BESS deployment and Virtual Power Plant: Technical and financial analysis of the Senelec network to assess the relevance

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Abstract- This article analyses the operating data of the Senegalese electrical network (Senelec). It highlights the importance for it to implement Battery Energy Storage System (BESS) in the context of the massive deployment of photovoltaic and wind power plants connected to the HV network. It presents the technical and financial opportunities of a strategy for the development of storage solutions combined with a Virtual Power Plant (VPP) to manage their optimal operation. This study completes the work carried out on the same electrical network and which suggests BESS to optimize the penetration rate of photovoltaic energy in the Senelec network and to improve the stability of these network. Based on the simulations of Senelec's network previously carried out using Power Factory software and the operating data of the electrical system as well as the energy purchases made, it was demonstrated that there is a real financial impact of VPP implementation supported by the BESS. Indeed, the deployment of the VPP will allow Senelec to meet the requirements of primary frequency control on the Interconnected Network. The focus of this work consists in the installation of storage capacities managed by the VPP to allow the grid operator to store the overage of energy produced by the PV and Wind power plants and to restore it at peak hours. It has been shown that this solution also allows for savings of at least 1 billion (XOF) avoiding in addition to request additional generation (thermal or gas) to meet peak hour demands.

Keywords–Energy, BESS, Virtual Power Plant, photovoltaic, network stability.

I. INTRODUCTION

In order to optimize the penetration rate of photovoltaic energy in the Senelec (Senegalese company) electricity network, based on a choice of diversification of electricity production, the work in [1] and [2] consisted on the one hand in determining the maximum penetration rate of photovoltaic energy in the Senelec network. On the other hand, they consist also in proposing methods for optimizing this rate. Among the solutions, [2] proposed the implementation of electricity storage systems. The synthesis of these results is presented in Table 1. They show that it was possible to go from a PV penetration rate of 17.3% to a rate of 24.53% by opting for PV energy storage devices; stored power would be then by 26.25MW. Indeed, taking advantage of favorable weather conditions for the development of renewable energies, Senegal has built numerous wind and solar power plants with a total installed capacity of 324.7 MW [3] for a total grid capacity of 1499.04 MW, i.e. a ratio of 21.66%.

In this respect, it becomes essential to put in place technical solutions that will make all these investments profitable while maintaining the stability of the electricity network. On this basis, this paper aims firstly to present the technical applications of storage solutions and those that would correspond to Senelec's needs. Secondly, it will outline the

TABLE 2. MAXIMUM PENETRATION RATE [1]

	Taux de Penetration	
Without optimization [1]	17,3 %	
With Optimization (Connection of storage device) [2]	24,53 %	Storage capacity 26.25 MW

perspectives for the deployment of the "Virtual Power Plant" concept around storage solutions as a technical support. Finally, an analysis of the financial impact of these different solutions for the grid operator will be presented.

The Senelec power system used here is the one presented in [2]. The analyses will be based mainly on theoretical notions as well as on simulations and other calculations, with a view to highlighting the financial and technical opportunities that lie in the implementation of storage batteries and their operation as virtual power plants.

This article is structured in five sections. Following the introductory part, the second section presents the theoretical study on BESS (Battery Energy Storage System) and on VPP (Virtual Power Plant). The third section details the results obtained. The fourth step is devoted to the discussion of these results. This is followed by the fifth section, which contains the main conclusions.

II. THEORETICAL STUDY

In this section we will first study the grid applications of battery energy storage systems and then present the Virtual Power Plant solutions.

A. Grid Applications Of Battery Energy Storage System

Different use cases for energy storage are possible, depending on the use and the type of user. These are for :

- Network owners: peak management or deferring investment in system reinforcement.
- Network operators: to provide ancillary services such as frequency control or voltage maintenance.
- Behind-the-meter customer services: increased self-consumption of solar PV, backup power, peak load reduction, etc.

