Moderately** more important than $\boldsymbol{j}$
7	factor $\boldsymbol{i}$ is **Strongly** more important of than $\boldsymbol{j}$
9	factor $\boldsymbol{i}$ is **Extremely** more important of than $\boldsymbol{j}$
2,4,6,8	Intermediate values

- **Step (3):** Due to the nature of human judgment, a reasonable level of inconsistency is expected and tolerated between all comparisons, and it is abnormal for these to be consistent. In order to control the consistency of the calculated weighted values, the consistency ratio (CR) should be calculated. The CR is estimated as follows:

(i) Firstly, the maximum eigenvalue λ_{max} for each matrix is obtained.

(ii) Secondly, using Eq.2 to calculate Consistency Index (CI).

$$CI = \frac{\lambda_{max} - n}{n-1} \qquad \text{(Eq.2)}$$

(iii) Finally, the Consistency Ratio (CR) is calculated using Eq.3:

$$CR = \frac{CI}{RI} \qquad \text{(Eq.3)}$$

where RI is the random index of matrix M and can be estimated using the standard **Table.2** [69]. The pair - wise comparisons findings are sufficient if the CR value is equal to or less than 0.10 (≤ 10 %).

Table .2: Random Index for different values of number of criteria.

n	2	3	4	5	6	7	8	9
RI	0	0.58	0.90	1.12	1.24	1.32	1.41	1.45

2.2.2 Criteria description and data preparation

During the site selection process for the PV farm to allow for analysis, the following variables were considered: distance from settlements (urban) areas, distance from agricultural (vegetation) areas, distance to roads, slope, lakes (dams) and distance to transmission lines. For the solar irradiation map developed by [56], as presented in **Fig.6**, the solar irradiation map of N'goussa region was extracted and examined separately based on the raster database using ArcGIS software. The results showed that the Global Horizontal Irradiation (GHI) values throughout the study area are between 2164 kWh/m²/year and 2192 kWh/m²/year (low variability). For this reason, this criterion was not evaluated as a decisional parameter for this work. Based on local conditions and circumstances, the selection process may change between one area to another [54]. Criteria of indicators are separated into three major classes: economic, environmental and orography (**Table 3**), and each criterion was detailed as follows.

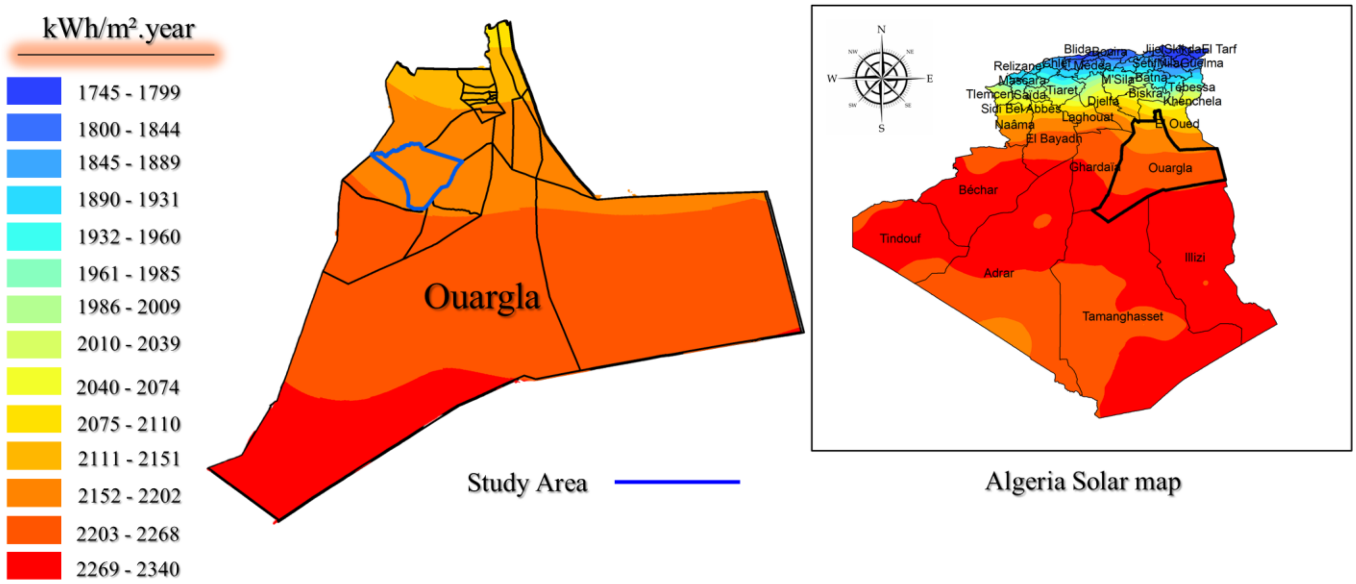


Fig. 6: Algeria's solar irradiation map showing the region of N'goussa.

Distance from power line (a). Close distance to existing power grid is an important economical point of view since the construction of new electrical transmission systems generally involves high cost. For this reason, the dependence on the exciting power grid would not only reduce the project's capital cost, but also decrease the power losses resulting from electricity transmission over extended distances (**Fig. 7.a).**

Distance from vegetation area (b) and urban area (c). From an environmental point of view, placing a solar farm near to urban areas has a negative impact on urban growth and population.

Distance from roads (d). The proximity of a solar farm site to roads is also considered an economic factor. In fact, it can give an idea about construction costs. Close proximity to roads avoids the additional cost of infrastructure construction and the resulting damage to the environment.

Lakes (e). In the study area, the lakes are considered as a constraint layer similar to vegetation area and land used for the development of infrastructure and facilities, which was not taken into account when determining optimal site locations for power plant.

Slope (f). In this study, the lands with very low slopes are more favorable, since they would require low investment costs. For this reason, only areas with slopes less than 5% were considered acceptable, to ensure that the selected sites will be relatively flat.??

