Demand Response in future power systems management – A conceptual framework and simulation tool

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RESUMO

No âmbito dos mercados competitivos de energia eléctrica, fortemente direccionados para a eficiência, a *demand response* torna-se especialmente importante. Espera-se que a *demand response* assuma um papel relevante nos sistemas eléctricos de energia com uso intensivo da produção distribuída, muito baseada em fontes de energia renováveis com a sua inerente intermitência. Uma participação mais activa dos consumidores poderá melhorar a fiabilidade do sistema e diminuir ou diferir investimentos em unidades de produção de energia eléctrica e outras infraestruturas do sistema de energia. Do ponto de vista dos consumidores, tal deverá resultar em redução dos custos, garantido sempre os requisitos mínimos de conforto. Uma vez que os níveis de *demand response* diminuíram desde a introdução dos mercados competitivos de energia eléctrica, são necessários novos modelos para tirar pleno partido da *demand response*.

O DemSi, um simulador de *demand response*, concebido e implementado no âmbito desta tese, permite o estudo das acções e programas de *demand response* relativos aos consumidores existentes nas redes de distribuição. Este simulador efectua a validação técnica das soluções obtidas através de uma simulação de rede efectuada em PSCAD. O DemSi apoia a decisão, no que diz respeito ao desenvolvimento e uso adequado dos programas de DR.

O simulador DemSi tem em conta as entidades envolvidas nas acções de DR, sendo os resultados analisados sob o ponto de vista de cada uma delas. Consideram-se cinco tipos de entidades: consumidores, fornecedores/retalhistas, operadores de rede de distribuição, *Curtailment Service Providers* (CSPs) e *Virtual Power Players* (VPPs). Os modelos permitem a minimização dos custos de operação ou a maximização dos lucros.

Foram desenvolvidos vários modelos, cobrindo uma ampla gama de programas de *demand response* com características diversas. Cada modelo é definido por diversas características, incluindo o *trigger*, a caracterização da resposta dos consumidores e a participação agregada de consumidores e produtores distribuídos.

ABSTRACT

In competitive electricity markets with deep efficiency concerns, demand response gains significant importance. Moreover, demand response can play a very relevant role in the context of power systems with an intensive use of distributed energy resources, from which renewable intermittent sources are a significant part. More active consumers' participation can help improving the system reliability and decrease or defer the required investments. From the consumers' point of view, it can result in reduced costs while guaranteeing adequate comfort levels. As demand response levels have decreased after the introduction of competition in the power industry, new approaches are required to take full advantage of demand response opportunities.

DemSi, a demand response simulator, designed and implemented in the scope of this thesis, allows studying demand response actions and schemes in distribution networks. It undertakes the technical validation of the solution using realistic network simulation based on PSCAD. DemSi is able to support decision making concerning demand response programs design and use.

DemSi considers the players involved in demand response actions, and the results can be analyzed from each specific player point of view. Five types of players are considered: electricity consumers, electricity retailers/suppliers, distribution network operators (DNO), Curtailment Service Providers, and Virtual Power Players (VPPs). Each model considers the minimization of the operation costs or the maximization of the profits.

Several models were developed covering a diversity of demand response programs. Each model is defined by a number of items such as the program event trigger (mostly based on Locational Marginal Prices), the response characterization, and the aggregated participation of players, namely consumers and DG owners.

Keywords: Demand Response; Distribution Networks; Electricity Markets; Energy Resource Management; Network Simulation.

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ACRONYMS

AC	Alternating Current
AS	Ancillary Services
ASM	Ancillary Services Markets
BUL	Balancing Up Load
CAISO	California Independent System Operator
CAMS	Customer and Asset Management System
CHP	Combined Heat and Power
CL	Critical Loads
CM	Capacity Market
CONOPT	CONtinuous global OPTimizer
CPLEX	Simplex and C programming
CPP	Critical Peak Pricing
CSP	Curtailment Service Provider
DADRP	Day-Ahead Demand Response Program
DALR	Day-Ahead Laod Response
DBB	Demand Bidding/Buyback
DDRI	Demand Response Resource type I
DDRII	Demand Response Resource type II
DemSi	Demand Simulator
DG	Distributed Generation
DICOPT	Discrete and Continuous OPTimizer

DLC	Direct Load Control
DM	Domestic consumer
DNO	Distribution Network Operators
DOE	Department Of Energy
DR	Demand Response
DS	Demand Side
DSASP	Demand Side Ancillary Services Program
EDR	Emergency Demand Response
EDR	Emergency Demand Response
EDRP	Emergency Demand Response Program
ELR	Economic Load Response
EM	Electricity Market
EMTDC	Electro-Magnetic Transients for DC
EnerNOC	Energy Network Operations Center
ERCOT	Electric Reliability Council of Texas
FERC	Federal Energy Regulatory Commission
FS	Flexible Supply contracts
GAMS	General Algebraic Modeling System
HVAC	Heating, Ventilation, and Air Conditioning
ICAP	Installed Capacity Program
ICS	Interruptible/Curtailable Service
ISO	Independent System Operator
ISONE	Independent System Operator of New England
LaaR	Load acting as Resource
LC	Large Commerce consumer

