



## Reliability Enhancement and Grid Performance of Regional Network through Strategic Load Expansion Planning with Photovoltaic Integration

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### Abstract

This paper presents a comprehensive analysis of load expansion planning through the integration of photovoltaic systems at the Bir Alganame 220/30 kV substation. An electrical planning system serves as a crucial tool for designing electrical systems that effectively meet evolving energy demands. The study investigates the impact of load expansion on hybrid photovoltaic system design, focusing on system reliability and total project cost as primary design objectives. The research methodology encompasses a detailed load flow study conducted in 2024, coupled with load forecasting for 5 and 10-year horizons at an 8% load increase rate. The investigation includes analyzing the optimal parameters of the PV system integration with the existing grid to ensure proper functionality. Additionally, the study addresses the probabilistic scenario set of load demand and natural characteristics of renewable energy, which is crucial for power system planning studies. The research emphasizes the importance of proper transmission system network development to reliably and securely evacuate the generated power to meet future domestic load demand. Through simulation and analysis, this study demonstrates an integrated approach to improving power system performance while considering geographical and environmental factors affecting PV output. The findings provide valuable insights into optimal electrical network planning procedures, incorporating both long and short-term perspectives through PV system integration.

**Keywords:** optimum planning approach; load forecasting; Photovoltaic system network design; rapid expansion town; future demand; Capacitor banks

### 1. Introduction

Bir Alganame, a village located 90 kilometres southwest of Tripoli, western Libya, was selected as a case study in the research, being a strategic interchange of western region's High Voltage (HV) Grid. Its 220/30 kV substation supplies 10 Medium Voltage (MV) substations 30/11 kV. In year 2024 (Base Year), the MV network's consumption escalated to 149.4 MW as reported by the General Electricity Company of Libya (GECOL) [1]. The increasing demand for electrical energy, attributed to both regular population growth and unplanned influx to the settlements surrounded Bir Alganame, has positioned the village as a pivotal hub in the economic and social spheres. Consequently, a comprehensive study of the electrical load flow for this town is imperative, motivating an investigation into the present and future energy



output of load flow, the capacity of the network to accommodate the escalating demand on electrical energy, and the ability to sustain the anticipated growth over the next decade.

The objective of the research of the Bir Algame network is to ensure the provision of essential electrical energy to customers. Therefore, when initiating the planning process, it is imperative to adopt a strategic perspective for the progressive development of the network at predefined junctures. This strategic outlook is actualized through the formulation of a master plan, the primary focus of which is the strategic advancement of an optimal network for a specified future timeframe. Subsequently, this envisioned ideal network will serve as a guiding framework for the implementation of accurate operational decisions on a day-to-day basis.

*Master Plan:* The primary goal of the Bir Algame network is to supply customers with electrical energy. The plan involves the implementation of a photovoltaic (PV) system to accommodate the increasing load over the next ten years, with adjustments scheduled every five years. Overloaded or underloaded network can result in equipment damage or uneconomical network operation. To mitigate these risks, it is imperative to take a strategic view of the network at specific time intervals [2]. Mostly Papers starts with introduction. It contains the brief idea of work, requirement for this research work, problem statement, and Authors contribution towards their research. Recent references [1] should be included for showing previous work done and importance of current work. This section should be succinct, with no subheadings unless unavoidable [2, 3]. State the objectives of the work and provide an adequate background related to your work, avoiding a detailed literature survey or a summary of the results. This section should be typed in character size 12pt Times New Roman and alignment justified

## 2. Methodology of Research

The research methodology employed in this study entails the examination of the load flow within Bir Algame network and the projection of future demand over ten-years period. This



Fig. 1: Master Plan for Strategic view of the Future Network



forecast will be grounded in the master plan, delineating the annual escalation, and will serve as a guiding framework throughout the entire process Fig. 1.

The master plan for the network aims to ensure a strategic view of the network at certain time intervals. It is divided into two parts. The first part involves studying the existing issues in the network and finding alternative solutions, as well as specifying the network's capability to provide regular electrical energy. The second part involves studying the future growth of the load in the network and planning for short-range and long-range load demand. The strategy is to improve the network step by step with economic factors in mind, managing any sudden changes and implementing a PV system to cover the demand of the network. All changes in the network implemented should follow up on the previous and base case network [3,4].

