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Maximizing Renewable Energy Integration in the Egyptian Power Grid Using the Coronavirus Optimization Algorithm

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Abstract

Global efforts are increasingly focused on achieving fully sustainable energy systems by mid-century to comply with the Paris Agreement targets. This study introduces a novel approach for the optimal operation of the Egyptian power grid, aiming to maximize renewable energy integration while minimizing voltage fluctuations and overall power losses. The optimization is implemented using the Corona Virus Optimization (CVO) algorithm. The proposed CVO method is benchmarked against the Teaching and Learning-Based Optimization (TLBO) algorithm for voltage deviation, power losses, and renewable energy share. The study uses real-world data on electricity demand, solar irradiation, and wind speed for representative winter and summer days. A 2020 Egyptian grid model is developed, simulated, and optimized using DlgSILENT software. Results demonstrate that CVO outperforms TLBO in enabling the grid to operate with the highest achievable share of renewable energy. This research contributes toward Egypt's national objectives of reaching 20% and 42% renewable energy penetration by 2022 and 2035, respectively.

Keywords Penetration level, Coronavirus optimization, Egyptian grid, Benban photovoltaic park, Wind farms, Hydropower plants

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Introduction

The global transition toward the Sustainable Development Goals (SDGs) [1] has emphasized the importance of clean energy, particularly SDG 7, which targets universal access to sustainable energy. Worldwide, nations are striving to achieve fully renewable energy systems to fulfill the 2016 Paris Agreement on climate change [2]. Several countries have made remarkable progress: Iceland relies entirely on renewable power, Norway generates over 98% of its electricity from renewable sources, and Costa Rica produces more than 95% of its electricity from renewable sources [3]. In Africa, Kenya achieves a 70% share of renewable energy as its primary electricity source, while Egypt has already deployed significant renewable installations, including hydro and photovoltaic generators [4]. Egypt aims to achieve 42% renewable energy penetration by 2035 [5].

Numerous studies have explored strategies for transitioning power systems to 100% renewable energy. Reference [6] proposed methods for secondary voltage control in fully renewable grids, while [7] examined Japan's transition to a fully sustainable power system. In Ref. [8], researchers addressed the parameter settings of power systems with high photovoltaic penetration. Policy, technical, and institutional strategies for converting conventional power systems to 100% renewable energy were analyzed in Ref. [9]. Similarly, Ref. [10] outlined a roadmap for Macedonia to achieve complete sustainability by 2050, and Ref. [11] presented techniques for operating high-renewable power systems efficiently while

minimizing generator costs. Sweden plans to generate 100% clean electricity by 2040 [12], whereas Portugal's energy system is optimized for 100% renewables by 2050 using hydropower solutions [13]. In Spain, studies [14, 15] highlighted wind turbine repowering as a means to enhance renewable energy penetration.

The role of information and communication technologies in supporting SDG 7 has also been examined [16]. Optimizing power system operations with both conventional and renewable generators has been widely applied to minimize costs and maximize renewable integration [17]. In Egypt, optimal power flow strategies have been utilized to increase renewable generation while reducing overall losses [4].

Various optimization techniques have been adopted to improve system performance. Genetic Algorithms (GA) were explored in Ref. [18], Particle Swarm Optimization (PSO) in Ref. [19], and the Teaching-Learning Based Optimization (TLBO) method was first introduced by Rao in 2011 [20]. TLBO has been applied in Egypt to maximize the contribution of renewable energy and minimize losses [4]. Since 2020, the global COVID-19 pandemic has inspired the development of the Corona Virus Optimization (CVO) algorithm [21], which models viral behavior as an optimization tool for complex systems.

This paper makes the following contributions:

- It focuses on maximizing renewable energy generation in Egypt while achieving minimal voltage deviations and total power losses.
- It demonstrates the application of the CVO algorithm for optimal power flow in the Egyptian grid and compares the results with those from TLBO and non-optimized cases.
- It emphasizes the operation of Upper Egypt with near-100% renewable energy supply during most daytime hours, leveraging a large photovoltaic park and two hydropower stations.

Egyptian Power System

The 2016 Egyptian grid was modeled in Ref. [22] using DlgSILENT PowerFactory, encompassing all generation units, transmission lines, transformers, reactors, and loads existing at that time. In Ref. [4], the model was updated to reflect the 2020 grid, incorporating newly commissioned plants such as the Benban photovoltaic park (planned 1.8 GW) and the expanded Gabal Zeet wind farm (0.54 GW), alongside three 4.8 GW combined-cycle power plants at Burullus, Beni Suef, and the New Capital, as depicted in **Figure 1**. These large-scale additions, along with upgraded transmission infrastructure, resulted in the system being partitioned into six geographic regions.

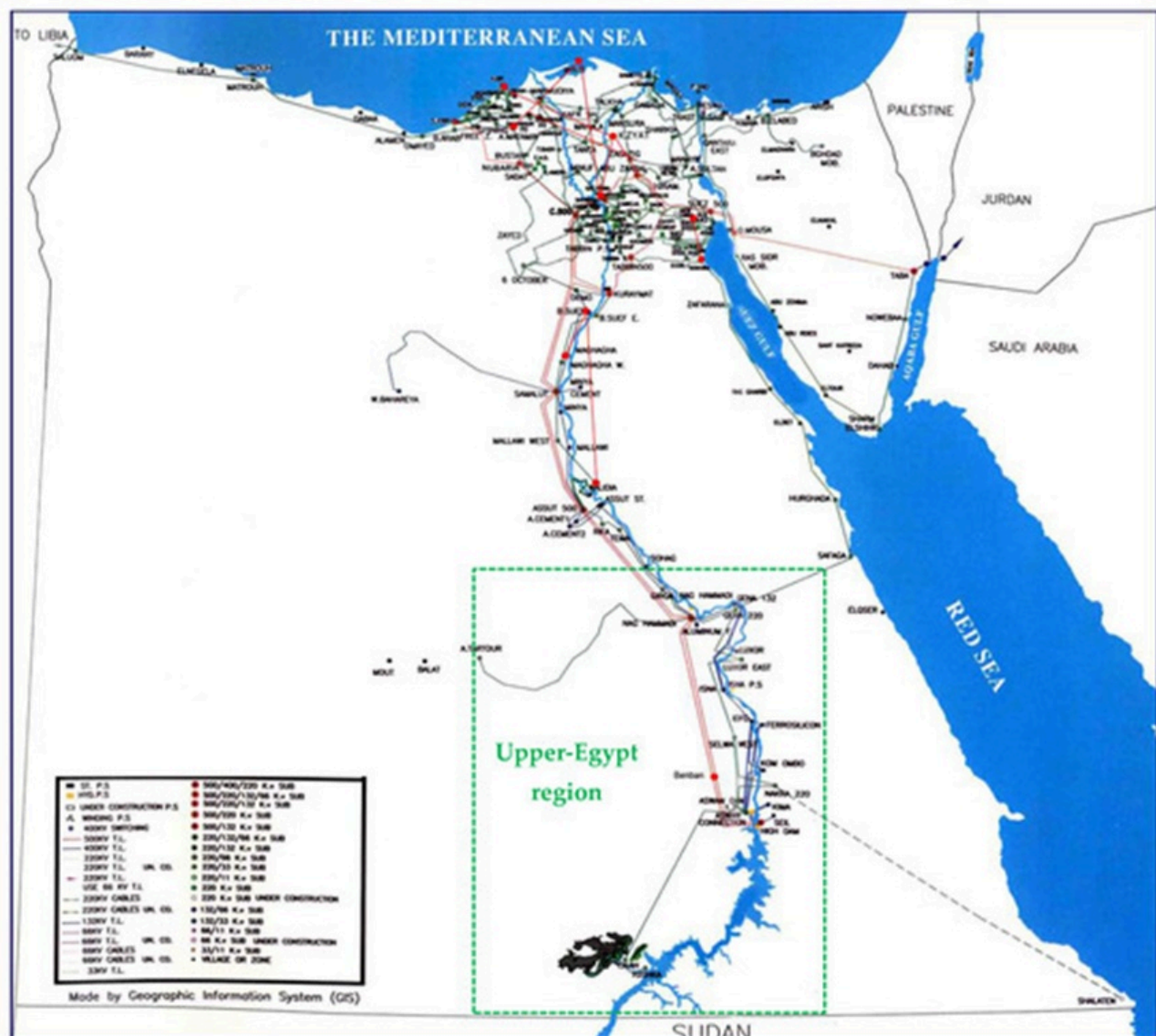


Figure 1. The Egyptian grid.

The Upper Egypt area contains three power generation facilities, all relying on renewable energy: the High Dam Power Plant with 2.1 GW capacity, the Aswan Reservoir Plant with 0.55 GW capacity, and the planned Benban Photovoltaic Park, which is expected to reach 1.8 GW. This region maintains electrical connections with both Middle Egypt and the Canal region, the latter comprising wind farms and conventional fossil-fuel-based power stations.

This study applies optimal operational strategies to the Egyptian grid to achieve maximum renewable energy integration, reduce overall power losses, and minimize voltage deviations. Additionally, the research evaluates the number of hours during which the Upper Egypt region could rely entirely on renewable energy without drawing power from fossil-fuel sources in the Middle Egypt region.