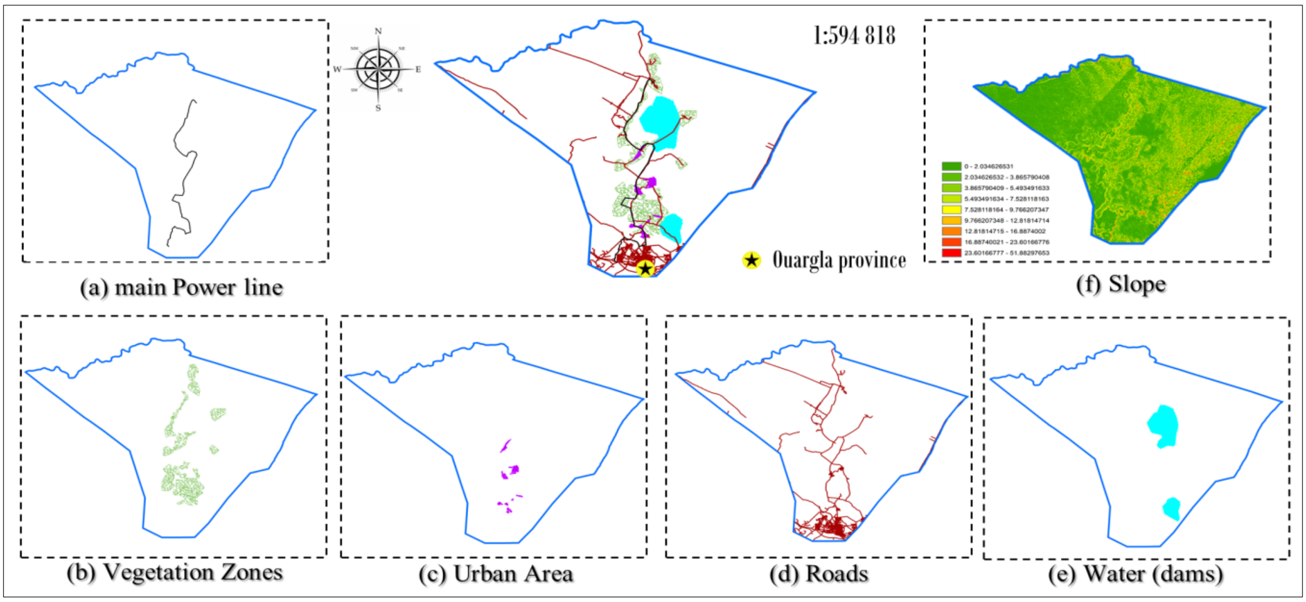


Fig.7: Spatial information on the evaluation criteria which includes main power line, Vegetation zones and Urban areas among other criteria such as slope, aspect and proximity factors.

All the evaluation criteria and constraints were developed as digitized maps (vector and raster) using GIS tools (ArcGIS software). Buffer zones were considered for each constraint criterion, separately, as detailed in **Table 3.** The weighting values for each evaluation criterion were calculated using the AHP method.

Table3. The criterions and the sub-criterions used on for the PV site suitability analysis.

Layers	Criterion	Sub-criterion	Source of data	Buffer	References / software used	
L1	Economic	Prox. to power line*		100 m	Google earth	[70–76]
L2		Prox. to Roads	Open street map	500 m	[77]	[70–76]
L3	Environment	Prox. to Urban area	Open street map	500 m	[77]	[63,70–72,74–76]
L4		Prox. to Vegetation areas*		200 m	Google earth	[63,71,75]
L5	Orography	Slope	Earth Explorer	< 5 %	[78]	[71–76]
L6		Distance to lakes	*	750 m	Google earth	[73,75,79]

* this map was developed by the authors.

2.3 Algorithm Backward/Forward Sweep process

As mentioned above, Backward/Forward Sweep method is commonly used to overcome radial problems due to its high computational performance and simplicity of implementation [80]. For this reason, in this paper BFS method is used to analyze the power flow in radial distribution systems in our study area. Load flow studies are performed on power systems to understand the nature of the installed network, where load flow is used to determine the static performance of the system [42][41]. This section proposes a BFS method-based methodology for optimal allocation of PV power plant (Distributed Generation) in distribution systems with the aim to minimize the total real power losses and voltage sensitivity index of the whole system. The impacts of DG power plant in voltage profile criterion are considered as optimization constraints. **Fig.8** presents BFS flow chart simulation of DG placement method as conducted on the 464-bus distribution network of N'goussa zone to investigate its performance under different DG penetration levels.

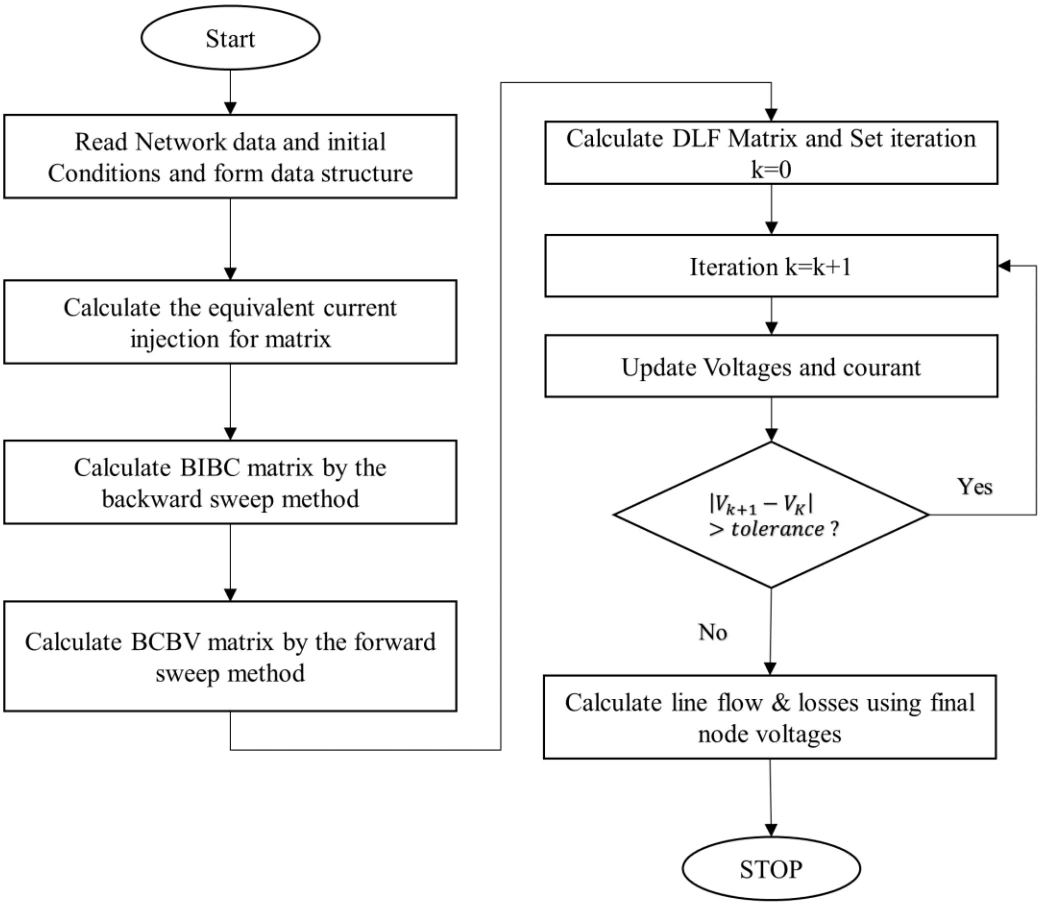


Fig.8: Flow chart for BFS method.

