Energy Management Strategies for Dwellings with Photovoltaic Production

Le Minh Hoang

Hanoi University of Science and Technology – No. 1, Dai Co Viet Str., Hai Ba Trung, Ha Noi, Viet Nam

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Abstract

Homes and offices are key elements in the sustainable urban development because they consume a large part of the electricity production in European countries. Because of the increasing part of renewable energy in electricity production, which is difficult to control, consumers will have to become more involved in the grid management by not only reducing but also by adjusting their consumption in order to reach equilibrium between production and consumption on the grid, on one hand, and to limit the use of production means with high emission of CO_2 on the other hand. In this paper we present a decision system that provides an active demand side management solution. This decision system is based on the weather forecasts and a variable cost of electricity. This paper states the problem of energy management in buildings and describes the optimization problem defined to adjust the energy consumption of buildings to local production constraints.

Keywords: Optimization, Energy management, MILP, Home Energy Scheduling Problem

1. Introduction

The management of the power grid becomes more and more complex due to increasing number of small electricity producers that are often also consumers. Up to now, equilibrium between the consumers and the producers has been reached in adjusting power production according to different dynamics that are related to an energy stock exchange, for instance, the European POWERNEXT that contains different energy markets: day-ahead market, intra-day market, equilibrium market, out the counter market.

The massive introduction of production means based on renewable energy yields new upcoming issues because the producers on the energy markets become more and more dependent of the environmental conditions. Because controlling the production is becoming harder, the control of the loads is studied: it is named dynamic demand side management or dynamic demand response.

Two ways for controlling the loads are usually considered:

- The direct control of the loads, where stop signals are sent by power resellers or by new actors named aggregators, to some categories of loads. With the direct control approach, only stop signals are sent to the customers, who may refuse to stop an appliance but probably with some penalties. This is a load shedding mechanism.

- The control by cost, where electricity tariffs vary with time according to the availability of energy. With this approach, it is up to the consumer to decide whether he will modify or not its behaviors taking into account the energy prices. Customers are free to decide but they have to be more involved in the management of their consumption.

The objective of this study is to setup a general mathematical formulation that makes it possible to design optimized building electric energy management systems able to determine the best energy assignment plan, according to given criteria. In this paper the Home Energy Scheduling Problem (HESP) is addressed. It aims at adjusting power consumption in housing according to the inhabitants' requests in one hand, and to the energy cost on the other hand. The energy cost may consist in both the price of the consumed energy and also its CO_2 equivalent rejection. During the consumption peak periods when power plants rejecting higher quantities of CO_2 are used and when the energy price is high, it could be possible to decide to delay some consumption activities according inhabitants' requests, or to reduce some heater set-points according to weather forecasts thanks to the thermal storage capability of buildings.

The HESP problem can be compared to the Energy Scheduling Problem (EnSP) defined in [2] with some additional constraints. A mathematical formulation of this problem is proposed that can be written as a MILP. A lot of data are assumed in this formulation such as weather forecasts and inhabitants' requests. An optimal energy planning is

* Corresponding author: Tel.: (+84) 904120984
Email: hoang.leminh@hust.edu.vn

proposed over a given planning horizon, typically one day. Optimization is done on the general solving framework proposed in [4].

From a general point of view all the appliances in the house aim at satisfying the inhabitants by delivering services. The services can be decomposed into two types: the end-user services that directly satisfy a request of the inhabitants and the provider service that produces electrical power to the end-user services. The provider services can derive the power thanks to various primary energies, typically the grid and photovoltaic system. Different kinds of end-user services for the HESP are introduced as well as their mathematical formulation in section 2. In section 3, different provider services are proposed with different economical models. The architecture of the information system in which this decision process has been implemented is briefly depicted in section 4.

2. End-user services for dynamic response

The end-user services are the activities required by the inhabitants that are energy consuming. One can distinguish several types of consumer services that can be defined in the optimization problem according to the type of involved control. First of all let us notice that the predictable activities are the only addressed in the anticipative process that is studied in this paper. The unsupervised service is associated to the set of activities that cannot be planned because they are totally driven by the inhabitants. The supervised activities are associated to more regular activities for which a planning is meaningful. One can distinguish the permanent services to be controlled all over the planning horizon and the shift-able services to be scheduled in a time window according to the inhabitant's requests.

Let $H = \{1, 2, ..., T\}$ be the planning horizon composed of T time periods of length Δ. At every time period k the amount of energy allocated to each service has to be decided. [2] proposes a formulation of the energy management problem in which the execution of the services are assumed to be synchronized to the time period.