LI	Large Industrial consumer
LM	Load Management
LMP	Locational Marginal Price
MATLAB	MATrix LABoratory
MI	Medium Industrial consumer
MINLP	Mixed Integer Non Linear Programming
NERC	North American Electric Reliability Corporation
NSBO	North Square Blue Oak
NSL	Non-Supplied Load
NSP	Non-Supplied Power
NYISO	New York Independent System Operator
PJM	PJM Interconnection LLC
PLP	Participating Load Program
PSCAD	Power System Computer Aided Design
PSO	Particle Swarm Optimization
PSO-MUT	Particle Swarm Optimization with MUTation
RDR	Real-time Demand Response
RL	Regular Loads
RPR	Real-time Price Response
RTO	Regional Transmission Operator
RTP	Real Time Pricing
SC	Small Commerce consumer
SCADA	Supervisory Control And Data Acquisition
SCI	Science Citation Index
ST	Source Types

TOU	Time Of Use
TSO	Transmission System Operator
VLR	Voluntary Load Response
VOLL	Value Of Lost Load
VPP	Virtual Power Player

NOMENCLATURE

ε	Price elasticity of demand
a	Day-of adjustment
b	Baseline average
c	Consumer index
C	Highest kW energy consumption for a given time interval t
d	Non-event day
dn	Nth highest energy usage day among previous 10 non-event days
e	Total time intervals during event
Ca_{CHP}	CHP fixed cost [m.u./h]
$Ca^{e}_{Gen(g)}$	Generator g fixed cost, for the energy product [m.u./h]
$Ca^{e}_{Red(c)}$	Consumer c reduction fixed cost, for the energy product [m.u./h]
$Ca^{e}_{Supplier(sp)}$	Supplier sp fixed cost, for the energy product [m.u./h]
Ca_{O1}	Other generation of group 1 fixed cost [m.u./h]
Ca_{O2}	Other generation of group 2 fixed cost [m.u./h]
$Ca^{r}_{Gen(g)}$	Generator g fixed cost, for the reserve product [m.u./h]
$Ca^{r}_{Red(c)}$	Consumer c reduction fixed cost, for the reserve product [m.u./h]
$Ca^{r}_{Supplier(sp)}$	Supplier sp fixed cost, for the reserve product [m.u./h]
Cb_{CHP}	CHP linear cost [m.u./kWh]
$Cb^{e}_{Gen(g)}$	Generator g linear cost, for the energy product [m.u./kWh]
$Cb^{e}_{Red(c)}$	Consumer c reduction linear cost, for the energy product [m.u./kWh]
$Cb^{e}_{Supplier(sp)}$	Supplier sp linear cost, for the energy product [m.u./kWh]

Cb_{O1}	Other generation of group 1 linear cost [m.u./kWh]
Cb_{O2}	Other generation of group 2 linear cost [m.u./kWh]
$Cb^{r}_{Gen(g)}$	Generator *g* linear cost, for the reserve product [m.u./kWh]
$Cb^{r}_{Red(c)}$	Consumer *c* reduction linear cost, for the reserve product [m.u./kWh]
$Cb^{r}_{Supplier(sp)}$	Supplier *sp* linear cost, for the reserve product [m.u./kWh]
Cc_{CHP}	CHP quadratic cost [m.u./kWh^2]
$Cc^{e}_{Gen(g)}$	Generator *g* quadratic cost, for the energy product [m.u./kWh^2]
$Cc^{e}_{Red(c)}$	Consumer *c* reduction quadratic cost, for the energy product [m.u./kWh^2]
$Cc^{e}_{Supplier(sp)}$	Supplier *sp* quadratic cost, for the energy product [m.u./kWh^2]
Cc_{O1}	Other generation of group 1 quadratic cost [m.u./kWh^2]
Cc_{O2}	Other generation of group 2 quadratic cost [m.u./kWh^2]
$Cc^{r}_{Gen(g)}$	Generator *g* quadratic cost, for the reserve product [m.u./kWh^2]
$Cc^{r}_{Red(c)}$	Consumer *c* reduction quadratic cost, for the reserve product [m.u./kWh^2]
$Cc^{r}_{Supplier(sp)}$	Supplier *sp* quadratic cost, for the reserve product [m.u./kWh^2]
$C_{Cut(c)}$	Cost of power curtailment *Cut* in the load of consumer *c* [m.u./kWh]
$C_{CutA(c)}$	Cost of power curtailment *CutA* in the load of consumer *c* [m.u./kWh]
$C_{CutB(c)}$	Cost of power curtailment *CutB* in the load of consumer *c* [m.u./kWh]
$C_{CutC(c)}$	Cost of power curtailment *CutC* in the load of consumer *c* [m.u./kWh]
$C_{Day-ahead}$	Cost of the day-ahead market energy [m.u./kWh]
$C_{DR-Contract(c)}$	Cost of power curtailment in the *DR-Contract* capacity, in the load of consumer *c* [m.u./kWh]
$C_{DR-Event(c)}$	Cost of power curtailment in the *DR-Event* capacity, in the load of consumer *c* [m.u./kWh]
C_{EGP}	Cost of excess generated power [m.u./kWh]

