AN OPTIMIZATION MODEL FOR THE MANAGEMENT OF ENERGY SUPPLY AND DEMAND IN SMART GRIDS

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ABSTRACT

A fully-monitored smart grid prototype by Wattpic Energia Intel·ligent S.L. in Llagostera (Girona, Spain) is addressed as a case study for developing tools for modelling and optimizing the management of energy supply and demand. A preliminary project phase seeks to develop short term scheduling of energy production tasks including the integrated timing of energy loads. Thus, the demand profile is flexible and can be managed, but the economic objective function penalizes the loads that are not meet at due time. The Mixed-Integer Linear Programming model for the optimization of detailed 24-hour deterministic scenarios is presented. The promising results produced encourage further research regarding the development of decision-making tools for the enhanced design and operation of micro-grids.

Index Terms. Control, management and optimization; Distributed generation and active demand; Energy storage; Smart cities and smart buildings.

1. INTRODUCTION

Energy production and management is becoming of increasing importance in recent years. The current energy model is mostly based in a static structure where large power plants generate electricity, to be used at local level (industrial or domestic). Electricity is transmitted at high voltage to reduce energy losses in long-distance transmission and it is subsequently adapted to the distribution network. The large-scale centralized production model requires solving the transportation problems arising from the physical separation of energy production and energy demand.

Presently, due to the increase of the price of fossil fuels and the concern on environmental aspects, there is growing interest in obtaining energy from renewable resources [1]. In contrast to traditional power plants, renewable energy plants have less capacity, and are installed in a more distributed manner at different locations, potentially near the consumption. In this context, new local infrastructures become a challenge. These infrastructures are called smart grids, which are intelligent bi-directional electricity networks. These distribution networks may use information technology (IT) to manage energy production and distribution in order to timely match supply and demand between production sources and consumers. Conversely, the distributed-production model requires dealing with its inherent flexibility and solving the management problems arising from it.

Flexible management requires the availability of prompt and reliable information. Therefore, smart grids (or micro grids) involve the integration of electricity management controllers, usually called smart meters [2], capable of providing detailed billing by time slot so that not only consumers can choose the best rates among the different electricity companies (providing real-time electricity prices), but also to discern between the hours of consumption, enabling better use of the network. In addition, the use of data from smart meters can reduce the costs incurred for flexible demands, anticipating future needs at local level.

Hence, demand side management will include different benefits, such as integration of intermittent renewable energy sources at the distribution level [3], the demand response and energy savings, due to the fact that customers access to real-time information could allow smart consumption behaviour.

Flexible process management also requires storage to decouple production peaks and demand peaks. While this concept is evident in any facility producing material goods, it seemed unrealistic and denied in the case of energy. Currently, though, micro-grids make an extensive use of energy storage systems, in order to cope with the fluctuating availability of the related renewable resources.

For the previous reasons, an efficient energy planning and scheduling tool has to coordinate generation, storage and use of energy to maximize efficiency and adjust production and demand profiles. The design problem under weather uncertainty was addressed using stochastic programming [4]. In addition, energy planning in process industries using aggregated algebraic models [5] has also been recently presented. However, detailed operation optimization contemplating scheduling and control issues have been hardly addressed.

Furthermore, energy planning and scheduling should consider the flexibility of managing energy loads, thus addressing the integrated management of energy demand and energy production [6].

Towards this end, this work presents a further step to the short-term energy scheduling of micro grids for a prototype case called NOBADIS (acronym of Distributed Basic Nodes) developed by Wattpic Energia Intel·ligent S.L. and installed at Mas Roig, a farm situated in Llagostera (Girona, Spain), which is further described in the following sections. NOBADIS integrates local generation (renewables and micro-CHP), interconnection to the main grid and loads management according to different priorities. Each NOBADIS is aimed at becoming the building block of future interconnected micro-grid systems.

Wattpic Energia Intel·ligent S.L. [7] is a SME (Small and Medium Enterprise) from Barcelona (Spain) working on the development of technologies for a future grid-parity scenario and producing research for achieving competitive electricity production costs from islanded micro-grids. Hence, Wattpic has produced the fully monitored NOBADIS concept and prototype, which is co-funded by the Government of Catalonia (ACC1Ó) [8], 2009-11. The background of the NOBADIS project was the "INTEGRAL project - Integrated ICT-platform based Distributed Control in Electricity Grids" co-funded by the EC in the 6th Framework Programme [9], 2007-2011.