The Figure 1 illustrates these types of use. On this basis, the applications identified are as follows:

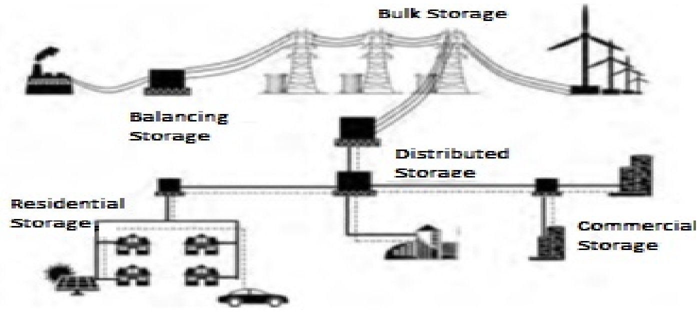

Fig. 1 : Forms of use of electricity storage [4]

TABLE 3. TECHNICAL CONSIDERATIONS FOR STORAGE APPLICATIONS

Grid Application	Technical Considerations
Electric Energy time-shift	Storage system size range: 1 – 500 MW Target discharge duration range: < 1 hour Minimum cycles/year: 250 +
Electric supply capacity	Storage system size range: 1–500 MW Target discharge duration range: 2–6 hours Minimum cycles/year: 5–100
Regulation	Storage system size range: 10–40 MW Target discharge duration range: 15 minutes to 1 hour Minimum cycles/year: 250–10,000
Spinning, non-spinning, supplemental reserves	Storage system size range: 10–100 MW Target discharge duration range: 15 minutes to 1 hour Minimum cycles/year: 20–50
Voltage support	Storage system size range: 1–10 MVAr Target discharge duration range: N/A Minimum cycles/year: N/A
Black start	Storage system size range: 5–50 MW Target discharge duration range: 15 minutes to 1 hour Minimum cycles/year: 10–20

1) Electric Energy time-shift

Time-shifting of electrical energy involves purchasing low-cost electrical energy, available during periods of low prices or marginal system costs, to charge the storage system so that the stored energy can be used or sold later when prices or costs are high. Alternatively, the storage can provide a similar time-shifting service by storing excess energy production, which would otherwise be curtailed, from renewable sources such as wind or photovoltaics.

2) Electric supply capacity

For a given power system, energy storage could be used to defer or reduce the need to purchase new plant generation capacity or purchase capacity on the wholesale electricity market.

3) Regulation

Regulation is one of the ancillary services for which storage is particularly well suited. It is about managing trade flows with other control areas to closely match scheduled trade flows with momentary variations in demand within the control area.

The main reason for including regulation in the power system is to maintain the frequency of the grid.

4) Spinning, non-spinning and supplemental reserves

The operation of a power system requires reserve capacity that can be called upon when part of the normal power supply resources become unexpectedly unavailable. Typically, reserves are at least as large as the largest resource (e.g., the largest generating unit) serving the system, and reserve capacity is equivalent to 15-20% of the normal power supply capacity. Since power plants, both wind and PV, do not contribute to the reserve, storage systems are a solution to this constraint [2].

5) Voltage support

Normally, designated power plants are used to generate reactive power (expressed in VAr) to compensate for reactance in the grid. These power plants could be displaced by strategically placed energy storage within the grid at central locations or by multiple VAr-supported storage systems placed near large loads, depending on the distributed approach. The storage systems used for voltage support must be able to operate at a power factor different from unity to generate and absorb reactive power.

6) Black start

Storage systems provide an active reserve of power and energy within the grid and can be used to power transmission and distribution lines and provide power to stations to bring power plants online after a catastrophic grid failure. Storage can provide similar start-up power to large power plants, if the storage system is suitably located and if there is a clear transmission path to the power plant from the storage system location.

The technical considerations for each application are summarized in the Table 2.

For Senelec, the need to install BESS would correspond to the Electric Energy time-shift and Electric Supply capacity applications which would allow savings on energy purchases.

B. Virtual Power Plant Deployment

In July 2021, Senegal adopted a new Electricity Code that enshrines electricity generation, storage and grid injection activities as well as ancillary service activities, including grid management for system balance. On this basis, the development of a virtual power plant makes it possible to manage the various electricity storage systems. A distinction can be made in the literature between technical and commercial virtual power plants. Thus, in the literature, VPP projects differ according to the objectives sought by their developers. Thus, one can find a VPP that :

- allows the management of a set of electricity generators through a "smart grid" approach (harmonizing production capacities and consumptions) in real time (this type of virtual power plant can operate without trading with the wholesale market).
- is set up to manage power generation systems with trading on the electricity market. It allows the economies of scale needed to produce electricity from a decentralized network and sell it back to the distribution network.
- manages power generation systems using renewable energy. The aim of this plant is to supply 100% of its electricity from renewable energy sources. It can therefore operate autonomously without trading with the wholesale market.
- is only a tool for auctioning and buying electricity.
- is created for the management of electricity generation systems. It can be used to establish contracts (sale-purchase) on the electricity market or to request services from the system operator.