$C_{EGP(g)}$	Cost of excess generated power, in generator *g* [m.u./kWh]
$C_{Gen(gt)}$	Generation cost of generation type *gt* [m.u./kWh]
$C_{Gen(g)}$	Generation cost of generator *g* [m.u./kWh]
$C_{Initial(c)}$	Initial electricity price for consumer *c* [m.u./kWh]
$C_{MaxVar(c)}$	Maximum variation in the electricity price for consumer *c* [m.u./kWh]
C_{NSP}	Cost of non-supplied power [m.u./kWh]
$C_{NSP(c)}$	Cost of excess generated power, for consumer *c* [m.u./kWh]
C_{Other}	Value of other costs [m.u.]
C_{PV}	Photovoltaic generation cost [m.u./kWh]
$C_{Real-time}$	Cost of the real-time market energy [m.u./kWh]
$C_{Red(c)}$	Cost of power reduction *Cut* in the load of consumer *c* [m.u./kWh]
$C_{RedA(c)}$	Cost of power reduction *CutA* in the load of consumer *c* [m.u./kWh]
$C_{RedB(c)}$	Cost of power reduction *CutB* in the load of consumer *c* [m.u./kWh]
$C_{RedC(c)}$	Cost of power reduction *CutC* in the load of consumer *c* [m.u./kWh]
$C_{StorageCharge}$	Cost of storage units charge [m.u./kWh]
$C_{StorageCharge(s)}$	Cost of storage unit *s* charge [m.u./kWh]
$C_{StorageDischarge}$	Cost of storage units discharge [m.u./kWh]
$C_{StorageDischarge(s)}$	Cost of storage unit *s* discharge [m.u./kWh]
$C_{Supplier}$	Cost of energy acquisition to supplier [m.u./kWh]
$C_{Supplier(sp)}$	Cost of energy acquisition to supplier *sp* [m.u./kWh]
$C_{Var(c)}$	Variation in consumer *c* electricity price [m.u.]
C_{Wind}	Wind generation cost [m.u./kWh]
$Elasticity_{(c)}$	Price elasticity of consumer *c*
gt	Generation types index
Nc	Total number of consumers

Ng	Total number of generators
Ngt	Total number of generation types
Ns	Total number of storage units
OC	Total operation costs [m.u.]
p	Total performance [kW]
P_{CHP}	Power supplied by CHP [kW]
$P_{Cut(c)}$	Power curtailment *Cut* in the load of consumer *c* [kW]
$P_{CutA(c)}$	Power curtailment *CutA* in the load of consumer *c* [kW]
$P_{CutB(c)}$	Power curtailment *CutB* in the load of consumer *c* [kW]
$P_{CutC(c)}$	Power curtailment *CutC* in the load of consumer *c* [kW]
$P_{Day-ahead}$	Power acquired in the day-ahead market [kW]
P_{DG}	Power available from DG [kW]
$P_{DR-Contract(c)}$	Power curtailment in the *DR-Contract* capacity, in the load of consumer *c* [kW]
$P_{DR-Event(c)}$	Power curtailment in the *DR-Event* capacity, in the load of consumer *c* [kW]
$P^{e}_{Gen(g)}$	Generator *g* scheduled power, for the energy product [kW]
P_{EGP}	Excess generated power [kW]
$P_{EGP(g)}$	Excess generated power, by generator *g* [kW]
$P^{e}_{MaxGen(g)}$	Generator *g* maximum power for the energy product [kW]
$P^{e}_{MaxRed(c)}$	Maximum consumer *c* reduction power for the energy product [kW]
$P^{e}_{MaxSupplier(sp)}$	Supplier *sp* maximum schedulable power for the energy product [kW]
$P^{e}_{Red(c)}$	Consumer *c* scheduled load reduction, for the energy product [kW]
$P^{e}_{Supplier(sp)}$	Supplier *sp* scheduled power, for the energy product [kW]
$P_{Gen(g)}$	Generator *g* scheduled power [kW]
$P_{Gen(gt)}$	Generator type *gt* scheduled power [kW]

$P_{Load(c)}$	Initial power of load demand [kW]
P_{MaxCHP}	Maximum generation available in CHP [kW]
$P_{MaxCut(c)}$	Maximum power curtailment *Cut* in the load of consumer *c* [kW]
$P_{MaxCutA(c)}$	Maximum power curtailment *CutA* in the load of consumer *c* [kW]
$P_{MaxCutB(c)}$	Maximum power curtailment *CutB* in the load of consumer *c* [kW]
$P_{MaxCutC(c)}$	Maximum power curtailment *CutC* in the load of consumer *c* [kW]
$P_{MaxDay-ahead}$	Maximum power available from the day-ahead market [kW]
$P_{MaxDR-Contract(c)}$	Maximum power curtailment in the *DR-Contract* capacity, in the load of consumer *c* [kW]
$P_{MaxDR-Event(c)}$	Maximum power curtailment in the *DR-Event* capacity, in the load of consumer *c* [kW]
$P_{MaxGen(g)}$	Generator *g* maximum power [kW]
$P_{MaxGen(gt)}$	Generator type *gt* maximum power [kW]
P_{MaxO1}	Maximum power available in other technologies of group 1 [kW]
P_{MaxO2}	Maximum power available in other technologies of group 2 [kW]
P_{MaxPV}	Maximum power available in photovoltaic [kW]
$P_{MaxRed(c)}$	Maximum power curtailment *Red* in the load of consumer *c* [kW]
$P_{MaxRedA(c)}$	Maximum power curtailment *RedA* in the load of consumer *c* [kW]
$P_{MaxRedB(c)}$	Maximum power curtailment *RedB* in the load of consumer *c* [kW]
$P_{MaxRedC(c)}$	Maximum power curtailment *RedC* in the load of consumer *c* [kW]
$P_{MaxStorage}$	Maximum power available from storage [kW]
$P_{MaxStorageCharge}$	Maximum power storage charge [kW]
$P_{MaxStorageDischarge}$	Maximum power storage discharge [kW]
$P_{MaxSupplier(sp)}$	Maximum power available from supplier *sp* [kW]
$P_{MaxWind}$	Maximum power available in Wind [kW]