The planning criteria for network infrastructure are primarily determined by the requirements, principles, and objectives of the network operator, which are influenced by various factors, including environmental and other conditions. The key planning criteria include high reliability of the planned network, maintaining voltage within the range of 95% to 105% of the rated voltage under normal conditions (N), and voltage within the range of 90% to 110% of the rated voltage under emergency conditions (N-1) at each node.

The planning process involves acquiring base case data, network modelling, network data analysis, adhering to planning criteria, incorporating future load growth, verifying the planned network using E-TAP Electricity analysis tool software, fine-tuning the network, and progressing to the next period based on the finalized network [3]. These planning steps are to be implemented for all periods (2024, 2029, and 2034). The planning procedures involve the application of the aforementioned steps to the network [5]. Data for Bir Alganame network was provided by GECOL, representing the existing network in 2024 (Base Year), encompassing electrical data of lines, loads, transformers, and other network elements. The existing network is modelled using E-TAP software program, which is integrated with Power System Analysis software for Electrical Transmission, Distribution, and Industrial Networks, commonly used in GECOL. The first part of the master plan entails studying the actual situation of the electrical load flow energy, identifying existing problems such as changing voltages, overloading issues on transformers, under-voltage bus bars (weak points), and devising alternative solutions to address these problems.

The improved network is re-analyzed to ensure the effectiveness of the modifications. The second part of the master plan involves analyzing future networks based on the growth of electrical energy demand percentage, considering both short-range and long-range time scales. This strategy aims to improve the networks progressively while managing sudden changes and facilitating management planning [3].

Addressing under-voltage issues in bus bars requires a systematic approach to identify the underlying causes and implement appropriate solutions. The main steps to resolve under-voltage problems in bus bars include load analysis and management, transformer evaluation, and the inclusion of power capacitors for reactive power compensation, voltage regulation, enhanced power factor, load balancing, reduction of line losses, careful installation



considerations, caution with harmonic content, and professional evaluation. Integrating power capacitors into the bus bar system can effectively enhance voltage regulation, reduce fluctuations, and optimize overall electrical distribution network performance.

The growth in demand for electricity in the region serviced by a utility company is the main factor determining how the distribution system will expand. Therefore, predicting how much the demand will increase is crucial in planning.

A popular approach to technical forecasting involves analysing trends in the data by transforming it. In some cases, a straightforward straight line that does not match the original data may fit the data after applying logarithms, as observed with the exponential trend.

$$y_t = a b^x \quad (1)$$

This expression is sometimes called a growth equation since it is often used to explain the phenomenon of growth through time [4]. If the load growth rate is known, the load at the end of the  $n^{\text{th}}$  year is given by

$$P_n = P_o(1 + g)^n \quad (2)$$

Where  $P_n$  = load at the end of the  $n^{\text{th}}$  year.

$P_o$  = initial load.

$g$  = annual growth rate.

$n$  = number of years.

### 3. Case Study Bir Alaname Substation

The MV substations fed by Bir Alaname 220/30kV substation, are: Bir Alaname, Ras Alafaa, Bir Alaname village, Bir Aiad, Bir Hwesa, Naser, Wadi Alhay, South Sorman, Bin Rabhaa, and Alhajajiaa. The total supplied load in the base year (2024) was 149.4 MW, using 19 Power Transformers of (100 MVA, 63 MVA, 20 MVA, and 10 MVA). A single line diagram illustrated in Apdx 1 represents the network in the base year 2024.

The growth equation 2 was used to predict load demand for 2029 and 2034 based on the 2024 base year.

Table 1 shows the demand load for each load area in the base year 2024. The load growth was calculated for the next five years (2029) and ten years (2034) with an annual growth rate of 8%.

The data obtained from GECOL for Bir Alaname network reflects the existing network conditions as of 2024. Table 1 and Table 3 outline the electrical data related to transmission lines, loads, transformers, and other various components within the network.

