An economic evaluation model for the Energy Demand Response

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Abstract

The deregulation of the electricity market, the technological process in constant evolution, the focus on the environmental problem and the need to manage and protect energy loads more sensitive to disturbances in the grid, have revealed the need for new solutions for the generation, transmission and distribution of electricity. A significant research and development effort, that involves a large number of technology areas and requires a highly interdisciplinary design vision, has led to the emergence of the concept of Smart Grid. It is in this context that emerges attention towards the Demand Response, a particular tactic for the intelligent management of electrical loads of the users. The aim of this paper is to present an algorithm that helps the aggregator of energy loads in carrying out its daily decisions, using an economic objective function. A mathematical model for this aim it is developed and an heuristic solution to calculate a loads distribution configuration. Finally the model is tested to understand its effectiveness and the capability of an aggregator to have revenues from the application of a Demand Response tactic.

Keywords: Demand response; Smart grid; Energy; Economic evaluation model.

Introduction

The term Smart Grid indicates an active system capable to decide independently, efficiently and intelligently by itself to maximize the efficiency of the grid. Basically it refers to a power grid that can intelligently integrate the behaviours and actions of all users connected to it, in order to ensure sustainable supplies of electricity efficiently, economically and safely.

The electricity grid of the most part of the western countries bases its *modus operandi* on a structure that can be defined unidirectional and passive. In fact, it relies on the presence of a limited number of production plants that focus on the production of electricity using fossil fuels and nuclear power plants, then the energy produced is transmitted in large dorsal of high voltage capacity. From there, grid lines branch from the dorsal to utilities absorb energy. With the increase of the national energy demand the first problem for the traditional grid was to manifest itself in keeping standards of reliability in the load energy supply. The electrical grid bases its operation on the perfect balance between demand and supply of energy over time. This balance is the crucial aspect of the delivery operation since it is the operational constraint that ensures that each user connected to the grid, may have a certain degree of reliability in the delivery. So, during the years the electricity companies have enforced the capacity of the grid structure to ensure the service and the reliability for the clients. For several reasons, such as (i) energy consumers are geographically distributed over large areas, (ii) the control stations of energy flows had a limited interconnection capacity and (iii) the production was entrusted to a few large power plants, the most logical choice to ensure the supply for the consumers was to intervene on the side of power supply by increasing the capacity of production so as to increase the amount of energy to be made available on the grid. Therefore, it has been developed a number of additional installations, most of which are carried out according to the geographic distribution of generation sources (places near coal mines, water sources, etc..). These interventions were carried out according to the logic of economies of scale for the production: centralized systems have been installed in increasingly large proportion that would allow a more profitable investment and a greater production capacity available. Having raised the amount of energy produced, also the flow of energy to operate on the grid has increased; consequently it was not only the production side that has changed, but also the transmission and distribution of electricity tried to follow this capacity development.

The result of this evolutionary process is that the current structure has a pattern with a strong vertical integration, that in order to meet further increases in demand for energy with the installation of new power plants needs investment very high. Furthermore, with the increase of the flow of data and information available from the grid, the current transmission structure has revealed the enormous difficulties in their control and management due to the presence of obsolete and unintelligent devices. Besides it is inefficient from the point of view of the management of the electrical flows, since the grid requires an high number of steps that the energy flow has to respect to supply the final user. In addition, a well-defined structure is inherently static: as the flow of energy travels in a unidirectional, from the place of production to the consumer, in this context, the end user is solely a passive load of the network. A brief characterization of the traditional grid is reported in figure 1.

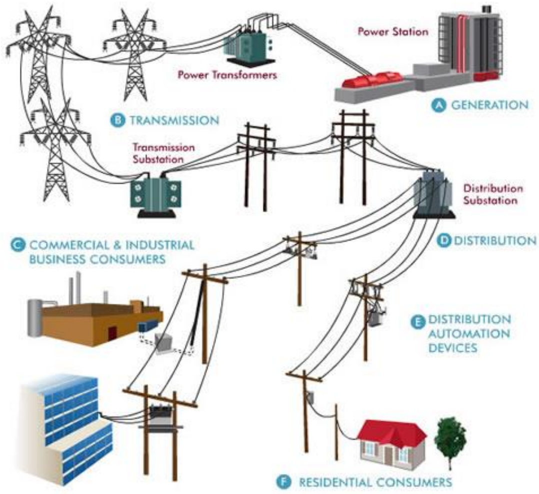

Figure 1: The traditional energy transmission and distribution scheme.

There are many disadvantages associated with the use of this type of network structure, and in particular:

- high Joule losses suffered along the connecting line from large power plants to utilities;
- inability to effectively manage the energy flow to convey the energy where it is needed (this is due to the lack of protocols in the dynamic management of energy flows);
- difficulty to fully use renewable energy sources like wind and solar power;
- response time too long in the event of a blackout, with inability to stem the cascading effects in the voltage drop and consequent interruption of energy flow.

Each of these factors contributes to increase the cost of the energy; actually, the operation and management of the transmission and distribution systems are granted, in most cases, by national or regional entities, that have a monopoly and the only obligation to respond to the control of the National Energy Authority is to ensure the access to the grid for all customers.

Over the past years, however, we are witnessing a major change in the trend that has led the scientific community to define new strategies for the development of electricity grids. This scientific effort revealed the need to make a major breakthrough in the electricity management (Sheikhi 2015, R. W. Wang 2014, Gangolells 2015). In fact this research enforcement leaded to some considerations.