$P_{MinGen(gt)}$	Minimum schedulable power in generation type *gt* [kW]
P_{NSP}	Non-supplied power [kW]
$P_{NSP(c)}$	Non-supplied power in consumer *c* [kW]
P_{O1}	Power supplied by other technologies of group 1 [kW]
P_{O2}	Power supplied by other technologies of group 2 [kW]
P_{PV}	Power supplied by photovoltaic [kW]
pr	Reserve use probability
$P_{Real-time}$	Power acquired in the real-time market [kW]
$P_{Red(c)}$	Power reduction *Cut* in the load of consumer *c* [kW]
$P_{RedA(c)}$	Power reduction *CutA* in the load of consumer *c* [kW]
$P_{RedB(c)}$	Power reduction *CutB* in the load of consumer *c* [kW]
$P_{RedC(c)}$	Power reduction *CutC* in the load of consumer *c* [kW]
$P^{r}_{Gen(g)}$	Generator *g* scheduled power in the reserve product [kW]
$P^{r}_{MaxGen(g)}$	Generator *g* maximum power for the reserve product [kW]
$P^{r}_{MaxRed(c)}$	Maximum consumer *c* reduction power for the reserve product [kW]
$P^{r}_{MaxSupplier(sp)}$	Supplier *sp* maximum schedulable power for the reserve product [kW]
$Profit$	Retailer profit [m.u.]
$P^{r}_{Red(c)}$	Consumer *c* scheduled reduction power for the reserve product [kW]
$P^{r}_{Required}$	Reserve product required power [kW]
$P^{r}_{Supplier(sp)}$	Supplier *sp* scheduled power for the reserve product [kW]
$P_{Storage}$	Storage scheduled power [kW]
$P_{StorageCharge}$	Storage scheduled charge power [kW]
$P_{StorageCharge(s)}$	Storage unit *s* scheduled charge power [kW]
$P_{StorageDischarge}$	Storage scheduled discharge power [kW]

$P_{StorageDischarge(s)}$	Storage unit *s* scheduled discharge power [kW]
$P_{StorageInitial}$	Initial power available in storage [kW]
$P_{Supplier}$	Supplier scheduled power [kW]
$P_{Supplier(sp)}$	Supplier *sp* scheduled power [kW]
P_{Wind}	Power supplied by wind [kW]
sp	Supplier index
t	Time interval
$t-n$	Time interval starting n hours prior to event notification
X_{CHP}	Binary variable of CHP
$X_{Cut(c)}$	Binary variable related to the power curtailment in the load of consumer *c*
X_{Event}	Binary variable related to the existence of a DR event
$X_{Gen(gt)}$	Binary variable related to the use of generation type *gt*
$X_{Gen(g)}$	Binary variable related to the use of generator *g*
X_{O1}	Binary variable related to the use of other technologies of group1
X_{O2}	Binary variable related to the use of other technologies of group2
$X_{Storage}$	Binary variable related to the use of storage charge
$Y_{Storage}$	Binary variable related to the use of storage discharge

Chapter 1

Introduction

1 INTRODUCTION

This chapter exposes the motivation of the work developed in the scope of this thesis. The importance of demand response in the context of the present and future power systems is explained and based on a short but highly relevant reference list.

The chapter provides readers with the work objectives and presents a brief overview of the demand response simulator designed and implemented. The work main achievements are summarized. Finally, the organization of the thesis is presented.

1.1 MOTIVATION

1.1.1 Background

The concept of Electricity Markets (EMs) appeared in the most developed countries as a consequence of power system deregulation and power sector restructuring [Kirschen-2003]. EMs involve a large number of players that are expected to act in a competitive environment, taking advantage of the available opportunities and strategies to accomplish their individual goals. Moreover, the whole power system should be able to attain global requirements, guaranteeing demand satisfaction within accepted reliability levels [Cigré-2011].

The implementation of EMs was expected to lead to relevant advantages concerning the increase in power system efficiency and price reduction due to the end of monopolies [Kirschen-2003]. However, the experience has shown some problems in achieving these goals [Charles-2010], [Torriti-2010], [Wang-2010], due to the very specific electrical energy characteristics which make some rules and methods usually used in other commodity markets not useful in the EM context. This is mainly due to the unique characteristic of electrical energy that is a commodity, for which the balance between supply and demand must be assured at all instants. Moreover, at the current state of the art, electrical energy can only be stored in very limited quantities, because of economic reasons.

One of the areas expected to grow in the scope of EMs is the Demand Response (DR), as it appears as a very promising opportunity for consumers and brings several advantages for the whole system [Aalami-2010a], [Walawalkar-2010]. This is due to the fact that the power system infrastructure is highly capital-intensive and DR is one of the cheaper resources [Albadi-2008]. On the other hand, DR programs can provide the system operator with a known load curtailment capacity which is highly valuable to deal with unexpected changes in both supply and demand levels.