2.1. Permanent services

The permanent services depict services that are continuously delivered and controlled all over the planning horizon. Typically the room heating and refrigerating services are permanent services. Let us assume $SRV(i)$ such a permanent service characterized by the following data:

- $P(i)$ the required power in execution [W]
- $T_{opt}(i,t)$, $T_{\min}(i,t)$ and $T_{\max}(i,t)$ respectively the requested, minimum and maximum temperature at time t [°C]

For example, the inhabitant requires a temperature in his room in the satisfying interval [18°C, 20°C]. The optimization problem aims at setting the best temperature at each time to minimize the energy cost and maximize the inhabitant's satisfaction.

In this paper, the permanent services that are modeled by a first order dynamic are addressed. In order to highlight the models and without loss of generality, the room heating service is the example used as reference. For a room heating service $SRV(i)$, the discrete time dynamic model is as follows in (1) and (2).

$$T_{in}[i,k+1] = e^{\frac{-\Delta}{\tau(i)}} T_{in}[i,k] + \left(1 - e^{\frac{-\Delta}{\tau(i)}}\right)\left(T_{out}[i,k] + G(i)E[i,k] + G_s(i)\phi_s[i,k]\right) \tag{1}$$

$$T_{\min}(i,k) \le T_{in}(i,k) \le T_{\max}(i,k) \tag{2}$$

This model allows a rather precise description of the indoor temperature dynamic variations with the following parameters:

- T_{in}, T_{out}, the indoor and outdoor temperatures [°C]
- ϕ_s, the equivalent electric power generated by the solar radiation [W]
- G, G_s, the gains of the first order dynamic from the heating power and the solar thermal impact.
- τ the constant time of the first order dynamic [s].

$T_{in}(i,k)$, $E(i,k)$ are the decision variables. For a given type of thermal space and a given quality of the environment a generic model of dissatisfaction index $D(i,k)$ is proposed. The following equation is used to compute the dissatisfaction index for the permanent service $SRV(i)$ at each time period k:

$$D(i,k) = \begin{cases} \dfrac{T_{opt}(i,k) - T_{in}(i,k)}{T_{opt}(i,k) - T_{\min}(i,k)} & \text{if} \quad T_{in}(i,k) < T_{opt}(i,k) \\ \dfrac{T_{in}(i,k) - T_{opt}(i,k)}{T_{\max}(i,k) - T_{opt}(i,k)} & \text{if} \quad T_{in}(i,k) > T_{opt}(i,k) \end{cases} \tag{3}$$

The global dissatisfaction $D(i)$ associated to $SRV(i)$ can then be defined:

$$D(i)=\sum_{k=1}^{T} D(i,k) \quad (4)$$

2.2. Temporary services

A temporary service depicts an activity that is required at some time and whose execution has a given duration. Typically washing dishes is a temporary service. A temporary service $SRV(i)$ is characterized by the following input data:

- $P(i)$, the required power in execution [W]
- $f_{\min}(i)$, $f_{\max}(i)$, respectively the earliest and latest requested ending times
- $d(i)$, the execution time [s]

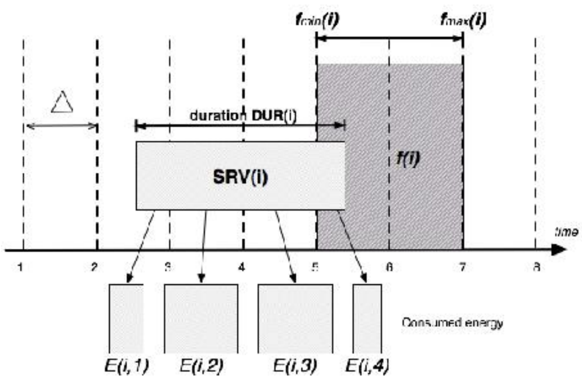


Fig. 1. Scheduling of temporary services

The ending time $f(i)$ is the decision variable associated to the temporary service. The earliest and latest requested ending times are given by the inhabitant or predicted from the user's behavior. The set of temporary services is a set of tasks to be scheduled under time windows constraints (ready times and deadlines) and resource sharing constraints. Preemption is not available.

In the scientific literature, continuous time formulations of scheduling problems exist [3] and [8]. However, these results concern scheduling problems with disjunctive resource constraints. Instead of computing the starting time of tasks, the aim is to determine the execution sequence of tasks on disjunctive shared resources. Both discrete and continuous models exist for the Resource-Constrained Project Scheduling Problem (RCPSP) [1], [5] and [7]. However in such models the availability of the cumulative resource is a given data that is constant over the planning horizon. In the HESP it is a given data that is constant only over a planning period.