**Table 1** Load Demand for Bir Alganame

Town/Year ( Load place)	2024	2029	2034
Bir Alganame 1	14.7	21.6	31.7
Bir Alganame 2	8.8	13.0	19.0
Ras Alafaa 1	2.9	4.3	6.3
Ras Alafaa 2	4.7	6.9	10.2
Bir Alganame village	2.9	4.3	6.3
Bir Aiad 1	6.6	9.7	14.3
Bir Aiad 2	3.7	5.4	7.9
Bir Hwesa 1	16.2	23.7	34.9
Bir Hwesa 2	17.6	25.9	38.1
Naser 1	13.2	19.4	28.5
Naser 2	11.8	17.3	25.4
Wadi Alhay	5.9	8.6	12.7
South Sorman 1	5.9	8.6	12.7
South Sorman 2	9.6	14.0	20.6
Bin Rabhaa 1	8.8	13.0	19.0
Bin Rabhaa 2	10.3	15.1	22.2
Alhajajiaa	5.9	8.6	12.7
Total Load demand	149.4	219.6	322.6

**Table 2** Transformer data of Bir Alganame

N°	Sr	Ur1	Ur2	Srmax (high)	Description	From	Un	To	Un
	MVA	kV	kV	MVA					
1	20	30	11	20	30/11KV 20MVA	Alhajajiaa	30	Alhajajiaa	11
2	10	32	11	10	30/11KV 10MVA	Ras Alafaa 1-30	30	Ras Alafaa Load2	10
3	100	220	30	100	220/30KV 100MVA	Bir Alganame	220	Bir Alganame 2-30	30
4	10	32	11	10	30/11KV 10MVA	Bir Alganame 1-30	30	Bir Alganame Load2	11
5	20	30	11	20	30/11KV 20MVA	Bir Alganame 2-31	30	Bir Alganame Load1	11
6	20	30	11	20	30/11KV 20MVA	South Sorman 1-30	30	South Sorman load3	11
7	20	30	11	20	30/11KV 20MVA	South Sorman 1-30	30	South Sorman load4	11
8	20	30	11	20	30/11KV 20MVA	Bir Aiad 1-30	30	Bir Aiad load5	11
9	20	30	11	10	30/11KV 20MVA	Bir Aiad 1-30	30	Bir Aiad load6	11
10	20	30	11	20	30/11KV 10MVA	Naser 1-30	30	Naser Load8	11
11	20	30	11	10	30/11KV 20MVA	Naser 1-30	30	Naser Load7	11
12	20	30	11	20	30/11KV 10MVA	Bir Hwesa 2-30	30	Bir Hwesa Load9	11
13	20	30	11	20	30/11KV 20MVA	Bir Hwesa 1-30	30	Bir Hwesa Load10	11
14	20	30	11	20	30/11KV 20MVA	Bin Rabhaa 1-30	30	Bin Rabhaa Load11	11
15	20	30	11	20	30/11KV 20MVA	Bin Rabhaa 1-31	30	Bin Rabhaa Load12	11
16	10	30	11	10	30/11KV 10MVA	Ras Alafaa 1-30	30	Ras Alafaa Load1	11
17	20	30	11	20	30/11KV 20MVA	Bir Alganame	30	Bir Alganame V Load13	11
18	63	220	30	63	220/30KV 100MVA	Bir Alganame	220	Bir Alganame 1-30	30
19	30	30	11	20	30/11KV 20MVA	Wadi Alhay 1-30	30	Wadi Alhay Load	11

