The impact of tie line capacity on the energy planning of the multi-lateral grid by considering Bi-facial PV

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***Abstract*— The global energy landscape faces the pressing challenges of resource scarcity and environmental degradation due to fossil fuel dependency. This study investigates the integration of Bi-facial Photovoltaic (BPV) panels within a multi-lateral grid framework, emphasizing their impact on cost, profit, and pollution. By employing a multi-objective optimization approach, the problem is modeled as Mixed Integer Linear Programming (MILP) and solved using GAMS with advanced solvers like CPLEX and Baron. Four distinct scenarios are analyzed to evaluate the proposed energy strategy. The findings highlight the substantial benefits of BPV integration, demonstrating optimized values: a total cost of $19.751, a profit of $270.628, and a pollution level of 1003.268 kg.**

Furthermore, increasing tie line capacity significantly enhances economic outcomes without compromising environmental standards, yielding a recalibrated profit of $44.269 for building 1, a reduced cost of $265.671 for building 2, and a maintained pollution level. These results underscore the critical role of grid infrastructure optimization in balancing economic efficiency and sustainability. This research provides a novel perspective on renewable energy planning, showcasing BPV panels as a cost-effective, environmentally advantageous solution. It also highlights the strategic importance of enhancing transmission infrastructure to improve economic returns while maintaining ecological responsibility. The insights presented offer a robust framework for academics, policymakers, and industry stakeholders, advancing sustainable energy system optimization and long-term energy resilience.

***Index Terms*—Bi-facial photovoltaic (BPV); Energy management System (EMS); Multi-lateral grid; Multi-objective optimization; Renewable energy sources (RES); Tie line capacity.**

I. INTRODUCTION

A. General background of the study

The rising global electricity demand has intensified fossil fuel consumption, exacerbating environmental issues like global warming. Sustainable energy planning is crucial, as economic growth (3–4% annually) accelerates fossil fuel overuse and environmental degradation. Businesses must optimize efficiency to balance energy needs with sustainability in modern energy management [1]. According to OECD and BP reports, China, India, and the United States dominate global GDP growth, driving energy demand and impacting sustainability efforts [2, 3]. Despite leading GDP growth, China, India, and the U.S. face severe air quality issues due to power generation, transportation, and industry. The transportation sector alone consumes 56% of oil, with flight and freight services as major contributors, highlighting the urgency for sustainable solutions [4]. The electricity sector, consuming only 2% of oil, still faces challenges in reducing emissions. Despite UNFCCC commitments, limiting temperature rise to 2°C by 2035 is difficult, with projected CO_2 levels reaching 13.7 billion tons—60% above the target [5]. The power sector faces rising demand, GHG emissions, and dwindling fossil fuels. In order to ensure sustainable energy security, nations are accelerating the adoption of renewable energy sources like solar, wind, and biomass to reduce reliance on fossil fuels and curb emissions [6, 7].

With renewable energy transforming distribution systems into active networks, efficient energy management is crucial. IEC 61970 defines an energy management system as a computer-based platform supporting power generation and transmission [8]. Buildings play a crucial role in energy management, consuming over 40% of generated power and contributing more than 30% of total greenhouse gas emissions [9]. A thorough understanding of building characteristics is essential. Hence, the most relevant and recent studies are reviewed in the following sections.

B. Survey on the recent research on the subject

Researchers worldwide have evaluated the diverse states and energy management and planning scenarios. For instance, He et al. [10] proposed a hybrid electricity-hydrogen sharing system in California, integrating residential solar panels, hydrogen vehicles, a hydrogen station, and microgrids. Advanced energy management strategies improved grid stability and reduced costs. The renewable-to-hydrogen approach minimized reliance on external hydrogen, while peer-to-peer microgrid sharing enhanced efficiency. The system significantly lowered hydrogen consumption in transportation and reduced household energy costs, offering a scalable model for carbon-neutral communities. Aliero et al. [11] examined smart home energy management systems, identifying security, privacy, scalability, and interoperability challenges. The study highlighted issues in managing residents' thermal comfort, posing health risks. Findings underscore the need for future research to enhance energy efficiency, minimize unnecessary consumption, and mitigate cybersecurity threats in smart homes. Saleem et al. [12] developed a smart energy management system for optimizing energy use in smart environments, focusing on air conditioning units. The system, integrated with IoT middleware, utilized sensors to collect consumption data processed via a cloud server. Tested in four buildings, it achieved energy savings between 15%