Let us remind that $d(i)$ and $P(i)$ denote respectively the duration and the consumed power related to the temporary service $SRV(i)$ and $f(i)$ the ending time to be scheduled with respect to the inhabitant's request given by the time window $[f_{\min}(i), f_{\max}(i)]$. According to [6] and the energy reasoning, the consumption duration $d(i,k)$ of a service $SRV(i)$ during a planning period k is given by (see figure 1):

$$d(i,k)= \max\left\{0, \min\left(f(i),(k+1)\Delta\right)-\max\left(f(i)-d(i),k\Delta\right)\right\} \quad (5)$$

Therefore, the consumption energy $E(i,k)$ of the service $SRV(i)$ during a planning period k is given by:

$$E(i,k)=d(i,k)P(i) \quad (6)$$

Temporary services such as washing machine are expected by the inhabitant to be finished at a given preferred time denoted $f_{opt}(i)$. Therefore, the service quality achievement depends on the amount of time it is shifted from this preferred value. Then the following dissatisfaction index $D(i)$ can be computed for a temporary service:

$$D(i)=\begin{cases} \dfrac{f_{opt}(i)-f(i)}{f_{opt}(i)-f_{\min}(i)} & \text{if} \quad f(i)<f_{opt}(i) \\ \dfrac{f(i)-f_{opt}(i)}{f_{\max}(i)-f_{opt}(i)} & \text{if} \quad f(i)>f_{opt}(i) \end{cases} \quad (7)$$

2.3. Unsupervised service

All energy consuming activities (ex. lighting...) in housing cannot be taken into account as services to be planned. Indeed put the light on is totally dependent on the inhabitant's presence in a room, a parameter that is neither controllable nor predictable at the planning level. Then all activities that cannot be controlled and/or individually predicted have no interest to be planned to optimality. Those activities are merged together into one unsupervised service. The unsupervised service is defined by the power $P_u(k)$ consumed in the time period $\left[k\Delta,(k+1)\Delta\right]$ given as a data for the optimization problem. No decision variable is associated to the unsupervised activities in the scheduling problem.

2.4. Energy balance

The total amount of energy provided to the end-user services is a very important variable that can be written as follows:

$$E_c(k) = \sum_{i \in I_c} E(i,k) + P_u(k)\Delta, \forall k \qquad (8)$$

where I_c is the set of indexes of the end-user services and $E_c(k)$ stands for the provided energy during the time window $[k\Delta, (k+1)\Delta]$.

3. Provider services:

First of all, the power grid supply is assumed. It is a grid operator with whom a supply subscription is signed. In the quantity dependent cost, the energy price depends on the total amount of consumed energy every time period. A photovoltaic system is also assumed including a local consumption cost, a cost associated to the resale to the grid and a cost associated to energy bought from the grid.

3.1. Power grid supply with the maximal power tariff

The power supply service represents the available power over the planning horizon and the associated cost at every time period of the production means connected to the grid. Two parameters allow characterizing the power supply activity with maximal power tariff that are input data of the optimization problem:

- $P(k)$, the subscripted maximal power at time period k [W]
- $c(k)$, the price of the electric resource at time period k.

Then a power supply service is associated to the following constraint:

$$E_c(k) \leq P(k)\Delta, \forall k \qquad (9)$$

This constraint aims at translating the available power into a maximal amount of energy per time period. The cost associated with this kind of subscription can be computed as follows:

$$C_1(k) = c(k)E_c(k), \forall k \qquad (10)$$

3.2. Local renewable production service

The photovoltaic production is used as example of local renewable mean of electricity production. The local renewable productions have two main differences with the grid supply. The first one is due to the intermittent production. The available maximal power is a predicted value that varies in time. This paper focuses on the anticipative scheduling of the consumption from the predicted values. The second difference is due to the fatal property of the local production. That means that the photovoltaic production has to be consumed or stored but it cannot be ignored. This is an important difference with the grid supply that is available but it can be partially consumed. Then from these characteristics, the photovoltaic supply can be modeled as follows:

$$E_{PV}(k) = \eta S \phi(k) \qquad (11)$$

with:

- $E_{PV}(k)$, the total amount of local production means at the time period k [W]
- η, the yield of the equipment
- S, the surface of the panels [m2]
- $\phi(k)$, the power of the solar radiation per m^2 at the time period k [W]