2.3.1 Optimum site dependency on the Index of Voltage Sensitivity (VSI)

The voltage sensitive nodes are first identified for each penetrating DG (from 10% to 100 %), then the VSI of the total feeder loading potential at each node is calculated [81]. VSI for bus j is defined as shown in Eq.4 when DG is connected to bus j:

$$VSI_j = \frac{\sqrt{\sum_{j=1}^{n}(1-V_j)^2}}{n} \tag{Eq.4}$$

where V_j is voltage at the j^{th} node and n refers to the number of branches (nodes) (n = 464 in our case study). The node with the least VSI will be selected by the DG as the best place for placement. The following steps are taken to determine the optimum DG size:

(i) Initially, the DG is installed at the node which has the least VSI value.
(ii) The DG size is varied in constant steps “10%” from a minimum value “10%” to a value equal to the feeder loading capacity “100%”, until the minimum device loss is found.
(iii) The size of the DG that results in minimal losses shall be considered as optimal.

2.3.2 The Impact of DG on Voltage Profile and Power Losses

In order to minimize losses of total real power in a distribution system there are three different formulae to be used: the loss formula of Elgerd (Ref?), the branch current loss formula, and the power loss formula of the branch [82]. In this study, the power loss formula is used as an objective function. In a distribution system with n buses the active and reactive power injection are functions of all buses and can be calculated using Eq.5 [83]:

$$P_{Lozz} = \sum_{i=1}^{n} \left(\frac{P_{bi}^2 + Q_{bi}^2}{|V_i|^2} \right) R_{bi} \qquad \text{(Eq.5)}$$

where P_{bi} and Q_{bi} are the active and reactive power flow through branch i, respectively.

DG is supposed to support and improve the system's voltage, such as over-voltages and under-voltages which is one of the most critical problems that must be faced in the improvement of voltage profile [84]. However, excessive DG penetration may negatively impact the performance of the system and may lead to serious overvoltage problems [8].

2.4 LCOE analysis for each strategy

The integration of PV power plant into a distribution system has recently become an important strategy of saving energy and reducing GHG emissions from low voltage distribution systems. The techno-economic evaluation of the solar power plant (PV) systems integrated into low voltage distribution systems is very important to ensure their compatibility with the distribution system. For the purpose of comparing a serval strategy (for each penetration rate from 10% to 100% we calculate the LCOE and we compare them.)? (penetration rates 10-100%) from an economic perspective, the cost of generating electricity is calculated as the levelised cost of electricity (LCOE) (Eq.6) [85]. The technology specific $LCOE_j$ per technology j (PV power plant and conventional power plants) encompasses all cost during the lifetime of the electricity production, including Capital Cost (*Io),* Replacement cost *(Rc)* and Operation & Maintenance cost *(O&M).* Such cost elements are given as annual values and standardized by the electricity supplied annually *(Eel).* Using the weighted average cost of capital WACC, the turnkey cost of the power producing units is discounted, N is equal to the lifetime of the technologies considered.

$$LCOE_{\ PV} = \frac{\frac{I_0}{\sum_{n=1}^{N} \frac{1}{(1+WACC)^n}} + C_{Rc} + C_{M\&O,j}}{\sum_{t=1}^{n} \frac{E_{el,j}}{(1+r)^t}} \qquad \text{(Eq.6)}$$

According to LCOE systems, the average cost of electricity per region is given as aggregated values (Eq. 7). The share of electricity indicates the share of electricity delivered by the technology of power plants j. The price of electricity in Algeria is equivalent to $ 0.25/kWh [86].

$$LCOE_{\ sys} = \sum_j LCOE_j es_j \qquad \text{(Eq.7)}$$

Table 4: Technical and cost data of converter.

Parameter	Specification	
	Converter	PV module
Efficiency	90%	16.8 %
Capital cost	$ 800/kW	$ 750/kW
Replacement cost	$ 750/kW	$ 23.12/kW
O&M cost	0	$ 38.54/kW
Lifetime	20 years	20 years

The power sector has seen a dramatic transition in recent years, notwithstanding continued growth in pollution. The average carbon intensity of produced electricity today is 475 gCO_2/kWh [87]. The emissions offset or reduced by solar PV (power plant) capacity is calculated by taking the amount of fossil fuel (natural gas) generation offset by PV and multiplying it by the average emissions intensity for those fuels. The annual CO_2 emission reduced is calculated by (Eq.8).

$$Annual\ CO_2\ emission\ (metric\ ton) = E_{el,PV} \times Ci_{Co_2} \tag{Eq.8}$$

By using photovoltaic power plant to produce an amount $(E_{el,PV})$ of electricity, which will economized it's equivalent quantity of fossil fuel. Based on a standard Algerian power plant, a cubic meter of natural gas consumed will produce 0.246 kWh of electricity [88]. **Table 5** presents PV module characteristics at standard test conditions which is used in this study.

Table 5: PV module characteristics at standard test conditions

Trina Model Number	TSM-275DD05A.05 (II)
standard test conditions Rating	275.0 Watts
PTC Rating	251.1
Open Circuit Voltage (Voc)	38.7 Volts
Short Circuit Current (Isc)	9.26 Amps
Power Tolerance	-0 / +5W
Module Efficiency	16.8%
Area	1.64 m²
Weight	18.5 kg
Length	165 cm
Width	99 cm.

3 Results and discussion

The proposed methodology for optimal placement and penetration levels of solar power plant (PV) DG units was tested using the 30 kV, 464-bus radial distribution network in this paper. This test system's single line diagram is shown in **Fig.4.** The total load is the (4.4708 + 3.2332i) MVA unit of puissance (Mega Voltage Amber). To do so, the proposed methodology has two stages. Firstly, a spatial analysis based on combined GIS and AHP as MCDM methods is used to identify the possible buses (potential sites). Secondly, using the results of the first stage to find the optimal bus bar (location), the penetration levels of solar DG are achieved by minimizing the formulated objective functions (VSI and power losses) using the BFS approach. The maximum limit of DG penetration was evaluated based on the voltage profile improvement, and a techno-economic and environmental assessment for each penetration level was estimated.

3.1 Suitability of index map

In this part of proposed methodology (**Fig. 3**), a site for the most suitable location of solar power plants was identified using 6 criteria. In order to calculate the suitability index, **Table 6** presents the pairwise comparison matrix obtained from the AHP method, and the weightings of the criteria used in this analysis were determined. These results (of pairwise comparison) can be considered acceptable and their values are highly consistent since the Consistency Ratio (CR) equals 3.5 % which is less than 10%. The calculations returned a weighting of 41.74 % for distance to power line, 28.55 % for the distance from the Roads, 12.57 % for the distance from urban areas, 8.91 % for the distance from vegetation, 4.89 % for slope, and 3.34 % for distance from lakes.

