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Optimization of Building Energy Exchange Using Simulated Annealing

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Abstract

Exchange of energy between buildings is in nowadays a major field of research. The demanding for clean energy production have led a lot of households to install photovoltaics (PV) in order to produce energy and reduce their overall energy cost. This paper presents an energy exchange model between buildings with different load demands during the day according to their use. Four categories of buildings are examined: Residential, Public, Commerce and Entertainment. Assuming that PVs with different levels of power generation are installed and that all buildings are available for cooperation results to a Linear Optimization (LP) problem. The unknown variables are the presentence of energy that each building can provide to a set of other cooperative buildings from the remaining PV energy in order to reduce the overall total energy demand from the grid. LP problems are easy to solve with a small number of unknowns but large-scale problems cannot always be solved. Thus, Simulated Annealing (SA) algorithm is used for the optimization. SA is used to a variety of optimization problems giving very good results, has very low complexity and is easy to implement. MatLab is used for both implementing SA and analyzing the results. Implementation of the proposed cooperative model results to an energy saving up to 22% of total energy demand from the grid without cooperation between buildings.

1. Introduction

In nowadays energy consumption demands are getting higher as households are using more electrical devices than some years before. In order to reduce energy consumption, cost and their dependency from the electrical network there is a trend to install renewable energy resources. With such an installation, automatically the consumer becomes a provider too. In Greece where the most of the days within the year are sunny PVs are the optimum solution for a clean energy production. But during the day potentially household's energy needs are low because residents are outside and when they return PVs are not capable to produce the maximum they can during the day. For that purpose, the common practice that it been used is to sell the energy to the provider and to get a reduced energy bill as a result, paying only the difference between production and consumption.

This work proposes a model in which all buildings that produce energy that they don't use in that current moment of the day to be able to provide it to another building in which current needs are high. In that way a micro grid is formed in which total energy demand for all the buildings

participating in the coalition is smaller than the case which every building work autonomously. Reducing the energy demand from the powerline provider network is in fact beneficial for both consumer and provider in case the last has not got the efficiency to produce the total amount of energy and has to invest to a new infrastructure in order to respond to the demand.

In this paper a microgrid is formed between a number of buildings dynamically during the day in order to achieve minimum energy consumption from the grid. First a related work around this topic is presented. Section three presents Simulated Annealing (SA) optimization algorithm which is used to solve the optimization problem. Section four presents the definition of the problem, the model formulation and model assumptions. The results of the simulation are presented in section five and discussed in section six.

2. Related Work

Microgrid operation efficiency using several renewable energy resources and forming microgrid alliance using a game theory protocol is proposed in [1]. Taking into account different methods of energy production, the load characteristics as constraints and the minimum operating cost as an objective function. Based on cooperative game theory proposes an alliance protocol in order to maximize the benefits of the microgrid. For the benefits distribution the Shapley value method is used. The model implementation compared with the independent operation of microgrid, produces profits for the microgrid alliance up to 40%.

The energy management problem for two cooperative microgrids is examined in [2] taking into consideration that each microgrid has its own individual renewable energy generator and an Energy Storage System (ESS). Firstly, solve the off-line energy management problem optimally and then based on that solution proposes online algorithms for the real time energy management of two microgrids and finally extends the method in case of more buildings.

Operation and Control of Microgrids Using IoT is examined in [3]. Smart meters and communication among buildings and with the provider is a capability that smart grids can use to exchange information related with consumption, production, current and future state of the demand. In this paper that capability is used extensively as all buildings must have full knowledge of their neighbors needs. In [3] an Energy Management System (EMS) is used to minimize the overall energy drawn from the grid using Particle Swarm Optimization (POS) [4]. Current work uses Simulated Annealing (SA) Optimization algorithm [5] which will be briefly presented in section IV. Though SA coexist POS is much easier to implement and gives very good results in a small period of time.

Interconnection of all buildings and a cooperative microgrid team model among smart buildings is proposed in [6]which finally reduces total energy in an amount of 64% to97% according to the type of the microgrid. Also uses ElectricVehicles (EV) as batteries for exceed energy storage with theability to recharge the hours that peak load is high and loadagain to be ready for the pedestrian mobility needs.

A cooperative game approach between Multi Microgrid Systems is used in [7] to achieve the global optimum of network cost. As [1] it uses Shapley Value to reach a fair allocated cost between Micro Grids. Model is formulated as a mixed-integer linear programming problem which is evaluated using a standard test system of three microgrids. In the end the use of a cooperative method reduces the cost than the isolated status.