and 49%. The system enhances energy efficiency and building sustainability by featuring real-time monitoring and advanced algorithms. Ferahtia et al. [13] proposed an optimized Energy Management Strategy (EMS) for a DC microgrid in a commercial building, integrating PV, Fuel Cell, Battery Storage, and a DC/AC converter. The EMS addressed stability, power quality, and fuel consumption challenges using the Salp Swarm Algorithm (SSA) for improved convergence and efficiency. Hardware-in-the-loop (HIL) tests validated its performance, showing a 5.2% fuel saving over State Machine Control (SMC) and superior power quality compared to Particle Swarm Optimization (PSO)-based EMS. Liu et al. in [14] explored net-zero energy management in urban commercial buildings using renewable energy, pumped hydro storage, and hydrogen taxis. The study assessed solar PV and offshore wind potential and introduced a time-of-use strategy for peak shifting in high-renewable scenarios. Multi-objective optimization identified optimal pumped hydro configurations balancing technology, cost, and environmental impact. Results showed a 9.24% increase in renewable self-consumption, a 6.10% rise in load coverage, and a 25.21% reduction in annual electricity costs, highlighting the strategy's effectiveness in decarbonization and energy efficiency. Cutore et al. [15] optimized the Renewable Energy Community (REC) design under the Italian regulatory framework, assisting energy planners in capacity sizing and flow management. With comparing physical and virtual sharing in centralized and decentralized setups, findings showed greater economic benefits with virtual sharing in a centralized system. Sustainability indicators highlighted a 34% reduction in carbon emission and decreased energy poverty, benefiting 14 low-income families through REC participation. Alim et al. [16] analyzed green roof performance in Australia, comparing it with global data. While widely adopted in Europe, the USA, and Canada, Australia lags in implementation. Green roofs retain 60–70% of stormwater, reduce building temperatures by 4–6°C, and offer energy savings of 9–50%. However, saturated roofs can temporarily act as pollution sources. The average payback period is 16 years, influenced by costs and maintenance. The study underscores the role of policies and awareness in adoption and highlights key challenges and future research directions. Hakimi and Hasankhani [17] explored energy interactions among smart homes to enhance renewable integration and optimize residential energy use. The study aimed to increase consumer involvement, improve economic efficiency, and reduce peak-hour grid reliance. An energy exchange method for off-grid smart buildings was proposed, balancing renewable energy, thermal/electrical equilibrium, and lighting loads using Mixed Integer Linear Programming (MILP). The approach optimized energy costs while maintaining consumer comfort. Results demonstrated reduced total smart building costs, with significant savings in lighting load management. Based on above, the key findings and most important hypothesis behind this paper are explained in the following.

C. The key points hypothesis behind the subject

Based on the explanations and according to recent research papers, it seems that the energy management and planning of the multi-lateral grid, by considering novel technologies such as Bi-facial PV panels, still need more attention. As the world progresses, utilizing complex concepts that are connected, such as what has been assumed in this paper (Two buildings and an upstream network), to meet consumers' needs looks crucial. The problem is modeled as Mixed Integer Linear Programming (MILP) and solved in GAMS software. According to the application of various solvers for solving the MILP model, the responses of the optimization problem are computed by using some of the popular solvers to show their performance for the presented planning.

D. Paper's organization

The remainder of the paper is organized as follows: the modeling and introduction of renewable and non-renewable-based units are expressed in Section II. Furthermore, the most important limitations and restrictions that affect the energy planning of the assumed multi-lateral grid are explained in this section. Section III presents the solving manner and understudy test system characteristics and parameters. Sections IV and V elaborate on the results and conclusion, respectively.