The present state of DR around the world has been summarized in [Woo-2010]. Experiences of DR in the wholesale market are taking place in the United States [Cappers-2010], Europe [Torriti-2010], China [Wang-2010] and also in other places around the world [Charles-2010]. However, DR use has not yet attained the envisaged levels and some difficulties in the transition from a traditionally regulated industry to a competitive environment can be justified by the lack of retail demand response.

DR is not being as successful as expected in the context of competitive markets. In some cases, the EM implementation caused a reduction in demand participation [Albadi-2008], [USDE-2006], [Bushnell-2009], [Morais-2010], [Vale-2009]. In the United States load management (LM) decreased 32% between 1996 and 2006 because of weak load management services offered by utilities [USDE-2006]. This can be explained by the 10% reduction of the money spent in LM programs since 1990. Between 1996 and 2004, 32% of U.S. utilities stopped providing LM programs [USDE-2006].

Demand Side (DS) has been unable to use all the business opportunities in the scope of EMs in a satisfactory way. This participation difficulty is verified for large DS players and also obviously applies to small DS players, in a larger extent. Aggregation is being more and more used; therefore, the EM players can join their resources and efforts to obtain competitive advantage [Morais-2010] in EM. However, DR has very specific needs that even large aggregators face serious difficulties in dealing with.

In response to this, system operators and utilities are taking new initiatives, recognizing the value of DR for grid reliability and for the enhancement of organized spot markets' efficiency [FERC-2010]. However, the current state of the art does not answer the pointed problems and does not show any sign of finding the correct path so that the required solutions are obtained in a short time period. As the efforts that have been put in DR issues are very relevant, the poor results evidence the need to use a different approach to address DR issues [Faria-2010]. This thesis presents a work that contributes to such approaches. The main focus of this thesis is DR program modeling and simulation. DemSi, a DR simulator is one of the main results of the developed work. DemSi constitutes a platform to support decision making concerning DR in the scope of distribution networks, including economic analysis and technical validation of the solutions.

1.1.2 DR importance

1.1.2.1 Benefits of Demand Response

The main benefit of DR is the improvement of power system efficiency, since a closer alignment between customers’ electricity prices and the value they place on electricity is established. A variety of benefits related to this increase of efficiency can be summarized in four groups, namely customers, whole market, reliability, and market performance benefits [Sioshansi-2009].

Customers financial benefits are mainly the bill savings and the incentive payments earned due to the adjustment of their electricity demand in response to time-varying electricity rates or incentive-based programs.

Lower wholesale market prices is a benefit for the whole market since DR can avoid the need to use the electricity generation provided by high cost power plants.

Other benefit can be seen at the level of the reliability by the improvement of operational security. This way, the probability and consequences of forced outages, which lead financial costs and inconveniences to customers, can be reduced.

Lastly, DR can increase market performance mitigating the market power made by raising power prices above production costs.

1.1.2.2 Why is Demand Response Important?

Several financial and operational benefits of demand response for electricity customers, load-serving entities and system operators are nowadays recognized.

Since electricity cannot be economically stored, load and generation balance must be maintained in real time. Moreover, grid conditions can change in both short and medium term and even within moments. Another feature is that the electric system is highly capital-intensive, and generation and transmission system investments have long lead times and multi-decade economic lifetimes. These features of electric power systems require power grids planning and management to assure the reliability of the system considering uncertainties on future demand and fuel sources.

In a competitive electricity market, load entities and retailers buy or sell their electrical energy in advance considering that they will be able to generate or purchase enough electricity to meet changes on system demand.

These challenges and uncertainties make demand response higher valuable since it offers flexibility at relative low cost. System operators can use demand response programs to curtail, reduce, or shift loads preventing the need of building more generation plants. In spite of requiring time to establish contracts with customers, well-structured price and incentive-based demand response can produce significant savings making possible lower costs than supply-side resources [FERC-2009].

1.1.3 DR programs

Demand response programs can be divided in two wide groups, namely price-based demand response and incentive-based demand response [USDE-2006].

Price-based demand response is related to the changes in energy consumption by customers in response to the variations in their purchase prices. This group includes Time-Of-Use (TOU), Real Time Pricing (RTP) and Critical-Peak Pricing (CPP) rates. For different hours or time periods, if the price varies significantly, customers can respond to price variations with changes in energy use. Their energy bills can be reduced if they adjust the time of the energy usage taking advantages of lower prices in some periods or reduce consumption when prices are higher. Currently, the response to price-based demand response programs by adjusting the time of consumption is entirely voluntary. However, some advantages of mandatory response can be found (see section 2.3).

TOU includes different prices for usage during different periods, usually defined for periods of 24 hours. This rate reflects the average cost of generating and delivering power during those periods.

For RTP the price of electricity is defined for shorter periods of time, usually 1 hour [Sioshansi-2009], reflecting the changes in the wholesale price of electricity. Customers usually have the information about prices on a day-ahead or hour-ahead basis.

CPP is a hybrid of the TOU and RTP programs and is harder to implement. The base program is TOU and a much higher peak pricing is used in specified conditions (e.g. when system reliability is compromised or when supply costs are very high).