All simulations and optimization processes are executed using DiGSILENT PowerFactory due to its versatile capabilities for large-scale grid studies, including the ability to:

- Conduct power flow analyses

- Solve optimal power flow problems
- Perform short-circuit evaluations
- Analyze contingencies
- Execute transient stability simulations [22]

Renewable Energy in Egypt

Currently, Egypt uses three main renewable energy technologies: solar photovoltaics, hydropower plants, and wind energy.

Solar photovoltaics

Egypt enjoys abundant solar resources throughout the year, with daily average radiation levels ranging from 5 to 8 kWh/m² [23], and Aswan alone exhibits an average solar intensity of 0.367 kW/m² [24]. In line with the 2035 Sustainable Development Strategy, a decision was made in September 2014 to construct a large-scale photovoltaic park in Aswan [25].

Upon completion, the Benban Photovoltaic Park is expected to have an installed capacity of 1800 MW, making it among the largest PV parks in the world without storage systems. The facility is situated about 40 km northwest of Aswan in the Western Desert. It is integrated into the national grid via four substations: three connected to the 220 kV network, and the fourth to the 500 kV network via a 220/500 kV step-up transformer [20].

A standard PV system is composed of photovoltaic modules, a DC/DC converter, a DC/AC inverter, and a transformer, as shown in Figure 2.

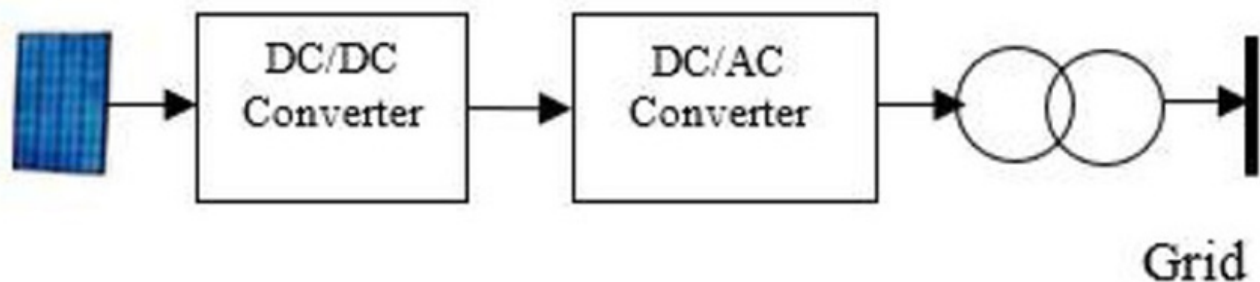


Figure 2. PV system layout

In the DigSILENT PowerFactory environment, the Benban photovoltaic installation is represented as a static PV generator [23, 24]. This generator can operate in one of three modes:

- PQ mode, controlling active and reactive power independently
- Voltage regulation mode, maintaining grid voltage within desired limits
- Droop control mode, adjusting output according to frequency variations

For this research, the Benban park is configured to function in voltage regulation mode. According to the Egyptian grid code requirements for large-scale solar plants, the reactive power of the Benban system is constrained within a range of

−0.33 p.u. to +0.33 p.u. when operating at its rated active power, as depicted in [Figure 3](#).

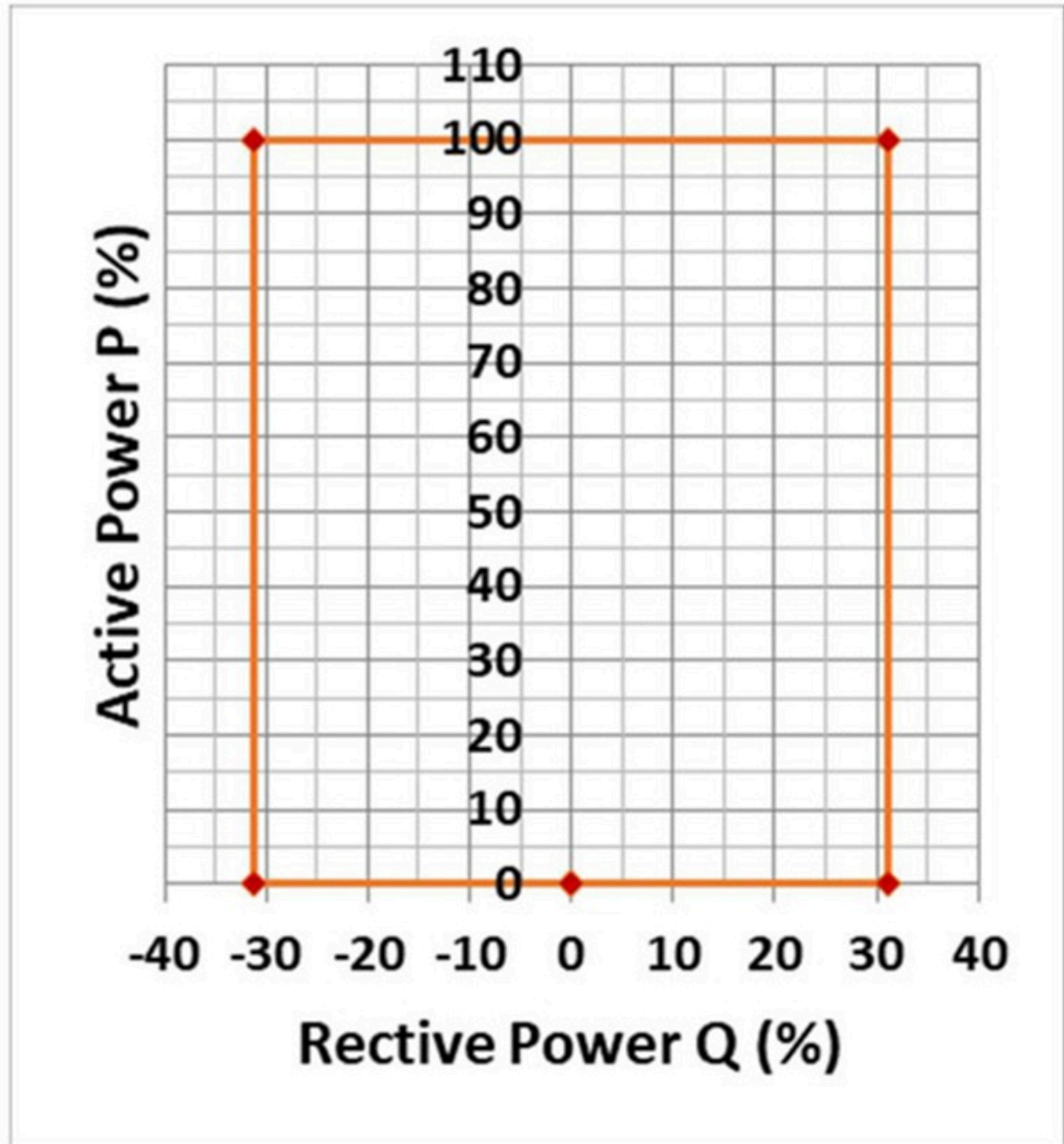


Figure 3. P-Q capability curve for large-scale renewable energy plants [4, 26, 27] (Reprinted with permission from ref. [4]. Copyright 2021 IEEE).

Hydropower plants

Egypt hosts two historically significant hydropower facilities: the Aswan Dam and the High Dam. The Aswan Dam, which began operation in 1899, currently provides a total installed capacity of 0.55 GW. The High Dam, commissioned in 1960, consists of 12 generating units, each rated at 175 MW, resulting in a combined capacity of 2.1 GW.

Wind energy

The Red Sea coastal region of Egypt offers substantial wind energy potential. The country's first large-scale wind installation, the Zaafarana Wind Farm, was commissioned in 2001 with a total capacity of 0.745 GW and is located approximately 120 km south of Suez.

Another key site along the Gulf of Suez is the Gabal Zeet region, which hosts extensive wind resources. The Gabal Zeet Wind Project has been developed in three stages [28]: Stage 1 established a 240 MW wind farm, Stage 2 added 220 MW, and Stage 3 contributed an additional 120 MW. In 2016, only the first stage (240 MW) was included in simulations of the Egyptian power system, but the current total capacity has been expanded to 580 MW.

For this study, all wind farms are modeled as Type 3 systems equipped with Doubly Fed Induction Generators (DFIG).

Figure 4 illustrates a simplified schematic of a Type 3 wind turbine represented as a generator bus [29].

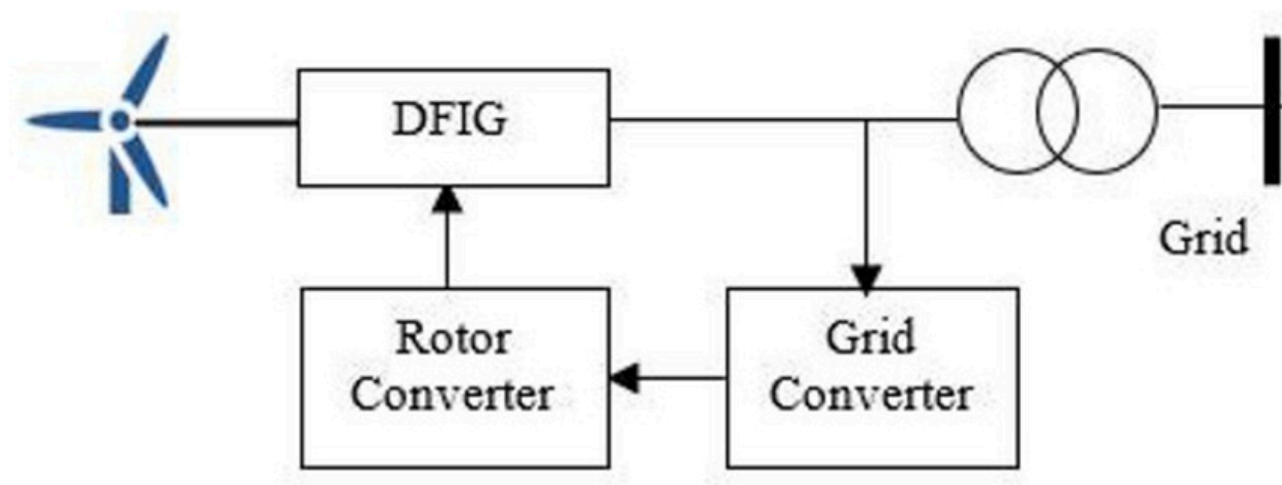


Figure 4. Type 3 wind turbine and associated wind farm.