**Table 3** Transformer data of Bir Alganame

No	Length	R(1)	X(1)	C(1)	B(1)	I <sub>rmax</sub> (high)	I <sub>Ermax</sub>	Red.factor	Q	Material	From	To
	km	uS/...	uF/	ohm/	ohm/	A	A		mm <sup>2</sup>			
1	19.8	0.21	0.38	0.009	2.997	380	0	1	240	Cu	BirAlganame1-30	Bir Hwesa 2-
2	12	0.275	0.40	0.010	3.3	360	0	1	0	Cu	BirAlganame1-30	Naser 1-30
3	32	0.202	0.37	0.009	2.997	380	0	1	240	Cu	Bir Alganame2-30	SouthSorman1
4	14	0.202	0.37	0.009	2.997	380	0	1	240	Cu	South Sorman1-30	Bin Rabhaa 1-
5	32	0.202	0.37	0.009	2.997	380	0	1	240	Cu	South Sorman1-30	BirAlganame2
6	26.4	0.202	0.37	0.009	2.997	380	0	1	240	Cu	Bir Alganame2-30	Ras Alafaa 1-
7	14	0.202	0.37	0.009	2.997	380	0	1	240	Cu	South Sorman1-30	Bin Rabhaa 1-
8	19.8	0.21	0.38	0.009	2.997	380	0	1	240	Cu	Bir Alganame1-30	Bir Hwesa 2-
9	1.2	0.087	0.14	0.191	60.004	289	0	1	240	Cu	Bir Alganame2-30	Bir Alganame
10	7.5	0.21	0.38	0.009	3.016	300	0	1	0	Cu	Bir Alganame2-30	N107-60
11	25	0.21	0.38	0.009	3.016	300	0	1	0	Cu	Bir Alganame	Bir Aiad 1-30
12	1.2	0.087	0.14	0.191	60.004	289	0	1	240	Cu	N107-401	Bir Aiad 1-30
13	25	0.21	0.38	0.009	3.016	300	0	1	0	Cu	Bir Alganame	Bir Aiad 1-30
14	1.2	0.087	0.14	0.191	60.004	289	0	1	240	Cu	N107-414	Bir Aiad 1-31
15	14	0.21	0.38	0.009	3.016	300	0	1	0	Cu	Alhajajiaa	SouthSorman1
16	12.5	0.21	0.38	0.009	3.016	300	0	1	0	Cu	Bir Alganame1-30	Wadi Alhay

An evaluation of load flow for Bir Alganame network conducted in 2024 is shown in Apdx 1. The assessment was performed in accordance with planning criteria utilizing the E-TAP application. The analysis revealed several issues, particularly concerning undervoltage conditions existing in multiple bus bars within the base network.

To address the issues identified in the base year, several remedial actions were implemented. One key intervention involved adjusting the tap settings of the transformers connected to the buses. Despite these interventions, certain challenges persisted. To enhance the situation, power capacitor banks were installed at selected bus bars to address the ongoing under-voltage issues, which resulted in some improvements to the network. However, challenges persisted [6,7].

Consequently, a decision was made to integrate photovoltaic (PV) systems into the network. Several PV systems were deployed across the buses, each consisting of a PV array, inverter, 11 kV bus, and 11/30 kV transformer rated at 20 MVA[5,7]. These PV systems were strategically installed on buses with interconnections that significantly influence each other. New PV systems

were implemented within the network, specifically at Ras Alafaa, Naser, Bir Hwesa, and Bin Rabhaa .

From the base year, forecasting of next five-year (2029) and ten-year (2034) periods will be initiated. The analysis reflected an increase in load demand in 2029. The load flow analysis using E-TAP highlighted renewed issues, in other several busbars with undervoltage conditions, and transformers overloading [8,9], so there will be a resizing of the existing PV systems located at Ras Alafaa, Naser, Bir Hwesa, and Bin Rabhaa. Other new PV systems will be implemented within the network, specifically at Bir Aiad, South Sorman, Alhajajiaa, and Wadi Alhay. Furthermore, some transformers are experiencing overloading, thus necessitating replacements with higher rated transformer. The network improved conditions for 2029 following the resolution of all identified issues.

Projections for the network conditions in 2034 were developed based on the assessments of year 2029, and subsequent load flow analyses revealed additional challenges, including undervoltage conditions in multiple busbars and overloading of PV arrays by applying an annual growth rate of 8% for load expansion .[10,11]. The analysis indicated that there would be further increases in load demand by 2029, specifically at Wadi Alhay busbar. Therefore, the PV system was increased at Wadi Alhay.