1. despite the current period of financial crisis, a minimal growth in energy demand has stimulated the formulation of plans of widening and strengthening of the existing electricity grids;
2. the liberalization has brought the energy market to move according to the logic of competitiveness, getting not only that consumers have the opportunity to benefit from better choices at lower prices but also that the whole system is inspired to realize technological progress and continuous innovation for a steady growth in energy efficiency by the presence of economic incentives;
3. fossil fuels began a downward spiral due to the progressive depletion of deposits and therefore of available stocks. Since a progressive and constant increase in energy demand, this factor has led to a consequent rise in prices for the fossil gases and oil barrel. This price increase is why, in recent times, the countries have been accentuated policies to diversify the energy sources, encouraging the development of alternative energy supply systems to fossil fuels;
4. aging transmission and distribution infrastructure in Europe is threatening the security, the reliability and quality of the energy supply;
5. increasingly high emissions of CO_2, SO_2 and NO_x and other pollutants and the resulting environmental problems such as climate change due to greenhouse gases, recognized as one of the most important problems that humanity is facing, have prompted the EU to put ambitious goals to reach. They were issued by Directive 2009/28/EC of 5 June 2009, known as the most famous slogan "20 20 20" in which the EU provides a 20% reduction in CO_2 emissions, reaching a 20% of production from renewables and rising to 20% of energy saving as goals to be achieved by 2020;
6. continuing advances in the ICT (Information & Communications Technology) have created a convergence of scientific and industrial interests on the use of new technologies.

On the basis of the starting point represented by this grid today, it is clarified that it is possible, through a gradual progress rather than a revolutionary approach, modify the existing vertical structure of the electric system and ensure effective solutions to the difficulties currently encountered (Eising 2014, Connor 2014). The ultimate goal to be achieved is to equip the National Electrical System of a structure that has high performance in terms of "intelligence", "reliability", "sustainability", "economy", "accessibility" and "flexibility"; in other terms many countries have decided to make their traditional grids “Smart Grids”.

The main point on which the Smart Grid bases its operation and that makes the road to take for the future of the electricity grid is the ability to handle near-instantaneous two-way communication between each node of the grid. The model structure is less unidirectional flow from a few large power stations and branches, through large-scale infrastructure for transmission and distribution, to all utilities. It will enter into the logic of a large grid in which each node can represent both a producer and a consumer (that can be called "*prosumers*").

In fact, the capacity of a Smart Grid to manage energy flows from various parts of the grid ensures the integration and involvement of distributed energy resources. These are called DER (Distributed Energy Resources) which includes generators, accumulators, controllable loads and all the devices that are connected to the electrical distribution system. A possible representation of the Smart Grid systems are in figure 2.

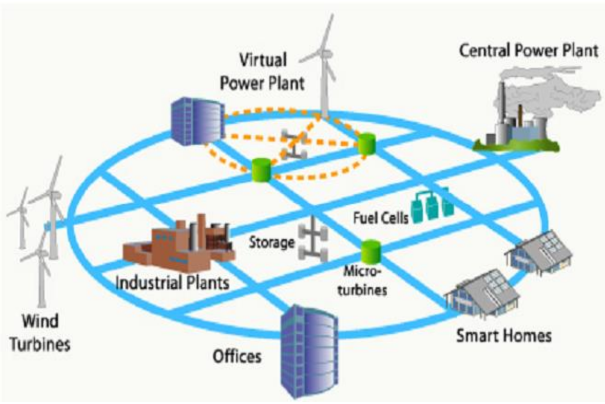

Figure 2: The Smart Grid energy transmission and distribution scheme.

In this context many tactics to apply the Smart Grid logic are possible, but a first step to approach the problem is to manage the loads from the clients' part, trying to reduce their request in particular time slots in which the whole request of the grid is too high. Between these techniques there is one that tries to do exactly what it was said before, its name is Demand Response.

The Demand Response (DR) leads to the change of load profiles of customers, not necessarily results in a lowering of their total level of consumption. The underlying concept on which it is based is the possibility of a customer to reschedule the timing of its loads, trying to lower the level of consumption during peak hours and shift activities in the hours when energy demand is lower. To ensure the implementation of DR programs must be installed on structures that ensure a high level of communication and interaction between the consumer and the utility. Given this collaboration, generally two kind of DR are possible to be defined:

- Incentive-Based;
- Price-Based.

For the first one a remuneration for the client is given, while for the second a reduction of the price is proposed.

Some authors (Palensky P 2011) in the past suggested also other categorizations as following:

- Market DR;
- Phisical DR.

For market DR programs price signals and incentives are delivered to customers in real-time, while in Physical DR are covered only events necessary for the management of emergency situations on the grid.

To make more clear the field in which we are start to study, it is worth to note that the substantial difference between the measures of Energy Efficiency and those of Demand Response is the fact that the latter determine a change in the load curves of the customer without producing a lowering of the total level of energy consumption. The DR can be useful not only for the efficiency of the grid but also to manage critical moments of overload of the grid shifting the loads from the critical moment to another one.

The possible tactics for the DR applications are:

- Energy Shift and
- Energy Lowering.

The first one is when the energy load is transferred from a pick to the valleys of a load profile, as reported in figure 3.

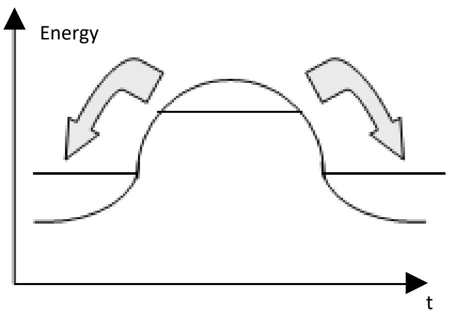

Fig. 3: The energy shift

The second tactic is when the energy load is reduced, having the permission of the customer to reduce the power absorbed by the grid. The energy lowering is reported in figure 4.

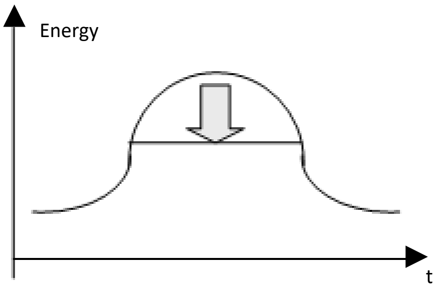

Figure 4: The "Rebound Effect"

Aim of this paper is to present a new economic evaluation method for ones that want to apply models of Demand Side Management and in particular the Demand Response.

The paper is organised as follows: firstly it is conducted a deep analysis of the state of the art, where many contributions to the matter are presented to understand the taxonomies of the problem and the models created in the past to manage the DR; after the state of the art, the economic optimization model and its heuristic solution are presented; finally a case study implementing the model and the heuristic are implemented in MATLAB simulating several market scenarios to test the effectiveness of the method.