Table 6: The pairwise comparison matrix and Consistency ratio

	criteria	Cr1	Cr2	Cr3	Cr4	Cr5	Cr6	Weighting [%]	C.R
Prox. to Power line	Cr1	1	2	4	6	7	9	41.74	0.041
Prox. to Roads	Cr2	½	1	3	5	6	7	28.55	
Prox. to Urban area	Cr3	¼	1/3	1	2	4	3	12.57	
Prox. to Vegetation areas	Cr4	1/6	1/5	1/2	1	2	5	8.91	
Slope	Cr5	1/7	1/6	1/4	1/2	1	2	4.89	
Prox. to lakes	Cr6	1/9	1/7	1/3	1/5	1/2	1	3.34	

As mentioned earlier the combination of AHP and GIS for optimal location of solar farms site will generate a Land Suitability Index (LSI) map of N'goussa zone as represented in **Fig. 9.** The authors used the evaluation criteria (**Fig. 7**) to calculate the suitability indices, based on the attributes of study area 6 and the criteria that effect the site selection decision. These criteria were prepared using ArcGIS with weighting values using AHP. A grading system from excellent (most suitable) to mild (least suitable) has been used to classify (using an equal interval classification method) the various regions on the study area deemed exploitable for PV infrastructure deployment.

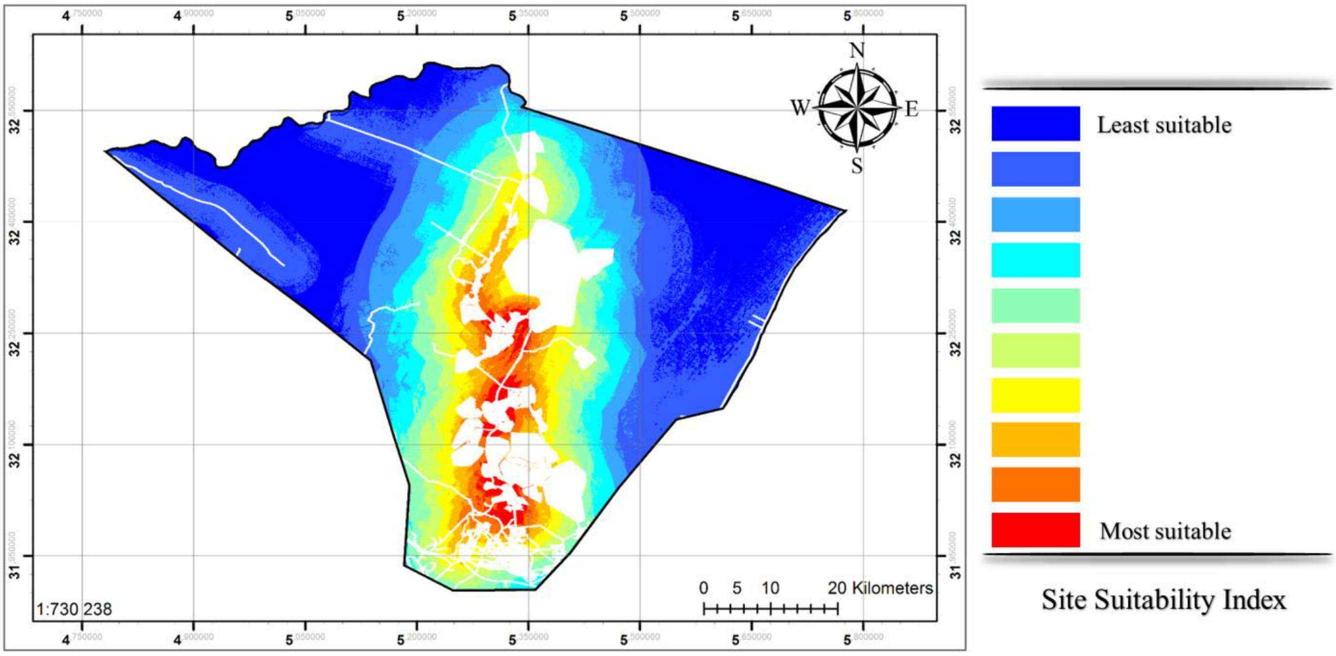


Fig. 9: land suitability index map.

The map reveals the most suitable location of PV farms are the northern and southern regions districts of N'goussa city, as well as the southern parts of Bour-Aicha, EL-bour and the Northern parts of H. Miloud (Fig.4) (refer to Fig. 4 for these sites). These sites are the most suitable due to larger their distance to cities compared with other sites such as H. Khefif.

As a result, the suitable area represents 77.95 % (3,013.31 km²) of study area which has been divided into ten intervals, with an equal interval classification method from 26.47% (797.62 km^2) as a least suitable to 1.52% (45.81 km²) as most suitable. A portion of the study area equal to 22.05% (852.62 km²) is not suitable for solar farm areas (which include the buffer zones power line, roads, vegetation, urban areas and lakes). **Fig. 10** presents a detailed land area distribution in km² by constraints types (on right hand side) and Land Suitability Index (on left side). The results are directly dependent on the selected criteria, which are determined, categorized and then arranged for this case study based on the expertise and decision maker views, and taking into consideration the data availability.

