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Integration Of Responsive Hybrid Loads Into An Electrical System With High Penetration Of Photovoltaic in Senegal

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***Abstract*— Pursuing the objective of improving the photovoltaic penetration rate in an electric mix dominated by thermal energy, the integration of the demand response is solicited to absorb the fluctuations and intermittencies induced by the energy from PV. In the work presented in this article hybrid loads (LPG and electrical) participate in the demand response, offering the advantage of targeting a household activity not yet taken into account in the load profile, but also avoiding the report and rebound effects often seen in Demand Side Management. It will be a question here of evaluating the capacity for these loads to absorb the energy surplus of origin PV whose quantity exceeds at certain time the demand coming from the conventional loads.**

***Keywords*— PV penetration, demand response, cooking plate, excess green energy, unit commitment, LPG, EGE**

I. INTRODUCTION

Many studies have shown that it is possible to achieve a significant photovoltaic (PV) penetration rate, beyond the limits set for an electrical system that does not integrate a flexible energy management, in a realistic scenario with as another benefit the mobilization of a small amount of synchronous reserve and backup ([1]). This situation is, however, accompanied by the presence of excess PV energy, which is therefore unusable, by conventional loads, since the demand on a global scale is already satisfied ([2]).

The objective of the work presented in this article is to direct this energy towards loads previously unmanaged by the electrical system.

There are several ways to involve loads in a smart grid as described in Mr Papavasiliou's PhD dissertation [3]. We will focus here on the model of direct coupling of loads to fluctuating and intermittent energy producers, in an improved version. This can be achieved by using the network operator that adapts the inter-temporal energy demand of the responding loads to use the available renewable resource while minimizing its dependency on the backup generators of the system.

This paper will describe the modeling of smart-grid type electrical system in order to involve hybrid loads able to consume this energy in a market evolving according to the presence or not of the surplus energy originated from photovoltaic. In the following, we will call it "Excess Green energy (EGE)".

II. STUDY CONTEXT

A. *Reminder of the fundamentals of the demand response and hypotheses*

To address the variability of renewable energy supply through Demand Response (DR), three basic approaches are often used [3]:

- Centralized load distribution by the system operator,
- Coupling renewable energy generation with a deferrable demand,
- Price-elastic demand bids.

In order to meet the objectives presented above while managing the associated constraints as well as the shortcomings noted on each of the main demand response models, hypotheses as to the choices that will be made are presented below.

We recall a few operating rules of the charges involved so that the producers, the network operator and the consumers find an interest to be a player of the smart-grid:

- Users must acquire this energy based on incentives;
- The mode of consumption must be transparent for the user;
- The network operator saves the costs related to the provision of the synchronous reserve;
- The network must support the power flows induced by high penetration of the PV.
- The overall load profile must not be modified in an unpredictable way because of the report and rebound effects often observed on the networks where the demand response is present [4].

As consumption within the scope of this study is residential, our attention will be paid to this sector in order to identify the charges that can be considered in relation to the objectives set. In this context, it is therefore important to present the structure of national consumption in households with the level of participation of each energy source.

In Figure 1 we note that nationally, on average, more LPG is consumed, generally for cooking, than electricity, all equipment combined.

In fact, the energy charges using LPG could in part be converted into electrical charges in order to benefit from the EGE.

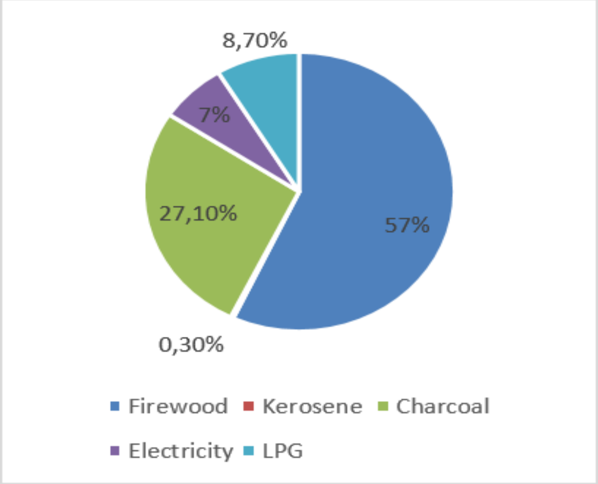


Figure 1: Final consumption "household sector" by product [5]

An important point mentioned above indicates that the implication of the load should be as transparent as possible to its user. To achieve this, the cooking equipment that participates in responding to the demand must be able to be turned on whenever the need is expressed by the user. This is impossible due to the fact that EVE is a very fluctuating and intermittent energy, being the most variable component of energy from PV plants.