State of the art

The Management of the Electricity Demand, known by the English term originally Demand-Side Management (DSM) is a methodology that was developed in the 80s and 90s in Canada and the USA, where they were fundamental studies of EPRI (Electric Power Research Institute 1984), reaching a rapid spread in Europe. The DSM can be divided in two main families: (i) the Energy Response and (ii) the Demand Response. The Energy Response aims to lower power consumption while the Demand Response (DR) involves also the change of load profiles of customers, not necessarily resulting in a lowering of their level of total consumption. The underlying concept on which they are based is the capacity of a customer to reschedule the timing of its loads, trying to lower the level of consumption during peak hours and shift the load during the hours when the energy demand is lower.

Over the years attention has focused much to the development of systems capable of improving communication between the various parts of the grid, ensuring information flows increasingly stable and slender.

With regard to the interactions that occur between the many parts involved in an intelligent system an important study is provided by Mohagheghi et al. (Mohagheghi 2010). The analysis, in fact, points out the way to transform the distribution infrastructure from a vertical hierarchy of control in a collaborative environment. The direction of the energy flow in this context is no longer related only to the instructions defined by the side of production, but is also highly dependent on the actions and responses of consumers. It also highlights how the implementation of an architecture that enables the participation of consumers in Demand Response programs can bring benefits to the whole structure of the grid based on the intelligent management of electrical loads.

In the literature there are paths relative to the information flows in a grid, made real by the use of systems that are able to handle such flows. For example in a paper by Wang et al. (Wang 2011), the authors present a system, called ITMBS (Intelligent Trading Metering Billing System), that is able to handle almost all of the interactions that occur in a Smart Grid. In fact, this system has enabled the management of trade operations, measurement and data exchange in future smart grids. The system described in this article consists of a series of smart meters, communication infrastructure, a system for the collection and management of information, a website and DCU (Display and Control Units). It has been shown by the authors that the ITMBS can perform tasks from the information management to guaranteeing the remote control of some home-made applications.

Beside the studies about the optimization of loads of the whole system, there are other studies that relate the various elements of a grid. With the explosion in renewable generation that has occurred in recent years, more and more authors have focused their attention and efforts in this area. In fact, the optimization of the management of the flows of energy produced by these sources is one of the key-points in the implementation of management tactics of loads. In this regard the paper by John and Westermann (Westermann 2007) is particularly interesting. In this paper the authors demonstrate how a system of remote monitoring can optimize a grid powered by a wind park. Given the high variability of production of the renewable energy sources, the combination of wide-ranging measures and information signals for demand management determines a check on the power that can guarantee at any time the balance of the load of the considered area. In addition to a general overview of two power technologies that have been combined, discusses the technical architecture for the development of such a system in addition to present the economic benefits that can be gained with its use. The proposed control system, in fact, reduces the peak load with a load redistributed according to the signals determined by monitoring the consumption and attempting to chase the generation curve.

The points, which, over the years, have been the topics of many scientific studies are the involvement of users in the management of loads for the clients. To cope with the behaviour of the consumer, which, as we will analyse later is reluctant to change at first glance, several scientists have focused on the development of models which allow us to highlight the goodness of the results that each participant can achieve with DSM programs. In particular, Gudi et al. (Gudi 2010) in their paper describe a simulation tool they created that highlights which is the best operation solution to guarantee the energy supply in a context characterized by DSM. The main purpose of the simulation tool developed is to illustrate the operation of the customer Demand Side Management and evaluate an estimate the electric energy consumption at home, guaranteeing the possibility to minimize its costs. As for the simulation of the management of resources, Particle Swarm Optimization algorithm is used, which determines the distribution of energy obtained from various sources according to the load. The validity of the tool is illustrated through a case study that considers various scenarios for the home-client.

Bello et al. (Bello 2012) enhance the figure of the aggregator. They, in fact, have created a model with which is possible to analyse the tasks performed by an aggregator engaged in the management of loads of consumers, that are flexible for definition. In their paper all the advantages that the adoption of such a management tactic to ensure the economic level for both customer and for the aggregator are presented.

Also Bel et al. (Álvarez Bel 2009), analyse a key point in the functions of the aggregator. They describe a method to ensure the participation of the customer to electricity markets and negotiate bilateral contracts with agents able to use the variable price of the market in order to improve the electrical behaviour of the Energy Systems. The first step is the identification of the technical potential of each individual customer, i.e. define the amount of energy needed and the reduction of consumption that is able to realize at any time (or for shorter periods), for a given period considered (week, year). The second step is to complete the picture of the technical flexibility with information on the costs, direct and indirect, arising from the use of the flexibility that each customer can implement. This method provides to the aggregator all the information he needs to trade the flexibility of a client. The paper also discusses an application of this instrument.

In the paper by Partovi et al. (Partovi 2011) the authors present a model for the allocation of loads of energy and determination of the optimal amount of reserve power that can be obtained from the flexibility of demand. The objective achieved is to ensure the amount of load required in order to ensure the optimal conditions of the system taken into consideration. In addition, another aim achieved by the paper is a minimization of the costs of the system and the total load on the grid. The methodology proposed in this publication is an important guideline for aggregators that can exploit the consequences of their decision on the time span.

Other authors investigated which are the positive effects that a DR policy can lead to the clients (Parvania 2010) and to the distributors (Algarni 2009).

In this general framework, in this paper the attention is focused on the subject named aggregator. He is characterized as who sells and buys controllable amount of energy in the electricity market. The aggregator collects, predicts, monitors and manages a portfolio of distributed energy resources in order to minimize the cost of energy for flexible consumers (able to change their energy consumption) and creating packages of Active Demand (AD) that are capable to be sold to the market. By his actions, he is able to optimize both the inputs of energy in the grid with the Distributed Generation (DG) and the flexibility of the grid through the management of its customers. By aggregation he allows the interaction of small *prosumers* with the energy market and grid. With the variety of operations which are handled by the aggregator, he interacts with the vast majority of the actors involved in the energy system, as shown in figure 5. In the figure the TSO/DSO are the subjects that are responsible for the transmission and distribution of energy.