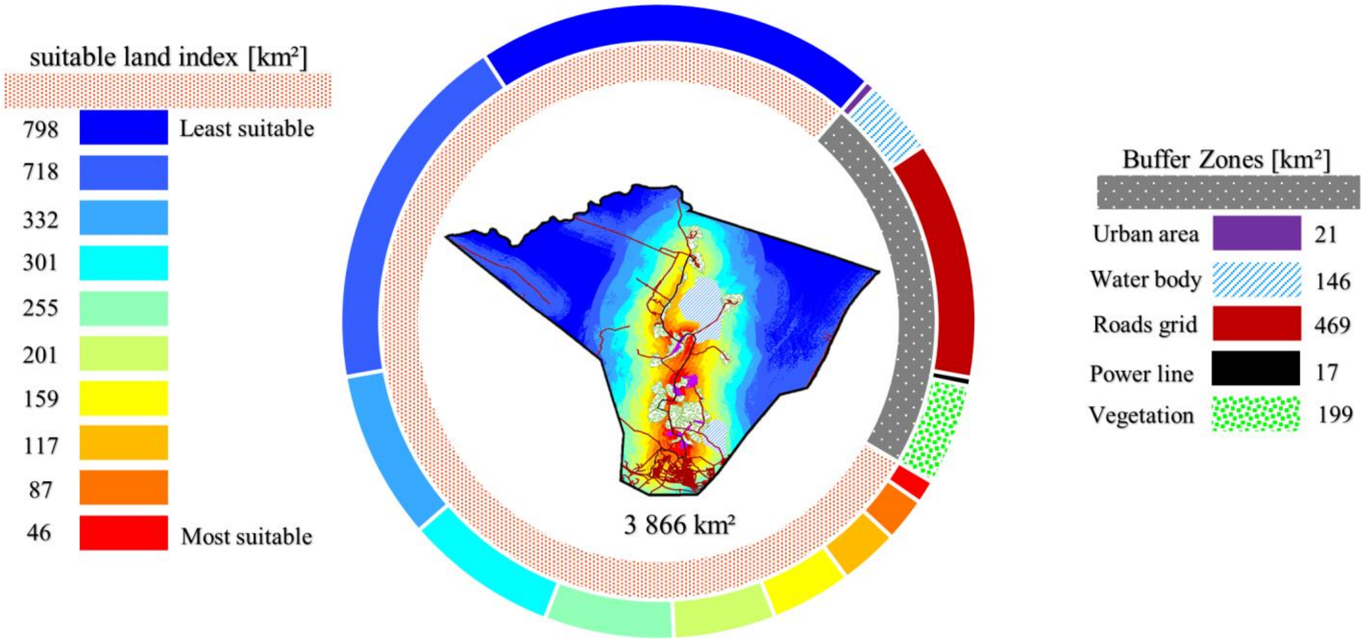


Fig. 10: Distribution of land areas of study area suitability index/ constraints [km²].

3.2 Check potential sites on Google Earth

The results of land suitability index show that there are 7 potential sites that can be classed as most suitable, and which are examined in Google Earth. Two sites are far away from the existing grid busbars (substation), making them unsuitable for installing solar power plant. Five sites appear to be appropriate due to existing grid busbars. These sites are classified as the most suitable to support a large solar power plant installation. **Fig.11** shows the manual checking of results (validation of suitability) using Google Earth. The 5 potential sites are zoomed in Google Earth. **Fig.11** demonstrates that the areas with the greatest potential for solar PV production are best alternatives. This is clear when we consider each criterion separately, each has important aspects (technical, economic and environmental aspect). The obtained results that demonstrate the reliable performance of the proposed methodology.

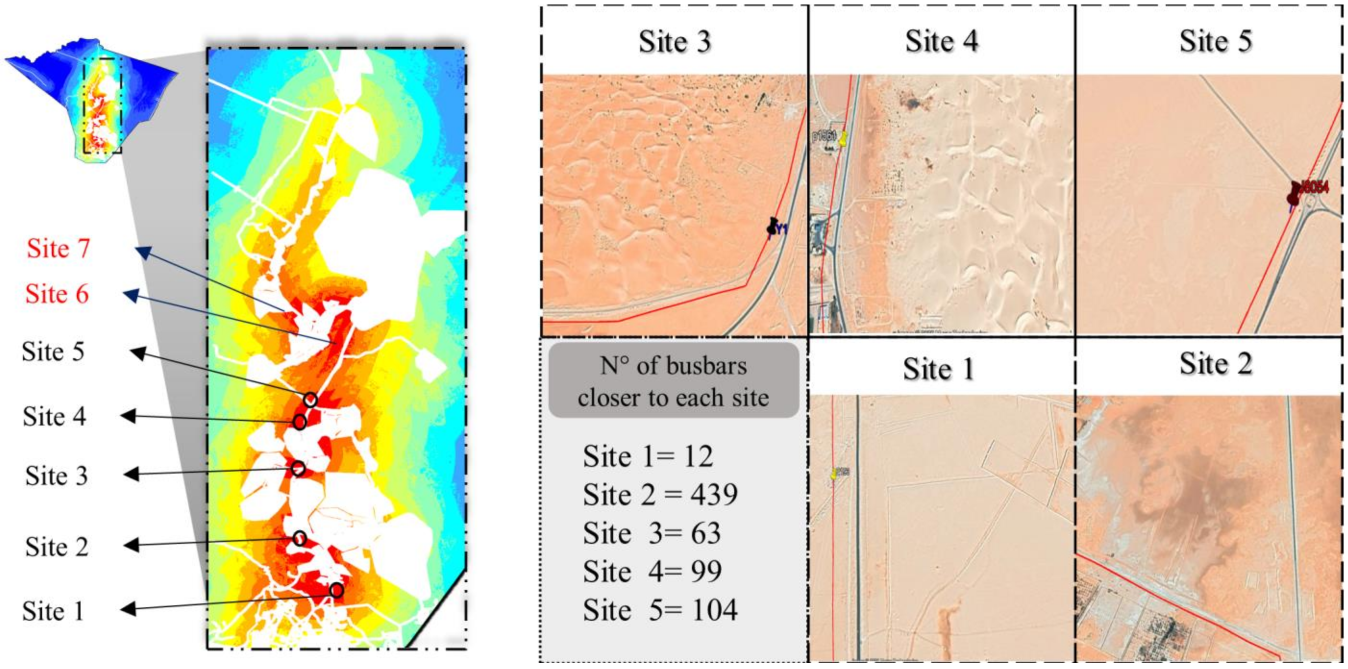


Fig.11: Suitability accuracy checking using Google Earth by sites and by busbars.