Optimization of the Egyptian Power Grid

Definition of the optimization problem

Among the six regions, Upper Egypt hosts three power stations that use sustainable energy technologies, offering the potential to supply the majority of its electricity demand from renewable sources for most hours of the day. This region is interconnected with both the Canal and Middle Egypt regions. Carbon dioxide emissions in Upper Egypt can be reduced by importing electricity from wind farms in the Canal region while decreasing reliance on generation from Middle Egypt. The optimization of the Egyptian power system can thus be formulated as follows:

Objective function (F): Maximize renewable energy penetration ($F1$), minimize overall power losses ($F2$), and reduce voltage deviations ($F3$). The multi-objective function is constructed with equal weighting for $F1$, $F2$, and $F3$.

Objective Functions:

Maximizing the proportion of renewable energy

The goal is to increase the utilization of sustainable energy by minimizing the curtailed output from each renewable power plant, park, or farm.

$$F_1 = \min F = \sum_{t=1}^{N_T} \sum_{i=1}^{N_R} P_{CurrR} \Delta t \quad (1)$$

Minimizing total power losses

The total active power loss, P_{Loss} , can be expressed as:

$$F_2 = \min F = \sum_{i \in N_L} P_{Loss} = \sum_{i \in N_L} G_{ij} (V_i^2 + V_j^2 - 2V_i V_j \cos \theta_{ij}) \quad (2)$$

Where N_L is the number of transmission lines or cables in the system, G_{ij} is the conductance of the line connecting bus i and j , V_i and V_j are the voltages at buses i and j , respectively, and θ_{ij} is the voltage phase angle difference between the two buses.

Minimizing voltage deviations

$$F_3 = \min F = \sum_{i=1}^{N_B} (1 - V_i) \quad (3)$$

Decision Variables: Voltages at each bus, transformer tap settings, and the active/reactive power outputs of all generators.

Constraints:

- Equality constraints representing load flow equations.

$$P_{Gi} - P_{Di} - V_i \sum_{j=1}^{N_B} V_j (G_{ij} \cos(\delta_i - \delta_j) + B_{ij} \sin(\delta_i - \delta_j)) = 0 \quad (4)$$

$$Q_{Gi} - Q_{Di} - V_i \sum_{j=1}^{N_B} V_j (G_{ij} \sin(\delta_i - \delta_j) + B_{ij} \cos(\delta_i - \delta_j)) = 0 \quad (5)$$

- Inequality constraints reflecting operational limits.
- Generation capacity limits for each power station.

$$P_{Gimin} \leq P_{Gi} \leq P_{Gimax} \quad (6)$$

$$Q_{Gimin} \leq Q_{Gi} \leq Q_{Gimax} \quad (7)$$

- Voltage magnitude bounds at each bus.

$$V_{tmin} \leq V_t \leq V_{tmax} \quad (8)$$

- Maximum loading limits for cables and transmission lines.

$$P_{line} \leq P_{line max} \quad (9)$$

- Transformer tap changing limits.

$$T_{kmin} \leq T_k \leq T_{kmax} \quad (10)$$

- Capacitor reactive power limits.

$$Q_{clmin} \leq Q_{cl} \leq Q_{clmax} \quad (11)$$

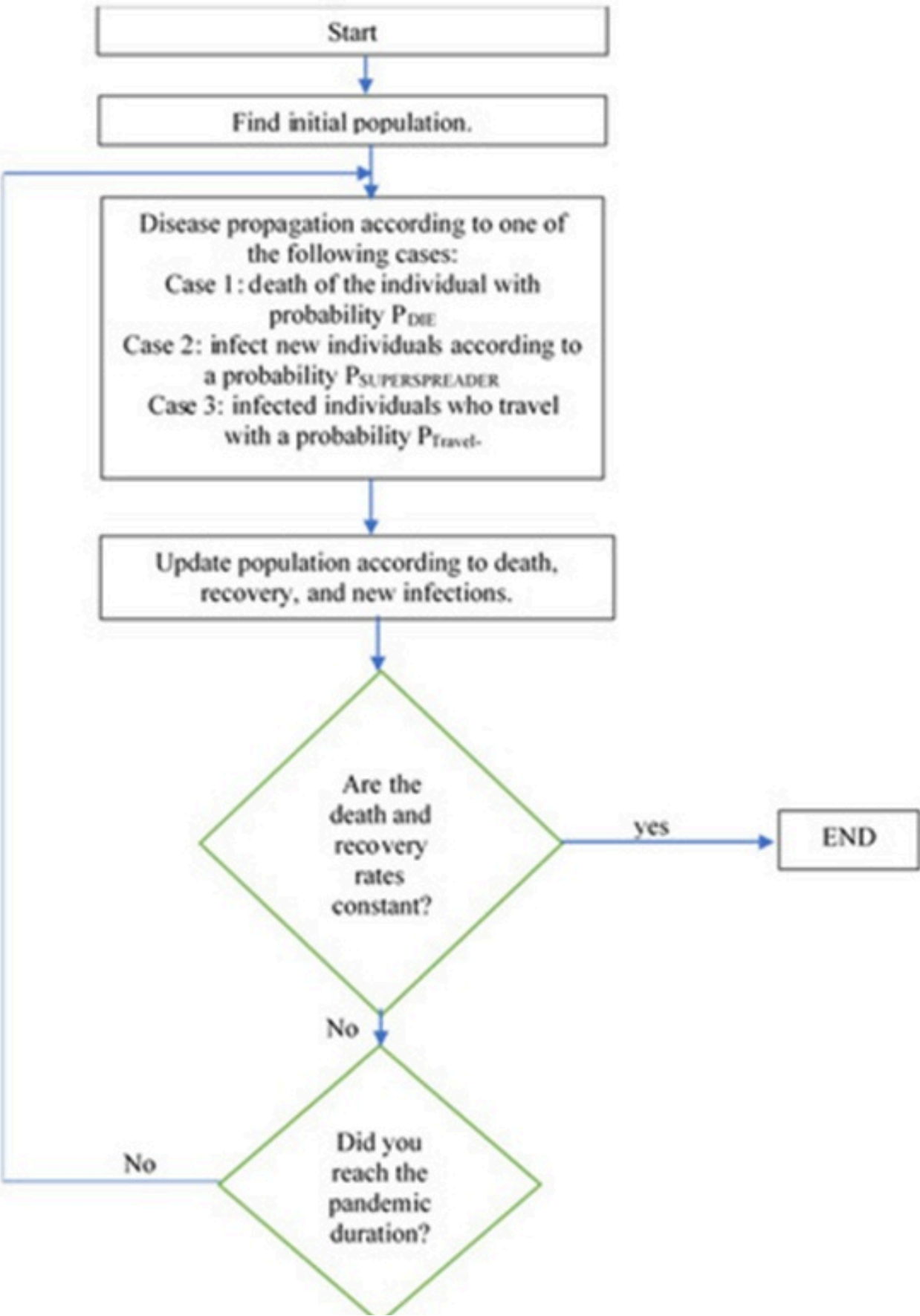
Where NB represents the total number of buses, δ_i is the voltage angle at bus i , B_{ij} is the susceptance between buses i and j , T_k denotes the transformer tap range, Q_{ci} is the reactive power of capacitor i , PG_i and QG_i are the active and reactive power outputs of generator i , and PD_i and QD_i correspond to the active and reactive power demands at bus i .

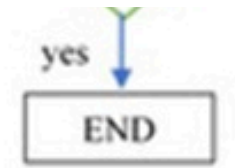
CVO algorithm design

Since December 2019, the world has faced the rapid spread of the respiratory virus COVID-19, which infected over 83,000,000 people globally in 2020, resulting in approximately 1,800,000 deaths and 60,000,000 recoveries [30]. Inspired by the efficiency of bio-inspired optimization techniques in various machine learning applications, researchers have introduced the COVID-19 Variants Optimization (CVO) as a novel metaheuristic algorithm. CVO offers several advantages over existing methods:

- Its parameters are predefined with actual rates and probabilities, eliminating the need for additional tuning studies.
- The search process can terminate after a set number of iterations without manual configuration.
- The rapid spread mechanism mimics careful exploration of promising solution regions, while parallel draining ensures consistent coverage of the entire search space.

The flow of the CVO algorithm is illustrated in **Figure 5** and follows the procedural steps outlined next.





The process begins by generating the initial population, representing the first individuals infected with COVID-19. If no prior optimal solution exists, the initial population is assigned randomly.