In the case of the Senelec network, the VPP could perform both technical and commercial functions as described above. It would interface with the national control center (dispatching) and will control the operation of the BESS. It should communicate with the generation plants in the grid, especially the PV and wind plants. The state of load of the grid is also an input for an optimal management of the VPP. The principle is illustrated in Figure 2.

On the Figure 2, the VPP "supplements" the dispatching for the management of the BESS deployed in the network. It issues orders and receives information to/from the BESS control bodies. The VPP evaluates the purchase prices of the plants and connects the BESS accordingly. At the same time, the off-peak energy output of the PV and wind power plants will be used to charge the storage batteries.

III. ANALYSIS

A. *Power System Operating Data*

Senelec's load curves for typical days with minimum and maximum peaks are presented in the Table 3 and illustrated in Figure 3.

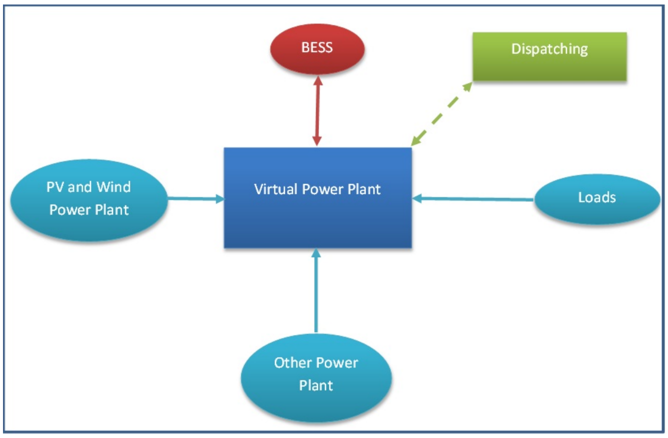

Fig. 2 : Principle of the Virtual Power Plant

TABLE 4. EVOLUTION OF HOURLY CHARGES - MAXIMUM AND MINIMUM PEAK DAYS

Time	P to Max Peak (MW)	P to Min Peak (MW)
01H0	754	348
02H00	726	333
03H00	701,4	309
04H00	687,4	307
05H00	673,9	315
06H00	675,1	326
07H00	653,7	325
08H00	659,1	326
09H00	688,1	340
10H00	715	368
11H00	710,2	376
12H00	513	378
13H00	692	381
14H00	688,2	386
15H00	714	384
16H00	737	390
17H00	718,5	395
18H00	677,6	403
19H00	679,9	409
19H30	724,4	467
20H00	736,7	489
20H30	747	490
21H00	754,2	498
21H30	770,8	503
22H00	765,7	490
22H30	792,9	444
23H00	797,9	391

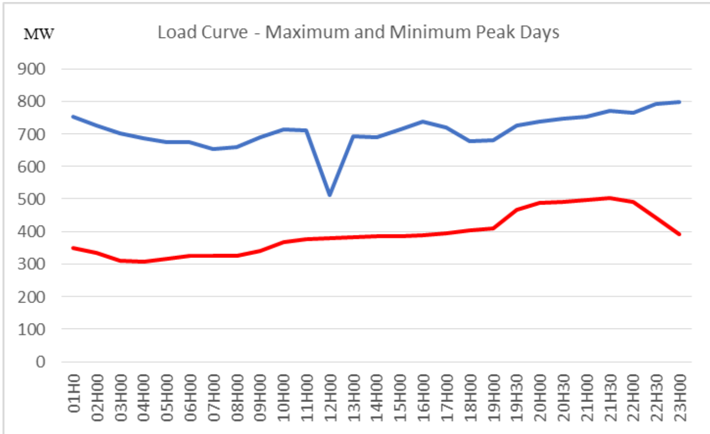

Fig. 3: Evolution of daily loads

In both cases, the common peak period is between 19:00 and 23:00, when there is no photovoltaic production. On the other hand, the maximum wind production coincides with the consumption peaks only for a short period.