Within the wide scope of the NOBADIS project, this work addresses a first phase of the optimal energy management problem and concentrates in formulating and solving the short-term scheduling (24h) of the NOBADIS prototype at the Mas Roig farm, in Llagostera (Spain).

2. PROBLEM FORMULATION

The system under study consists of a set of physical elements (resources and demands, namely, power generators, energy storages, energy loads, etc.) as well as a set as of decisions (when, where, who, how much) that define the managerial problem (resource allocation).

The problem and the subsequent formulation presented is to determine not only the production and storage levels to be managed by the micro grid along a given time period, but also to manage the consumption in order to minimize the total cost, including production, storage and penalty cost.

The mathematical model presented contemplates two main aspects: the energy balances describing the energy flows, generation, storage and consumption, and the capacity constraints associated to the equipment and technologies involved in the micro grid. These aspects are next introduced along with the nomenclature.

Indexes:

$i=1,\dots I$	Set of energy production source
$j=1,\dots J$	Set of energy consumers
$k=1,\dots K$	Set of energy storage system
$f=1, \dots F_j$	Set of demands of a consumer *j*
$t=1,\dots T$	Time intervals

Parameters:

DT	Span of the time interval [h]
P_{it}^{max}	Maximum energy supply of source *i* at interval *t* [kW·h]
P_{it}^{min}	Minimum energy supply of source *i* at interval *t* [kW·h]
SE_{kt}^{max}	Maximum electricity storage of system *k* at interval *t* [kW·h]
SE_{kt}^{min}	Minimum electricity storage of system *k* at interval *t* [kW·h]
Tin_{jf}	Minimum initial time for the *f*-th consumption of consumer *j*
$Tfmax_{jf}$	Maximum final time for the *f*-th consumption of consumer *j*
c_pro_{it}	Production energy cost [€ per kW·h] for producer *i* at interval *t*
c_sto_{kt}	Storage energy cost [€ per kW·h] for storage *k* at interval *t*
c_pen_{jft}	Penalty cost [€ per time unit] for the *f*-th consumption of consumer *j*
$Cons_{jf}$	Total energy demand of consumption *jf* [kW·h]
Dur_{jf}	Duration of the *f*-th consumption of consumer *j* [DT]

Variables:

P_{it}	Energy supply of source *i* at interval *t* [hW·h]
SE_{kt}	Electricity storage level of system *k* at the end of the interval *t* [kW·h]
SP_{kt}	Energy supplied by (or given) to system *k* during interval *t* [kW·h]
PT_t	Total energy supply at interval *t* [kW·h]
Ts_{jf}	Initial time for each task *j*
Tf_{jf}	Final time for each task *j*
$Demj_{jft}$	Consumption of each device at interval *t* [kW·h]
$DemT_t$	Total consumption at interval *t* [kW·h]
$CPro_t$	Production cost at interval *t* [€]
$CSto_t$	Storage cost at interval *t* [€]
$CPen_t$	Penalty cost at interval *t* [€]
$TCost$	Total Cost. Objective function
X_{it}	Binary variable indicating whether or not supply *i* is used at interval *t*
Y_{jf}	Binary variable indicating if consumer *j* has started the *f*–th consumption at interval *t*
Z_{jft}	Binary variable indicating if consumer *j* has finished the *f*–th consumption at interval *t*
$TCPro$	Total production cost
$TCSto$	Total storage cost
$TCPen$	Total penalty cost

The decisions to be made are whether or not a production unit *i* is switched on at a given period *t*, according to different consumption units *j*. For this purpose, production, storage and penalty costs have been taken into account.

The different consumptions had been initially classified into 3 groups, corresponding to high, medium and low priority demands. The problem formulation has generalized this concept so that in case an energy demand cannot be satisfied according to its programming, it incurs in a specific penalty cost.

The constraints that the model needs to satisfy are the following. The energy that each producer can supply is zero in case it is not used and it is bounded in case it is switched on:

$$P_{it}^{\min} \cdot X_{it} \le P_{it} \le P_{it}^{\max} \cdot X_{it} \qquad \forall i,t \qquad (1)$$

Thus, the total amount of energy produced at each interval *t* is given by:

$$PT_t = \sum_{i=1}^{I} P_{it} \qquad \forall t \qquad (2)$$

The energy in each energy storage *k* at each time interval *t* is bounded within a minimum value (far from a battery being completely discharged) and a maximum value (battery full).