We consider the possibility to have a cooking equipment in a hybrid form which could work under the EGE when this one is available, and conversely it would switch to LPG mode in case of intermittence of the EGE, without human intervention.

Another point mentioned limits the use of the network beyond the authorized flow limits due to the high penetration of the PV. Thus in our scenario we will limit the aggregate maximum PV output to the same level as that observed during peak consumption as shown in Figure 2.

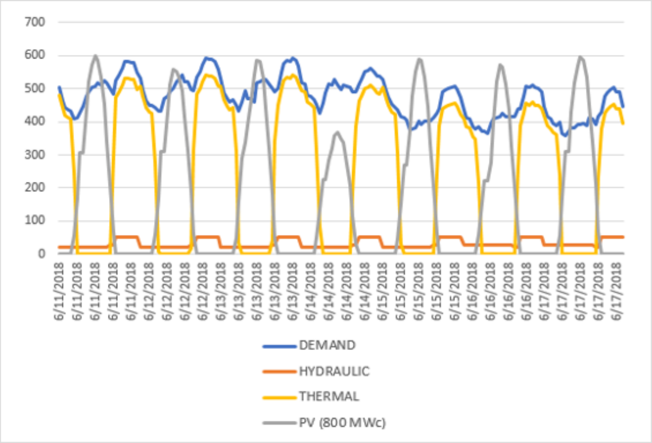


Figure 2: Electricity consumption from June 11 to 17, 2018 (MW)

III. SYSTEM MODELING

A. Modeling Unit Commitment

In the studied system, we consider N production units connected to a single busbar serving a given aggregate load. The entry for each unit, indicated by F_i, represents the unit cost rate. The output of each unit, P_i, is the electrical power generated by this unit as shown in Figure 3. The total cost of this system is of course the sum of the costs from each of these units. The essential constraint on the operation of this system is that the sum of the output power must be equal to the load demand.

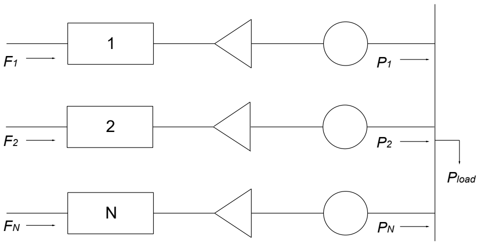


Figure 3: Diagram of N units committed to satisfy the load P_{load}.

Mathematically, this can be considered as an objective function, F_T, that is equal to the total cost of producing the indicated load, as expressed in equation 1. The problem is to minimize F_T under the constraint that the sum of the power generated must be equal to the received load. We specify that all the transmission losses are neglected but the operating limits will be explicitly indicated during the formulation of the problem.

$$F_T = F_1 + F_2 + F_3 + \cdots + F_N = \sum_{i=1}^{N} F_i(P_i) \quad (1)$$

$$\emptyset = 0 = P_{load} - \sum_{i=1}^{N} P_i \quad (2)$$

This optimization problem is known as the Lagrangian function and is expressed as follows:

$$\mathcal{L} = F_T + \lambda\phi \quad (3)$$

Where, λ, the incremental cost rate of producer *i*.

