Optimal household energy management and participation in ancillary services with PV production

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Abstract

This article presents a project designed to increase the monetary value of photovoltaic (PV) solar production for residential applications. To contribute to developing new functionalities for this type of PV system and an efficient control system for optimising its operation, this article explains how the proposed system could contract to provide ancillary services, particularly the supply of active power services. This provision of service by a PV-based system for domestic applications, not currently available, has prompted a market design proposal related to the distribution system. The mathematical model for calculating the system's optimal operation (sources, load and exchanges of power with the grid) results in a linear mix integer optimisation problem in which the objective is to maximise the profits achieved by taking part in the electricity market. Our approach is illustrated in a case study. PV producers could gain by taking part in the markets for balancing power or ancillary services despite the negative impact on profit of several types of uncertainty, notably the intermittent nature of the PV source.

Keywords : energy management, ancillary services, PV production, household application

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NOMENCLATURE

Model Parameters

$c_g(t)$ = grid electricity price (c€/kWh)

$c_{pen}(t)$ = Penalty cost (c€/kWh)

$c_s(t)$ = Price for purchasing PV production from the network (c€/kWh)

G = Available radiation [W/m^2]

P_{gn} = Contractual grid power limit [kW]

P_{PVc} = Peak power of PV generator [kWp]

r_{ch} = Charge rate [kWh/h]

r_{dch} = Discharge rate [kWh/h]

S_{max} = Storage system capacity [kWh]

SOC_{max} = Storage upper capacity limit [kWh]

SOC_{min} = Storage lower capacity limit [kWh]

T = Calculation step time [hour]

Decision variables

$P_{bin}(t)$ = Charge power [kW]

$P_{bout}(t)$ = Disharge power set point [kW]

$P_g(t)$ = Consumed grid power [kW]

$P_L(t)$ = Electricity demand [kW]

$P_{LP}(t)$ = Power consumed by controllable loads

$P_{NLP}(t)$ = Power consumed by uncontrollable loads

$P_{PV}(t)$ = PV available power [kW]

$P_s(t)$ = PV power to be used locally [kW]

$SOC(t)$ = State of charge [kWh] at time (t)

$z(t)$ = PV power fed into the network [kW]

Greek symbols - Model Parameters

τ = Ambient temperature [°C]

η_B = Storage efficiency

Greek symbols - Decision variables

$\alpha(t)$ = Binary decision variable, $\alpha(t)$ = 1 if the battery is in charge mode, $\alpha(t)$ = 0 if the battery is in discharge mode

$\beta(t)$ = Binary decision variable, $\beta(t)$ = 1 if the system imports grid energy, $\beta(t)$ = 0 if the system purchases its PV production

$\omega(t)$ = Decision variable, used to translate the absolute relation into linear representation

1. INTRODUCTION

In Europe the household sector is one of the largest consumers of electricity, accounting for about 33% of total electricity consumption [1]. The household sector is also a major source of greenhouse gas emissions [2]. The problem of energy management in housing is currently the focus of considerable interest and management of both the demand and supply sides in housing has been studied worldwide. On the demand side considerable savings are expected to be achieved in energy consumption through more intelligent load management [3], [4]. On the supply side grid-connected photovoltaic (PV) systems are commonly proposed for residential users [5], [6]. Encouraged by numerous support programmes – investment subsidies, feed-in tariffs, green certificates, etc. [7] – promoting the use of renewable energies, attention has focussed in particular on optimising PV production being fed into the network.

However as technological progress over the last decade has led to a considerable decrease in the cost of PV modules [8] and boosted the use of PV solutions [9], the current trend towards growing use of PV energy will evolve. Raugei and Frankl [9] note that costs decrease of 20% each time the production increases twofold. Such decrease could make PV production competitive with peak generation between 2010-2020 with constant subsidies. They also show several scenarios of PV development. In the realistic scenario, PV generation could reach 2400 GWp in 2050 in the world. Incentives policies could be reduced because of a more mature PV technology. But, these PV production could impact the management of the distribution network. So, the profitability of PV production is increasing, either when deployed on its own or coupled with other sources [10], [11], while reducing greenhouse gas emissions [12]. Erdil and Al [10] study a hybrid system composed of PV production and solar thermal collector. They show the profitability of this installation because the payback period is 1.7 year. So, investment costs of PV modules could be reduced because of savings made with the thermal collector. Reichling and Kulacki [11] have shown the performance of a hybrid wind-solar power plant in Minesota. They note deregulation has led to hourly local power market. So, many locational based marginal prices are available within these markets, including those based on the day-ahead, hour ahead or real time markets. They also say that “because a larger fraction of the solar output occurs during peak hours, a wind-solar hybrid power plant is expected to produce electricity with a higher average retail value than a wind only power plant” [11]. According to Stoppato [12], PV generation has rapidly increased since 1994. He shows that in the new context of sustainable development described by Lund [13] or Lund and Mathiesen [14], solar energy could be a real solution of production, particularly for small distributed (household) thermal or electric energy production. He shows that PV production pays back the energy needed for its production several times along panels' longlife (28 years). The technology development of PV production has improved significantly during last years. So, De Wild-Scholten and Al [15] or Jungbluth and Al [16] have shown that, for a rooftop PV system in Europe, the energy pay back time is between 1 and 3.5 years so PV production is advantageous for environment, also considering the panel production process. This energy pay back time depends on PV technology and radiation. We can also note that Kaldellis and Al [17] have shown that this energy pay back time could be greater for insular regions where more complex systems in PV production are used. Incentive policies will need to be cut back or replaced by other less costly systems in keeping with market pressures [18-19]. For example a market component is being introduced into some incentive policies, such as in Spain [20-21]. In the medium term, with the likelihood that PV production will increase [9;22], distribution networks will not be able to tolerate major fluctuations (in input), making it necessary to introduce further constraints – scope for restricting power fed into the network; higher quality of service standards (current and voltage profile); provision of ancillary services. Ancillary services may, for example, include the supply of reactive power to the grid, voltage or frequency support. Some studies have been made to introduce wind power into networks and provide ancillary services [23]. Hvelplund [24] shows that wind penetration in Danmark in phase 1 has had no impact on the grid. But, In phase 2, wave-, wind- and PV energy are fluctuating sources which require an infrastructure able to cope with the fluctuations in a cost-efficient way. Increasing renewable market share results in growing visibility, enhancing the need for local participation. The local management, with a local market (distribution grid level) where local power production and consumers "give incentives to trade internally and to cope locally with the power fluctuations, would promote the renewable energy (RE) development in a more efficient way" [24]. His third conclusion is "linked to the question of creating an infrastructure which can cope with the fluctuations involving, when large amounts of RE is included in the supply system"[24]. Local and regional markets will be necessary as a needed regulation infrastructure. Lund [13] says that RE development asks matter of introducing and adding flexible technologies and designing integrated energy system solutions. RE must participate to ancillary services. PV generation and its potential must lead to include this technology in the ancillary services of maintaining voltage and frequency in the electricity supply at distribution level.