$$SE_{kt}^{\min} \le SE_{kt} \le SE_{kt}^{\max} \qquad \forall k,t \qquad (3)$$

Thus, the energy supplied (or accepted) by each storage system *k* is at each interval *t* is given by the variation of storage level:

$$SP_{kt} = -SE_{kt} + SE_{k(t-1)} \qquad \forall k,t \qquad (4)$$

Regarding the management of energy loads, i.e. the energy demand, some constraints are required regarding the time window within energy consumers *j* are allowed to consume for the *f*-th time. The starting time is required to be greater or equal than minimum starting time Tin_{jf}, and less or equal to the time allowing due completion:

$$Tin_{jf} \le Ts_{jf} \le Tfmax_{jf} - Dur_{jf} \qquad \forall j, f \in Fj \qquad (5)$$

The final time of each consumption *jf* is given by the starting time and its duration:

$$Tf_{jf} = Ts_{jf} + Dur_{jf} \qquad \forall j, f \in Fj \qquad (6)$$

The values of Y_{jft} indicating whether or not consumption *f* of consumer *j* has started at time slot t are constrained by the value of the corresponding starting time:

$$Y_{jft} = \begin{cases} 1 & if\ t \ge Ts_{jf} \quad (has\ started) \\ 0 & if\ t < Ts_{jf} \quad (has\ not) \end{cases} \qquad \forall t, j, f \in Fj \qquad (7)$$

Accordingly, the values of Z_{jft} indicating whether or not consumption *f* of consumer *j* has finished at time slot *t* are constrained by the value of the corresponding final time:

$$Z_{jft} = \begin{cases} 1 & if\ t \ge Tf_{jf} \quad (has\ finished) \\ 0 & if\ t < Tf_{jf} \quad (has\ not) \end{cases} \qquad \forall t, j, f \in Fj, t \qquad (8)$$

These logical restrictions can be reformulated as a set of Big-M constraints:

$$(t - Ts_{jf}) - M \cdot Y_{jft} \le 0 \qquad \forall j, f \in Fj, t \qquad (9)$$

$$(t - Ts_{jf}) + M \cdot (1 - Y_{jft}) \ge 0 \qquad \forall j, f \in Fj, t \qquad (10)$$

$$(t - Tf_{jf} - 1) - M \cdot Z_{jft} \le 0 \qquad \forall j, f \in Fj, t \qquad (11)$$

$$(t - Tf_{jf} - 1) + M \cdot (1 - Z_{jft}) \ge 0 \qquad \forall j, f \in Fj, t \qquad (12)$$

Furthermore, energy loads of a given consumer cannot overlap in the same time slot:

$$\sum_{t=1}^{T} Y_{jft} - Z_{jft} \le 1 \quad \forall j, f \in Fj, t \qquad (13)$$

Thus, the existence of an energy demand due to load *jf* at time slot t is alternatively given by:

$$Y_{jft} - Z_{jft} = \begin{cases} 1 & (On) \\ 0 & (Off) \end{cases} \qquad \forall t, j, f \in Fj, t \qquad (14)$$

Hence, the energy demand of load *jf* at time slot *t* is:

$$Demj_{jft} = Cons_{jf} \cdot (Y_{jft} - Z_{jft}) \qquad \forall j, f \in Fj, t \qquad (15)$$

The total energy demand at time interval *t* is given by all the active loads at this time:

$$DemT_t = \sum_{j=1}^{J} \sum_{f=1}^{F} Demj_{jft} \qquad \forall t \qquad (16)$$

The energy balance requires the energy supply and demand to meet:

$$\sum_{k=1}^{K} SP_{kt} + PT_t - DemT_t = 0 \qquad \forall t \qquad (17)$$

The total cost associated to production is given by:

$$TCPro = \sum_{t=1}^{T} \sum_{i=1}^{I} c\_pro_{it} \cdot P_{it} \qquad (18)$$

The total cost associated to storage is given by:

$$TCSto = \sum_{t=1}^{T} \sum_{k=1}^{K} c\_sto_{kt} \cdot SE_{kt} \qquad (19)$$

The total penalty cost is determined as a function of the delay in satisfying each energy demand:

$$TCPen = \sum_{t=1}^{T} \sum_{j=1}^{J} \sum_{f=1}^{F_j} c\_pen_{jft} \cdot (Ts_{jf} - Tin_{jf}) \qquad (20)$$

Hence, the economic objective function to be minimized subject to the previous constraints is:

$$\min\ TCost = TCProd + TCSto + TCPen \qquad (21)$$

3. CASE STUDY

The main objective of this case study is to consider the optimization of the operation of the appliances within a single farm, Mas Roig, in Llagostera (Figure 1). Mas Roig is a real test site where a family is living in. The main activities are self-agriculture, sustainability divulgation activities (agriculture, forest, energy, wastes) and an Astronomy Observatory.