For sure it is possible to say that the most important interaction that the aggregator will manage in the performance of his duties is entertained with customers.

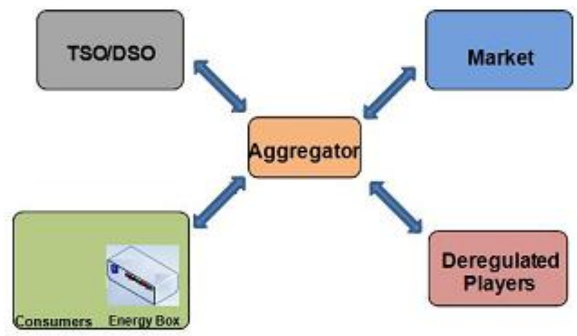

Figure 5: Positioning of the Aggregator in the Energy Market

The main role for the aggregator is the trade between consumers, which collects and sells the load flexibility, and the market in which it trades. To do so, in general, the actions that the aggregator performs in carrying out his duties as trade agent are:

- **collect the flexibility** of consumers to create products in Active Demand (AD) for sale in the market. For this reason it is expected that the aggregator has a good knowledge of loading flexibility guaranteed by its portfolio consumers. He also needs to develop technical and commercial solutions that allow consumers to take full advantage of its flexibility;
- **to be aware of requests for AD**. The aggregator must be able to get all the opportunities that will enable him to sell AD services and bring AD products to the other participants in the energy system. To do this, aggregators must collect the requests and signals coming from the various participants in the electricity system, then build offerings that meet the needs of these participants. In addition, the aggregator must also be able to adequately manage the demands of their consumers, identifying synergies, overlaps and

inconsistencies between the different requirements;

- **maximize the value of flexibility for consumers**, or collect and pack the consumer flexibility in AD so that, at the time of sale to the participants in the electricity system, its value is as large as possible. This pushes the aggregator to find in the market requests of AD with the higher added value, in order to optimize the exploitation of the flexibility of its consumers;
- **manage the risks** associated with market uncertainty, i.e. the price and the not capability to deliver the right flexibility to the right customers. In some cases, the aggregator could negotiate the transfer of these risks to other participants of the energy system in order to have better control.

The value created by the aggregator is revealed in different point of views:

- from an economic point of view: the economic value added that is divided between the participants regulated, de-regulated and the aggregator itself;
- from an environmental point of view: in fact the DR supports the development of renewable energy sources, and in the effective reduction of CO_2 emissions;
- from a technical point of view: with the investment in infrastructure that will facilitate the transition to a Smart Grid.

The crucial point for an aggregator and that is its strength or weakness at the same time, is the timing with which he is acting on the market. Whereas the trading activity for the aggregator have daily life time span, we realize that most of the decisions that he has to take are done in a very short time.

Aim of this paper is to present a decision making model for the aggregator able to facilitate him to assume the decisions above listed in the minimum time needed, maximizing its profit.

The model

The ultimate goal of this paper is the implementation of an algorithm that automates the process of redistribution of loads of customers belonging to the portfolio of an aggregator.

To better understand the dynamics of the activities examined, we should first make an overview of the management model that has been considered as the basis for this research.

Attention has been directed in particular towards the service sector, as they are still few studies in the literature relating to the management of loads of consumers belonging to this category. The idea comes from a study conducted by the International Energy Agency, in which the service sector is defined as the one with the highest potential for success in implementing policies in Demand Response as it turns out to be the one with technologies more easily to be managed temporally (Torriti 2010).

To realize a study that is manageable and understandable, only some particular kind of services companies consumers were selected. In particular, reference is made to the study conducted by CESI project called ECORET (CESI 2004). In fact, this research focuses on the benefits resulting from the application of load management to a network of MV/LV urban consumers. The kind of the consumers analysed are listed below:

- Banks
- Offices
- Hospitals
- Supermarkets (without perishable food)
- Supermarkets (with perishable food)
- Universities.

For each of these categories were analyzed and plotted consumption and load profiles. Aim of the aggregator is to consider the different needs of each customer to manage the whole load hour by hour. It is possible to assume that the aggregator knows hourly the sum of the energy required by all its portfolio clients. Its ultimate task is to flatten the peak of the consumption curve which is obtained by the action of aggregation of the loads.

To do this in a better way and especially from the technical and economic point of view, in this paper it is presented a model, that is represented in figure 6.

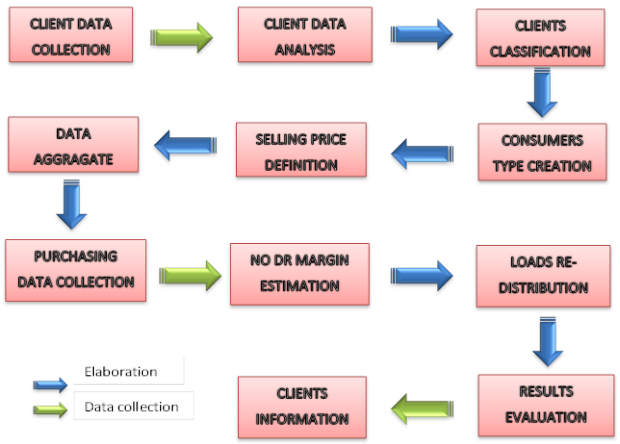

Figure 6: the decision model for the aggregator

The logical process of the aggregator consists of a series of steps. The first phase is surely linked to the acquisition of customer information. Each customer has to send to the aggregator at least the following information:

- the hour consumption;
- the maximum amount of energy that he wants to shift from an hour to another;
- the hours in which he desires to recover the energy shifted.

It is worth to note that in this model it is considered just the problem of the shifting and not the reduction of consumption, that can be seen as a particular case of the shifting; i.e. the reduction of the load can be seen as the shift to a unknown hour with load shifted equal to zero.