In all the above works the target is to either reduce total energy demand from the network or total operational cost of the network. They use different approaches and methods to achieve optimum results. In the proposed paper a Simulated Annealing algorithm is used to reach a minimum network demand during the day while PVs are producing energy for two different scenarios winter and summer.

3. Simulated Annealing

Simulated Annealing (SA) algorithm is a metaheuristic method for optimizing an objective function that was discovered in the early 80s. Its name and structure come from the metalworking process that involves controlled heating and cooling of the material. When the material is heated the atoms show great mobility and accordingly the algorithm considers many possible solutions. When the temperature decreases the mobility of individuals decreases so in this case the solutions considered are fewer. Eventually the atoms will end up in a stable position in the metal when it is in its solid state and this position will correspond to the optimal solution calculated by the algorithm. This process can only be done if the initial temperature is high enough and the cooling is done at a slow rate.

As mentioned, SA algorithm is used to find an optimal solution to difficult combinatorial problems. The correspondence between the physical and the mathematical problem is as follows:

3.1 Temperature: Convergence Parameter

As the temperature decreases, we are led to a cold state of the material in which it cannot be further processed and correspondingly to the optimal solution. Therefore, the initial temperature entered is the basic parameter of the algorithm. A second parameter is the rate at which it decreases and is expressed through the temperature reduction factor.

3.2 Action: Objective Function Value

Every material that is heated processed and eventually cooled it changes its energy. The value of the energy it has in each phase of the processing is the value of the objective function whose optimization is requested. The energy distribution of the molecules of a material obeys Boltzmann's law (1).

$$P_{(E)} \approx e^{-\frac{\Delta E}{k \cdot T}} \quad (1)$$

In (1) ΔE is the energy change, k is the Boltzmann constant and T is the temperature. The Boltzmann constant for the running process of the algorithm is taken to be unity, so for the optimization we have k=1.

3.3 System Status: Possible Solution

The state (or better, the energy the material has) in which the material we work at any moment is a stage of its shaping into the final desired shape. Thus, corresponding to the mathematical problem, the intermediate states are feasible solutions but not optimal.

3.4 System State Change: Neighboring Feasible Solution

Each time the metalworker hits it with the hammer, the material changes form and therefore energy, but its new shape does not differ greatly from the previous one. So the feasible solutions we find will be close to the previous ones.

During the processing process, the metallurgist can reheat the material because its temperature has dropped enough, and it is not properly processed. This may be a natural explanation for the changes from a low energy value to a high one during the execution of the algorithm.

3.5 Cold System Status: Optimal Solution

When the metal has the desired shape (optimal solution) then its temperature is minimal. The energy value at the moment when the temperature is minimum constitutes the optimal solution of the objective function.

The algorithm can also terminate in a certain number of execution cycles (machining - hammering) corresponding to the fatigue of the metal worker.

Some fluctuations in the energy of the material (objective function) being processed. Also, when the temperature value is minimal then the solution is optimal.

3.6 Structure of the Algorithm

Based on all that was mentioned we can say that the algorithm is structured as follows:

STAGE 1: Data Entry and Initial Calculations

We give the initial temperature with which we want the algorithm to work. With this temperature, the initial energy is calculated, i.e. the value of the objective function. The temperature reduction factor and the maximum number of execution cycles are also given in the data.

STAGE 2: Find New Energy Price

With a small change in the variables of the objective function, a new solution is calculated, i.e. a new energy value.

STAGE 3: New Energy Price Assessment

If the solution found leads to an energy value smaller if we are looking for the minimum optimal value or larger if we are looking for the maximum, then this is accepted for the calculations of the next cycle. If not, then an evaluation is made with the Metropolis criterion, which is described below. This acceptance of a worse energy value is done to avoid trapping the algorithm in a local extrema.

Metropolis Criterion

We calculate the value of the energy from the relation 1 and then we choose a random number from 0 to 1. If the number we chose is less than the energy we calculated then the solution (new value of the energy) is accepted. If not then it is rejected.

STAGE 4: Reduce Temperature

We reduce the temperature according to the reduction factor we have chosen. If, for example, the coefficient is α then the new temperature will be given by (2).

$$T_{i+1} = \alpha \cdot T_i \quad (2)$$

STAGE 5: End of Cycle – Return to Stage 2

If the maximum number of cycles has not been completed then with the new energy value, if it has been accepted, and the new temperature value we return to stage 2 for a new execution of the algorithm.

If the maximum number of cycles (or whatever termination criterion we have) has been met, then the current (last) value of the energy is the optimal solution to the problem.