Step 2: disease propagation

Propagation of the “disease” occurs according to the following scenarios:

1. Case 1: Each individual has a probability of death (PDIE) based on COVID-19 mortality rates; deceased individuals cannot infect others.
2. Case 2: Surviving individuals can infect new ones according to the probability PSUPERSPREADER, which considers:
 - Ordinary spreaders: Infect others based on the normal spreading rate (RSpreading).
 - Super spreaders: Infect others at a higher rate (RSuperspreading).
3. Case 3: Individuals (ordinary or super spreaders) may travel and explore new solutions in the search space. The probability of travel (PTravel) and the infection rate due to travel (RTravel) govern this behavior.

Step 3: population updating

Three populations are updated at each iteration:

- Death population: Individuals who die are recorded and excluded from further iterations.
- Recovered population: Individuals who recover are tracked and may be re-infected in future iterations with probability PReinfected. Properly isolated individuals may also join the recovered population with probability PIsolated.
- Newly infected population: All newly infected individuals in the current iteration are recorded; duplicates are removed before proceeding to the next iteration.

Step 4: termination criteria

The process can end automatically when death and recovery rates stabilize, and the newly infected population no longer spreads the infection. In some iterations, the number of infected individuals may fluctuate due to large numbers of deaths or recoveries. Additionally, the process can stop after a predefined number of iterations (pandemic duration) or after a predefined period based on social distancing measures.

Parameter Settings:

PDIE = 0.05, PSUPERSPREADER = 0.1, PTravel = 0.1, PReinfected = 0.02, PIsolated = 0.8, Pandemic duration = 30, Social distance = 8 [21, 31].

To prevent premature convergence to local optima, optimal parameter values are chosen by adjusting population size, social distance, and pandemic duration within DIgSILENT. Multiple optimization runs are conducted to further reduce the risk of local minima.

CVO has been applied since its inception to problems such as transportation networks [32] and neural network training [31]. The algorithm is implemented in DIgSILENT using the DPL programming language and employed for optimal power

flow (OPF) calculations.

Simulation Results

The simulation studies aim to evaluate the ability to maximize renewable energy penetration while simultaneously minimizing total power losses and voltage deviations. The analysis considers two representative days: one typical summer day and one typical winter day. **Tables 1 and 2** summarize daily electricity demand, solar irradiance, and wind speed for the summer and winter cases, respectively, along with the corresponding renewable energy penetration levels in the Upper Egypt region.

Table 1. Summer daily load, solar radiation, and wind speed in Egypt.

Time (h)	Total load (MW)	Solar radiation (W/m ²)	Wind speed (m/s)
0	29,184	0	5.5
1	28,799	0	5.1
2	27,904	0	4.6
3	27,396	0	4.0
4	26,728	0	4.2
5	25,949	0	4.3
6	25,208	14	4.8
7	25,329	63	4.4
8	26,086	172	4.3
9	28,170	395	4.1
10	29,147	653	4.3
11	29,512	849	4.5
12	30,250	979	4.8
13	30,476	1020	4.9
14	30,830	978	5.3
15	30,546	856	6.2
16	30,654	663	7.1
17	30,613	417	7.9
18	30,190	184	8.2
19	30,746	49	8.6
20	31,751	2	7.5
21	31,348	0	6.8
22	30,829	0	5.9
23	30,558	0	5.6

Table 2. Winter daily load, solar radiation, and wind speed in Egypt.

Time (h)	Total load (MW)	Solar radiation (W/m ²)	Wind speed (m/s)
0	18,313	0	3.8
1	17,210	0	3.9
2	16,376	0	3.8
3	15,672	0	3.9
4	15,268	0	4.0
5	15,184	0	3.9
6	16,057	24	3.9
7	17,261	72	4.0
8	18,035	271	4.5
9	19,130	608	5.0
10	19,975	718	5.2
11	20,494	623	5.4
12	20,920	491	6.0
13	21,113	554	6.3
14	21,375	112	6.4
15	21,763	45	6.6
16	21,984	8	6.5
17	22,297	1	6.4
18	24,588	0	6.2
19	24,154	0	5.8
20	23,456	0	5.2
21	22,688	0	4.7
22	21,733	0	4.4
23	20,592	0	4.1

Case Study 1: summer-day operation of the egyptian power grid

The contribution of renewable energy within Upper Egypt and across the entire national grid is depicted in [Figure 6](#), calculated following [Eqs. 12 and 13](#). Total system losses, along with the voltage deviation index, are presented in [Figure 7](#) [6], while [Figure 8](#) details the individual penetration levels of PV, wind, and hydro sources, as defined by [Eqs. 14, 15,](#)

and 16. The analysis evaluates three distinct approaches: (i) optimization via the CVO algorithm, (ii) implementation of TLBO, and (iii) operation without any optimization applied.

$$\text{Penetration level of renewables in Upper Egypt} = \frac{P_{PV} + P_{Hydro} + P_{Wind_imported}}{\text{Total power feeding the region}} \quad (12)$$

$$\text{Penetration level of renewables in whole grid} = \frac{P_{PV} + P_{Hydro} + P_{Wind}}{\text{Total power generated in the grid}} \quad (13)$$

$$\text{Penetration level of photovoltaics in whole grid} = \frac{P_{PV}}{\text{Total power generated in the grid}} \quad (14)$$

$$\text{Penetration level of wind in whole grid} = \frac{P_{Wind}}{\text{Total power generated in the grid}} \quad (15)$$

$$\text{Penetration level of hydro in whole grid} = \frac{P_{Hydro}}{\text{Total power generated in the grid}} \quad (16)$$

For clarity, PPV corresponds to the electricity generated by the Benban PV station, $PHydro$ represents output from the High Dam and Aswan Reservoir hydropower stations, $PWind$ denotes wind generation within the Canal region, and $PWind_imported$ refers to the portion of Canal-region wind power transmitted to Upper Egypt, assuming an operational 220 kV interconnection.

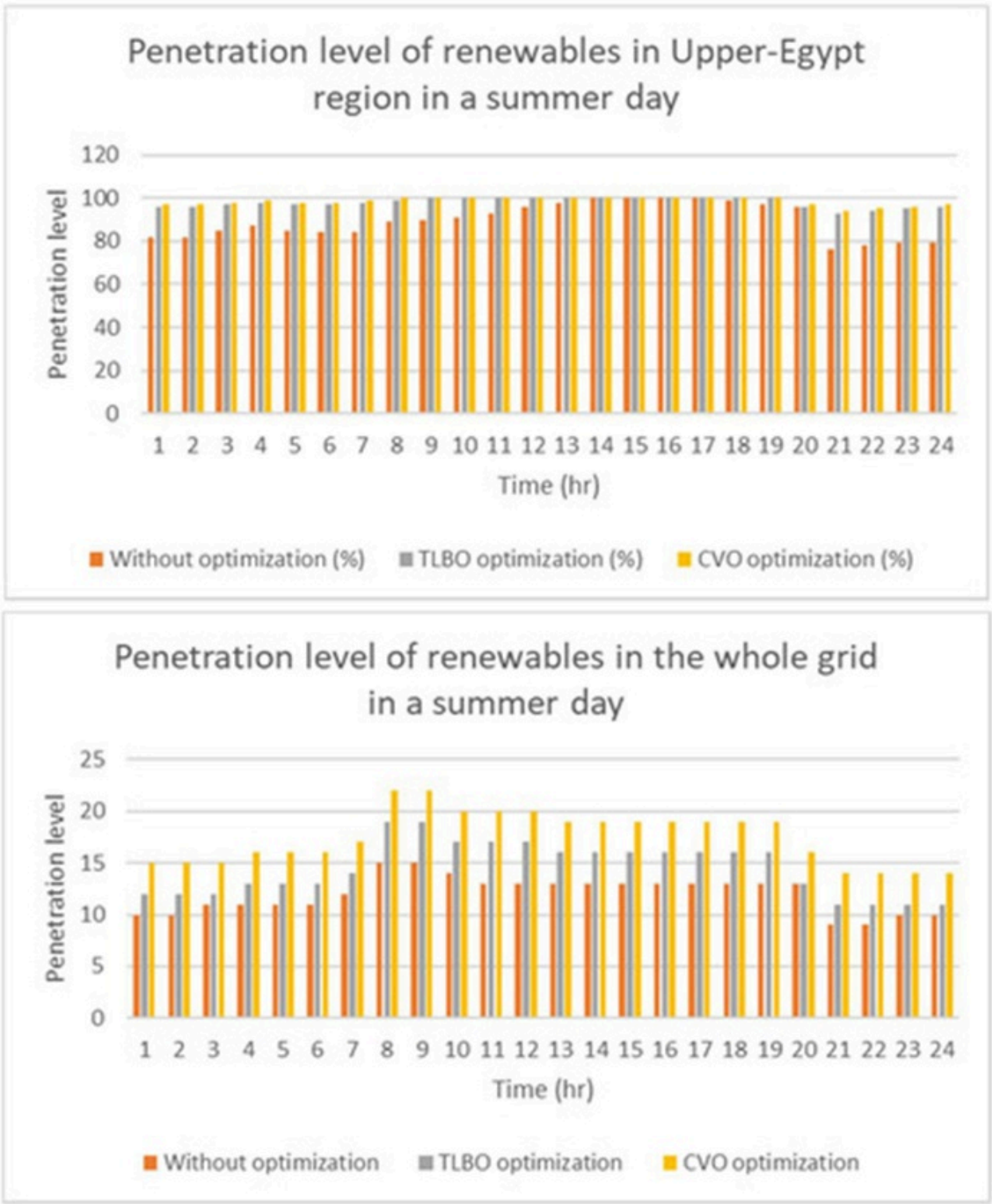


Figure 6. Renewable energy contribution in Upper Egypt and across the entire Egyptian grid during a summer day