II. Renewable and Non-Renewable Based Unit Modeling and Limitations

A. Bi-facial PV and common panels (PV & BPV)

Bi-facial photovoltaic (PV) panels are a revolutionary advancement in solar technology that offers increased efficiency and versatility compared to traditional PV panels. Bi-facial PV panels harness sunlight from both sides, utilizing the reflection of sunlight off the ground or nearby surfaces. This allows them to capture more energy throughout the day, especially during mornings, evenings, and cloudy conditions. They have advantages over common PV panels, such as 1- Bi-facial panels can generate more electricity due to their ability to capture sunlight from both sides. 2- They can be installed in various environments, including rooftops, ground-mounted systems, and vertically on building facades. 3- Bi-facial panels perform better in low-light conditions, making them suitable for regions with fluctuating weather patterns [18-20]. For simplicity and based on what has been expressed, the equations of these PV panels are the same as those of the common PV panels. Therefore, Eq. (1) computes the PV panels' temperature, and Eq. (2) can be used for output power calculation. The bi-facial PV panels are supposed to generate more power than the common ones; thus, a coefficient is considered, and by multiplying this by Eq. (2), the output power of Bi-facial PV can be reached. Due to the ability to receive light reflected from the environment and the underlying surface on the rear of the Bi-facial PV panels and more power generation than the single-sided photovoltaic panels, additional rear radiation enables P_{MAX} to up to 20 % under certain conditions. It should be noted that this increase in the conditions of use of different albedo increases from 8.3 % to 39 %. Eq. (3) demonstrates the output power of these turbines. Figure (1) shows the diagram of the BPV's performance that can absorb the radiation from both sides.

$$T_j(t) = \left(T_{amp} + \frac{G_T(t)}{G_{T_{STC}}} \times \left(NOCT - 20 \right) \right) \quad (1)$$

$$P_i(t)=\left(\left[P_{PV,STC}\times\frac{G_T(t)}{G_{T_{STC}}}\times\left(1-\gamma\times\left(T_j(t)-T_{j_{STC}}\right)\right)\right]\times N_{PVs}\times N_{PVp}\right) \quad (2)$$

$\{i \in PV\}$

$$P_{BPV}(t)=P_{PV}\times 1.2 \quad (3)$$

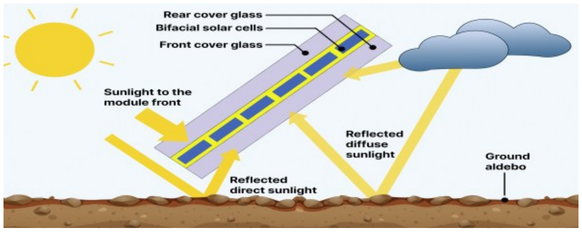

Fig. 1. The overall performance of the Bi-facial PV panels.

B. Wind turbine (WT)

Wind turbines play a vital role in sustainable energy transition, efficiently harnessing wind power to reduce emissions, enhance energy security, and support economic growth. Ongoing research and innovation ensure that wind energy remains a key component of the renewable energy landscape[21-23]. Eq. (4) represents the output power of the wind turbine, which is considered in this paper.

$$P_i(t)=\begin{cases}0 & \forall t: V^{Cut-in-WT}\geq V_t \text{ and } V^{Cut-out-WT}\leq V_t\\ 0.5\times\rho_{WT}\times A_{WT}\times\eta^{WT}\times V_t^3 & \forall t: V^{Cut-in-WT}\leq V_t\leq V^{Cut-out-WT}\end{cases} \quad (4)$$

$\{i \in WT\}$

It should be noted that the electrical and thermal energy storages are used and proposed in this paper to increase the reliability and resiliency of the presented multi-lateral grid and also overcome the intermittency of renewable energy resources. Eq. (5) – (7) demonstrates all related formulations of such these systems [8, 19, 24].