Our framework is in line with all these researches as we will see below. PV producers wishing to exchange energy with the network would be treated in the same way as any other independent power producer (IPP) with similar obligations. As a result PV production systems, instead of only considering their own objectives, must also plan and coordinate their activities with the Distribution System Operator (DSO).

These issues have prompted the investigation of an innovative energy architecture for domestic applications, the assumption being that in the future housing will no longer be a passive entity but an *active*, *intelligent, environmentally aware* entity.

The Multisol project, which underpins this article, aims to design an economically and technically efficient framework for domestic energy management. It is profitable under several conditions, without incentives policies [25]. A new architecture is proposed with a PV-based, multiple-source system on the supply side, coupled with optimal supply and demand side co-management. To contribute to developing new functionalities for such a system and building an efficient control system for optimising its operation, this article raises the possibility of the proposed system providing ancillary services, in particular active power services. In Europe there are few markets for ancillary services at distribution level. The DSO often provides all these services, their cost being covered by distribution tariffs. The disadvantage is that with new renewable energy producers taking no part in the provision of such services, there is no incentive for them to make allowance for their impact on distribution activity. We also consider concepts other than network innovations [26]. We assume the existence of a local distribution market . [24] and we study the financial income of PV producers making power bids on the local spot market or ancillary services market. Our PV producers use the Multisol system to optimise power bids and meet demand for electricity. PV producers could earn profit from energy they feed to the grid. So, pay back period of PV investment could be reduced. Beside the alternative to exchange power with the DSO, PV producer could manage production-consumption equilibrium with a Multisol system. This system optimises the use of PV production and consumption. So, producers could use this system to comply with their power bid, to reduce the impact of uncertainty and penalties of imbalances.

The present article proposes a market-oriented distribution system for PV-based services targeting domestic applications. The mathematical model for calculating optimal system operation (sources, load, and the exchange of power with the grid) results in a linear mix integer optimisation problem, in which the objective is to maximise profits derived from supplying the electricity market. We investigate the ways in which PV producers could gain from supplying ancillary services or taking part in balancing mechanisms, using a system to optimise production and consumption. The intermittent nature of output makes the result less conclusive but, depending on the level of penalties, there is still an incentive. Our approach is illustrated in an example. The impact on profits of several kinds of uncertainty, in particular the intermittency of the PV source and unpredictable consumer behaviour, are analysed. Building study will be a case study too. We do not consider it here despite it is a great application to focus on domestic production that could strongly impact the management of distribution network. The Multisol system could reduce imbalances between power bids and electricity fed into the network using :

- consumption management depending on PV production;
- allocation of part of PV production to consumption, the other part to satisfy power bids to DSO, if necessary with th delay of some forecasted consumptions (washing-machine, etc…)
- DSO profits in grid management and additional profits for PV producers .

We know that intermittency could be solved by regional profusion of renewable energies or by virtual power plants. Our added value is to promote a system that reduces imbalances. In a virtual power plant, some members could know imbalances, incurring penalties of the manager of the virtual power plant. A Multisol system could reduce these imbalances and restore PV producers' incentives to participate in ancillary services or local spot markets.