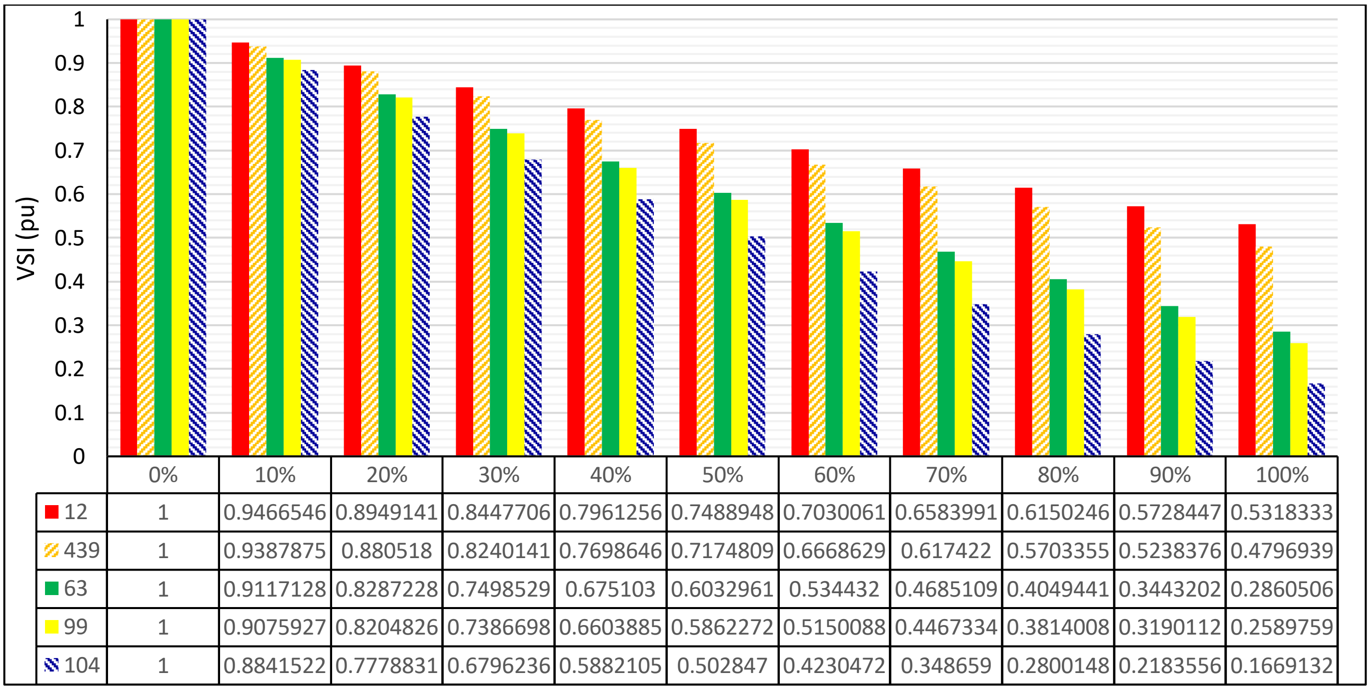
3.3 BFS Method for load flow analysis

In this paper, the most suitable potentials sites are determined by an analysis of power flow based on utilization the BFS method to find the appropriate site, the selected objective functions (Voltage Sensitivity Index, power losses) are minimized and voltage profile improvement (the improvement of the voltage profile mean that all values of busbars are good when they close to “1” (Fig14).), the results of the three technical indices (VSI, power losses and voltage improvement) are discussed next.

3.3.1 Optimal allocation based on Voltage Sensitivity Index (VSI)

The purpose of finding VSI is to find the most sensitive node of the system from voltage sensitivity index point of view. After calculation of sensitivities at all buses, the bus with the least VSI value will be used as the optimal location. Penetration levels of DG were examined with a step size of 10% of total load.

The results show that busbar 104 has the least value of VSI in each penetration level from 0.884 p. u at 10 % to 0.166 p.u at 100 % DG penetration. In addition, in case of integration a 10 % of DG, the difference between the five cases is approximately 0.05 p.u. Whenever the penetration rate increases, the difference also increases to 0.365 p.u between busbar 12 and 104 as the best and least busbars from VSI point of view. The Voltage Sensitivity Index in baseline case and after DG integration with different penetration rates for the 5 candidates busbars are shown in **Fig.12**.

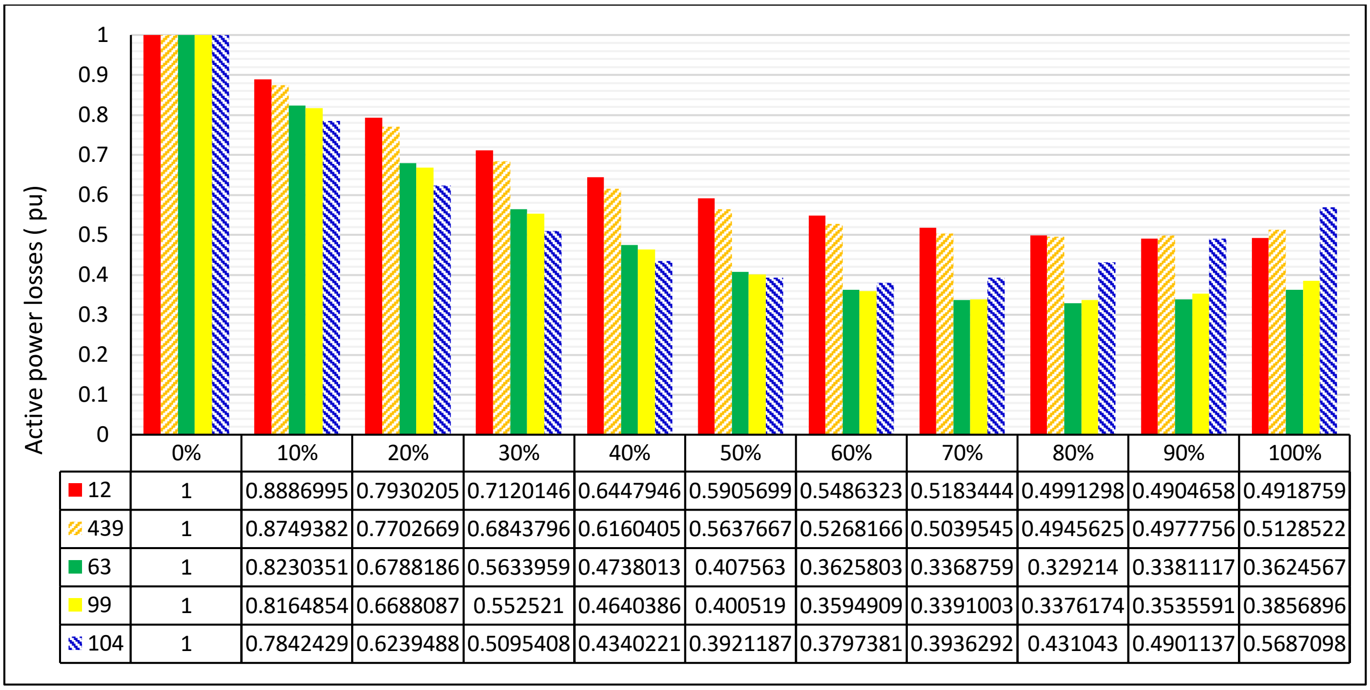


	0%	10%	20%	30%	40%	50%	60%	70%	80%	90%	100%
🟥 12	1	0.9466546	0.8949141	0.8447706	0.7961256	0.7488948	0.7030061	0.6583991	0.6150246	0.5728447	0.5318333
▨ 439	1	0.9387875	0.880518	0.8240141	0.7698646	0.7174809	0.6668629	0.617422	0.5703355	0.5238376	0.4796939
🟩 63	1	0.9117128	0.8287228	0.7498529	0.675103	0.6032961	0.534432	0.4685109	0.4049441	0.3443202	0.2860506
🟨 99	1	0.9075927	0.8204826	0.7386698	0.6603885	0.5862272	0.5150088	0.4467334	0.3814008	0.3190112	0.2589759
▨ 104	1	0.8841522	0.7778831	0.6796236	0.5882105	0.502847	0.4230472	0.348659	0.2800148	0.2183556	0.1669132

Fig.12: Voltage Sensitivity Index variation with DG size (penetration rate) using BFS method.