There are several appliances and devices that have been organised depending on their priority (Table 1).The problem involves the consumption of 30 devices, classified in high, medium and low priority, depending on their characteristics. The possibility that one device can be used several times or that its use can be interrupted during the period of time, is also considered.

Table 1. List of loads and priorities

- HIGH PRIORITY LOADS
    - *Lights on the living room (35 W) x2*
    - *Light in the toilet (11W)*
    - *Refrigerator (90 W)*
    - *Pressure group (264 W)*
    - *Freezer (225 W)*
- MEDIUM PRIORITY LOADS
    - *Light on kitchen (24W)*
    - *Light on room (24W) x2*
    - *Washing machine (750 W)*
    - *Tumble dryer (1200 W)*
    - *Vacuum Cleaner (1200 W)*
    - *Air Conditioning (258 W) x3*
    - *Water pump (1000 W)*
    - *Water pump (750 W)*
    - *Computer iMAC (125 W)*
- LOW PRIORITY
    - *Entrance light (24 W)*
    - *Studio light (35 W)*
    - *Exterior lights (22 W)*
- MOBILE LOADS
    - *Microwave (1050 W)*
    - *Bread Toaster (1050 W)*
    - *Iron (1200 W)*
    - *Scanner (19 W)*
    - *Printer (44 W)*
    - *Fax (66 W)*
    - *Television (65 W)*
    - *Power Audio amplifier (10 W)*
    - *DVD (12 W)*

The energy sources include a set of solar panels (2.5 kWp of aggregate photovoltaic mounted over a FA a patented [10] single axis tracker) and a micro-wind turbine (3 kWn). In addition to renewables, an independent micro-CHP (15 kVA) and the connection to the power grid are options that are also considered. Furthermore, a battery is considered (1400Ah C10), in order to storage energy. The production, storage and acquisition cost of energy are also taken into account.

Figure 1. NOBADIS micro grid in Llagostera (Spain).

The power electronics for the micro-grid operation is from SMA Solar Technology [11]. All the loads and generation units have a smart node communicated by ZigBee through a mesh network and controlled by an expert system hosted in a local computer. Each ZigBee node can measure electric parameters and switching on/off the loads (Figure 2).

Figure 2. Mas Roig, Llagostera (41.825040, 2.910419). Scope of the mesh network communications.

Figure 3. Node. Measurement of energy consumptions parameters and switching on/off. ZigBee communications.

Figure 4. Web interface for the monitoring of the NOBADIS consumptions.

The problem to be solved includes energy production, storage and consumption patterns. Data related to these fields are obtained every 15 minutes. The time horizon considered is 24 hours, thus resulting 96 time slots (T). Some typical days have been characterized for being considered by the optimization process.

Data includes a minimum initial time and a maximum final time for each consumption is given, including a penalty cost in case of delaying the starting time of a certain consumption.

4. RESULTS

The MILP model has been implemented in GAMS [12] and solved using CPLEX. The mathematical model for the specific case study consists of 27,052 equations, involving 14,937 continuous variables and 9,271 discrete variables. This problem was solved to optimality (gap of 0%) in a Pentium Intel® Core™ i5 CPU 650 @ 3.20 GHz, which consumed an average computational time of 0.078 s.

The resolution of the proposed mathematical model provides the optimal generation and consumption decisions in order to minimize the total energy cost. The computational results for this case study can be found in figures 5, 6 and 7. Figure 5 shows the graph which correlates the energy produced or stored by each source (solar energy, wind energy, generator, power grid and storage resource) for each discrete time period considered.

In addition to these raw results, Figure 6 plots the mean power supplied along the time. It can be observed that during the day, the solar energy is the source used, due to its operation cost is lower that other sources. At night, wind energy and stored energy are the sources used in order to supply energy.

These results indicate that further parameter tuning is required in order to accurately model the system reality and the targets intended. The results show that potential solar energy is wasted since energy production incurs in a cost (although minor) and no economical reward has been declared for an advisable proactive storage of energy for a subsequent 24-h period. Hence, this first step should be regarded as helpful insight into the optimization problem motivating the discussion on the objective function.