2. MARKET DESIGN

Looking at the development of the electricity market it is apparent that the purpose of the active power market is to balance the transmission system. The basic concept is that the Transmission System Operator (TSO) asks energy producers to make power bids to balance the system and provide certain ancillary services. These bids are made on a day-ahead basis (day D-1 for hours in day D) or on an "hour-ahead" basis (for example, hour H-1 for delivery in hour H). They are often paid at the marginal price that balances the system or at nodal prices (zonal marginal prices) if nodal areas exist. If producers cannot fulfil their bids, they incur imbalance costs computed on the basis of marginal balancing prices. So they may be rewarded or penalised for their bids, depending on their position in production. The renewable power fed into the grid shifts this problem to local energy markets [24] and distribution grids.

It is assumed that the electricity market developed for the distribution network reproduces the behaviour of the transmission network's balancing market. PV-based systems are asked to supply power to keep the local distribution network balanced and safe. Suppliers must make day-ahead active power bids, covering the next 24-hours or the hours before the balancing time. In addition to such bids they may provide ancillary services, paid at the zonal marginal price. We use an approximation of these prices based on market or balancing-market prices. Zonal prices, related to distribution zones, may thus be introduced, opening the way for Zonal Marginal Prices (ZMP) for balancing the distribution network. PV generation is intermittent. So there is likely to be a gap between forecast and actual production supplied. The forecast power for the next day may differ from the actual power fed into the distribution network. In this case PV producers would be penalised for failing to fulfil their previous power bid. The penalty cost is computed on the basis of the zonal market price and balancing patterns (see Table 1). For example, if the balancing trend of the market is upward (production deficit) and PV producers feed more power into the grid than forecast, the production surplus reduces the imbalance. PV producers are paid the zonal marginal price.

In addition to bidding to supply active power, producers may also bid to supply reactive power, either at a standard rate or through a specific market for reactive power. PV-based systems, which are controlled by an inverter, can produce the necessary reactive power [27]. The trade-off between active and reactive power depends on the standard rate or on the respective prices of the two types of supply.

Here we have assumed that the DSO requires contracting parties to supply reactive power. It is also assumed that PV producers will saturate their reactive power constraints, optimising profits with active power bids or PV power consumption. The reactive power rate leads to a reduction in the value of the active power bid on the day-ahead balancing market. If the standard rate is too high, then a tariff for reactive power may be necessary to compensate for increases in the cost of supplying reactive power and for a drop in profits as the amount of active power being consumed decreases. Losses may be incurred on both consumed electricity (with a high constraint on reactive power PV producers may opt to consume less PV electricity) and on active power sold to the ancillary services market or the day-ahead balancing market (less active power being sold on this market).

In any case, as the reactive power produced by the system is based on local production (a certain percentage of supplied power) it makes no difference to how the optimisation problem is formulated. So without loss of generality, in the following, we shall assume the standard rate to be zero.

3. DESCRIPTION OF MODEL FRAMEWORK

3.1. System architecture

The proposed PV-based multi-source system with energy management for housing applications is shown in Fig. 1 [6], [28].

A separation is made between the production and consumption sides with a control and monitoring unit for both. Production resources (PV generator, network, battery storage system and other complementary sources) are connected to the "*Power production control board*" to supply loads via a conventional electrical delivery unit, referred to here as the "*Power delivery control board*". A coupling and multi-source management module integrated in the production-side control unit optimises the various power flows. A demand-side control unit could be located in the electrical delivery unit to control loads. The system also includes power electronics interfaces to serve as flow control actuators. Measurement and telecommunication resources are also essential. The "*Expert and Predictive System*" is the core which receives data (on the weather, electricity market, metering, user characteristics and preferences, etc.), calculates optimal control strategy and sends instructions to equipment.

3.2. Impact of intermittency characteristics

PV producers must cope with two types of uncertainty.

The first uncertainty is PV production capacity which is calculated by forecasting on-site radiation and temperature. As may seen in Fig. 2 and 3 uncertainty is relatively high. Fig. 2 plots the temperature on a specific day (July, 5th) over a 10-year period (1998-2007), [29]. Deviation may thus exceed ±5°C. Uncertainty regarding radiation, recorded for a reference day and shown in Fig. 3 [30], could result in mean variation of as much as 40% in relation to the forecast value. It is consequently difficult for PV producers to anticipate exactly their output and fulfil power bids made to the DSO, unless a solution can be found.

The second uncertainty affecting the proposed system relates to consumption patterns. Any change in forecast consumption requires a change to the operating schedule and, in practice, a deviation in the power supplied to the grid. Imbalances may therefore occur and PV generators may not be able to fulfil their commitments regarding ancillary services.

However it is apparent that more serious damage is done by the intermittent nature of the PV source. Deviation may be even greater than in our example, but on the other hand, the system also has a load management mechanism for rescheduling consumption or shedding part of the load if necessary.

4. PROBLEM FORMULATION

The problem of optimal operation of a PV-based system presented above can be formulated as an optimisation problem using the Mixed Integer Linear Programming (MILP) algorithm. Its standard form representation is given in [31] as (1).

$$\begin{aligned} \text{Minimise} \quad & f(x), \\ \text{Subject to :} \quad & Ax \leq b, \\ & A_{eq}.x = b_{eq}, \\ & lb \leq x \leq ub. \end{aligned} \qquad (1)$$

The x vector (unknown variables) includes the hourly operating power of each source: charge power $P_{bin}(t)$, discharge power $P_{bout}(t)$, consumed grid power $P_g(t)$, surplus power z(t), controllable load power $P_{LP}(t)$, non-controllable load power $P_{NLP}(t)$. Each variable is limited by its lower (lb) and upper (ub) bounds. A, b, A_{eq}, b_{eq} represent the inequality and equality equation constraints of x. f is the vector of the objective function.