In the end, the conditions of equality and inequality can be summarized as presented in the series of equations (4), (5) and (6).

$$\frac{dF_i}{dP_i} = \lambda \quad (4)$$

$$P_{i,min} \leq P_i \leq P_{i,max} \quad (5)$$

$$\sum_{i=1}^{N} P_i = P_{loadTh} \quad (6)$$

The Unit Commitment model used in the suite is a customized version, from the one developed by Vladimir Stanojevic in March 2011 under Matlab, based on [6], [7] and [8]. We added the PV production prioritization, as well as the output calculation of the "EGE" model. Particulary with the equations and conditions below:

$$\frac{dF_i}{dP_i} = \lambda \tag{7}$$

$$P_{i,min} \leq P_i \leq P_{i,max} \tag{8}$$

$$P_{loadTh} = P_{load} - P_{PV}\ if\ (P_{load} - P_{PV}) \geq 0;\ else\ 0 \tag{9}$$

$$\sum_{i=1}^{N} P_i = P_{loadTh} \tag{10}$$

$$P_{eve} = P_{PV} - P_{load}\ if\ (P_{load} - P_{PV}) \leq 0, else\ 0 \tag{11}$$

Where,

P_{loadTh}, the power of the load satisfied by the thermal output,

P_{eve}, the excess power from renewable sources.

B. Case study

The model thus developed is subject to the case of Senegal national grid with a period of 72 hours from june the 14th to the 16th of 2018, using real data and a simulation tool developed by Cissé et al. [9], with for each day a typical case. The first day is a working day of the week, the second day is a business day with significant cloud cover (Octas 6 mean) across the country, and the third is a weekend day. The level of cloud cover is based on a scale of 0 to 8 (Octas scale [10]). The basic assumptions which constitute the inputs of the model are given in table 1 which is an extract.

Table I : Extract from the model input table “Unit Comittment”

Unit	Pmin	Pmax	Inc.heat_rate	No_load_cost	Start_cost_cold	Fuel_cost	Min_up_time	Min_down_time	Ramp-up	Ramp-down
	[MW]	[MW]	[BTU/kWh]	[$/h]	[$]	[$/MBTU]	[h]	[h]	[MW/h]	[MW/h]
1	25	80	10440	213.00	350	2.00	4	2	50	75
2	60	150	9000	585.62	400	2.00	5	3	80	120
3	75	200	8730	684.74	1100	2.00	5	4	100	150
4	20	60	11900	252.00	0.02	2.00	3	3	80	120
5	10	30	12900	190.00	0.02	2.00	1	1	80	120
6	10	15	12900	190.00	0.02	2.00	1	1	80	120
7	10	15	12900	190.00	0.02	2.00	1	1	80	120
8	10	15	12900	190.00	0.02	2.00	2	2	80	120
9	10	15	12900	190.00	0.02	2.00	2	2	80	120
10	10	15	12900	190.00	0.02	2.00	2	2	80	120

Where:

- Unit is the number of the production unit,
- Pmin is the minimum power that the unit can deliver in operation,
- Pmax is the maximum available power that the generator can provide,
- Inc.heat_rate is the incremental cost of the group,
- No_load_cost is the cost incurred during the downtime,
- Fuel_cost, the cost of fuel for each group,
- Min_up_time is the minimum running time before a new stop instruction and
- Min_down_time is the minimum shutdown time before a new start.

At the output of the model following a simulation, as shown in Table II, we obtain the list of the commitments of the units in steps of one hour taking into account the constraints posed in the equations presented above. The PV surplus (EGE) is also evaluated over the entire period. Its 72h profile is shown in Figure 4.

We can note that during the working days, with a sunshine broadly satisfying (Oktas 3 mean), the Green Surplus energy reaches levels below the 100 MW mark, while the weekend following the same climatic conditions this energy is doubled.

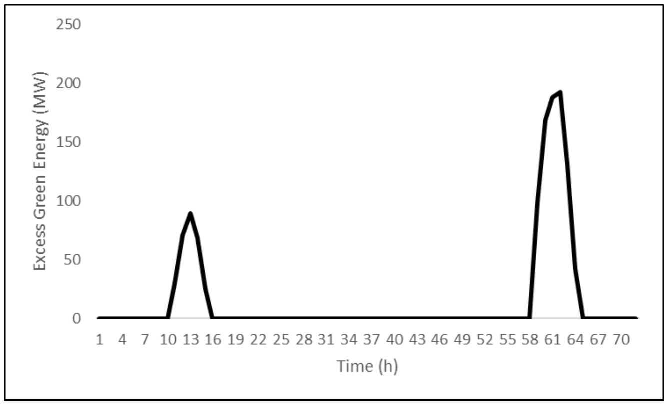


Figure 4: Excess Green Energy profile after running Unit Commitment model for a period of 72h.