Incentive-based demand response includes programs that give customers fixed or time varying incentives in addition to their electricity rates. These can be established by utilities, load-serving entities, or by a regional grid operator. Some of these programs penalize customers that fail the contractual response when events are declared. This group includes the 6 programs listed below [Cappers-2010a], [Su-2009]:

Direct Load Control (DLC) is a program that considers a remote control or cycle of a customer's electrical equipment by the DR program operator. These programs are primarily offered to residential or small commercial customers;

Interruptible/Curtailable Service (ICS) is based on curtailment options integrated into retail tariffs that provide a rate discount or bill credit by agreeing to reduce load during system contingencies and includes penalties for contractual response failures. These programs are traditionally offered to larger industrial customers;

In Demand Bidding/Buyback (DBB) programs, customers offer curtailment capacity bids and large customers are normally preferred;

Emergency Demand Response (EDR) can be seen as a mix of DLC and ICS and is targeted for periods when reserve becomes insufficient;

In Capacity Market (CM) programs, customers offer load curtailment as system capacity to replace conventional generation or delivery resources;

Ancillary Services Market (ASM) programs are basically similar to DBB programs, whereas in this case the offer is just made for the ancillary services market. As in traditional ancillary services, the remuneration can be separately paid for reserve capacity and for energy provision.

Figure 1.1 [USDE-2006] shows the integration of DR programs in the power system operation and planning, from a time horizon point of view, in the context of EMs. An important demand-side resource that can be considered independently, but not necessarily disconnected from the above described DR programs is the energy efficiency. This has to be considered in the long time system planning.

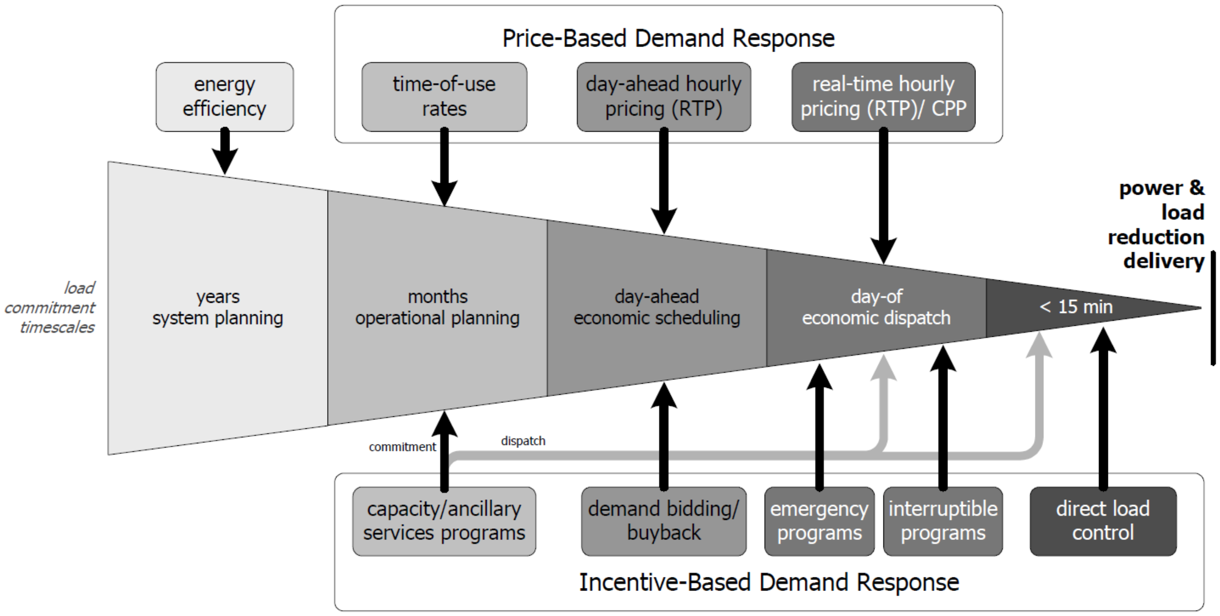

Figure 1.1. A Demand response in electric system planning and operations [USDE-2006]

1.1.4 DR tools

The positive impact of DR on power systems and on the involved players' business may be enhanced by adequate tools which are able to simulate DR programs and events, from the point of view of the relevant players. Several tools have been developed to support decision making and validation concerning demand response programs. A list of some tools can be found in [USDE-2010]. Generally, the existing software aims to assess the cost savings opportunities based on building and load characterization (HVAC, ventilation, lighting, electronic, etc.). As an example, a simulator from the U.S. Department Of Energy (DOE) with these characteristics has been upgraded to a new version (DOE-2) and includes a link to MATLAB/Simulink which integrates the control logic. These simulators generally advise users about the best DR programs at each specific context.

References [Bel-2009] and [Alcazar-2011] describe tools that deal with commercial customers. [Bel-2009] presents a tool which considers end-use resources costs (primary energy, storage, control, monitoring and measurement, and communication) to provide customers with the ability of evaluating DR opportunities. [Alcazar-2011] presents a method to validate DR tools.

Recently advanced building control systems have been designed to improve the control mechanism for energy efficiency. New studies on how to use existing control systems in commercial buildings to integrate energy efficiency and demand response are reported in [Kiliccote-2006].

DemSi, the DR simulator developed in the scope of this thesis presents several innovative features when compared with other existing tools. One important point is that the other tools deal with specific installations (e.g. commercial or residential buildings) whereas DemSi is able to deal with the application of DR programs to a large set of consumers. Moreover, it uses realistic models that allow to simultaneously take into account detailed contractual constraints and to undertake the technical validation from the point of view of the electrical behavior of the power system.