4.1. Objective definition

Optimisation is carried out in two steps:

- *Step* 1: Based on data forecasts (weather, local demand, electricity prices, etc.), the owner of a PV-based multi-source system anticipates the operating plan for their facility for the following 24 hour period. The main objective is to:

- allocate the sources to satisfy the forecast demand and scheduling of local consumption,
- compute the active power bid to be sent to the DSO.

The operating plan allows the owner to determine the expected gain MB_{S1} to be maximised:

$$MB_{S1} = \sum_{T} \left(z(t).c_s(t) - P_g(t) \cdot c_g(t) \right). \qquad (2)$$

The first term is the gain from selling local production to the grid. The second term is the purchase of energy from the grid to meet local demand.

- *Step* 2: To deal with the intermittency of primary sources and demand, the owner assesses the risks in order to make the right decision in the event of disturbances. As any change in supply or demand affects the surplus, i.e. the actual power supplied to the grid, the energy allocation must be re-adjusted, a process that is carried out gradually in real time, by the control system. The objective remains to fulfil the bid, thus minimising possible penalty costs:

$$Minimise \sum_T \left(\left| z(t) - z^*(t) \right| . c_{pen}(t) \right). \tag{3}$$

The effective gain of system MB_{S2} is therefore defined as:

$$MB_{S2} = \sum_T \left(z(t).c_s(t) - P_g(t) \cdot c_g(t) - \left| z(t) - z^*(t) \right| . c_{pen}(t) \right). \tag{4}$$

The first term in eq. 4 is the electricity sold to the network. The second one is the cost of consumed grid energy. The third one is the balancing cost incurred if the forecast active power on the day-ahead balancing market differs from the active power actually supplied.

As the objective expression in eq. 4 is not written in linear form, we propose to introduce the variable $\omega(t)$ so that:

$$\left| z(t) - z^*(t) \right| \leq \omega(t) . \tag{5}$$

The optimisation problem can be translated as:

$$MB_{S2} = \sum_T \left(z(t).c_s(t) - P_g(t) \cdot c_g(t) - \omega(t).c_{pen}(t) \right). \tag{6}$$

Subject to the constraints eqs 10-19 given in §4.2 and the following ones:

$$\omega(t) \geq 0 , \tag{7}$$

$$z(t) - \omega(t) \leq z^*(t) \ , \tag{8}$$

$$- z(t) - \omega(t) \leq z^*(t) \ . \tag{9}$$

4.2. Constraint description

The following constraints are considered.

- Production and consumption balance constraint:

$$P_{PV}(t) - P_{bin}(t) + P_{bout}(t) + P_g(t) = P_{LP}(t) + P_{LNP}(t) + z(t). \tag{10}$$

- Constraints related to battery operation:
  - Evolution of state of charge (SOC):

$SOC(t) = SOC(t\text{-}1) + P_{bin}(t) - P_{bout}(t),$ (11)

$SOC_{min} \leq SOC(t) \leq SOC_{max}(t).$ (12)

- Charge and discharge process constraint: these two operating modes are quite separate and cannot be used at the same time. It is consequently assumed that for all values of t:

$$P_{bin}(t).P_{bout}(t) = 0\,. \quad (13)$$

This constraint is not linear. However, by referring to [4], it may be translated into a linear form by introducing a binary decision variable $\alpha(t)$, so that:

$$\begin{cases} 0 \leq P_{bin}(t) \leq \alpha(t) \cdot \dfrac{S_{\max} \cdot r_{ch} \cdot \eta_B}{\Delta t} \\ -\dfrac{S_{\max} \cdot r_{dch}}{\Delta t} \cdot \dfrac{1}{\eta_B} \cdot (1-\alpha(t)) \leq P_{bout}(t) \leq 0 \end{cases}. \quad (14)$$

$$if\;\; \alpha(t)=1 \rightarrow \begin{cases} 0 \leq P_{bin}(t) \leq \dfrac{S_{max} \cdot r_{ch} \cdot \eta_B}{\Delta t} \\ P_{bout}(t)=0 \end{cases}. \quad \rightarrow \text{Battery in charge mode.}$$

$$if\;\; \alpha(t)=0 \rightarrow \begin{cases} P_{bin}(t)=0 \\ -\dfrac{S_{max} \cdot r_{dch}}{\Delta t} \cdot \dfrac{1}{\eta_B} \leq P_{bout}(t) \leq 0 \end{cases}. \rightarrow \text{Battery in discharge mode.}$$

- Constraints related to grid connection:
  - contractual limit of consumed grid power

$0 \leq P_g(t) \leq P_{gn}(t).$ (15)