By cons with a cloudy sky in most of the territory, the Green Energy Excess is nonexistent. This undistributed green energy will be used in the demand response model for consumption by responsive loads with the objective to minimize it as show in Figure 5.

As we mentioned, the target responsive load in this study in the residential sector is the cooktop, which has the advantage of being not yet taken into account in the load profile since more 95% of households use firewood, charcoal or LPG for cooking in Senegal. The LPG is used in the city at 80% [5].

Table II : Extract from the model output table “Unit Comittment”

Hour	Demand	Dth	PV	EVE	Min MW	Max MW	Prod.Cost	F-Cost	Units ON/OFF
1	503	503	0	0	190	505	11551	11901	1 1 1 1 0 0 1 0 0 0
2	464	464	0	0	180	490	10407	22308	1 1 1 1 0 0 0 0 0 0
3	443	443	0	0	180	490	9928	32236	1 1 1 1 0 0 0 0 0 0
4	435	435	0	0	170	445	9689	41925	1 1 1 0 0 0 0 0 0 1
5	431	431	0	0	170	445	9606	51531	1 1 1 0 0 0 0 0 0 1
6	407	351	56	0	160	430	7765	59296	1 1 1 0 0 0 0 0 0 0
7	411	244	167	0	100	280	5308	64605	1 0 1 0 0 0 0 0 0 0
8	426	119	307	0	75	200	2762	67367	0 0 1 0 0 0 0 0 0 0
9	446	139	307	0	75	200	3112	70479	0 0 1 0 0 0 0 0 0 0
10	476	44	432	0	20	45	1515	71994	0 0 0 0 1 0 1 0 0 0
11	491	0	521	30	0	0	0	71994	0 0 0 0 0 0 0 0 0 0
12	502	0	573	71	0	0	0	71994	0 0 0 0 0 0 0 0 0 0
13	508	0	597	89	0	0	0	71994	0 0 0 0 0 0 0 0 0 0
14	517	0	586	69	0	0	0	71994	0 0 0 0 0 0 0 0 0 0
15	510	0	535	25	0	0	0	71994	0 0 0 0 0 0 0 0 0 0
16	525	73	452	0	25	80	1737	74081	1 0 0 0 0 0 0 0 0 0
17	516	176	340	0	100	280	4056	79238	1 0 1 0 0 0 0 0 0 0
18	499	290	209	0	110	295	6508	85746	1 0 1 0 0 0 1 0 0 0
19	482	413	69	0	160	430	8991	95137	1 1 1 0 0 0 0 0 0 0
20	542	542	0	0	210	550	12937	108074	1 1 1 1 1 0 0 0 1 1
21	581	581	0	0	240	595	14514	122588	1 1 1 1 1 1 1 1 1 1
22	578	578	0	0	230	580	14246	136834	1 1 1 1 1 0 1 1 1 1
23	579	579	0	0	230	580	14272	151106	1 1 1 1 1 0 1 1 1 1
24	549	549	0	0	210	550	13118	164224	1 1 1 1 1 0 0 0 1 1

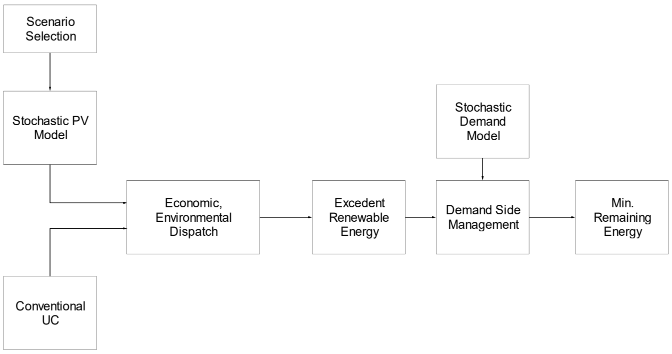


Figure 5: Integrated DR model with responsive loads

C. *Modeling of the responsive hybrid loads*

Let’s remember that an important principle that makes the load responsive is the fact that it can be cleared or change of setpoint is not or hardly felt by the user. This is the main reason why in this point we are implementing a hybrid cooktop in the sense that it will be able to switch between the electrical source and the LPG source according to the conditions calculated by the DR market. This principle will also make it possible to avoid the report effects observed in the most well-known DR schemes, since the demand not satisfied by the EGE is not reported; it is immediately satisfied by the LPG source.