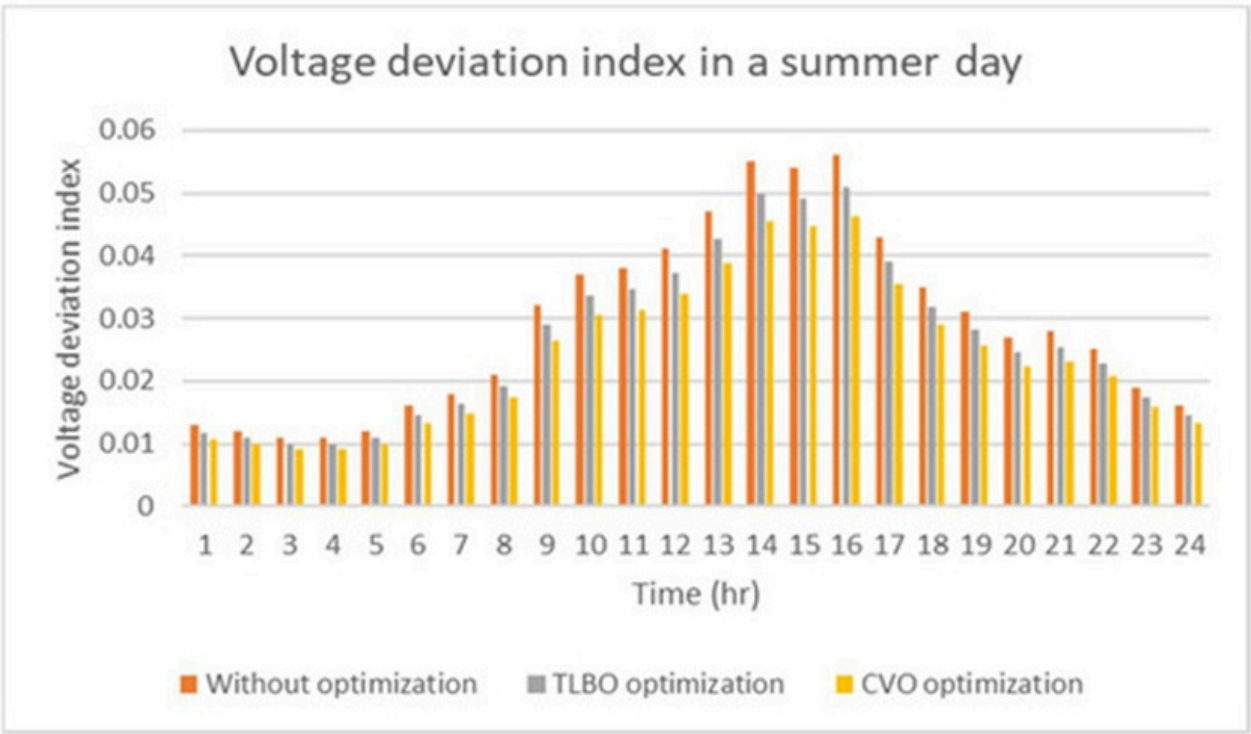
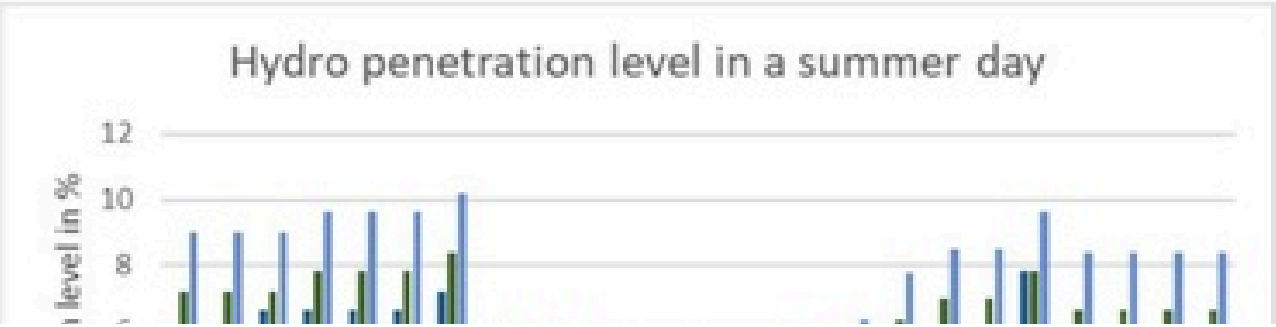
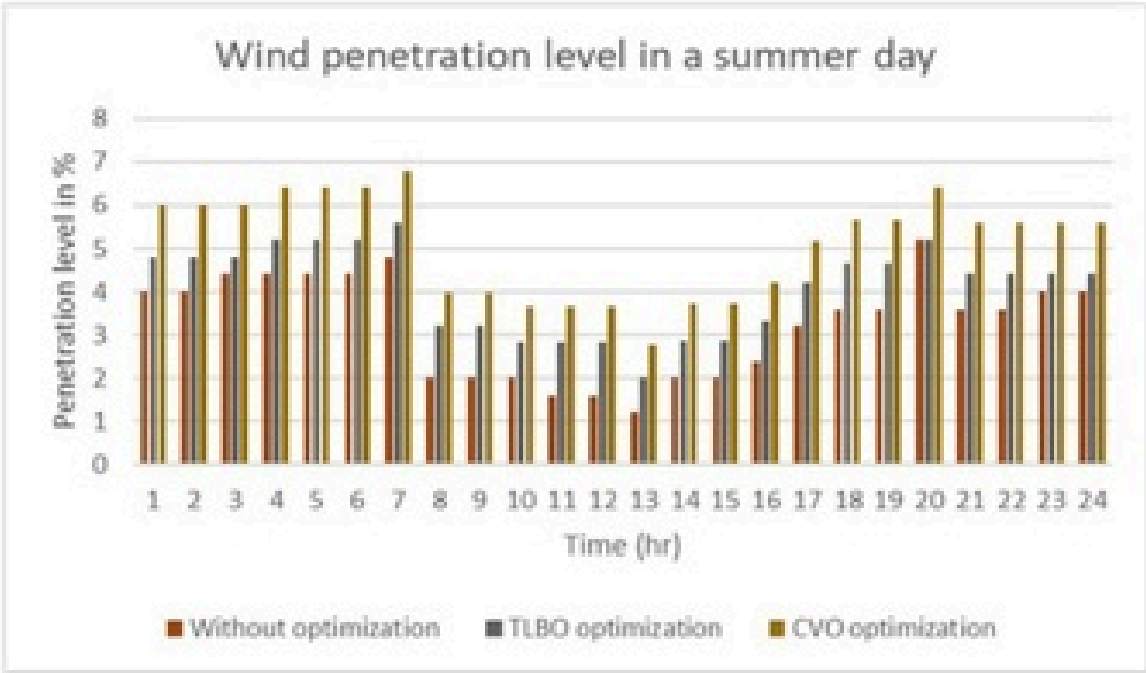
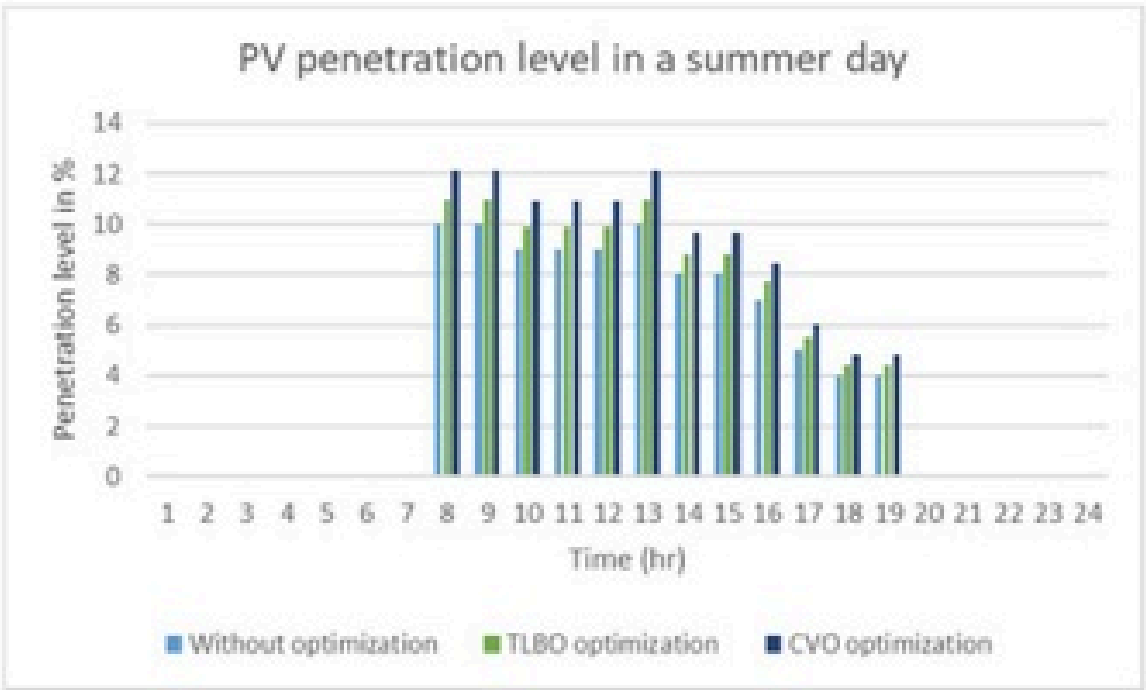