3.3.2 Optimal allocation based on real active power

In order to identify the optimal busbar and penetration of DG in distribution systems based on power losses, the BFS method was used in the 5 busbars established via spatial analysis with changes in penetration rate of DG. The results of power losses as presented in **Fig.13** show that the integration of DG into a distribution system will reduce power losses, although in cases of high penetration levels of DG’s, the power losses will increase. For busbar N° 12, the power loss reaches a minimum value of 0.4904 p.u at a penetration rate of 90 % , whereas in cases of busbars 439, 63 and 99 the power losses reach a minimum value at a penetration rate 80% (the power losses values are presented in **Fig.13**). In case of busbars 104, the optimal penetration of DG is 60% with a value of 0.3797 p.u.



	0%	10%	20%	30%	40%	50%	60%	70%	80%	90%	100%
🟥 12	1	0.8886995	0.7930205	0.7120146	0.6447946	0.5905699	0.5486323	0.5183444	0.4991298	0.4904658	0.4918759
▨ 439	1	0.8749382	0.7702669	0.6843796	0.6160405	0.5637667	0.5268166	0.5039545	0.4945625	0.4977756	0.5128522
🟩 63	1	0.8230351	0.6788186	0.5633959	0.4738013	0.407563	0.3625803	0.3368759	0.329214	0.3381117	0.3624567
🟨 99	1	0.8164854	0.6688087	0.552521	0.4640386	0.400519	0.3594909	0.3391003	0.3376174	0.3535591	0.3856896
▨ 104	1	0.7842429	0.6239488	0.5095408	0.4340221	0.3921187	0.3797381	0.3936292	0.431043	0.4901137	0.5687098

Fig.13: Total real power loss variation with DG size (penetration rate) using BFS method.

3.3.3 Voltage profile improvement using BFS

In this paper, the utilized BFS method for optimizing the most suitable location of DG should satisfy many constraints [89], one of these constraints is the bus voltage which should be within ± 5% of its nominal value. To do so, a comparison between five potential sites is performed using the approach proposed above, where the integration of different DG penetration in nominated busbars 12, 63, 99, 104 and 439 with/without DG's is presented in **Fig.14**.

Initially, it was thought that voltage profile improvement was not behaving the same way for all cases: there is a rise in the levels of voltage profile in each DG penetration by an average of 0.008084, 0.0124, 0.0142, 0.0120 and 0.00895 (p.u) for busbars 12, 99, 104, 63 and 439, respectively, as clearly demonstrated in **Fig.14.** However, the best voltage profile is achieved at busbar 104 for 70- 100 % as compared to other cases. In addition, our findings appear to confirm that the voltage profile improvement depends to the optimal DG penetration at appropriate busbars.

3.4 Techno-Economical Assessment (TEA)

As mention in Section 2.4, the techno-economic analysis is a helpful tool used in the evaluation of the performances of the system. In this section, the technical/ economical approach was based on three factors, such as LCOE, the amount of fuel saving (natural gas), and CO_2 avoided. **Fig.15** presents the three factors of techno-economic assessment considered in this analysis.

The results show that the LCOE value in baseline case (without DG integration) has a maximum value equal to 0.240 [$/kWh], while in each DG penetration (+10% of total load) the LCOE value will be decreased by 0.003 $/kWh, which means it reaches 0.205 $/kWh as final value of total LCOE. The estimation of the amount of fuel saving and CO_2 avoided was calculated based on Eq. (7) and the equivalent quantity of each 1 kWh of electricity in cubic meter of natural gas. **Fig.15** shows that the amount of CO_2 that will be avoided in case of 100% DG penetration is equal to 5,553 tonnes, whilst the amount of fuel saving is more than 3 million cubic meter in the case of 100% DG penetration.