DemSi considers the players involved in the DR actions and results can be analyzed from the point of view of each specific player. This includes five types of players, namely consumers, retailers (suppliers), DNOs, CSPs, and VPPs. This thesis considers the point of view of the retailer, but the analysis can also be done from the point of view of the consumers (both individually or in the scope of a load aggregator) or the DNO.

Another advantage of DemSi is that it includes a diversity of DR programs. Although this thesis focuses on the application of real time pricing, DemSi allows choosing among a large set of DR programs, each one modeled according to its specific characteristics.

1.2 OBJECTIVES

Looking at the power systems and electricity markets current context, demand response appears as a very promising way to solve several problems and challenges. However, recent implementations have revealed some difficulties that are not addressed in the current state of the art.

This thesis presents a work that contributes to the approaches required to address the DR issues implementation difficulties.

The developed work is part of a larger vision, which main objective is to develop, implement and validate several DR program models and a methodology to support decision making concerning Demand Response (DR) program and contract design and use. The Decision-Support System (DSS) to be designed is intended for the use of the players acting in the DR programs, namely consumers, Independent System Operator (ISO), Virtual Power Players (VPPs), and Curtailment Service Providers (CSPs).

Figure 1.2 shows the envisaged DR Decision-Support System scheme. The blocks within the area limited by the yellow dashed line are the ones resulting from the present thesis.

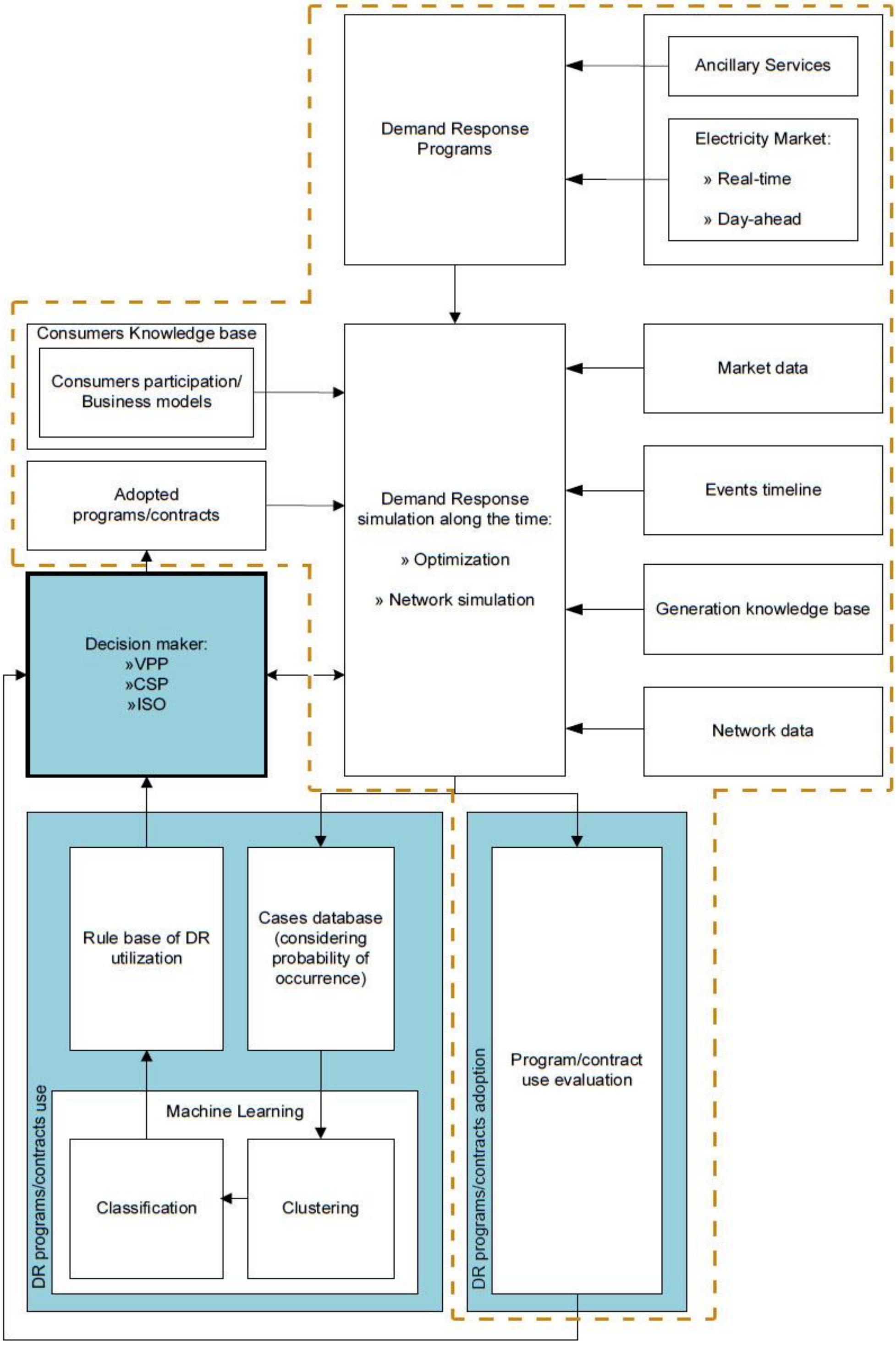

Figure 1.2. DR Decision-Support System

In the initial period of this thesis it was possible to identify the necessity of developing a simulator able to simulate a diversity of DR programs and their use by consumers. This simulator should be flexible enough to allow the consideration of existing and new DR programs with different philosophies and requirements. This flexibility need led to the design of the architecture presented in Figure 1.2 which includes a "Demand Response Programs" module. DR programs models are included in this module. The system should provide users with easy to use tools able to support the inclusion of new DR models.