  - Buying and purchasing possibility constraint: imposed by system architecture, these two processes cannot be performed at the same time. Similar to eq. 14 and by using a binary variable $\beta(t)$ we have:

$$\begin{cases} 0 \leq z(t) \leq P_{PV}(t) \cdot \beta(t) \\ 0 \leq P_g(t) \leq P_{\text{gmax}} \cdot (1-\beta(t)) \end{cases}. \quad (16)$$

$$if\;\; \beta(t)=1 \rightarrow \begin{cases} 0 \leq z(t) \leq P_{PV}(t) \\ P_g(t)=0 \end{cases}. \quad \rightarrow \text{The system serves the PV production to the grid.}$$

$$if\;\; \beta(t)=0 \rightarrow \begin{cases} z(t)=0 \\ 0 \leq P_g(t) \leq P_{gmax} \end{cases}. \quad \rightarrow \text{The system imports energy from the grid.}$$

  - Optionally the power supplied to the network may be limited. To prevent severe constraints on battery operation (which often cause damage, resulting in frequent replacement), we assume that energy stored in batteries cannot be fed into the network. The only limitation on the system's surplus is the availability of PV output:

$$0 \leq z(t) \leq P_{PV}(t). \tag{17}$$

- Scope for demand-side management introduces an additional constraint, involving the following approach. End users pay no attention to power consumption patterns providing they achieve their aims. For example, a user expects the service d to be completed at $t = a_d$, the consumed energy e_L^d required should be maintained over an appropriate prescribed period $[a_d\text{-}\delta_d : a_d]$ but consumed power would be deferred.

$$\sum_{\tau=(a_d-\delta_d)}^{a_d} P_L^d(\tau) = e_L^d\ . \tag{18}$$

with δ_d indicating the time within which the service d must be provided.

However actual energy consumption must be the same as in the case without load management:

$$\sum_t P_L(t) = \sum_t \left(P_{LP}(t) + P_{NLP}(t)\right). \tag{19}$$

4.3. Resolving the optimisation problem

The problem is formulated and implemented in Java. The CPLEX Mixed Integer Optimiser solver [32] was used to solve the optimisation problem, with a two-level algorithm. On the upper level the tree of the binary variables was explored using a branch-and-bound method. At each step a set of values are introduced for the binary variables and a Simplex algorithm is then applied to solve the problem with continuous variables.

5. CASE STUDY, APPLICATION AND DISCUSSION

The case study focuses on a residential house of about 100 m^2, having about 92 m^2 available surface for PV installation. The house is located at North 43° 39' and East 7° 1' and exposed to 5 kWh/m^2 mean daily radiation. The PV-based multi-source system consists of 50 PW850 PV modules, equivalent to 4 kWp, and a 15 kWh battery storage system. The system is connected to the network at the contractual grid power rate of 6 kW. The householder purchases energy from and sells energy to the market on which prices change every hour. Data forecasting indicates estimated load demand, available PV production and the price of electricity, as shown in the following figures (Fig. 4 and 5).

5.1 Role of Optimisation module in consumption scheduling

a. Without optimisation

The householder could :

- use solar energy when it is available and sell the surplus from the main grid;

- buy energy from the network to compensate the load needs when solar energy is not available;

So,

- the total consumption cost is : € 3.07;
- the total income from selling surplus is : € 3.19;
- the profit is : € + 0.11;
- the locally uses of his PV production: 13.7%.

b. With optimisation,

To anticipate system operation the algorithm indicates optimal use of the various available sources. Power supply is calculated by adding up locally consumed PV output, consumed grid power, and power discharged from the battery storage system to meet the demands of the house itself. At the same time some of the loads are rescheduled for other moments of the day to improve use of sources. The surplus is also computed for communication to the DSO. This is the optimal operating plan for the system that the owner makes on day D-1 for day D. The optimal sources and load management is illustrated in the Fig.6.

So,

- the total consumption cost is : € 2.79
- the total income from selling surplus is : € 4.01
- the profit is : € + 1.22
- the locally uses of his PV production: 25.6%

We saw here the interest of the optimisation that could reduce the global consumption cost and could increase the profit of PV producer.

5.2 Role of optimisation module in dealing with uncertainty:

In real-time operation during day *D*, several forms of uncertainty impact on operations and the profit that may be obtained. The following cases may occur:

- (1). An increase in consumption: the householder uses more energy than estimated. So, any available surplus would decrease to compensate local demand (with others sources). The impact of such an increase is greater at peak hours or at times when local production is insufficient or not available.
- (2). A decrease in consumption: this has no negative impact on profit because the owner of the system has several solutions:
    - (2.a) the available capacity of the battery can be charged with unused energy for subsequent use;
    - (2.b) unused energy may be fed into the grid, the owner accepting the penalty if the difference between income and penalty is positive;
    - (2.c) part of production is shed.

  The optimisation calculation algorithm will indicate the best decision to deal with such an event.
- (3). An increase in production: similar to (2).
- (4). A decrease in production: this event has the greatest impact on the system. The operating plan needs to be re-calculated for the rest of the day (from instant when incident occurs) to re-allocate the energy from available sources to loads; loads are also rescheduled if possible. The objective is to minimise the penalty cost caused by a drop in the power supplied.

A typical operating scenario might be as follows, with three unforeseen events (see also the following figures):

- t = 9 h: The householder goes out earlier than planned and a load device is consequently not used. The power consumed by the various loads drops by about 0.85 kW during an hour.
- t = 14 h: A storm occurs, stopping PV production for about an hour. Output drops by about 1.27 kW during the following hour.

- *t* = 20 h: The householder has a guest to dinner, and has to turn on the electrical stove, rated at about 1.25 kW, for an hour.