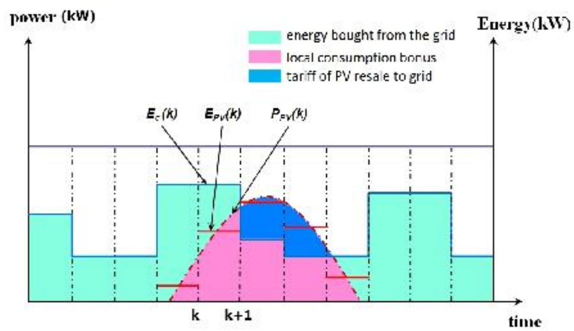
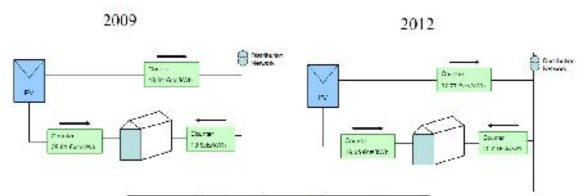


Fig. 2. Integration of photovoltaic generation in energy consumption



Year of installation	Feed-in €cts/kWh	SC tarif €cts/kWh	Total degression %
2009	43,01	25,01	
2010	39,57	23,01	8,00
2011	36,01	20,94	10,25
2012	32,77	18,05	23,81
2013	29,82	17,34	30,67
2014	27,13	15,76	36,91
2015	24,89	14,36	42,38
2016	22,47	13,07	47,75
2017	20,46	11,89	52,48

Fig. 3. Schematic diagram of German pricing

Due to the fatal property of the photovoltaic production at each time period k the entire amount of produced energy $E_{PV}(k)$ has to be consumed. No storage ability is assumed. In order to promote the self-consumption of the local production, let us assume three costs involved in the management of the local production (see Fig. 2). A benefit t_b is associated with the bonus of local consumption. This is a kind of subsidy for the local consumption. The price of resale the photovoltaic production to the grid is denoted t_r. These costs are assumed to be constant over the planning horizon. Finally, the cost of the energy supplied by the grid is denoted c_g. The described economic model exists in Germany (see Fig. 3). In this model, the values of three costs are such that the most economic decision is to locally consume and then resale the surplus of photovoltaic production.

The energy cost at the time period k can then be computed with the following equation:

$$\begin{aligned} C_2(k) &= c_g.\max\{E_c(k)-E_{PV}(k),0\} \\ &-t_b.\min\{E_{PV}(k),E_c(k)\}-t_r.\max\{E_{PV}(k)-E_c(k),0\} \end{aligned} \tag{12}$$

In this formulation the power grid supply with a constant tariff is assumed. The quantity dependent tariff could also be assumed. The cost c_g should be replaced by the regular, overtaking and high costs according to the comparison between $[E_c(k)-E_{PV}(k)]$ and the regular and high amount of energy defined by the subscription

3.3. Objective function

Depending on the inhabitants' requests, a compromise between the cost and the satisfaction has to be exhibited. An aggregation approach has been implemented to exhibit such a compromise. The corresponding objective function to be minimized is depicted by equation (13):

$$J = C_j(k) + \frac{\beta}{\sum_{i\in I_c}\alpha(i)}\sum_{i\in I_c}\alpha(i)D(i) \tag{13}$$

The cost $C_j(k)$ is one of the 2 energy costs $C_1(k)$ or $C_2(k)$ defined in the previous sections depending on the kind of power supply and grid subscription taken into account. The parameters $\alpha(i)$ depict the priorities between the end-user services and the parameter β depicts the relative importance given by the user to the energy cost and the comfort.

The optimization problem is defined by equations (1) to (13). All these equations have been linearized using integer variables.

4. Experimental results

To illustrate the effectiveness of HESP to optimize the management of photovoltaics, we chose a dwelling powered by electrical network *SRV(1)* with a subscription to 3kW. Active services in this dwelling are a heating service *SRV(2)* having a power of 1kW and a washing machine 2kW - *SRV(3)*. On the roof, solar panels type "Module Solar-Fabrik Series SF150/2A" has been installed with area of 50m2. The user's preferred temperature is 20°C and the acceptable minimum and maximum limits are 17°C and 23°C respectively. The laundry service must be completed within the time window [8h, 22h]. 18h is the time to end preferred by the user. This scenario uses the German tariff of 2009 (see Fig. 3): the energy purchased on the network is billed 19,01ct€/kWh, the PV energy which is sold directly to the network can be paid to the user 43,01ct€/kWh, finally the PV self-consumption has a bonus 25,01ct€/kWh.