The aggregator calculates the operations, determines the EGE, and then exchanges with the pool of cooking plates for consumption with the objective of minimizing the amount of remaining EGE.

According to this operating principle, the plate model receives inputs and after processes.

The inputs:

- The request: the user expressed a need to turn on a cooking plate.
- The signal informing the plate of the availability of surplus green energy.

The outputs:

- The state of the cooktop. Three values are possible, the first means that the plate is in operation and is supplied with gas, the second that means that the plate is in operation and is supplied with electricity, and the last state that indicates that the plate is stationary.
- The power and energy consumed in gas mode, and in electricity mode.

To operate the hob, a number of assumptions are considered in order to arrive at a simulation that closely matches the behavior of the cooking equipment in the context of the project.

1) *User command profile*

To simulate the start and stop command from the user, the mode of consumption of this resource was studied in order to develop a profile in line with the observed habits. Thus, over the 24 hours, operating probabilities at defined levels have been set as shown in the figure 6.

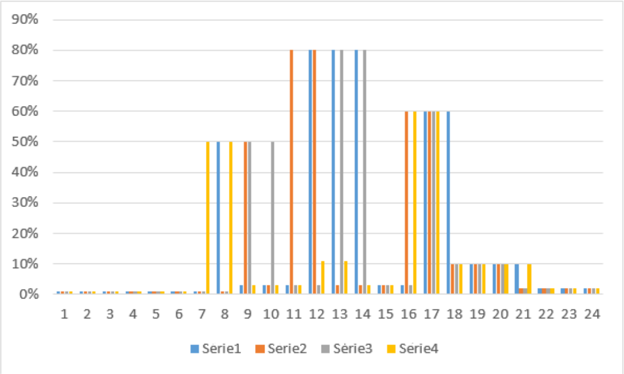


Figure 6: Probability series to be applied to simulate demand

Four probability series were thus defined so that the plates choose a series at random at the start of the simulation. It can be noted that the probabilities of switching on are greater during periods of preparation of the main meals.

2) *Using the power level*

The plate is implemented with three power levels Pmin, Pmoy and Pmax (respectively fixed at 1200, 1800 and 3000W). The power level chosen for each command is taken at random with an assigned probability of 33, 42 and 25% respectively for the min, average and max powers.

3) *Minimum operating time*

The minimum operating time of the plate in a given mode is also fixed according to the period between 5, 20 and 25 minutes to avoid inadvertent tripping or changing of mode.

4) *Evaluation of gas consumption*

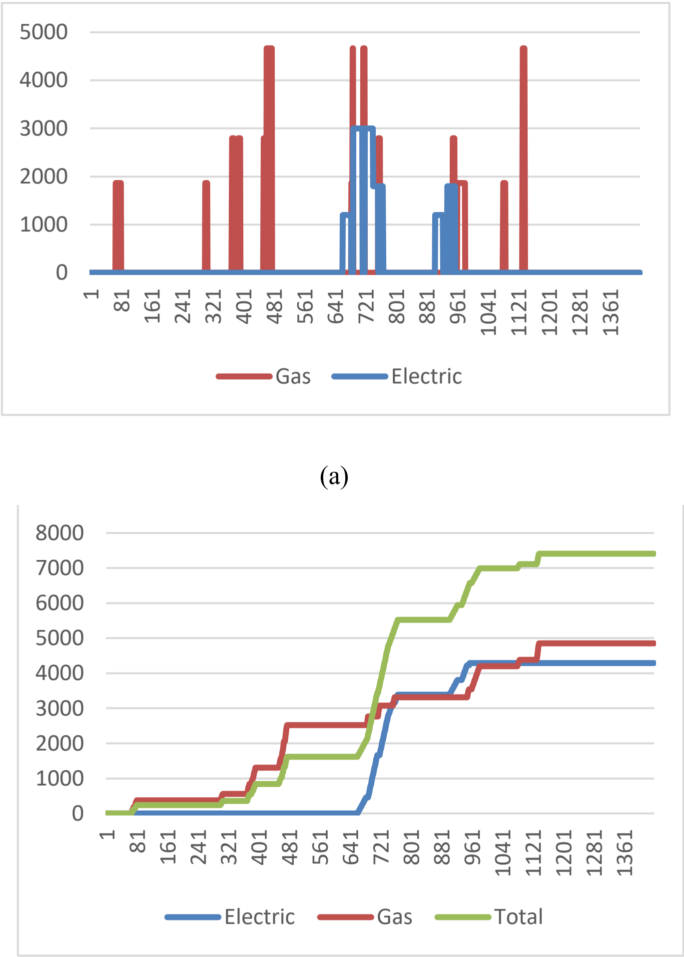
To assess the effective amount of gas consumed for the same need, we consider the efficiency of the gas used for cooking evaluated at 45%, while a ceramic hob has an efficiency close to 70%. We can on this basis reduce the power consumed when the hob is in gas mode to the following relation:

$$P_g = \left({}^{70}/_{45}\right) \times P_{el} \tag{12}$$

Where P_{el} is the equivalent electric power to be used in cooking the food.

To simulate the model before the full system is implemented, we set a profile describing the periods when excess green energy is available. This information, coordinated with the hypotheses presented above, produces the results shown in figure 7.

Over a thousand simulations carried out, the total energy consumed per day for cooking varies in a range between 4 and 10 kWh, which is close to the average consumption of a household per day is consistent, in the latter is 6 kWh [10].



(a)

(b)

Figure 7: Cooking equipment consumption related to EGE availabily.

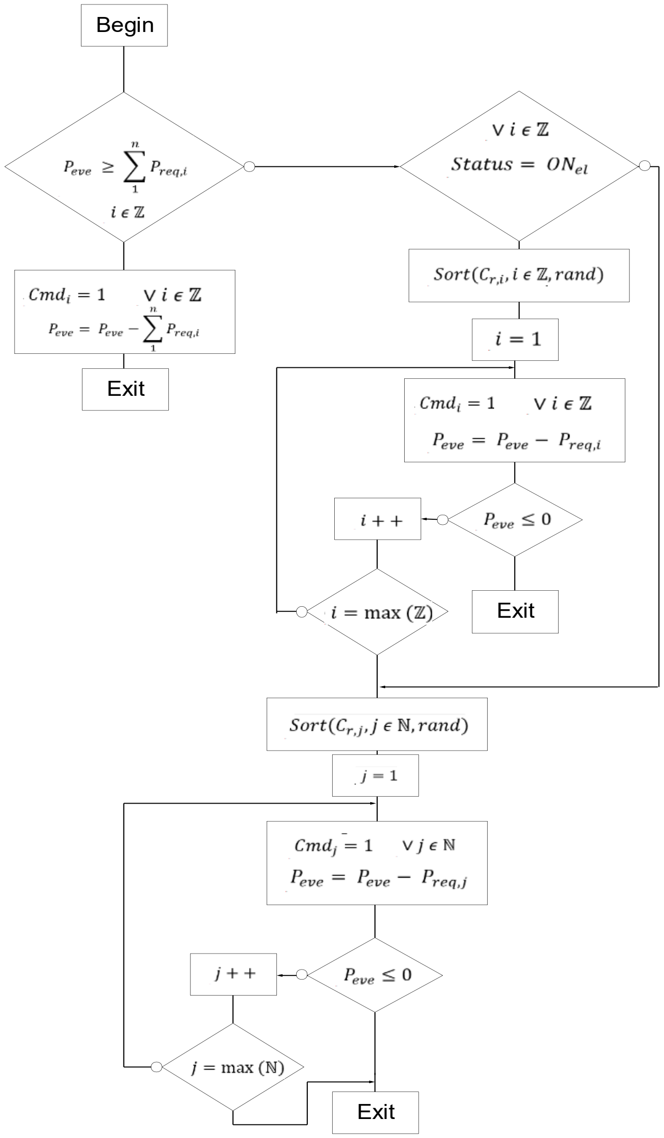


Fig. 8: Market model algorithm of DR

We also note that the useful electrical energy used during the 24 hours is about half of the total energy (electric + gas). This is due to the EGE, which is mostly available during a short time but coincides with the greatest daily consumption, the mid-day meal preparation.