4. Model Formulation

In the present work a model which finds the optimal percentage which every building with spare energy can exchange with other buildings to reduce the total energy demand from the network. The renewable energy that used is PVs only that's because of Greece climate conditions as the majority of the days during the year are shinning.

The problem is stated like this:

"Given a number of buildings with installed PVs, find the best percentage exchange from a building to others in such way that the total energy demand from the network to be minimum during a 24h time"

The objective function of the problem is formulated like this:

$$F = \sum_{i=1}^{N}(PC_i - a_i \cdot PV_i) - \sum_{i=1}^{N}\sum_{j=1}^{N} X_{ij} \cdot (1 - a_i) \cdot PV_i \quad (3)$$

were:

N : is the total number of the buildings

Xij : is the percentage that building i can offer to the building j

PCi: is the Power Consumption needs of the building i

PVi: is the PV energy that building i can produce

ai = PCi / PVi is the self consumption factor of the building i

$$a_i = \begin{cases} 1, & \text{if } \frac{PC_i}{PV_i} \geq 1 \\ a_i, & \text{if } \frac{PC_i}{PV_i} < 1 \end{cases} \quad (4)$$

Self consumption factor ai in (2) means that if the energythat a building need is greater than the one it can produce then it uses it only for itself and it is not capable to exchange energy with other buildings. In the opposite case it can provide to the other buildings the reminder of the energy that it produces.

For the solution of the problem a MatLab code was written. The parameters that change are the Xij thus the energy percentage that building i can provide to j. The pseudocode for the solution is given below.

1. Calculate self consumption for each building, ai
2. If ai=1 then that building can not provide energy

3. Create the table of Xij with random values
4. Calculate objective function, F1
5. Change Xij table
6. Recalculate objective function, F2
7. If F2<F1 then store the solution
8. If F2>F1 then use Boltzmann criterion to see if the solution will be accepted.
9. Return to step 5 until the number of cycles of the algorithm is reached.
10. Return to step 1 to begin the next time period optimization.

4.1 Restrictions

Xij > Minimum Energy Exchange percentage

In our case is set to 10% and it is used to take into consideration the powerline losses.

4.2 Model Assumptions

1. Every building is connected to each other
2. Every building has fully knowledge about the state of consumption of other buildings.
3. The optimization intervals during the day have a duration of 1 h.

4.3 Model Inputs

The simulation uses five different types of buildings with different energy needs during the day. Two types of residential buildings, one type of public building, one type of commerce building and one type of entertainment building. The energy demands for each type of building during the day is presented in the figures 1i,1ii,1iii,1iv,1v respectively while their PVs energy production is shown in figures 2i, 2ii, 2iii. Notice that residential buildings have the same PV production curve during the day and entertainment buildings did not produce any energy.

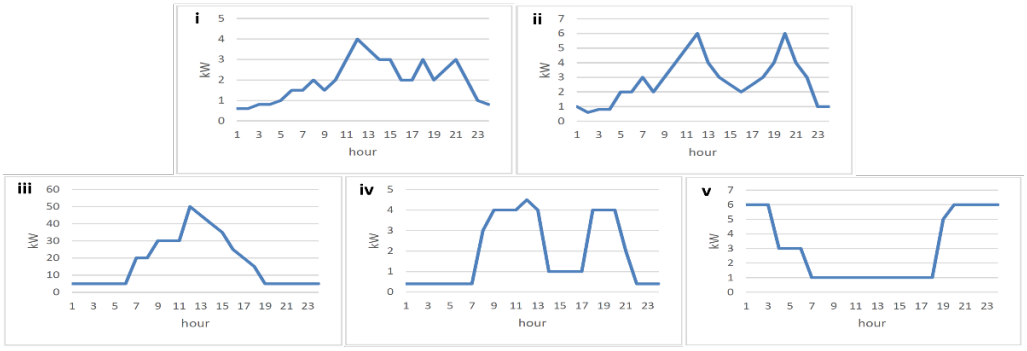

Figure 1: i) Residential type 1 consumption; ii) Residential type 2 consumption; iii) Public building consumption; iv) Commerce building consumption; v) Entertainment building consumption