$$SOC_E(t)=\begin{cases}SOC_E(0)+P_{E,ch}(t)*\eta_{E,ch}-\dfrac{P_{E,dech}(t)}{\eta_{E,dech}} & if:\ t=1\\ SOC_E(t-1)+P_{E,ch}(t)*\eta_{E,ch}-\dfrac{P_{E,dech}(t)}{\eta_{E,dech}} & if:\ t>1\\ (t=1,2,...,T)\end{cases} \quad (5)$$

$$SOC_E(t_6)=SOC_E(t_1) \quad (6)$$

Several non-renewable energy resources, such as combined heat and power (CHP), micro-turbine (MT), and boilers, are dispatchable and help supply various electrical and thermal demands in addition to renewable resources. These units help surly and reliably supply demands even when RERs cannot supply the presented loads. It is worth noting that all parameters and coefficients related to the units and their limitations are explained and introduced in detail in references [25, 26].

$$SOC_T(t)=\begin{cases}SOC_T\,0+P_{T,ch}(t)*\eta_{T,ch}-\dfrac{P_{T,dech}(t)}{\eta_{T,dech}} & if:\ t=1\\ SOC_T(t-1)+P_{T,ch}(t)*\eta_{T,ch}-\dfrac{P_{T,dech}(t)}{\eta_{T,dech}} & if:\ t>1\\ (t=1,2,...,T)\end{cases} \quad (7)$$

C. The most critical restrictions and objective functions

In order to optimize the assumed objective functions, different restrictions should be considered. Therefore, some of the notable and significant ones are expressed in the following.

According to Eqs. (8) and (9); objective functions include total performance, constant expenses of various generation and storage units, and the environmental pollution of several non-renewable energy resources.

$$\underset{Total\ cost\ (\$)}{\min}\ OF1=\begin{pmatrix}WT\_cost+BPV\_cost+PV\_cost+\\ MT\_cost+CHP\_cost+Boiler\_cost+\\ ES\_cost+TS\_cost\end{pmatrix} \quad (8)$$

$$\underset{Total\ Emission\ (kg)}{\min}\ OF2=\begin{pmatrix}MT\_emission+CHP\_emission+\\ Boiler\_emission+main\_grid\_emission\end{pmatrix} \quad (9)$$

The details of these expressions are explained in [19, 24]. Furthermore, some of the important constraints are ordered as follows:

$$E_{LD}(t)=\begin{pmatrix}P_{WT}(t)+P_{PV}(t)+P_{BPV}(t)+\\ P_{MT}(t)+P_{CHP}(t)+P_{ES}(t)\end{pmatrix} \quad (10)$$

$$T_{LD}(t)=\left(P_{CHP}(t)+P_{TS}(t)+P_{Boiler}(t)\right) \quad (11)$$

$$P_i(t)\leq P_i^{\max}(t) \quad (i\in MT, Boiler, CHP) \quad (12)$$

$$P_{Buy}(t)\ or\ P_{Sell}(t)\leq P_i^{Line}(t) \quad (i\in Building\,1, Building\,2, main\_grid) \quad (13)$$

Eqs. (10) - (11) shows the supply and demand side balance for both electrical and thermal units. Moreover, Eq. (12) depicts the limitation of generating dispatchable units. Furthermore, Eq. (13) is related to the tie line capacity of different connections of the proposed grid (Building 1 to Building 2 and main grid). All other constraints of Energy storage and reserve margins are described in the mentioned references.

III. SOLVING APPROACH AND TEST SYSTEM SPECIFICATIONS

A. Untackle approach and optimization manner

Optimizing objective functions is crucial in planning and engineering. By analyzing total expenses and utilizing advanced tools like GAMS, practitioners gain insights for informed decision-making and efficiency improvements. Robust modeling techniques like MILP drive optimization advancements, enhancing system performance and resource utilization. Various solvers in GAMS were used to evaluate responses effectively.[27, 28].

B. Test system of proposed multi-lateral grid

The presented multi-lateral grid includes various renewable and non-renewable energy resources, Energy storage, and electrical and thermal demands. Figure (2) depicts the proposed multi-lateral grid. The objective functions are the total cost and environmental pollution of all units and the main grid, which should be minimized simultaneously. All needed information on the presented plan can be found in [2, 25, 26].