To deal with these events, the operating plan needs to be re-calculated. As consumption dropped in the early morning, the algorithm proposes to charge unused energy into the battery for later use (Fig. 7). No change is made to power consumed from the grid and power supplied to the grid. At 14-15.00 PV output decreases, effectively reducing power fed into the network (Fig. 8) but any deviation between actual and forecast supply is minimised. Finally, in the evening, when neither PV production nor the battery storage system are available, the best solution is for the house to accept an increase in power drawn off the grid to meet local demand. System operation is thus optimised and the difference between the bid and actual supply is minimised.

So,

- the total consumption cost is : € 2.97
- the total income from selling surplus is : € 3.85
- the penalty cost : € 0.38
- the profit is : € + 0.5

Here again, the use of the optimisation system reduces the impact of uncertainty on PV producers' profits that stay positive and above the first case without optimisation

5.3 Analysis of balancing cost thresholds

As this example shows, the available surplus is lower than the value originally forecast and the PV-based system owner must consequently pay a penalty. The profit for participating in the market on day *D*, initially estimated at €1.22, drops to only €0.50 (down by about 60%).

If the price on the electricity market increases or if the cost of purchasing electricity decreases, the profit would be greater. Given the upward trend for energy prices [33], the strategy presented in this article might prove more profitable in the long term.

However with a larger deviation there would be no profit or even a loss, due to the cost of penalties. Fig. 9 analyses profits depending on the extent of deviation and the level of penalties.

If uncertainty has a positive impact on the surplus (positive deviation), incurring no penalty cost, profits will stay positive. If on the other hand the impact is negative, profits will suffer. PV operators must assume the cost of imbalances, continuing to make a profit as long as the cost of any imbalance is not too high. Table 2 shows the threshold values below which it is profitable to contract to provide ancillary services and supply the balancing market. It plots the coordinates (abscissa) of the A, B and C points in Fig. 10. If the penalty is lower than the threshold values, for a given uncertainty (10%, 20% or 30%) in PV output, there is a financial incentive for the PV producer to make bids in the market or to contract to supply ancillary services. The greater the uncertainty, the lower the penalties must be for PV producers to have an incentive to contract for ancillary services or make power bids in the market.

If penalties are lower than these thresholds, for a given uncertainty level, PV operators gain by participating in ancillary services or the balancing market. If the uncertainty is high, penalties must be reduced to maintain gains. For example on the French balancing market, with rising adjustment trends, an operator’s balancing costs might range from 0.07 €/kWh to 0.24 €/kWh. So, even with some uncertainty, PV producers still make a profit.

6. Conclusions

With the development of renewable-energy technology, incentive policies are being reviewed and may be cut back to reflect falling investment costs. Looking forward to the medium term, with less attractive terms for PV production (subsidies, feed-in tariffs, purchase obligations, etc.), an innovative energy architecture for residential applications will need to be developed. One solution involves merging PV production with other sources, such as thermal or wind generation [10;11]. We propose a PV-based multi-source system, with co-management of sources and loads. Optimal management of energy processes raises user-awareness of the system’s economic worth and enables them to optimise their facility, PV production itself, the use to which it is put and meeting market demands. We also present a methodology for computing the most effective solution for such a system to participate in ancillary services or a balancing mechanism. This approach has three key advantages:

- a distribution system facilitating integration of PV-based facilities wishing to provide ancillary services;

- an optimisation method for anticipating system operations, and coping with intermittency and uncertainty, thus improving the use of PV energy;
- an analysis of the profitability of the service.

In this way DSOs can quickly ask PV generators to participate in ancillary services or balancing mechanisms. The computational results of a case study illustrate the approach and clearly show that even with the intermittency of primary sources and uncertainty regarding patterns of consumption, there is potential for householders to derive economic benefit from providing such services.

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FIGURE CAPTIONS

Fig. 1. Muti-source system and system architecture for co-management of sources and loads

Fig. 2. Example of temperature uncertainty for July, 5-th [29]

Fig. 3. Variance of solar radiation for an average day in the month [29]

Fig. 4. Forecasting of load demand and available PV production

Fig. 5. Profile of electricity price for one day (source : www.powernext.fr)

Fig. 6. Optimal operating plan for allocation of sources to loads

Fig. 7. New plan for allocation of sources to loads

Fig. 8. Surplus supplied to the grid

Fig. 9. Impact of PV production uncertainty on profit obtained by participating in the power market as a function of average penalty cost