In figure 7 it is reported a sample of the data organization coming from the client to the aggregator. The first vector from the top to the bottom represent the total load of the actual consumption of the client, the second vector is the amount of energy he wants to shift in the specified hours and the third element in the figure 8 represent the matrix of transferring, that represent the hours in which the client wants to transfer the load transferred in the second vector.

The first vector obviously is composed of 24 positions and the same can be said for the second vector, while the third element, i.e. the matrix is a square matrix 24x24 positions.

The client in this phase also has the possibility to specify the maximum amount of load that over 24 hours is willing to move.

	Total supplied load																					
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22
	455	455	455	502	580	655	681	860	898	1012	1015	976	1058	978	904	871	770	713	588	519	499	401
	Transferred from																					
	0	0	0	0	0	70	70	50	50	120	0	0	0	0	50	60	0	171	70	0	0	0
	Transferred to																					
1	0	0	0	0	0	0	0	50	0	0	0	0	0	0	0	0	0	50	0	0	0	0
2	0	0	0	0	0	50	0	0	0	0	0	0	0	0	0	0	0	170	0	0	0	0
3	0	0	0	0	0	50	0	40	0	0	0	0	0	0	0	0	0	0	0	0	0	0
4	0	0	0	0	0	0	30	35	0	0	0	0	0	0	0	0	0	0	65	0	0	0
5	0	0	0	0	0	0	45	0	0	0	0	0	0	0	0	0	0	0	70	0	0	0
6	0	0	0	0	0	50	20	0	0	120	0	0	0	0	0	0	0	0	0	0	0	0
7	0	0	0	0	0	0	20	0	50	110	0	0	0	0	0	0	0	0	0	0	0	0
8	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0

Figure 7: Data from the clients collection

Received all the information from each customer, the next step for the aggregator is the analysis of all the data to classify consumers by type of consume. The categories that the aggregator creates have a key in the differentiation by price of energy sold. In particular, customers who have higher consumption (and therefore guarantee to the aggregator an higher cash input) benefits from more favorable prices compared to customers who consume less and for which the selling price is higher. Once the customers are divided in the different kind, it is possible to aggregate them.

Moving its focus on the market, the aggregator becomes aware of another parameter: the purchase price of the energy. On the variability of the purchasing price on hourly and daily interval the policies of Demand Response create their strength to produce an advantage for the aggregator and the customer. Depending on the amount of energy the aggregator buys and when he makes the purchase, it is possible to develop different scenarios for the management of customer needs with different resulting profits. In this perspective, important parameters to be managed and evaluated by the aggregator are:

1. the ability to correctly predict market trends;
2. the knowledge of its customers behaviours.

At this point, the aggregator has all the data to perform its task and then proceeds to the redistribution hourly load of its customers. The choice of the positioning of loads in the 24 hours of the day is made according to certain rules such as:

- **profit**: moving a quantity of kWh from an hour to another will take place only if the aggregator and the customer will benefit. More complex behaviours by the aggregator about the profit can be made thinking to the fact to move some loads from an hour to another to affect the market equilibrium.
- **user constraints**: the constraint is described above as daily shift and to the redistribution hours as introduced through the representation in figure 7.
- **constraints of the grid**: the shifts can be done as long as they do not go to violate the maximum capacity of the grid.

Given these general principles for the model, it is possible to formalize the problem in a mathematical way as it is done in the following description.

In the model the objective function wants to have the maximum profit transferring an amount of load from an hour *j* to an hour *i* for the *k-th* client, x_{ijk}, that is characterized by the profit for each *kWh* sold in the *j-th* hour or *i-th* hour, i.e. U_j and U_i. This objective function is subject to four main constraints. The first one is expressing the fact that the aggregator cannot move for the *k-th* client an amount of load greater than that defined by the customer for the *i-th* hour, i.e. v_{ik}. The second constraint makes it impossible to assign to the *j-th* hour a quantity of energy exceeding the maximum load capacity that the network can withstand, i.e. c_j. The third constraint ensures that the whole load in the 24 hours, that will be transferred for the single client *k-th*, will not exceed the maximum amount stated by the client, i.e. A_k. The fourth constraint ensures that the load amount to be transferred from the *i-th* hour to the *j-th* hour is less than the maximum quantity declared by the client, i.e. W_{ijk}. The other constraints express the domains in which all the elements are defined. For the parameter *U*, it is worth to note that they are defined in the real numbers set, but they are finally expressed as euros.

$$\boldsymbol{z = \sum_{ijk} x_{ijk} \left(U_j - U_i\right) \quad Max!}$$

s. to:

$$\textbf{1.}\quad \boldsymbol{\sum_j x_{ijk} \le v_{ik}} \qquad \boldsymbol{\forall i, \forall k}$$

$$\textbf{2.}\quad \boldsymbol{\sum_{ik} x_{ijk} \le c_j} \qquad \boldsymbol{\forall j}$$

3. $\sum_{ij} x_{ijk} \leq A_k \quad \forall k$
4. $x_{ijk} \leq W_{ijk} \quad \forall i, \forall j, \forall k$
5. $x_{ijk} \in R$
6. $U_i, U_j \in R$
7. $v_{ik} \in R$
8. $c_j \in R$
9. $A_k \in R^2$
10. $W_{ijk} \in R$

The complexity of the problem it was not demonstrated and not calculated, but a general survey about the reference to a known model was executed and no particular reference to problems such as lot-sizing, knapsack problem, etc., was found. For this reason the research group decided to choose an agile way to solve the problem, not in exact way, but identifying an heuristic. In the future, aim of the research is to demonstrate the complexity of the problem, and so understanding which is the best solution algorithm for it.

The heuristic

The heuristic algorithm, for a given size of the instances, is able to derive a solution reasonably close to the optimal one, making it available in a short time.

Considering the increase of profit as the ultimate goal, for both the consumer and the aggregator, motivates consumers to give flexibility to their consumption curves and the aggregator to develop its task; this means that the procedure follows the lowering of the cost of the bill for consumers and an increase in profit for the aggregator. To achieve this, starting from the availability of flexible loads that each customer provides, the algorithm proceeds to a redistribution of loads to maximize the profits.