Figure 7. Overall power losses and voltage deviation index for a summer-day scenario



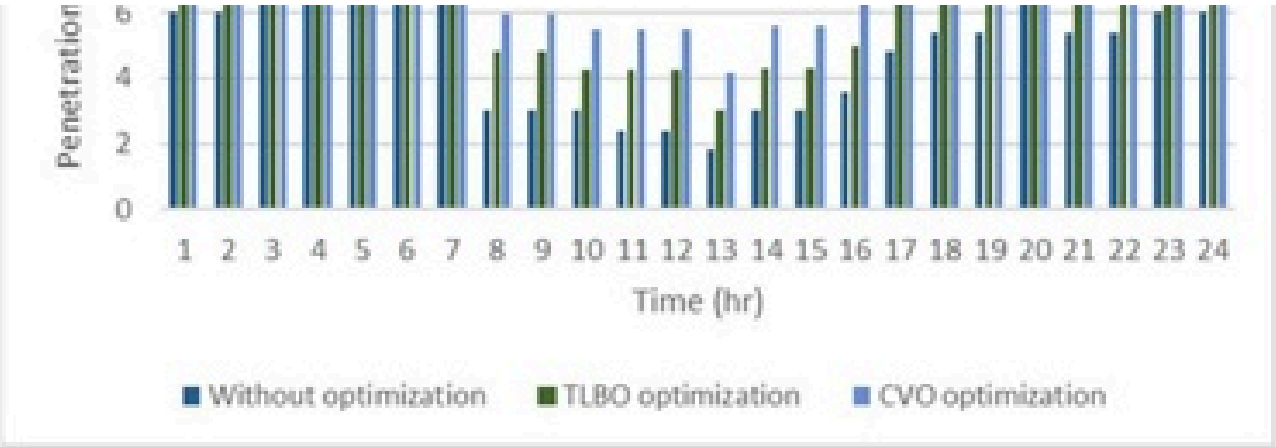


Figure 9 presents the share of renewable energy in Upper Egypt and across the entire grid during a winter day, while **Figure 10** shows total system losses and the voltage deviation index. **Figure 11** illustrates the penetration levels of PV, wind, and hydro for scenarios with and without CVO and TLBO optimization applied.

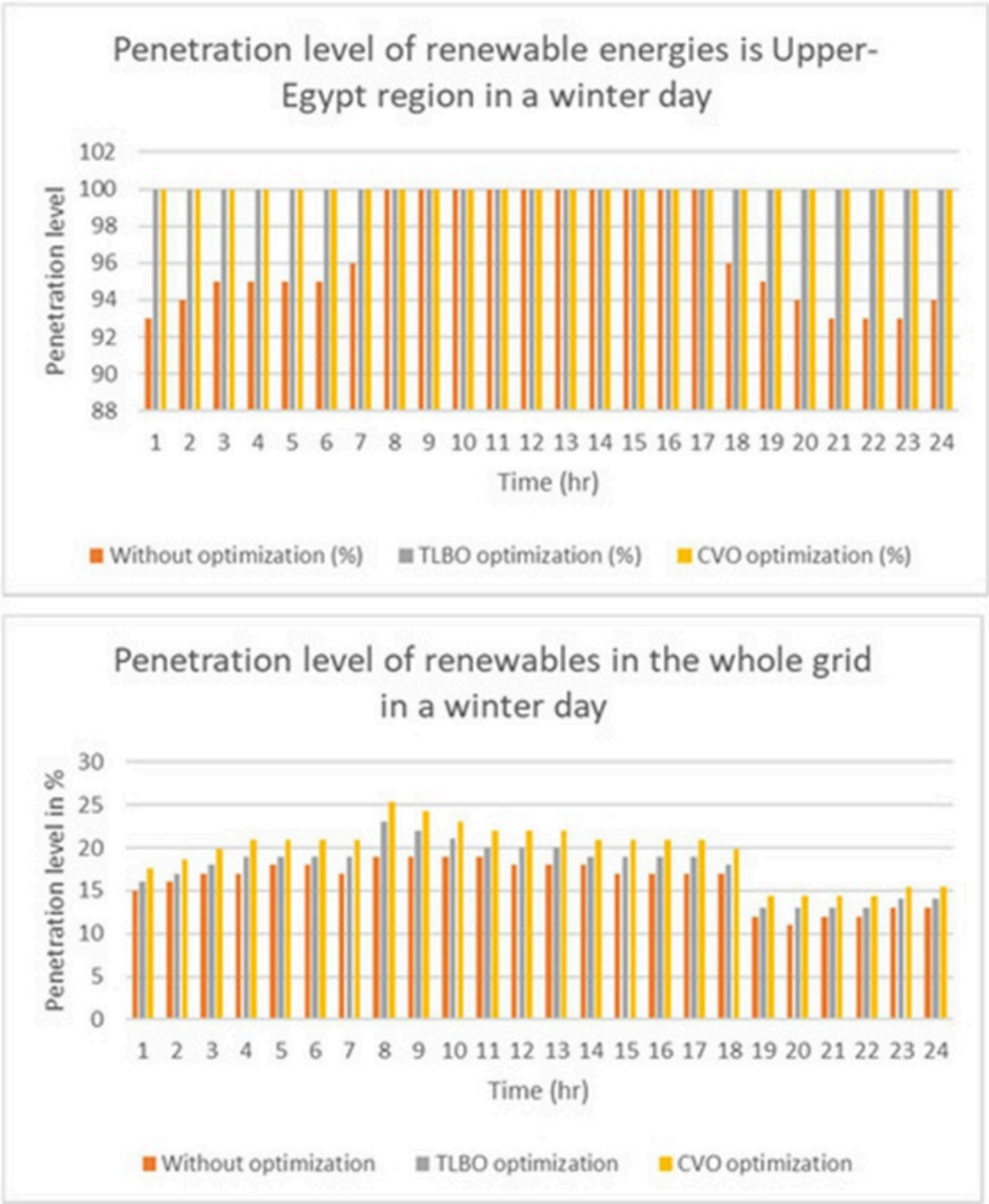


Figure 9. Contribution of renewable energy in Upper Egypt and across the entire grid during a winter day.