FIGURES

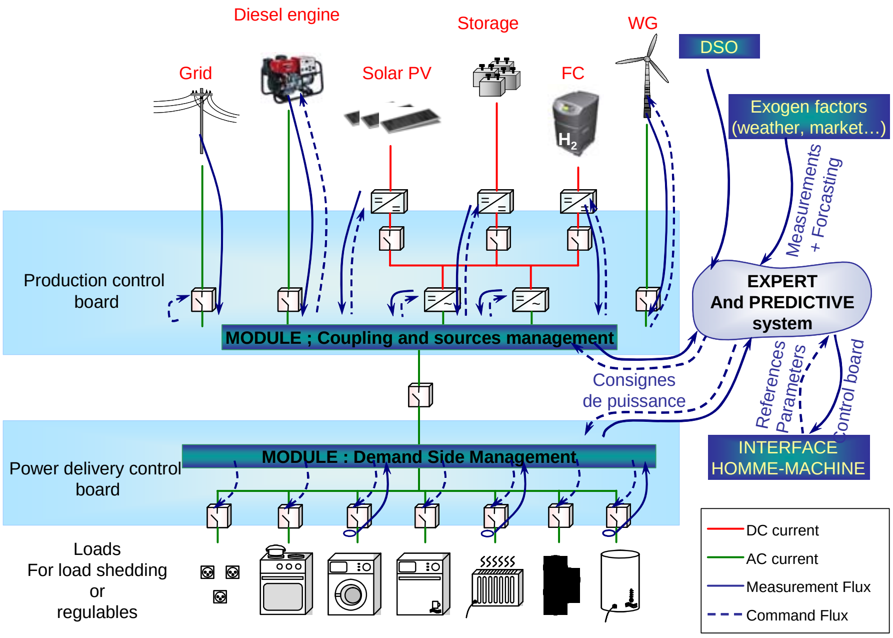

Fig. 1. Muti-sources system and sources and loads co-management system architecture

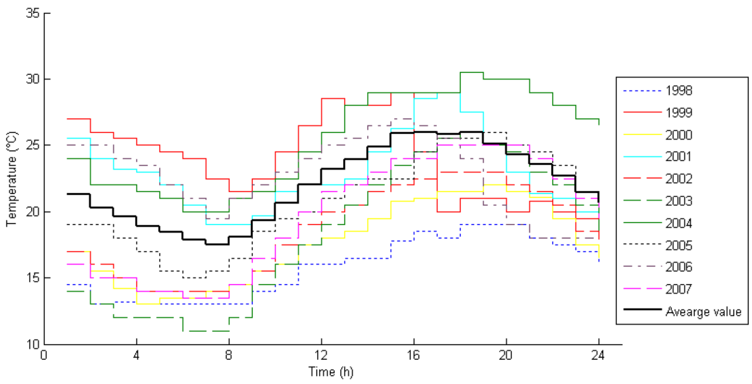

Fig. 2. Example of temperature volatility for July, 5th [29]

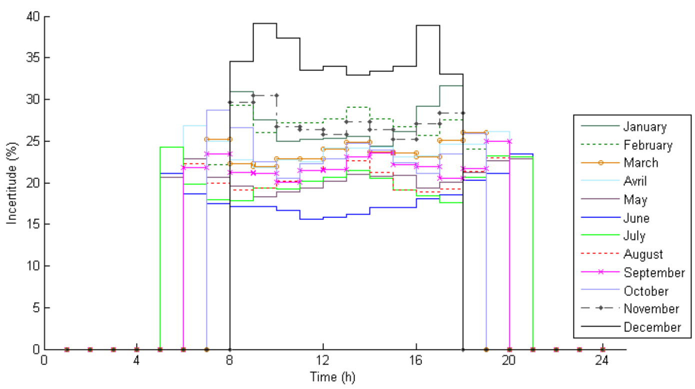

Fig. 3. Variance of solar radiation for an average day in the month [29]

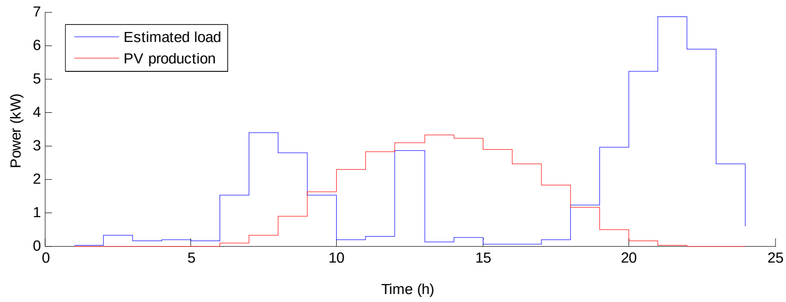

Fig. 4. Forecasting of load demand and available PV production

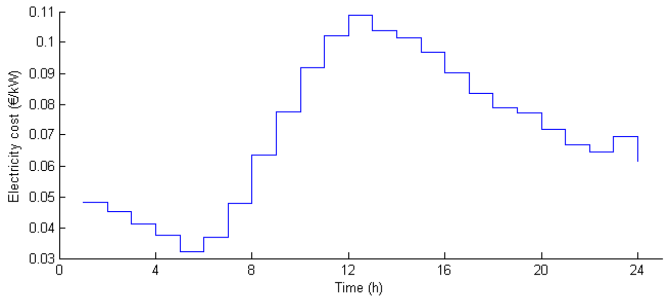

Fig. 5. Profile of electricity price for one day (source : www.powernext.fr)