The resulting model is thus ready to be integrated into the demand side management that will be developed later.

D. Market modeling

Once the unit commitment with PV considered has calculated the Excess Green Energy, this one constitutes an input of the algorithm of the market (see figure 8) in charge of the distribution of this energy to the various active loads in use. The different steps of the algorithm are described below.

a. If the available energy (EGE) is greater than the cumulative demand of the plates then this one is satisfied and the rest will constitute the undistributed energy;

b. Otherwise the plates that are already operating in electric mode are satisfied first randomly, this to prevent untimely starts, and to preserve equity between cooktops;

If the available energy can satisfy the demand of these cooking plates, the rest is transmitted to the plates that request it but which were not in electrical mode, randomly.

With :

$C_{r,i}$: Cooking plate i

$P_{req,i}$: requested power of $C_{r,i}$

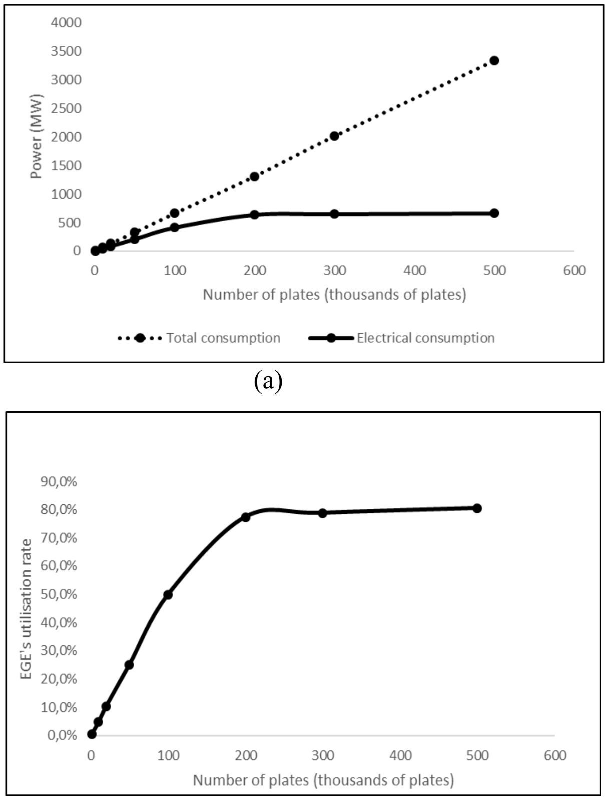
ON_{el} : Cooking plate state in electrical mode

Cmd_j : Indication from operateur to work in electrical mode

Sort, rand : Sorting cooking plates randomly

$\mathbb{Z}$: set of cooking plates that request to run

$\mathbb{N}$: set of cooking plates in LPG mode



(a)

(b)

Fig. 9: Progression of power and utilization rate of EGE related to the number of cooking equipment.

IV. RESULTS AND DISCUSSION

In this part, we present the following elements of answer:

- The capacity of the hybrid hotplate fleet to absorb excess green energy as its extent correlates to the level of overall sunlight and load profile;
- Jump in the penetration of the PV thus observed on the electric mix, taking into account the consumed EGE;
- The environmental benefit in terms of avoided greenhouse gas emissions;
- The strengths and weakness of the study.

A. Impact of the involvement of active loads on the use of EGE

We present in Figure 5 the progression of the consumption of the EGE according to the number of plates that constitutes the fleet of active loads, during a sunny working day.

During a day with a low level of sunshine observed throughout the territory, we find that the EGE is zero, which leads to a consumption of hybrid plates exclusively in gas.

On the other hand, for a holiday with a high level of sunshine, the EGE is evaluated in large quantities (see Figure 2), and its presence in the system induces a different behavior of the plates. The compaction of the curve of the energy used is observed starting from 200 thousand plates as shown in figure 5.a and remains practically constant beyond. In addition, figure 5.b indicates that from the same threshold the rate of use of the EGE is capped at 80%.