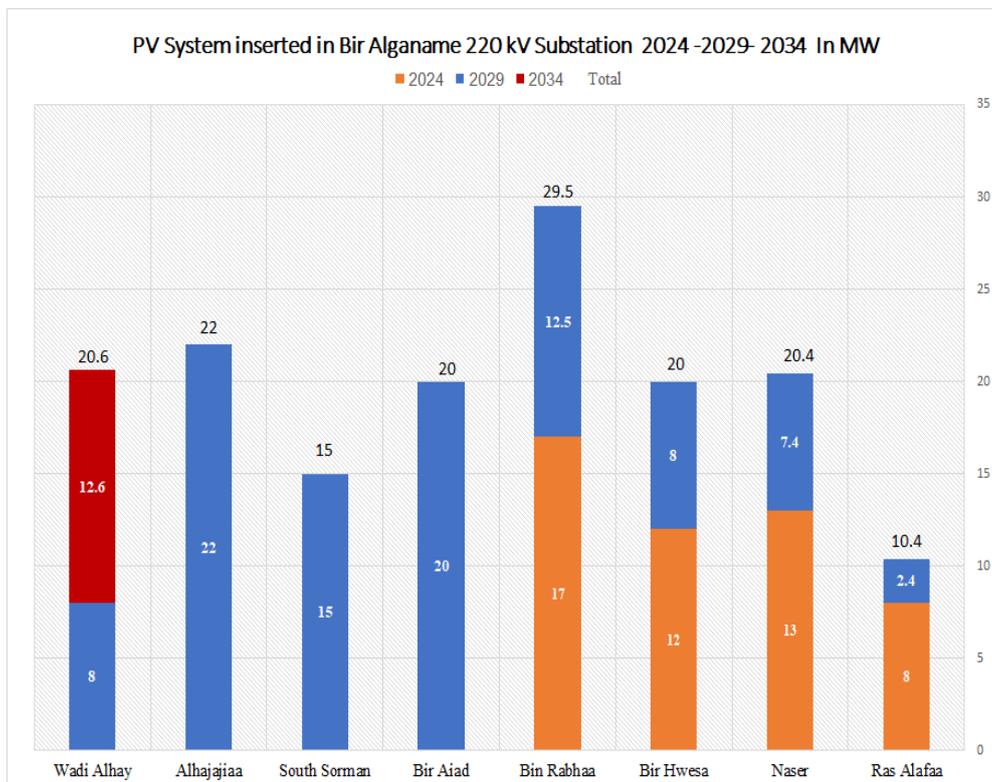


Fig. 2 PV Systems inserted in Bir Algame 220/30 KV S/S and Subsequent Network 2024 – 2029 – 2034

Notably, the transformer at Bin Rabhaa bus (30 kV) is also experiencing overload and requires replacement with a transformer rated 40MVA. The improved network conditions for 2034 will be illustrated following the successful resolution of all identified issues, in Apdx 2, providing an operational improvement within the Bir Algame network for that year.