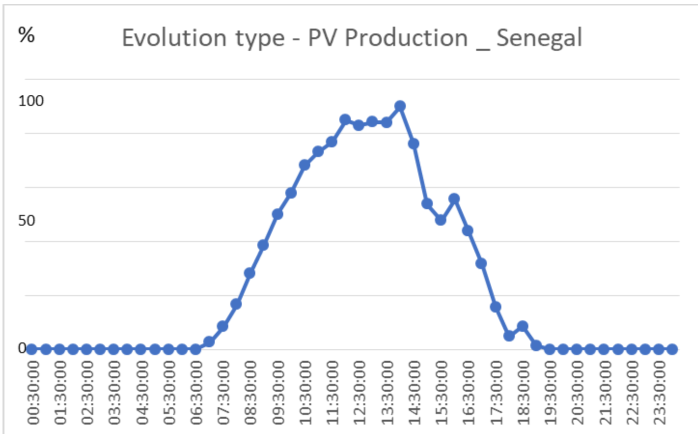

Fig. 4: Typical Development - PV _ Senegal

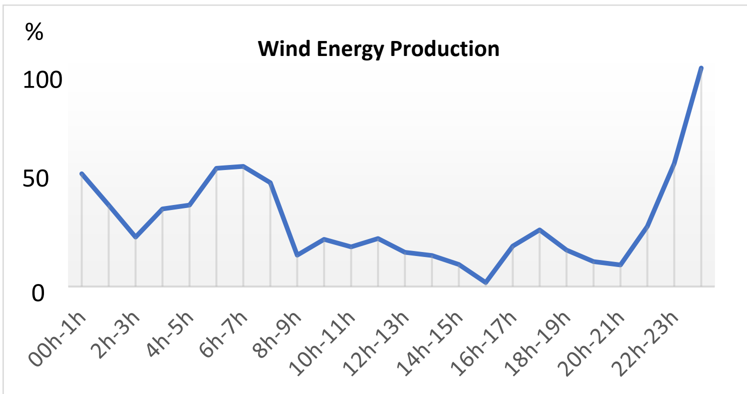

Fig. 5 : Typical Evolution of Wind Power Production in Senegal

These situations mean that PV and wind power generation create a lot of imbalances in the grid.

Hence the interest in implementing BESS as explained in [2]. Indeed, solar and wind power plants caused 224 load shedding events (35%) of the total number of load shedding events (620). The intermittency of these energy sources means that their integration into the grid results in power fluctuations and a reduction in the overall inertia of the grid, leading to frequency instability. The periods of high PV and wind power injected into the grid occur simultaneously with situations where the frequency dwell time in the range 49.8 Hz - 50.2 Hz is most degraded.

Thus, the deployment of these BESS would ensure the regulation function of the electricity system. It will also have the role of substituting the production of conventional power plants at peak times. With the Load Shifting function, it will be possible to capture the surplus of Renewable Energy (RE) produced at off-peak times and release it at peak times.

In 2021, the monthly consumption data (max and min) recorded in the interconnected network as in Table 5 and figure 7 show an almost constant trend (with slight peaks in September, October and November).

TABLE 5. NUMBER OF LOAD SHEDDING BY TYPE OF STRUCTURE

Structure/Power Plant	Number of load shedding
EDM (Mali)	97
Incidents HTB	88
Centrale CG	21
Groupes Senelec	35
KarPower Ship	39
Manantali	24
Parc Eolien	122
Centrales PV	102
Centrale Sendou	21
SOMELEC (Mauritanie)	65
Tobene Power	8
Total	**622**

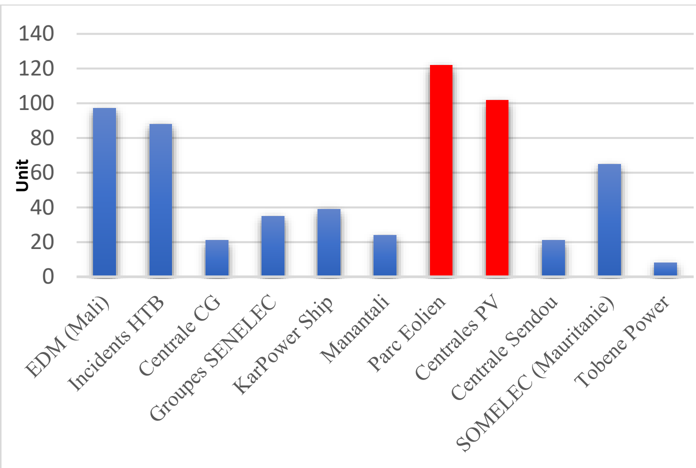

Fig. 6: Number of load shedding events by type of facility

TABLE 6. MINI AND MAXI PEAK EVOLUTION

Month	Maximum tip (MW)	Mini tip (MW)
January	599	335
February	590	307
March	603	347
April	650	385
May	664	408
June	747	422
July	758	481
August	763	475
September	804	451
October	805	526
November	762	459
December	668	405