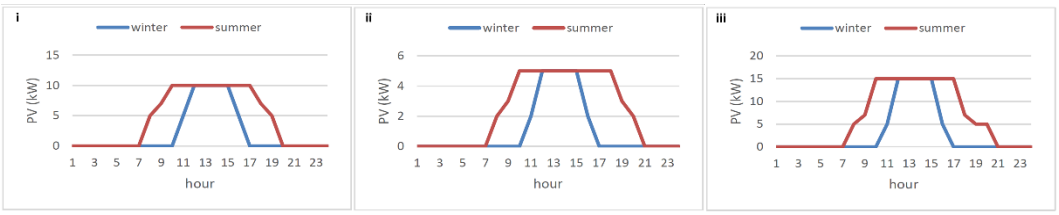

Figure 2: i) Residential building production; ii) Public building production; iii) Commerce building production

5. Results

For the optimization SA the optimal parameters were set as follows:

Temperature : 100

Reduction Factor : 0.75

Number of cycles : 5000

Three scenarios are taking into consideration. The first one has 20 buildings the second has 50 and the third 100 buildings. Considering two seasons for each year winter and summer six different cases were examined.

Scenarios	Parameters
1	20 buildings, winter
2	20 buildings, summer
3	50 buildings, winter
4	50 buildings, summer
5	100 buildings, winter
6	100 buildings, summer

Table 1. List of Parameters Scenarios

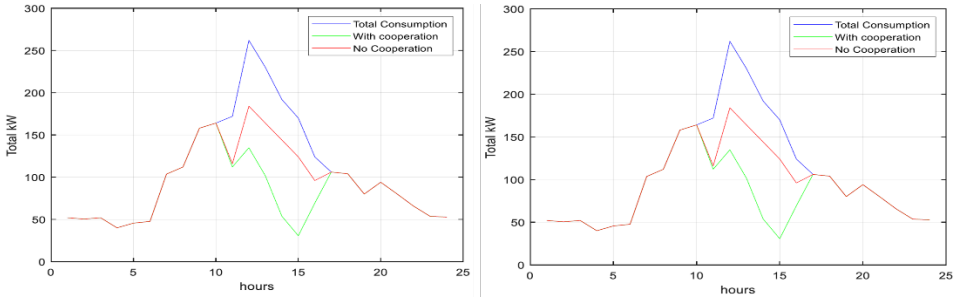

Figure 3: (left) Case 1: 20 buildings, winter; (right) Case 2: 20 buildings, summer

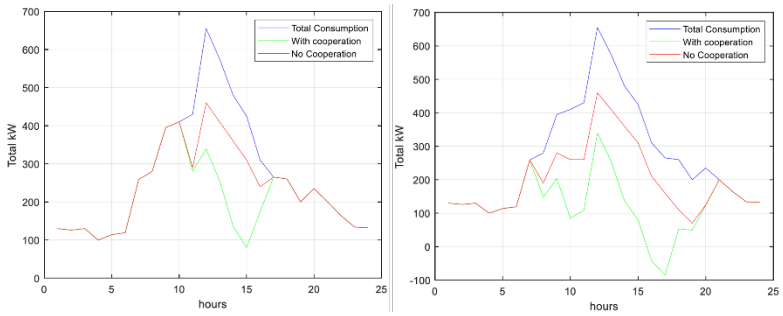

Figure 4: (left) Case 3: 50 buildings, winter; (right) Case 4: 50 buildings, summer

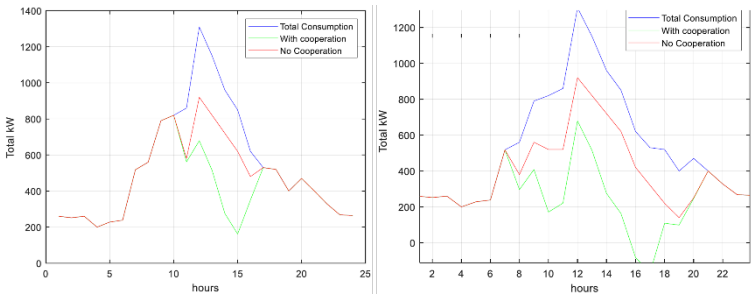

Figure 5: (left) Case 5: 100 buildings, winter; (right) Case 4: Case 6: 100 buildings, summer

6. Conclusions

Figures 3 through 5 show that the proposed model for building energy exchange gives satisfactory results reducing the overall energy during the PV production hours up to 22% in power peak, that means that without cooperation, when every building uses his own PV without sharing any energy with other buildings the overall consumption is much greater than with cooperation module. Furthermore, SA algorithm seems to work sufficiently providing the optimal solution for each period of time (1 hour).

The savings in microgrid demand from the network will be even expanded in case batteries are used to store excessive energy produced at times when it is not consumed. Further research can explore the effect of the batteries size on the optimization of energy economy.

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