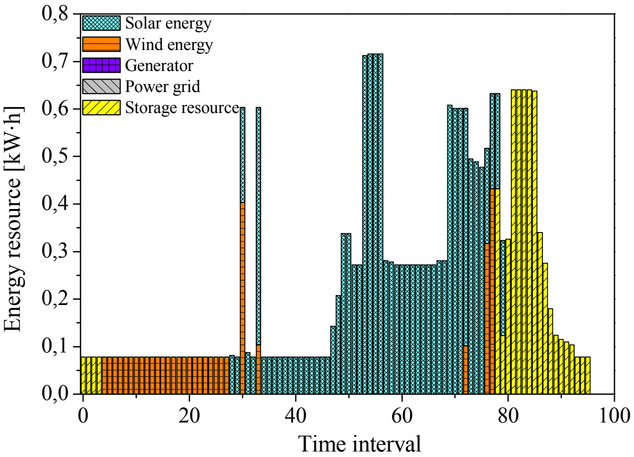

Figure 5. Energy resource in each time period.

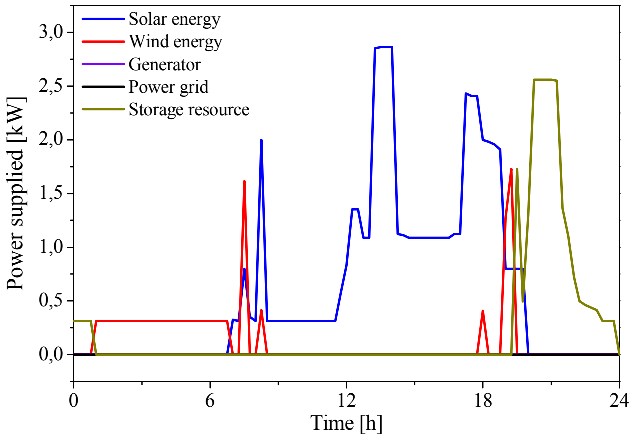

Figure 6. Mean power supplied along the time.

Finally, Figure 7 shows the best sequence of energy consumptions, regarding the considered objectives. These results demonstrate that energy loads may be efficiently scheduled in order to efficiently manage energy supply and demand.

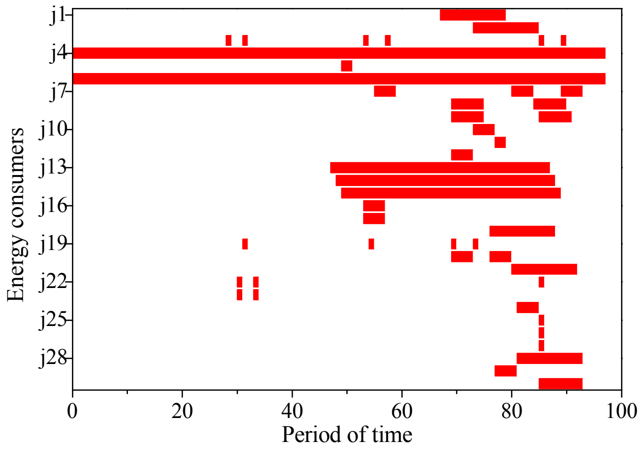

Figure 7. Active energy consumers in each time period.

5. CONCLUSIONS

This work addresses the short-term scheduling of an islanded micro grid in order to determine the best decisions in terms of energy production and consumption by minimizing the total economic cost. The motivating case study is the NOBADIS pilot system in Llagostera (Spain), an implementation of the concept for an autonomous settlement producing the energy required to satisfy its own needs.

The preliminary results attained show that the system can be duly modelled at the level of detail required by a short term (24h) scheduling horizon. Furthermore, this approach shows the potential of including the management of the energy demand profile (scheduling of energy loads) for enhancing flexibility and better matching energy supply and demand.

Further work is now required to deeply analyse the model, tune model parameters, and adapt the objective function to accurately discriminate the organizational alternatives. The approach has been revealed promising to address the mid-term planning problem involving uncertainty, seasonality, and the long-term design problem.

6. ACKNOWLEDGEMENTS

The authors would like to thank the financial support received from the Spanish Ministerio de Economía y Competitividad and the European Regional Development Fund (research Project EHMAN, DPI2009-09386, and Subprograma de Formación de Personal Investigador, BES-2010-036099).

The authors are also thankful to Dr. Francesc Sureda for his hospitality at Mas Roig and his humanistic vision of energy management that made possible the NOBADIS prototype in Llagostera (Girona, Spain).

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