As presented in the model, each customer will provide to the aggregator:

- curve of rated load for each hour;
- quantity hourly load capable to be transferred;
- maximum amount of load transferred in the day;
- availability hourly recovery of a load moved.

The amount of data to be analysed, that is directly proportional to the number of clients included in the portfolio of the aggregator, implies that it is necessary that the algorithm decides the priority with which to perform the shifting. The loads are moved following a specific rule of prioritization. The rule chosen is: it is moved before the load with lower profit and after the load with an higher profit. The new allocation of the loads follows the dual principle, i.e. it is allocated firstly the load with the higher profit and following the others with a decreasing profit. At each step taken, in order to ensure the validity of the process, it is necessary that the algorithm acts satisfying the constraints which the whole model is subject.

The heuristic to solve the mathematic problem, expression of the decision problem illustrated in figure 6, is divided in four main steps:

1. data collection;
2. data sorting;
3. loads allocation;
4. results elaboration.

The procedure is represented in the figure 9. The first category of information are:

- hourly purchase price of energy on the market. This information is organised as a vector of 24 (number of hours per day) elements called $P_{\_pur}$;
- sales prices relative to each end customer. It is a matrix that has as many rows as established bands and 24 columns;
- maximum load capacity of the grid available. It is a vector of 24 elements that has the name of $C_{\_grid}$.

The remaining part of the data to be inserted is relative to customers and therefore its size will vary in relation to the number of customers. The information required are listed below:

- curve of rated load for each customer grouped by band. They are grouped in different matrices, one for each band and each matrix is composed by 24 elements (hours) for the columns and as many rows as are the customers belonging to each band;
- quantity of load able to be transferred from one hour to another. The matrices (one for each band) are with as many rows as the number of customers belonging to the band and 24 columns.
- availability hourly recovery of loads moved. This data are organised in a three dimensional matrix, infact for each customer and for each its band and for each hour declared as flexible, it is possible to define a vector of loads distributed in 24 hours;
- maximum load able to be managed in DR. It is a column vector, for band containing the load limit.

After all these data are collected, they are sorted following the previous introduced priorization rules, and it is applied the allocation algorithm represented in figure 9 on phase 3. In particular the allocation is done following the sequence individuated in the phase two and a load is allocated in DR when all the constraints are satisfied or, if it is not, no load in DR is allocated. After that all the possible shifts are allocated or not, it is calculated the result of the DR procedure, calculating the profit for the aggregator, the cost for clients and new load curve. The method represented in this paper is quite simple but it will be demonstrated that gives good results in the management and it could be accepted as a good starting point for the people that needs to support their decisions in a so new field of operations.

Method application and experimental results

As already mentioned above, this study was conducted focusing the attention to the service sector and in particular the analysis of the six categories of utilities (to let the reader to remember the categories chosen before, they are replicated here following).

- Banks;
- offices;
- hospitals;
- department stores;
- supermarkets (Food Grade);
- universities.

The use of facilities within these utilities is varied; it is possible to imagine that the total load is composed from many utilities such as the loads associated with medical utilities, the loads for the security systems and the loads for the specific equipments. Despite each of these items contributes to the composition of the curve of total consumption of each user, in this work they have been taken into account the quantities of load that can be associated only to two facilities, both common (in varying quantities) in each category, i.e. the HVAC and the lighting. In this paper no technological facet is considered to make possible the DR on these facilities, because aim of this paper is to consider the DR from the economic point of view. Suffice it to say that for HVAC we consider the possibility for the clients to exploit the thermal inertias and for the lights the use of storage batteries.

The scenario in which it will be developed the following simulations is part of the hypothesis for which we can find an aggregator to manage customers in the six categories set out above. The number of total customers and each category will vary randomly within the extreme points evaluated in Table 1.

The sale of energy by the aggregator to its clients is done with different prices for each category. In particular, for the simulations were taken into account values obtained from those applied by Enel Energia (Italian company for energy selling) for the band tariff (table 2).

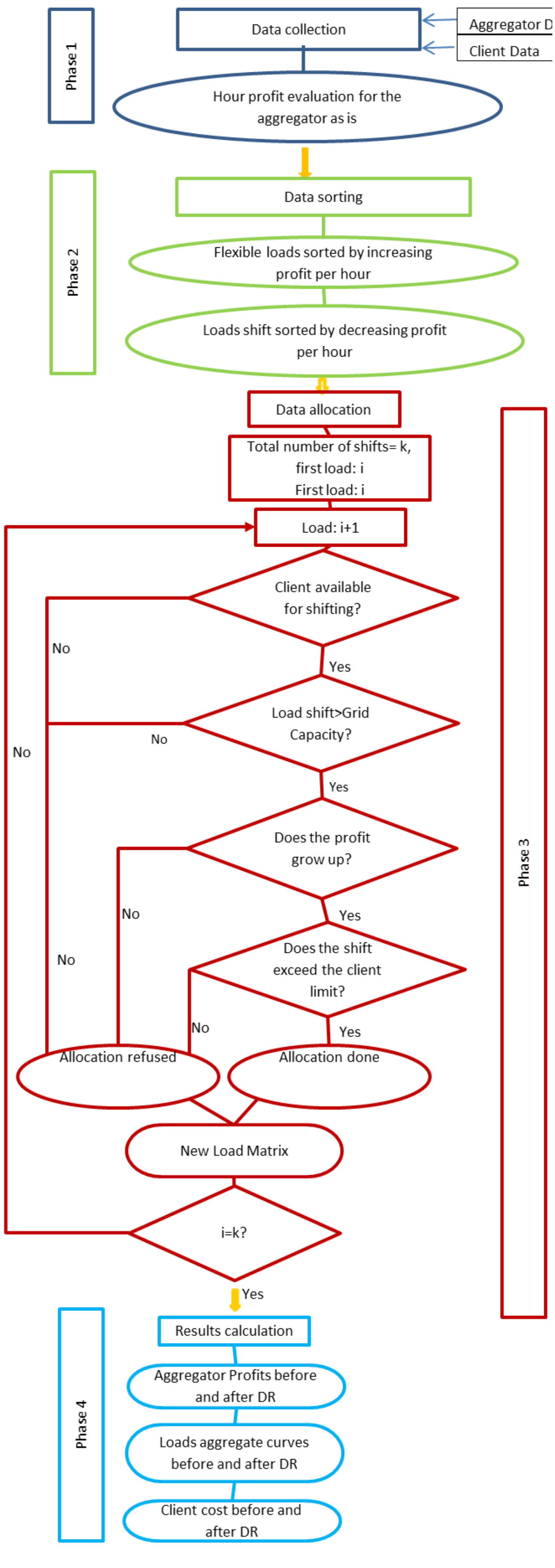

Figure 9: heuristic algorithm

	Hospitals	***Department stores***	***Super markets***	***Offices***	***Banks***	***Universities***
MIN	5	50	50	20	20	5
MAX	15	150	150	60	60	15