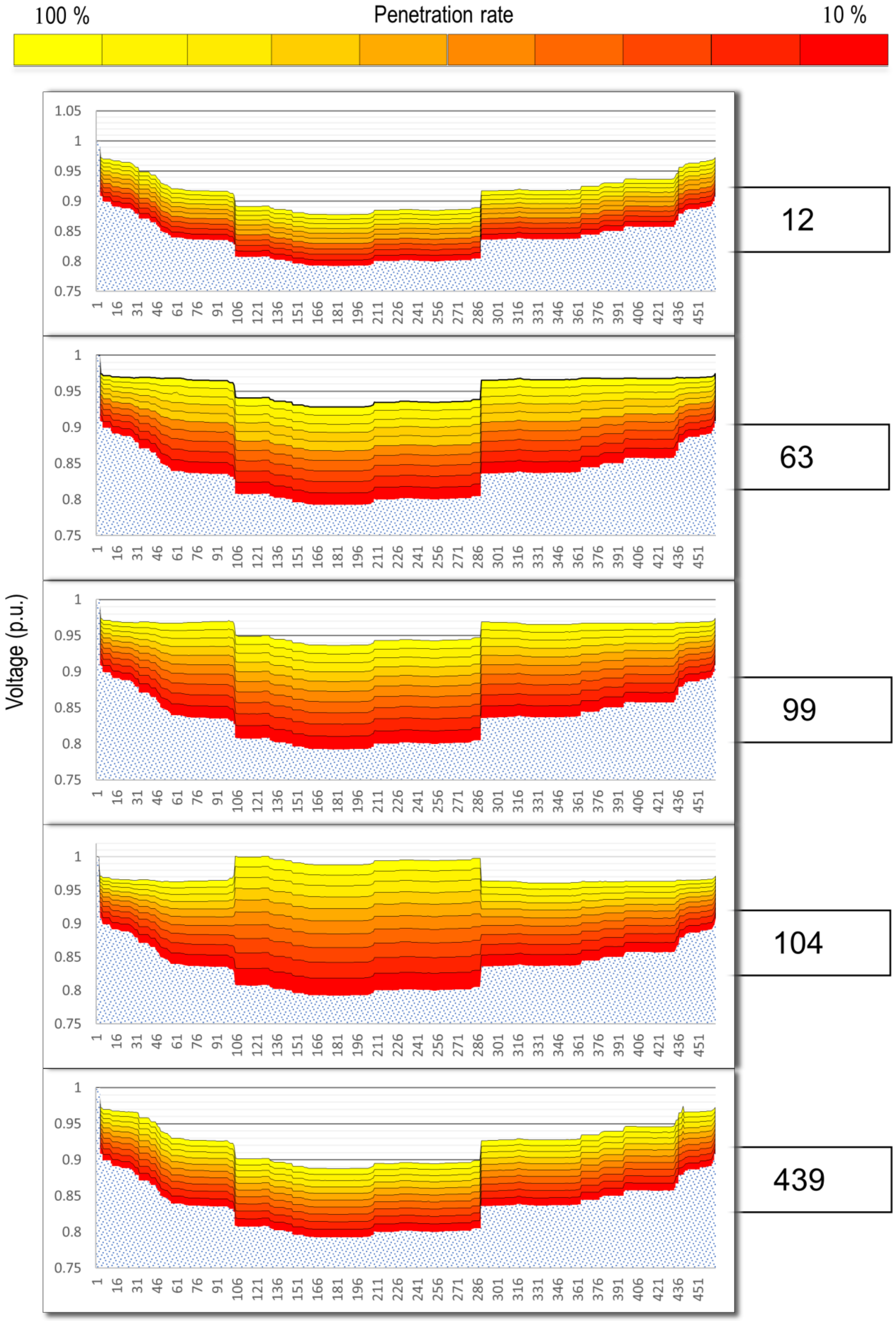


Fig.14: Voltage profile with variation of DG penetration.

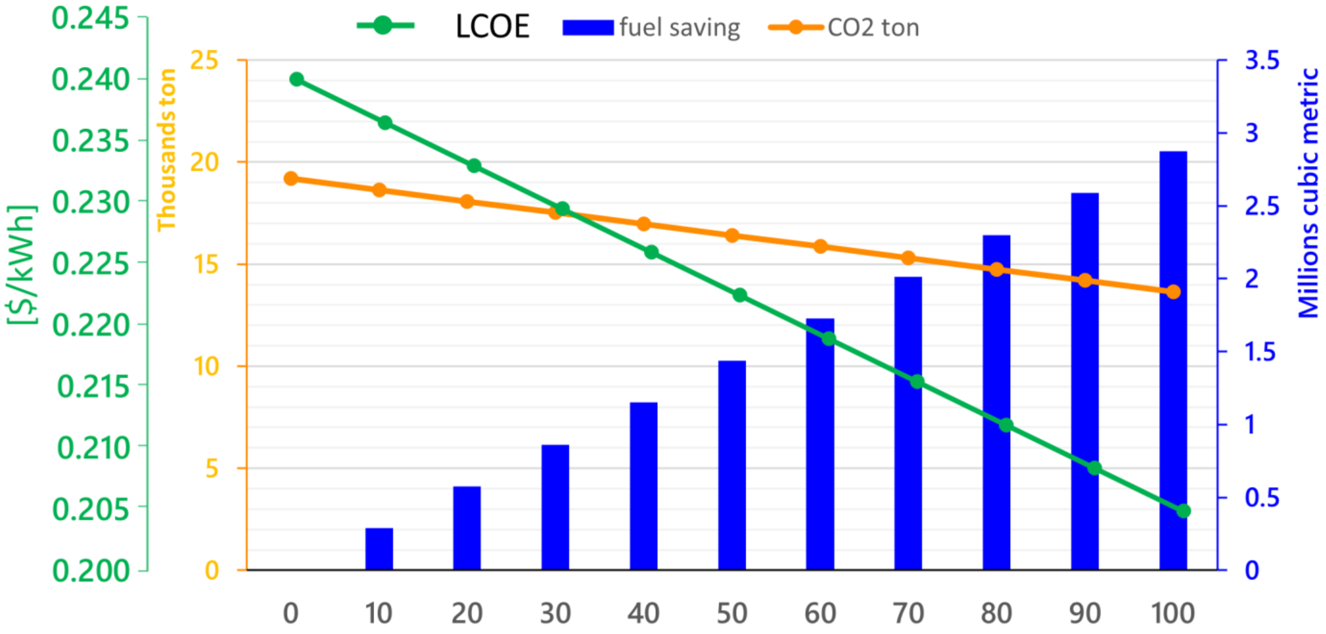


Fig.15: Techno-economic assessment in viewpoint of LCOE, fuel saving and avoided CO_2 emission.

4 Conclusions

This paper focuses on a Backward Forward Sweep approach and Geographic Information System based MCDM methods for optimal allocation of PV-DG considering environmental, technical, economic and orography performance factors. To do so, a multi-disciplinary framework is proposed which functions in two stages. Firstly, based on several criteria GIS and AHP are combined to identify the available potential sites. In the second stage, the identified sites are classified according to technical viewpoints to find the optimal allocation for solar power plant (PV). This stage is completed using BFS method based on some technical indices such as Voltage Sensitivity Index, profile voltage improvement and power losses in the studied distribution systems. Following this, a techno-economic assessment was done to estimate the amounts of avoided CO_2 emission, fuel saving and LCOE for each DG penetration level. The characteristics of N'goussa power grid are: the test system has 464 busbars, the total load used is (4.4708 + 3.2332i) MVA with a base voltage of 30 kV.

The results of the first part of the methodology presented in this paper show that the utilization of the AHP method in weighting criteria process is effective as one of the successful methods for spatial evaluation of sites. In terms of land suitable index (LSI), the final suitable map was classified into 10 equal intervals from the least suitable to the most suitable as the best location for host a PV power plant. The final LSI represents 77.95 % whilst the rest of land is reserved as constraints including buffer zones, roads, power lines, urban areas, and lakes. In addition, the most suitable zones show that there are 7 potential sites, two of them are unsuitable because they are far away from existing busbars of grid power line. Then, the remaining busbars are tested with the Backward Forward Sweep method taking into account the three technical indices of power line losses, profile voltage improvement and voltage sensitivity analysis. The results show that the busbar 104 is the optimal allocation in terms of VSI and profile voltage viewpoint with DG's penetration of 100%, but in active power losses the busbar 63 was found to be the optimal with a DG penetration of 80 %. The final part of results is a technical economic study which is based on three parameters (which are LCOE, amount of fuel saved and amount of CO_2 avoided). In case of DG's penetration of 100%, the LCOE is equal to 0.205 $/kWh, the amount of fuel saving (natural gas) is more than 3 million cubic meter and in terms of the amount of CO_2 emission avoided this is 5000 tonnes.

The main contribution of this paper is the combined use of GIS- MCDM application with optimization methods (for example BFS) for optimal allocation, as required for identifying the best sites for RES power plant. In future research, several MCDM methods will be compared including their effects on the results of LSI. In addition, there is a need to compare the results of this paper with a case of multi-DGs allocation on distribution systems in viewpoint of technical indices, utilization of MCDM method to select the main technical parameter (power losses, VSI, profile improvement) which is used in optimization of best allocation.

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