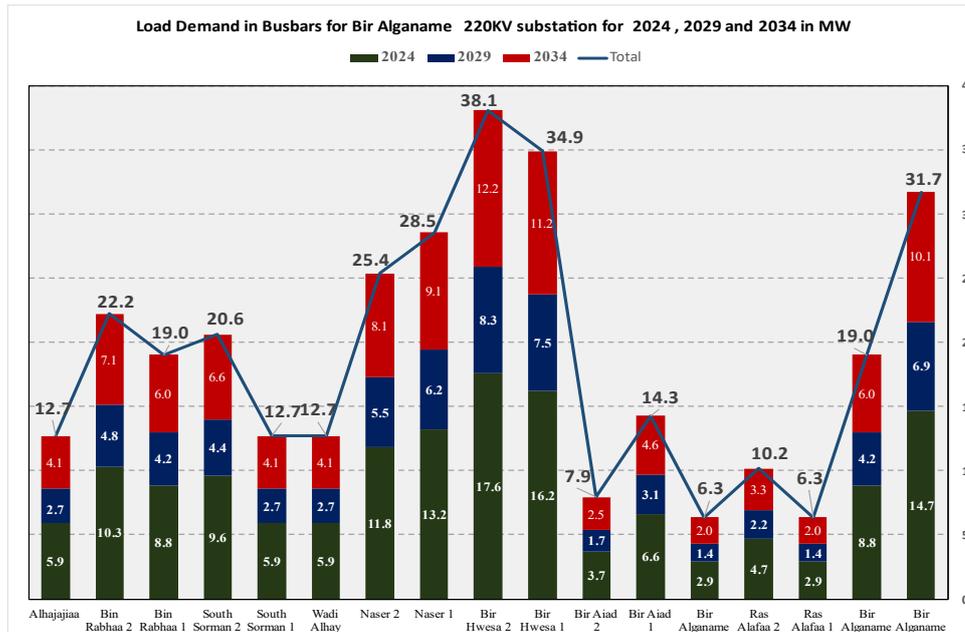


Fig. 3 Load Demand for Bir Algame in 2024,2029, and 2034

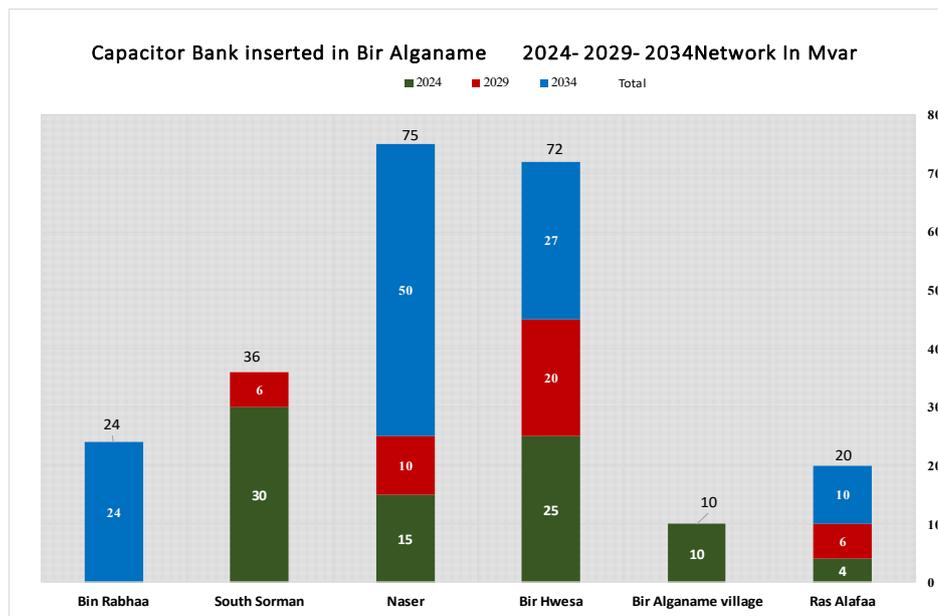


Fig. 4 Capacitor Bank inserted in Bir Algame 220 KV S/S and Subsequent Network 2024 – 2029 – 2034



The anticipated enhancements to network conditions for the year 2034 will be depicted upon successful resolution of the identified issues. Fig. 3 shows the load demand for each busbar in 2024, and over the next 10 years, 2029 to 2034. Furthermore, capacitor banks will be systematically installed throughout Bir Alaname network in 2024, 2029, and 2034 to augment performance, as shown in Fig. 4.

#### 4. Conclusion and Recommendation

There are two scenarios that can be applied [12]. The first is by making changes in Bir Alaname 220/30 kV step by step, which means that changing some equipment takes place in the first five years, then the next stage after the first period. The second scenario is by adopting the final result and implements equipment from the first period

##### A. Conclusion.

The goal and objectives of the research are to redesign, re-planning, and load forecast for Bir Alaname 220/30 kV S/S for the next 10 years.

The most known E-TAP software was used to analysis the load flow for the networks to ensure the accuracy and quality of the resultant system performance.

The methods of replanning, redesigning, and load forecasting was applied for normal (N) and emergency (N-1) operating conditions, considering the peak loading of the system.

In this study, we evaluated the existing electrical network of Bir Alaname and analyzed the electric energy demand, along with projected energy growth for the next ten years. Based on our findings, we developed a strategic plan for improvement, incorporating both short- and long-term initiatives. A timeline has been proposed to facilitate a smooth transition through each phase of implementation according to the outlined steps in this research.