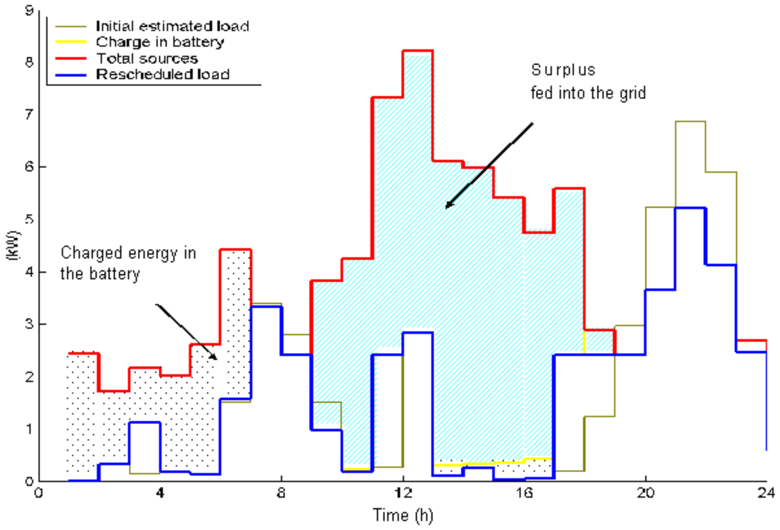

Fig. 6. Optimal operating plan for allocation of sources to loads

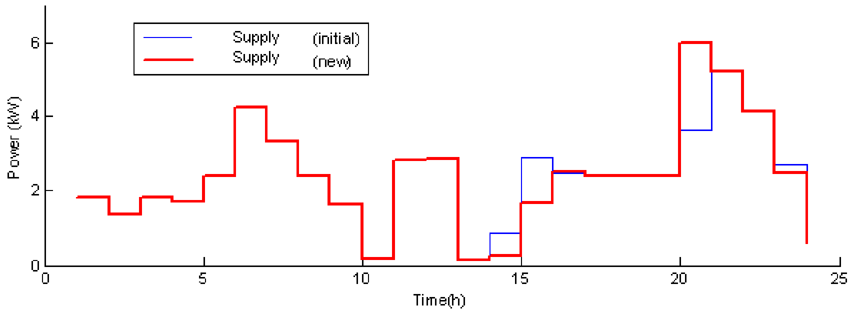

Fig. 7. New plan for allocation of sources to loads

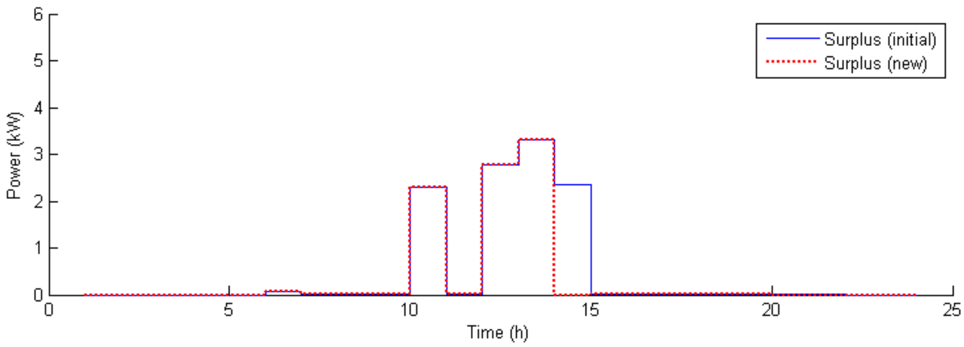

Fig. 8. Surplus supplied to the grid

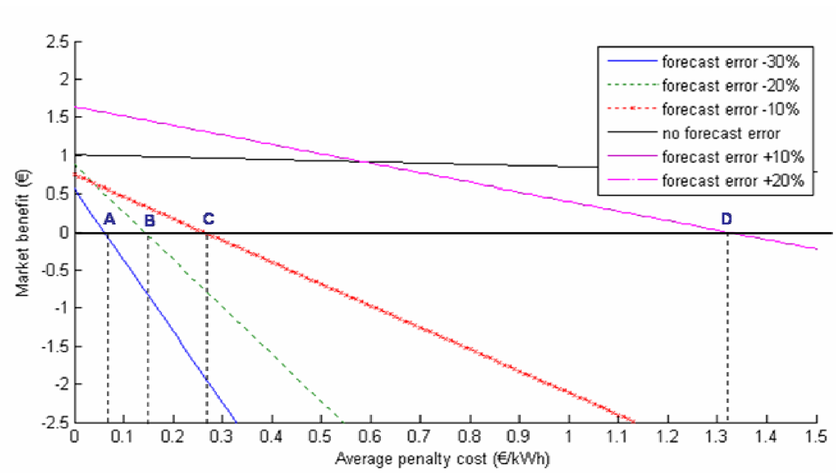

Fig. 9. Impact of PV production uncertainty on profit obtained by participating in the power market as a function of average penalty cost

TABLES

	Upward balancing trend	Downward balancing trend	Nil balancing trend
Positive gap (forecast power < actual power)	PV producer receives ZMP[1]	PV producer pays ZMP	PV producer pays ZMP
Negative gap (forecast power > actual power)	PV producer pays ZMP	PV producer receives ZMP	PV producer pays ZMP

Table.1 : Costs and balancing trends

[1] In each case, rather than paying or receiving ZMP, the PV producer could pay or receive weighted average prices of upward or downward balancing tendency. As in the TSO balancing system, these prices could be put up or cut by a factor value.

Forecast error (%)	Penalty or imbalance costs (€/kWh)
-10	[0.27 ; 0.28]
-20	[0.15 : 0.16]
-30	[0.07 : 0.08]

Table 2 : Thresholds of imbalance costs