Table 1: number of clients differentiated for category

With regard to the prices at which the aggregator buy energy on the market, these values, considered in the simulations, are based on the UNP - Unique National Price for Italy, dated 24/09/2013 and evaluated below, as in table 3.

[€/kWh]	***1***	***...***	***15***	***...***	***24***
Hospitals	0.076	...	0.0829	...	0.076
Department Stores	0.0765	...	0.0829	...	0.0765
Super markets	0.0801	...	0.0866	...	0.0801
Offices	0.0765	...	0.0829	...	0.0765
Banks	0.0741	...	0.0812	...	0.0741
Universities	0.0773	...	0.0821	...	0.0773

Table 2: selling price for different categories

[€/kWh]	***1***	***...***	***15***	***...***	***24***
UNP	0.0428	...	0.07153	...	0.04425

Table 3: UNP on 24th of September 2013

The maximum limit with regard to the hourly capacity of transport of the distribution network has been rated as 500 MW for all simulations, expressed in power since the physical limit of the network is represented by the amount of current, and therefore power, that instantly can transit on the grid.

To simulate the system, it was implemented the mathematical model and the heuristic, to solve it in MATLAB®. They were analysed six scenarios, with different possibility of availability to the flexibility of the loads measured with the percentage of the loads that can be moved from an hour to others. For each scenario the number of clients for each category is randomly calculated in the limit reported in table 1. All the scenarios characteristics simulated are reported in table 4.

	Sc. 1	Sc. 2	Sc. 3	Sc. 4	Sc. 5	Sc. 6
Number of clients (randomly generated)	321	344	397	328	312	220
Flexibility availability (% of load)	5	5	10	10	15	15

Table 4: scenarios simulated

It is worth to note that the hours in which the loads are re-allocated are chosen randomly by the MATLAB procedure, choosing between the hours close to the ones with higher costs, always respecting the constraints before cited.

The first simulation performed has a total of 321 clients distributed as follows:

- 15 hospitals;
- 99 department stores;
- 130 supermarkets;
- 25 offices;
- 37 banks;
- 15 university.

The number of each kind of client is generated randomly between the limits reported in table 1.

It has been supposed that customers in this simulation gave the flexibility availability for the 5% of their load in the time of 24 hours, the hours in which they are available is randomly distributed.

Making the sum of the load curves of all customers for each hour, the aggregator can define an aggregate curve reported in figure 10.

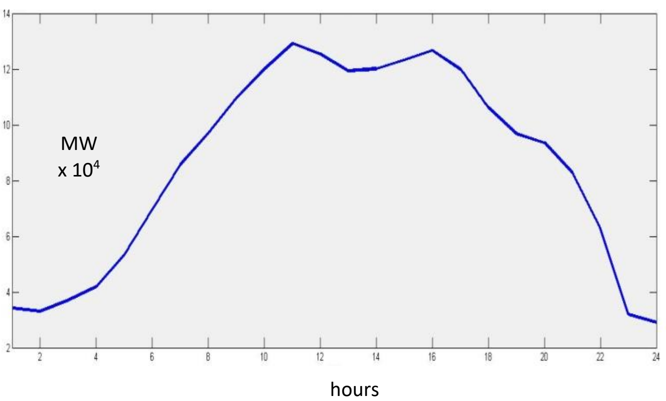

Figure 10: Aggregate loads curve before DR

Predictably, the figure 10 shows that, compared with a minimum consumption recorded during the night, the energy demand increases as the mid-day hours are reached. Calculated the aggregate curve, it was applied the algorithm to solve the mathematical model and the redistribution of loads was performed in order to achieve a common benefit. From figure 11 it is possible to observe the comparison between the two loads aggregate (before and after the DR). In particular at 11 of the day considered, the power demand is 130 MW, as a result of the process of DR, a lowering of the level of demand up to 123MW is achieved. With this solution, in addition to a lowering of the peaks in the hours of maximum crowding of the grid, the aggregator can achieve an increase of the revenues of about 4%.

Besides the advantages for the aggregator, this action of reallocation just described also ensures a gain for customers, which in front of a minimal discomfort due to the displacement of a slice of the load, obtain a saving on the bill. The principal effect of a DR policy is recognizable as a flattening of the load curve, that has multiple effects on the aggregator economy.

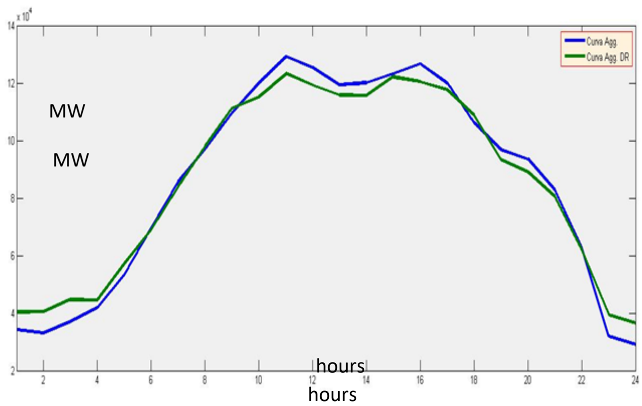

Figure 11: Aggregate loads curves before and after DR

Other similar experiments with comparable results were performed for all the scenarios reported in table 4. Following in table 5 the results of all the simulations, with the revenues results, the total load flattening and the customer saving, are reported.