The results indicate that the 220/30 kV network in Bir Alaname requires immediate re-planning and re-designing to accommodate future energy demands. Our analysis shows a need for expansion of the network both now and over the coming decade. Specifically, we recommend the installation of eight photovoltaic systems, the addition of six power capacitor banks, and resizing of two power transformers to 40 MVA, to ensure the network can meet anticipated energy requirements.

##### B. Recommendation

- The re-design and re-planning of the electric distribution system of Libya should be applied according to the scientific methods and studies instead of patching the network by random additions to provide electrical energy temporarily without using a strategic view to expand the systems.
- New methods may be applied for re-planning and re-designing of Bir Al-Aghnam 220/30 kV network and compared with this study.



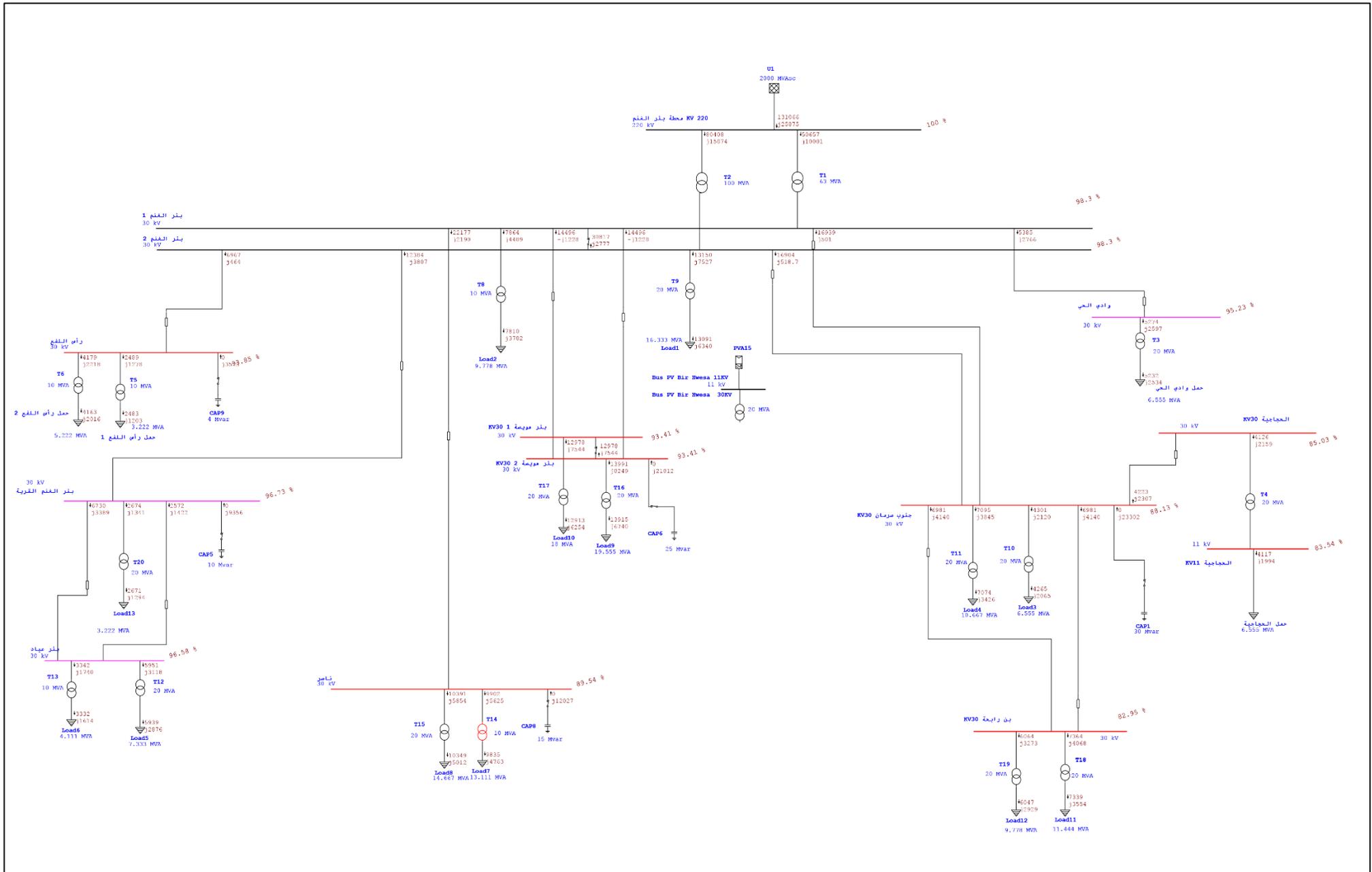


- The focus is directed towards areas adjacent to and near the capital, Tripoli, and big cities, which include densely populated urban centers. The objective is to integrate solar energy PV systems into their local substations network, thereby enhancing traditional energy production in these regions. This approach will facilitate the redistribution of energy to densely populated areas that lack adequate space for solar energy installations. Implementing PV systems in the replanning initiative aims to expand the Bir Al-Aghnam network's capacity over the next decade, targeting a total of 325 MW by 2034. This capacity is projected to meet more than 72% of the total energy demands of Bir Al-Aghnam network.

## References

- [1] Annual Report, "General Electricity Company of Libya" (GECOL), Tripoli, Libya, 2024. [https://www.gecol.ly/GAnnual\\_Report/ViewReport](https://www.gecol.ly/GAnnual_Report/ViewReport)
- [2] R. N. S. R. Mukhtaruddin, H. A. Rahman, M. Y. Hassan, and J. J. Jamian, "Impact of load expansion to the renewable energy system performance," 2013 IEEE Student Conference on Research and Development, Putrajaya, Malaysia, 2013, pp. 243-247.