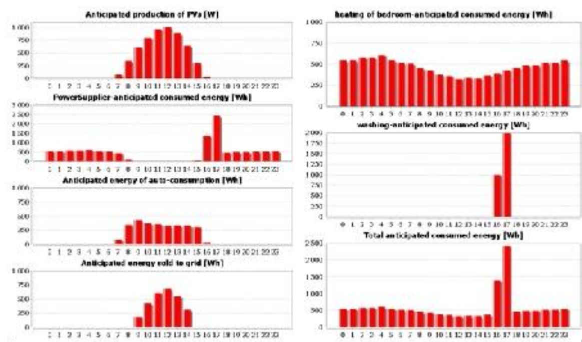


Fig. 4 Energy allocation plan of the reference scenario (without HESP)

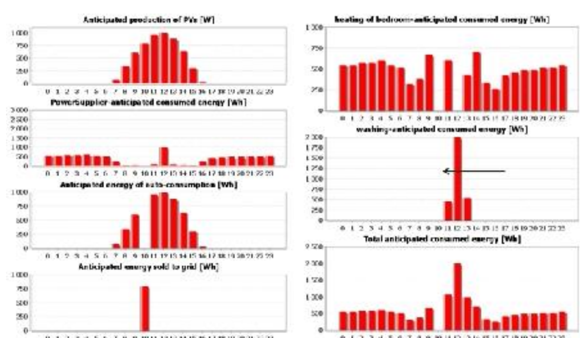


Fig. 5. Energy allocation plan given by HESP

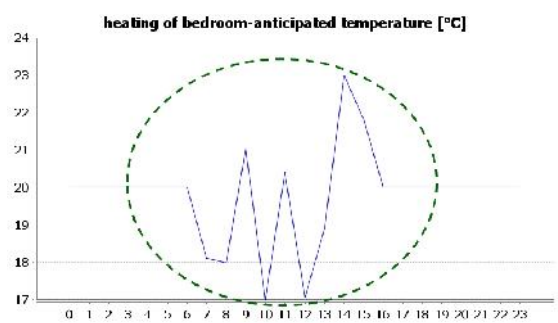


Fig. 6. Inside temperature set-points given by HESP

Fig. 4 shows the performance of all services in the reference scenario without local processing of photovoltaics. There are the two consumers: the washing machine and heating. The entire photovoltaic production in this scenario is sold to the grid.

Fig. 7. Evolution of the German photovoltaic energy pricing

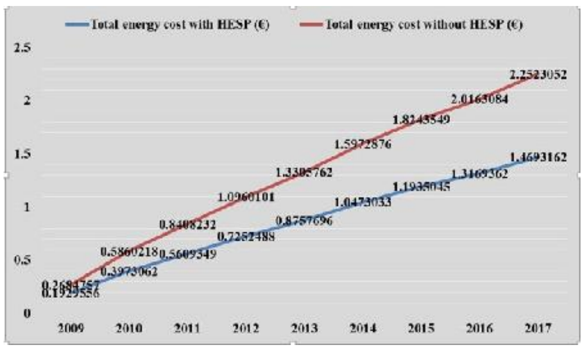


Fig. 8. Financial gain from HESP

In the scenario with recovery of local consumption of photovoltaics, HESP optimized use of energy by playing on the 2 services available: modulation of the heating operation using the heat storage capacity of housing and shifting of the washing machine's operation to consume as much photovoltaic energy. Execution of services is shown in Fig. 5, while the Fig. 6 shows the inside temperature of dwelling. The operation of the washing machine is offset at noon with maximum PV energy, the heating service is modulated with a slight overheating of the house to optimize the use of energy. It should be noted that this temperature variation remains within limits quite acceptable to the user.

Fig. 7 gives the evolution of these rates for the years from 2009 to 2017. Between 2015 and 2016, the cost of energy purchased on the network is greater than the resale price of photovoltaic energy, it will be "naturally" more interesting to self-consume local energy production. Figure 8 shows the economic criteria of two scenarios with and without the optimization of self-consumption by the HESP (for one day of operation).

5. Conclusions

Different kinds of end-user services for the Home Energy Scheduling Problem are introduced as well as their mathematical formulation. This optimization problem aims at adjusting power consumption in housing according to both the inhabitants' requests and the energy cost. This optimization problem provides an answer to the dynamic demand response including production of renewable energy. The presented application shows the effectiveness of the proposed approach for optimizing the self-consumption of PV energy in dwelling.

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