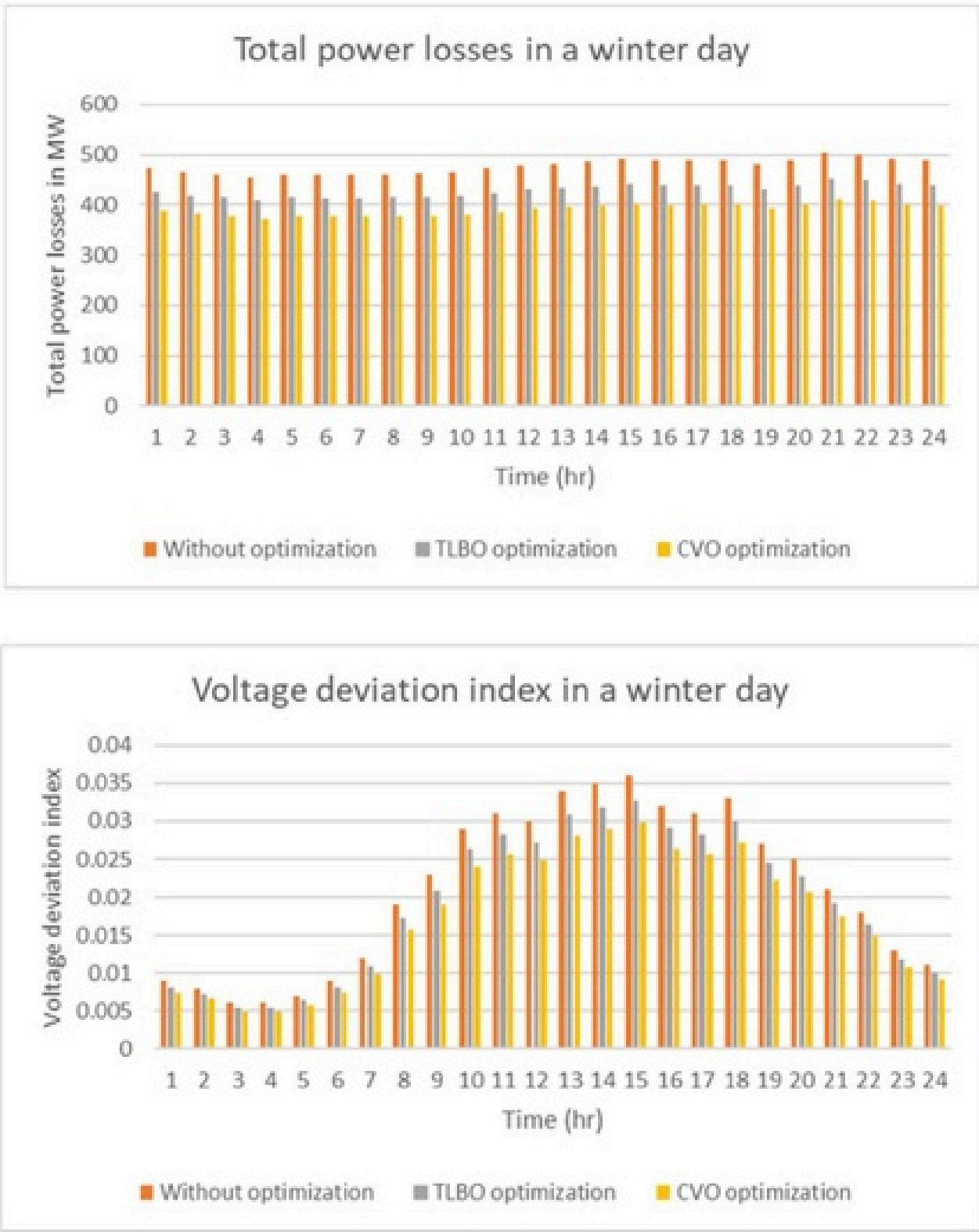
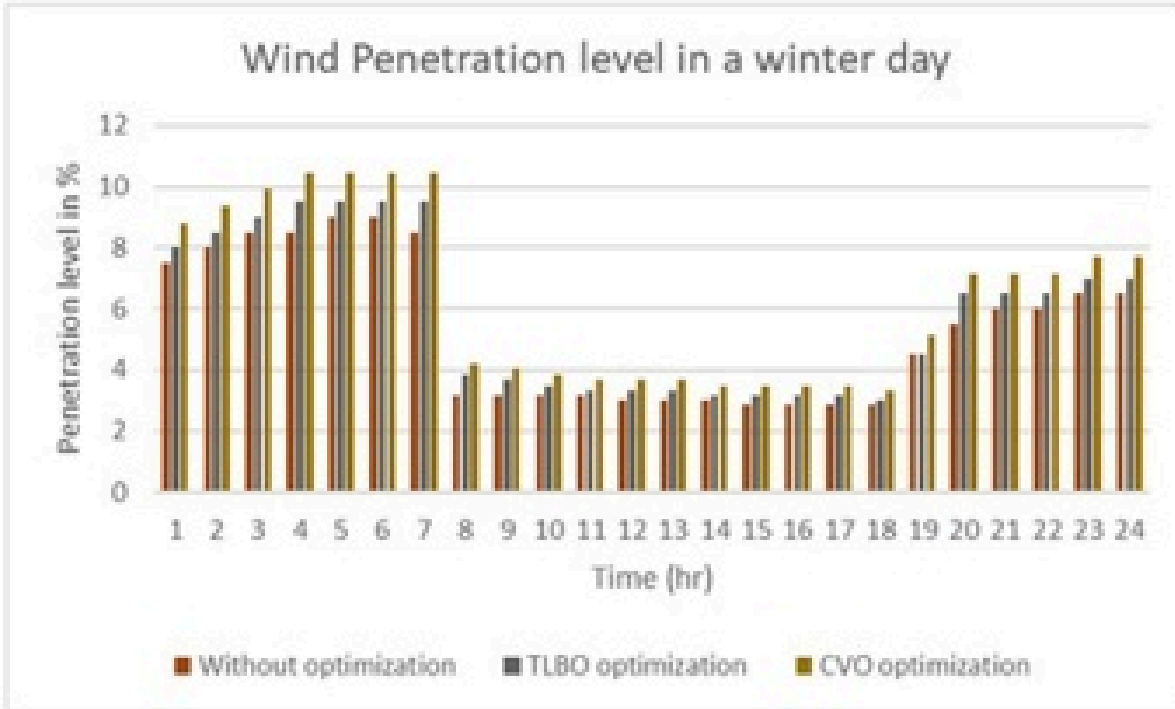
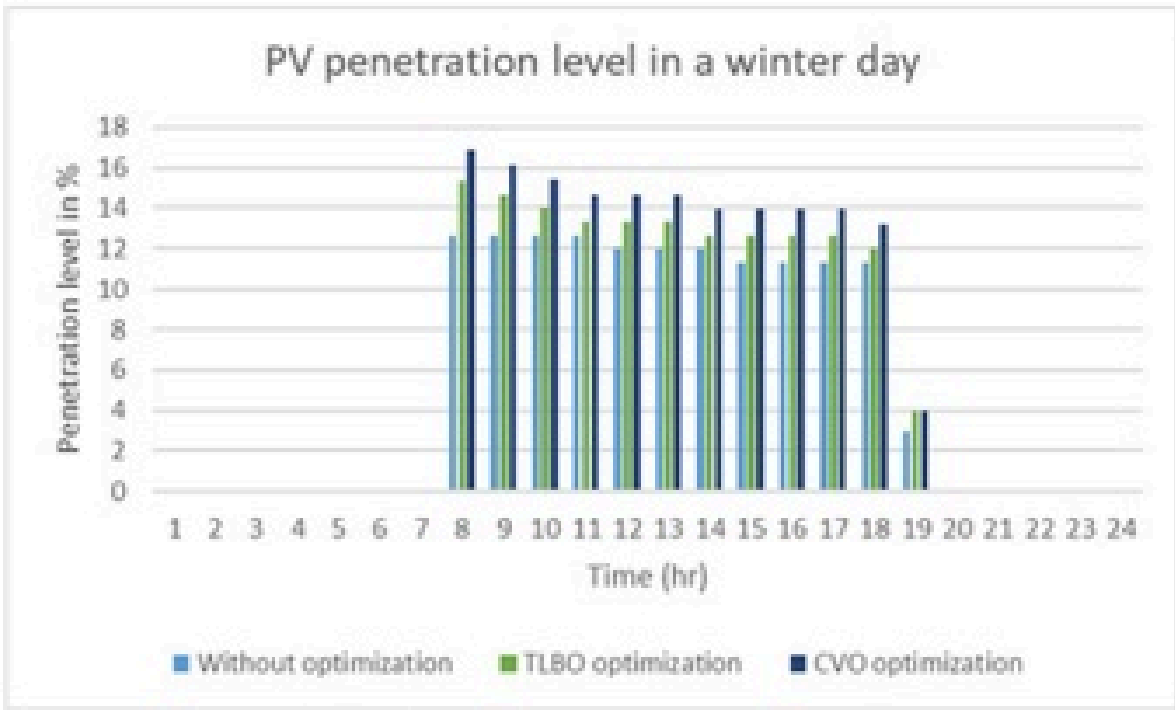


Figure 10. Overall power losses and voltage deviation index for a winter-day scenario.



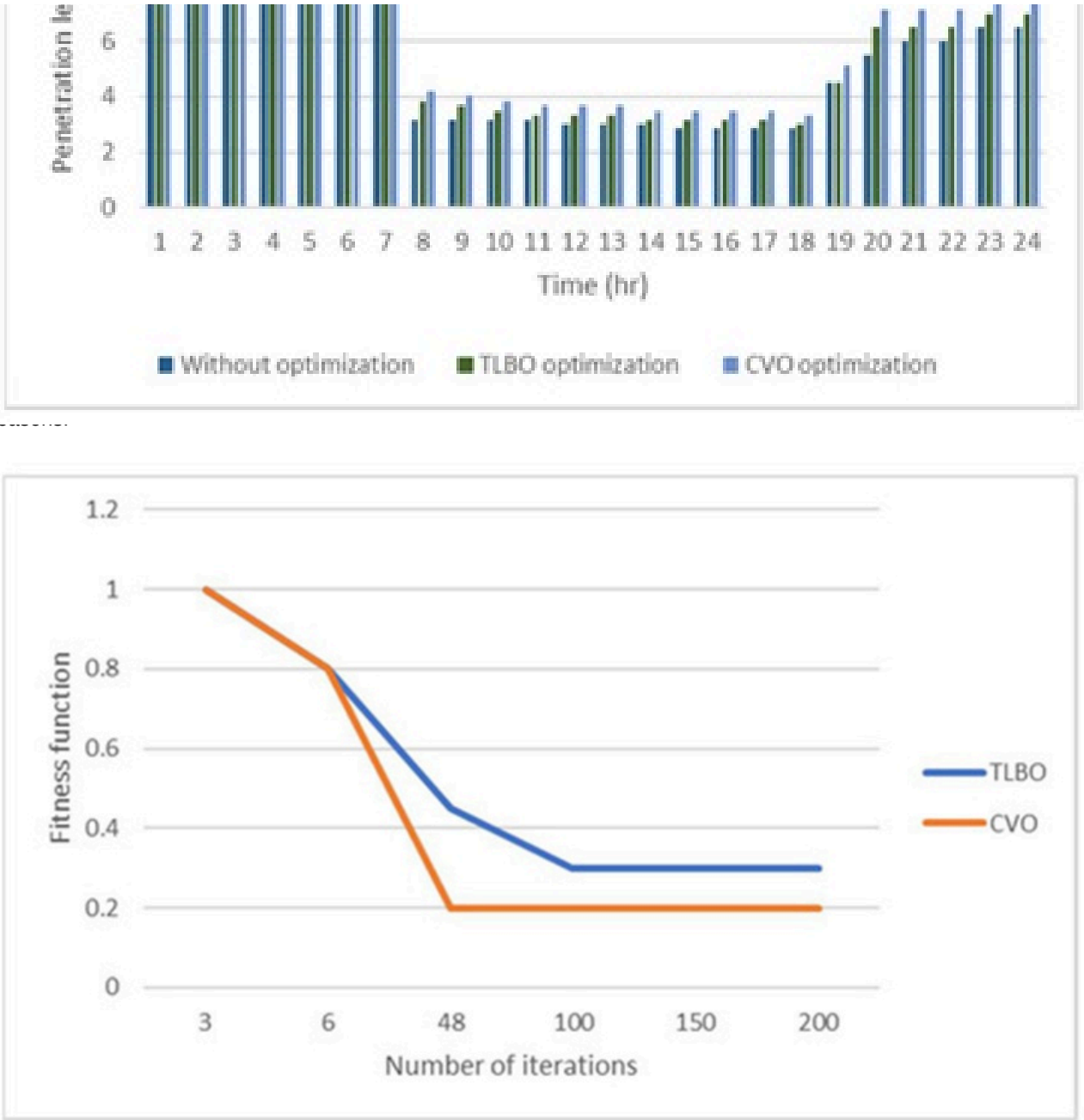


Figure 12. Convergence behavior of TLBO and CVO algorithms.