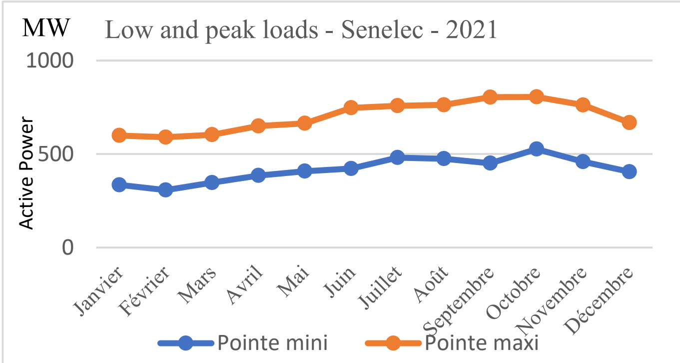

Fig. 7 : Min and max peak - Senelec network 2021

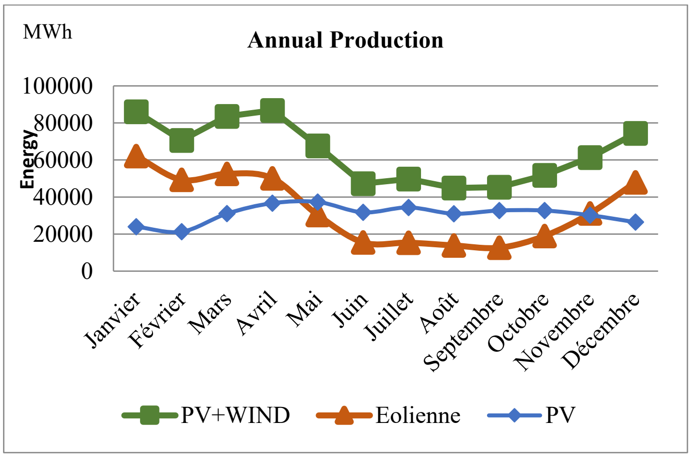

Fig. 8 : Annual production curves (PV and Wind)

Therefore, the need for battery storage compensation will arise throughout the year, especially as photovoltaic and wind energy production is also significant throughout the year. As a proof, in the same period, the photovoltaic and wind energy productions of the year 2021 are presented as illustrated in the Figure 8. During 2021, photovoltaic and wind production are remained complementary. They record a total of 769 GWh against an annual production of the interconnected network of 4916 GWh corresponding to a rate of 15%.

B. *Financial Impact of a VPP*

Based on the above statement, the financial impact of a BESS on the Senelec network should be assessed. The hypothesis adopted corresponds to the conclusions in [2] which suggests the installation of BESS with a minimum capacity of 30 MW.

With this in mind, we have presented the prices per kWh for each plant in the Table 6 and illustrated in Figure 9. These costs can be divided into three parts (low, medium and high). The PV and wind plants are in the medium category. They have costs ranging from 66.52 XOF (PV plant) to 80.11 XOF (maximum PV cost). The OMVS production comes from the common hydroelectric plant with interconnection to the neighboring networks of Mauritania and Mali.

Our hypothesis is that the BESS will have to replace the C4, Kahone 1, TAG 2 and TAG 4 power stations, which have a cumulative annual energy of 29,800 MWh. The BESS equivalent to a 100% availability rate would have a deliverable of 43,800 MWh.

TABLE 7. ANNUAL COST BREAKDOWN BY POWER PLANT

Item	Power Plants	Cost per year (F/kWh)	Pref (MW)
01	OMVS	20,69	70
02	ICS	43	6
03	C3	60,15	81
04	C6	62,37	93
05	CG	62,9	86
06	C7	64,33	90
07	PETN	66,52	158
08	KPS	66,55	220
09	TP	67,84	105
10	PV SAKAL	68,62	20
11	PV MALICOUNDA	69,44	20
12	PV TEN MERINA	74,1	29
13	KP	75,32	53
14	PV MEKHE	77,07	29
15	PV BOKHOL	77,56	20
16	PV KAHONE	80,11	20
17	C4	98,25	40
18	KAHONE 1	100,49	10
19	TAG 4	148,81	30
20	TAG 2	183,4	18
21	PV Scaling Kahone	19,61	35
22	PV Scaling Kael	19,69	25
23	SENDOU	25,83	115