Thus in the scenario offering the most surplus green energy we can finally retain that 20% of the EGE cannot be consumed by the hybrid cooking plates.

A. Evaluation of the level of PV penetration

In a context supported by the implication of the active loads in the context of a demand response, the scenario of a PV installation up to 800 MWp becomes realistic insofar as we have shown that the active loads can absorb a much of excess energy. In addition, the need for synchronous reserve to contain the fluctuations and intermittences of PV production becomes marginal.

At such a level of penetration in installed power, we indicate the correlations with respect to the electric mix in table 1.

TABLE III: Penetration rate for scenario with 800MWp PV

Sector	Power penetration	Energy participation rate
Thermic	94%	41%
Hydro electric	1067%	534%
Total production	77%	35%

For 77% power penetration of PV, energy participation is estimated at 35% of all production. The load profile becomes meanwhile change mid-day due to the presence of new charges that are the hybrid plates.

B. Assessment of environmental benefits

Environmental benefits are assessed at two different levels directly impacted. These include:

- The production of thermal energy avoided by the installation of a large photovoltaic capacity on the one hand, but also
- Decrease in the volume of LPG gas used in households due to the presence of hybrid cooktops.

By reducing the PV energy penetration rate to 35% over the study period, thermal energy production dropped by almost 42%, or nearly 31% of avoided CO2 emissions if we rely on the study of NH Reich et al [11].

As for the consumption of the hybrid plate, part of the EGE consumed will have prevented the use of LPG up to 48% (for days with a high presence of excess green energy), ie almost half of their consumption if we consider the optimal number of plates involved.

C. Strengths and weakness of the study

An important contribution of this study is the fact of incurring charges that are initially greenhouse gas producers to balance the network but also convert these charges that become consumers of clean energy.

The other advantage of this work is to rely on a sunshine evaluation tool [9] capable of faithfully reproducing the shape of the fluctuations actually observed. This makes it possible to observe the behavior of the electrical system in the face of the variability of the PV energy.

The program of the unit commitment, which determines the EGE, is executed in steps of one hour whereas for the simulations involving variables as fluctuating as the PV energy, it is preferable to have a resolution of very low time in the order of the minute [12].

The introduction of transmission constraints is not considered as it complicates scenario selection considerably because a number of cooktops can't access to the EGE when certain transmission lines are congested and the availability of renewable resources may be limited due to transmission constraints.

VII CONCLUSION

This work was done in the perspective of improving the penetration rate of PV on the electric mix by providing a flexible demand.

By fixing a level of penetration that could generally be supported by the electrical grid, we have intermittently observed an energy unused by the system, which has led to imply needs not yet or almost not supported by the electrical system in the residential sector. It is in this context that hybrid cooktops (with electrical source and LPG) have been used, offering the additional advantage of avoiding the effects of bounce back often observed in networks where the DR is implemented. In the scenario with the largest amount of PV energy not used by the conventional system, nearly 80% of this energy could be captured by the hybrid plate pool. This improves the penetration rate of the PV so to be evaluated at 35% for a day of strong sunshine. A portion of this excess green energy up to 50% replaces the energy consumed for cooking in a perimeter where LPG was used.

In addition, despite the involvement of these active loads to absorb the EGE, the rate of its use remains capped between 70 and 80% depending on the climatic conditions, which reflects the existence of nearly 20 to 30% of this energy that was left unused by the system. This observation leads to a new work in which hybrid plate coupled with water heater is envisaged, this latter having the inherent ability to store energy after its conversion into heat before use.

Moreover, the study having considered a uniform distribution of the responding loads on the network, an improvement at this level is desired because the constraints of use of the lines at the local level should be taken into account in the algorithm which generates the signal sent to active loads for their involvement in responding to the request.

Another challenge to be taken up is to speed up the simulation times, which in places requires manual actions, by automating the interactions between the different tools used to carry out the complete chain of the study, in order to extend the period over a full year in order to submit the model to all seasons.

Conflicts of Interest: The authors declare no conflicts of interest.

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