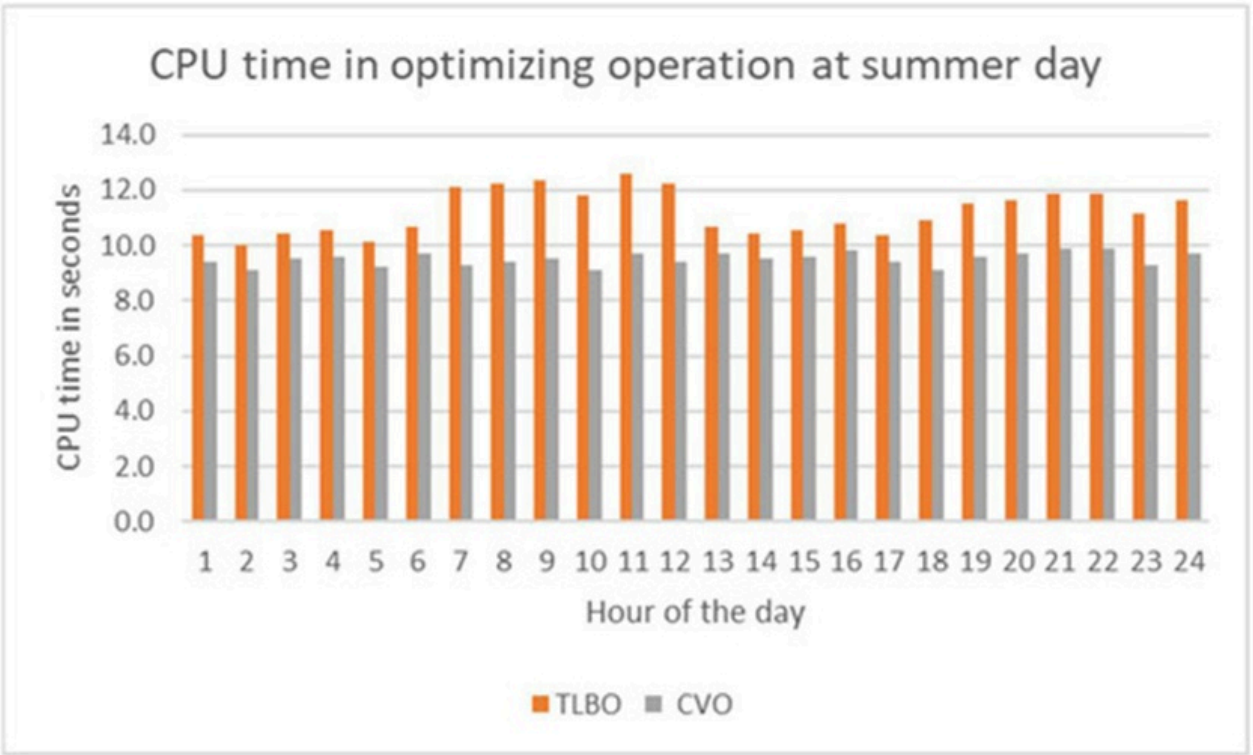


Figure 13. Hourly CPU time for TLBO and CVO during a summer-day operation.

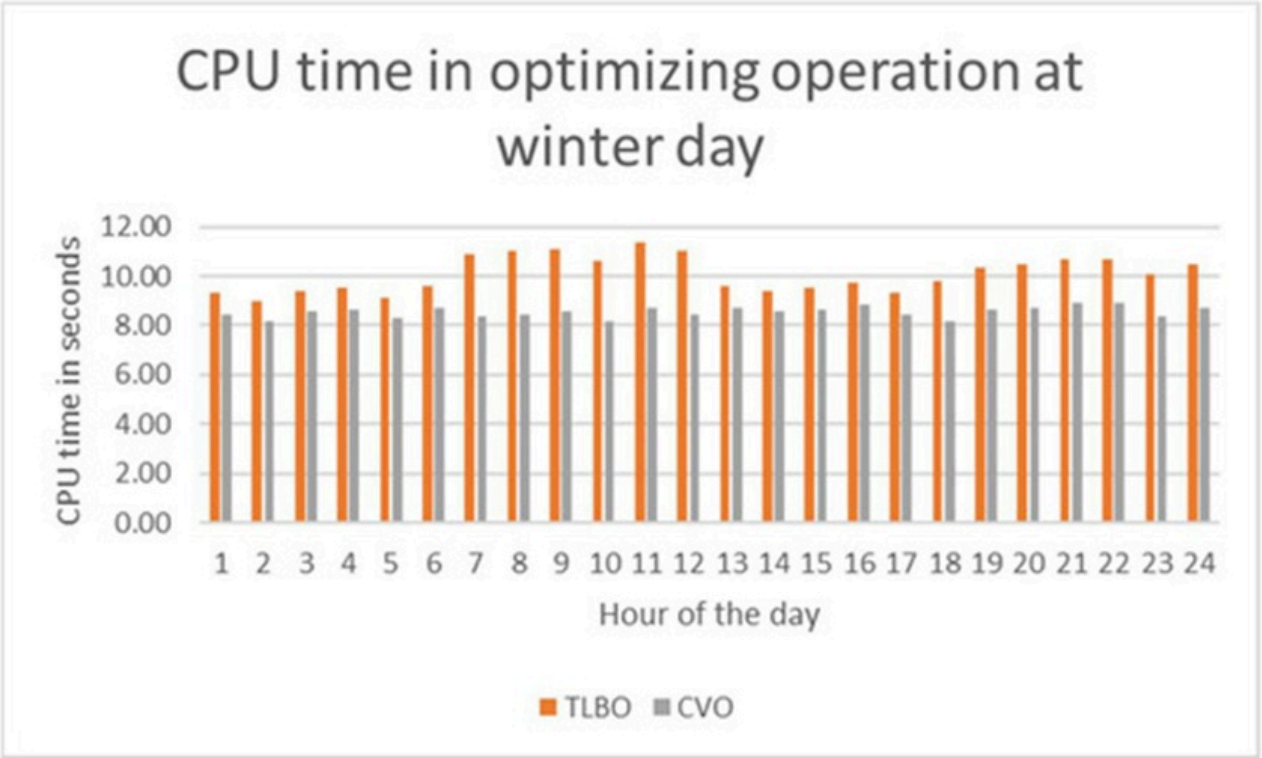


Figure 14. Hourly CPU time for TLBO and CVO during a winter-day operation

This study investigated the optimal operation of the Egyptian power system to maximize renewable energy penetration, minimize total power losses, and reduce voltage deviations. The optimization was carried out using both the CVO and TLBO algorithms within the DigSILENT software environment and the simulated grid model. The results demonstrate that CVO outperforms TLBO in achieving all three objectives, as summarized in [Table 3](#). Additionally, the convergence behavior of CVO is nearly linear, reflecting its faster response and quicker attainment of optimal solutions compared to TLBO.

Table 3. Error between CVO and TLBO in %.

Winter day	
Renewable energy share	38%
Power losses	10%
Voltage deviation	14%
CPU time	11%
Summer day	
Renewable energy share	40%
Power losses	20%
Voltage deviation	13%
CPU time	9%

The proposed CVO approach can be implemented in the Egyptian power grid by calculating optimal generation outputs for each power plant, with the national control center directing plants to adjust their production accordingly. Future work will focus on strategies to enhance renewable energy penetration throughout the year to meet the planned share of renewables in the Egyptian grid, as well as studying the effects of renewable generation uncertainties [\[33, 34\]](#) on the optimization outcomes.

Conclusion

This study introduced a novel CVO-based method to maximize the contribution of sustainable energy sources in the Egyptian power system while minimizing total line losses and voltage deviations. Compared to TLBO and the unoptimized case, the CVO optimization enables more efficient utilization of available renewable energy resources. During the simulated summer day, CVO achieved full renewable generation in Upper Egypt for 13 hours, compared to 11 hours with TLBO and only 4 hours without optimization. On a representative winter day, both CVO and TLBO enabled 100% renewable supply in Upper Egypt for 24 hours, whereas the system without optimization achieved this for only 10 hours. Across the full grid, CVO maintained renewable penetration above 20% for 15 hours during winter, versus 6 hours with TLBO; during summer, renewable share exceeded 15% for 20 hours with CVO compared to 12 hours with TLBO. The CVO method also reduced total power losses by over 10% relative to TLBO and 20–30% compared to the unoptimized system during summer and winter days. Furthermore, the multi-objective CVO-based power flow yielded the lowest voltage deviations across all scenarios. PV penetration reached up to 17% in winter and 12% in summer under CVO. The algorithm demonstrated faster convergence with fewer iterations and lower CPU time than TLBO, confirming its computational efficiency.

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