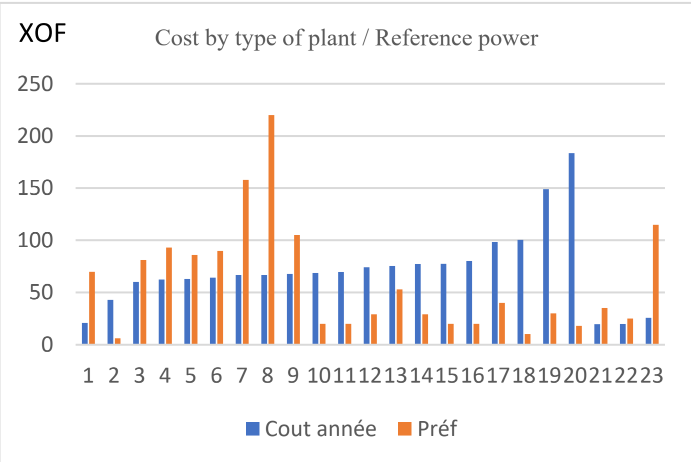

Fig. 9 : Evolution of the cost of power plants and reference powers

The VPP under consideration aims to form a production region [5] around the PV and wind power plants as illustrated in Figure 10.

To this end, to compensate for the chosen plants, our VPP should be able to return equivalent energy to the grid from the PV and wind power plant, for example, Scaling Kahone and Scaling Kael PV (representing the lower production price of all PV plants). The assumption is that a 30 MW BESS will be set up with a peak time of use of mainly four hours (04 h). The energy price considered is 70 FCFA/kWh [5]. It should be noted that the energy stored by the BESS returns to Senelec at marginal cost.

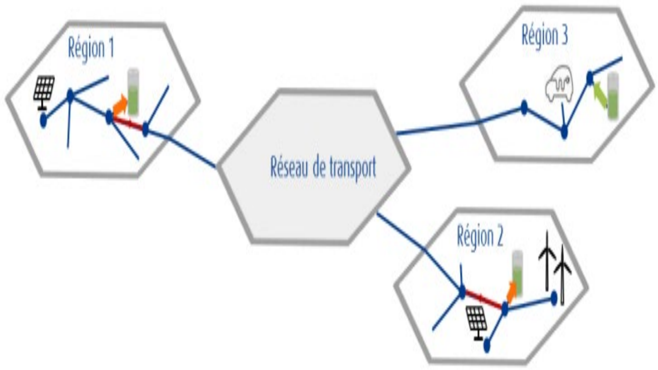

Fig. 10 : VPP Representation

TABLE 8. FINANCIAL COMPARISON

Item	C4	VPP
		BESS
Productivity (GWh)	29.5	29.5 (43.8 available)
Cost of production (MXOF)	3 402 953	2 065 000
Gain (MXOF)	1 337 953	

IV. DISCUSSION

Frequency management of the Senelec interconnected network is currently carried out manually due to the absence of generating units with automatic frequency control on the network. The Manantali power plant remains the only generation unit on the interconnection be able to perform primary control with a low mobilizable reserve (30% of the time) due to the full use of quotas by each OMVS utility and a slow reaction of the units when this reserve is available. The decisive issue of the VPP is that it allows Senelec to avoid heavy investments in production capacities that are only mobilized at peak times. In fact, apart from the Diass and CICAD power stations, all other solar power stations are IPPs with take or pay contracts. Other plants such as the wind farm could be integrated into the VPP for balancing functions.

Due to the structure of the load curve with a peak in the evening, it is important to remember that whatever the level of intermittent installed RE power (mainly solar), Senelec must to invest an equivalent amount of thermal power in parallel to meet the peak (these solar power stations only operate during the day). This also leads to additional operating costs. In addition, Senelec pays back heavy investments in thermal production capacity which is only mobilized at peak times (4 hours/day). This represents significant additional operating costs, including an increase in the cost of kWh, which will be passed on to the customer.

V. CONCLUSION

Senegal has one of the best solar potentials in the world, with an average of 5.5 kWh/m²/day of gross solar energy. The average sunshine is 3000 hours per year for a high solar potential area of about 12,500 km². In this respect, this paper has set out to determine the technical financial impact that the Virtual Power Plant (VPP) could have on the variable operating costs of the electricity system when it is used at times of high demand as a substitute for the interconnected electrical network power grid peak units. It was based on the work in [1] and [2] recently done on the same subject as well as on Senelec operating data for the year 2021.

The substitution of the C4 plant by the VPP has made it possible to make gains of more than one billion CFA francs and to avoid other plant investments with all the operating constraints that will be added to them.

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