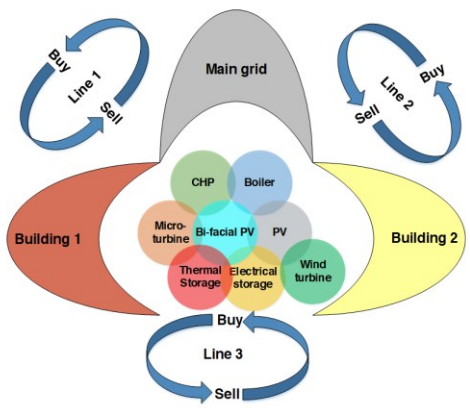

Fig. 2. The schematic and concept of the proposed multi-lateral grid.

IV. Numerical Results and Assessment

A. Deterministic scenario (First Scene)

This section examines the nominal scenario without Bi-facial PV panel integration or tie-line capacity considerations. The precise values for total cost, profit, and pollution are presented in Table (1).

Table 1. The results of the presented planning for the first scenario (deterministic).

Total Pollution (kg)	Total Cost ($)	
	Building 1	Building 2
1003.268	29.191	281.196

B. Tie line variations scenario (Second Scene)

This section assesses the effect of the tie line capacity on the various aspects of objective functions. Therefore, and based on the above, their accurate value is presented in Table 2. In this scenario, the capacity of the tie line for all lines has been changed and multiplied by two. This has caused a reduction in congestion of the transmission lines. Thus, the profit of Building 1 increased to $ 44.269. Moreover, the total cost of building 2 has also been reduced to $ 265.671. The pollution has not been changed due to this factor's impact on the proposed grid's exchangeable power.

Table 2. The results of the presented planning for the second scenario (tie line capacity).

Total Pollution (kg)	Total Cost ($)	
	Building 1	Building 2
1003.268	44.269	265.671

C. Bi-facial PV effect scenario (Third Scene)

This section expresses the value of the objective functions by considering novel Bi-facial PV panels. The results of this type of planning have been demonstrated in Table 3. As can be seen from the results, the total cost of building 2 has decreased properly. The power sold to the main grid has been grown for building 2, and the power sold to the main grid by building 1 has also been reduced. Because of the more power generated by BPV in Building 2, the buying power from Building 1 decreased for Building 2, which caused a reduction in both the profit and cost of Building 1 and Building 2 compared to the first scenario, respectively. Figure 3 illustrates the amount of power generated by using BPV.

Table 3. The results of the presented planning for the third scenario (Bi-facial PV panels).

Total Pollution (kg)	Total Cost ($)	
	Building 1	Building 2
1003.268	19.751	270.628

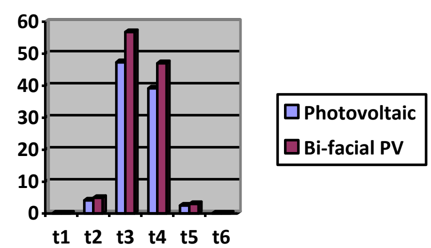

Fig. 3. The output power generated by PV & BPV in the third scenario.

D. Diverse solver (Fourth Scene)

In this section, the impact of the Baron solver on the objective functions is considered. As seen in Table 4, the amount of value for all functions has been the same as in the first scenario. This has happened because of the linear nature of the proposed programming.

Table 4. The results of the presented planning for the fourth scenario (Baron solver).

Total Pollution (kg)	Total Cost ($)	
	Building 1	Building 2
1003.268	29.191	281.196

V. Summary and Conclusion

This study presents a novel approach to energy management in a multi-lateral framework, integrating Bi-facial PV panels and assessing tie-line capacity impact. Four scenarios were analyzed using Mixed Integer Linear Programming (MILP) in GAMS with CPLEX and Baron solvers. Results show that advanced renewable technologies reduce costs while doubling transmission capacity improves building 1's profit to $44.269, reduces building 2's cost to $265.671, and maintains pollution at 1003.268 kg.

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