- [3] Abdulhakim TREKI. "An overview for network future development in a rapid expansion city" Libyan International Conference on Electrical Engineering and Technologies 7 – 3 March 2018 (1st ed., Vol. 1), Tripoli – Libya
- [4] Faraj AMARI and Matthias HABLE NETWORK DEVELOPMENT IN A FAST CHANGING SOCIETY – EXAMPLE TRIPOLI IN LIBYA, 19th International Conference on Electricity Distribution (CIRED) Vienna, 21-24 May 2007, paper 0440.
- [5] Abdulhakim. M. TREKI "Re Planning and Design Consideration of 30KV Power distribution Network for mid and western parts of Tripoli Network" M. Sc. Thesis Faculty of Engineering University of TRIPOLI, July 2011.
- [6] Turan Gönen , “ Electric Power Distribution System Engineering “ , copyright ©1986 .
- [7] Fettah, K., Salhi, A., Guia, T. *et al.* Optimal integration of photovoltaic sources and capacitor banks considering irradiance, temperature, and load changes in electric distribution system. *Sci Rep* **15**, 2670 (2025). <https://doi.org/10.1038/s41598-025-85484-3>.
- [8] J. Xu, B. Song, Y. Gong, B. Li and J. Jia, "Dynamic Capacity Expansion with Planning Method for Distribution Networks Based on Energy Storage," 2024 4th International Conference on Electrical Engineering and Control Science (IC2ECS), Nanjing, China, 2024, pp. 103-107, doi: 10.1109/IC2ECS64405.2024.10928568.
- [9] Gao, Chong, et al. "Generation of Typical Scenarios for Distribution Networks in Planning Stage Considering Photovoltaic and Load Growth Characteristics." *Frontiers in Energy Research*, vol. 13, Frontiers Media, Mar.
- [10] Motamedisedeh, O. *et al.* (2025) 'A comprehensive review of optimum integration of photovoltaic-based Energy Systems', *Renewable and Sustainable Energy Reviews*, 207, p. 114935. doi:10.1016/j.rser.2024.114935
- [11] SIEMENS PTD SE PT Report, Sub transmission Master Plan for Tripoli, February 2005.
- [12] K. Yurtseven and E. Karatepe, "Influence of Inherent Characteristic of PV Plants in Risk-Based Stochastic Dynamic Substation Expansion Planning Under MILP Framework," in *IEEE Transactions on Power Systems*, vol. 37, no. 1, pp. 750-763, Jan. 2022





Bir Algame 220/30 KV  
2024 Network  
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