	Sc. 1	Sc. 2	Sc. 3	Sc. 4	Sc. 5	Sc. 6
% Aggregator revenues	4	4.5	9	8.5	13	14
% Customer savings	0.15	0.15	0.3	0.27	0.4	0.4
% Load flattening in the peak	5.38	5.06	10.42	9.9	14.78	15.2

Table 5: scenarios simulations results

The results obtained showed always a win-win situation for all parties involved. In fact, in each of them it was found:

- lower values of load at peak hours;
- increased revenues obtained by the aggregator;
- savings in the bill by the customer.

In particular, the simulations showed that the last two items listed are directly related to the amount of load that customers makes available for shifting. In this regard, by analyzing the data obtained in the simulations it is possible to obtain the graphs of the following figures for average values of revenues and savings, grouped by percentage of load available for shifting.

In these figures (i.e. figures 12 and 13) it was put in evidence the trend that the rate of increase of the revenues for the aggregator and the percentage of the lowering of the costs that the customer obtains, moves accordingly to the percentage load flexibility. This is, probably, due to the fact that as the flexibility of loads grows up as the possibility to easier reallocate the loads on different hours.

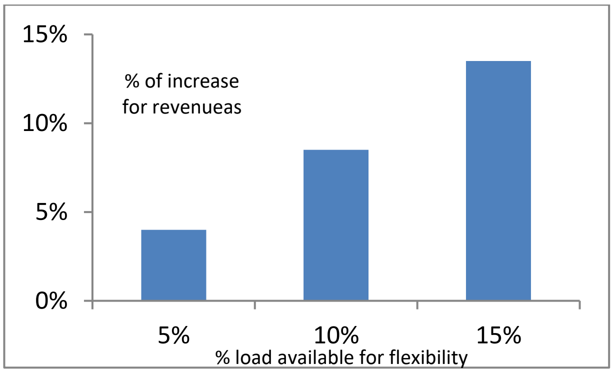

Figure 12: % increase of revenues varying the load flexibility availability by customers

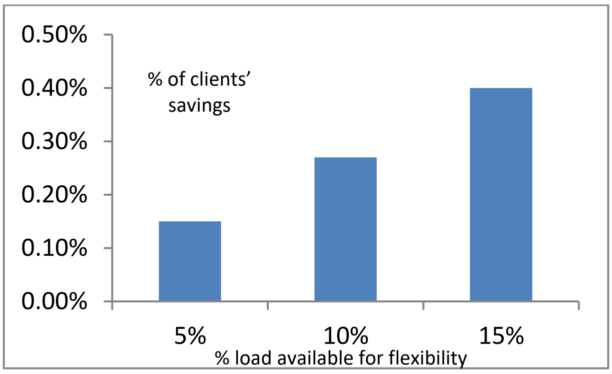

Figure 13: % of clients' savings varying the load flexibility availability by customers

In particular, a doubling of the amount of load subject to shift corresponds to an increase of about 2 times the amount of revenue that the aggregator produces and 2.7 times the savings to customers. In addition, tripling the amount of load shifted, the increase in revenues is more than 4 times compared to the initial one and the savings becomes greater than the initial 3.7.

What may seem at first glance, is that the percentage values obtained, especially those related to customer savings, are very low, but it is worth to note that:

- the simulations were performed with a number of customers very limited compared to the size of a common portfolio of an aggregator. In fact, usually it can even reach tens of thousands of customers.
- the values of average savings rate in the simulations are calculated on a daily basis. It is easy to see that, repeating the action over the medium/long term (months/year), the values at stake are beginning to reach large quantities. Also not to be overlooked is the opportunity to increase the adoption of a DR policy by the customers using an incentives policy paid by the aggregator, that can decide to share the increase of its revenues.

But along with the benefits guaranteed to the individual actor, it is important to remember that a lowering of the load values at peak hours, such as obtained in the simulations, it contributes to the reduction of network losses. Therefore, in addition to streamlining the flows that congest the network you get a reasonable energy saving as whole system. To enforce the advantage of this perspective is also the possibility of influencing the prices of the market which, as we said earlier, are contingent upon energy demand. It is possible to affirm that, having a flattening of the curves of consumption, during peak hours, it is possible to guarantee a lowering of the purchase price of the market and a reduction of the black-out risk. Naturally, this achievement is possible only in a future perspective, when the DR will be more widespread and other policies connected to the smart grids will be offered to the different echelons of the energy market.

Conclusions

In this paper it was analysed, studied and discussed an economic model for the evaluation of DR policies.

A wide literature analysis was conducted to understand what is the point of view of international literature about this energy policy in the modern world. It was identified a lack of international literature about the economic perspective for the demand response. A general framework was defined and a mathematical model was developed. In the paper it was not faced the complexity analysis of the model and it was decided to present and implement an heuristic to solve the problem.

The mathematic model is based on the assumption that the economic advantage can be understood comparing the profits passing from an hour to another the energy load. This objective function is constrained through the information available from the clients (for their availability to the shifting (or shedding) of a specific energy load and from the grid manager (for the power transmission and distribution capacity). Applying the resolution method (i.e. an heuristic method based on the vector ordering process) it was possible to find a solution to the problem of the aggregators.

In the paper it was also conducted an experimental campaign to demonstrate the effectiveness of the model and its heuristic and the demand response policy application. It was found that the DR policies application is convenient for both the main actors of this policy, i.e. for the aggregator and the client. In particular the first echelon is able to reduce the risk for the grid about the picks of consume and to increase the revenues shifting or shedding the power supplied to the clients. Instead for the clients it is possible to reduce the energy supply cost, having a little disturb in its normal consume behaviour.

So, it is possible to affirm that the DR is a good tool for improving the revenues performance for the aggregators and the cost savings for the clients, lowering the consumptions and having positive effects on the whole market of energy. Moreover, it is worth to note that the advantages, for this kind of applications, are not limited to the economic point but great advantage are achievable in the technical perspective, especially thinking to the whole load that the energy supplying companies have to handle and to manage, avoiding financial and black-out risks.

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