Moreover, the simulator should provide users with adequate economic and technic analysis of the simulated DR programs. The simulator should be able to analyze DR from the point of view of diverse players namely consumers, retailers (suppliers), DNOs, CSPs, and VPPs. This simulator, which is one of the main results of the present thesis, is of crucial importance to enable decision-support as seen in Figure 1.2.

In the context of this decision-support based vision of DR, the specific objectives defined for this thesis were the following:

- Identification of the opportunities of DR in the present and future power systems – several changes in the operation and planning of the power systems are being caused by the intensive use of DG (largely based on intermittent renewables), the implementation of EMs, the fast growing in the consumers demand, and the increase in the costs of energy obtained from fossil fuels. DR is a promising way of facing these challenges, while contributing for the efficiency and reliability of the system. The identification of specific characteristics of DR programs is needed in order to the adequately model DR programs;
- Modeling of DR programs – after identifying the opportunities of DR in the present and future power systems, several DR programs with specific characteristics must be designed and implemented. These programs should be able to use the opportunities identified in the previous item;
- DR simulator design and implementation – a network and respective scenarios are needed to simulate the developed models. The definition of the scenarios must include relevant system conditions and characteristics, namely in what regards DG;
- Result analysis and conclusions – the results analysis makes possible to take conclusions from the thesis work. Future improvements and further research and development lines should be identified.

1.3 RELATED PROJECTS AND PUBLICATIONS

The work developed in the scope of this thesis partially concerns the objectives and results of several projects under FCT *"Fundação para a Ciência e a Tecnologia"*, under the supervision of the Knowledge Engineering and Decision Support research Centre – GECAD. The regarded projects are:

- ViP-DiGEM - VIrtual power Producers and DIstributed Generation trading in Energy Markets (PTDC/ 72889);
- ID-MAP - Intelligent Decision Support for Electricity Market Players (PTDC/EEA-EEL/099832/2008);
- FIGURE – Flexible and Intelligent Grids for Intensive Use of Renewable Energy Sources (PTDC/SEN-ENR/099844/2008).

The work developed in this thesis has resulted in the publication of seven papers as listed below. Two of these papers were published in SCI[1] journals:

- Pedro Faria, Zita Vale, "Demand response in electrical energy supply: An optimal real time pricing approach", Energy, Volume 36, Issue 8, PRES 2010, August 2011, pp.5374-5384, ISSN 0360-5442, DOI: 10.1016/j.energy.2011.06.049 (IMPACT FACTOR in 2010: 3.565)
- Pedro Faria, Zita Vale, João Soares, Judite Ferreira, "Demand Response Management in Power Systems Using a Particle Swarm Optimization Approach", IEEE Intelligent Systems, doi: 10.1109/MIS.2011.35 (IMPACT FACTOR in 2010: 2.570).

The remaining five papers have been presented and published in the proceedings of top-level conferences in the power systems area:

- Zita Vale, Carlos Ramos, Hugo Morais, Pedro Faria, Marco Silva, "The role of demand response in future power systems", IEEE - T&D Asia 2009, Seoul, Korea, 27-30 October 2009

[1] *Science Citation Index® (SCI®);* http://thomsonreuters.com/products_services/science/science_products/a-z/science_citation_index/

- Zita Vale, Hugo Morais, Pedro Faria, Judite Ferreira, "Emergency energy resource management in SmartGrids", 5th International Conference on Critical Infrastructure (CRIS), pp.1-8, 20-22 September 2010
- Pedro Faria, Zita Vale, Judite Ferreira, "Demsi - A demand response simulator in the context of intensive use of distributed generation", IEEE International Conference on Systems Man and Cybernetics (SMC), pp.2025-2032, 10-13 October 2010
- Pedro Faria, Zita Vale, João Soares, Judite Ferreira, "Particle swarm optimization applied to integrated demand response resources scheduling", IEEE Symposium on Computational Intelligence Applications In Smart Grid (CIASG), pp.1-8, 11-15 April 2011
- Pedro Faria, Hugo Morais, Zita Vale, Judite Ferreira, "LMP triggered real time demand response events", 8th International Conference on the European Energy Market (EEM), pp.45-50, 25-27 May 2011

There are parts of the work that have originated other papers that are presently being considered for publication.

1.4 THESIS ORGANIZATION

This thesis is organized in five chapters. After the present introduction chapter, chapter 2 exposes the most important concepts, experiences and implementations concerning DR. A brief description of the proposed DR programs and of actual DR experiences is made. Several DR program implementation characteristics, including the event timing, trigger logic, overuse restriction, communications, deployment, and the baseline are explained. Consumer performance evaluation methods are also addressed.

Chapter 3 presents DemSi, the DR simulator developed in the scope of this thesis, which allows the analysis and validation of DR programs and models, both in what concerns the business and economic aspects and the technical validation of their impacts in the network. The models of DR programs that have been designed and implemented in the scope of the thesis are also presented. The used software tools are briefly described. The parameters that characterize the models and make the distinction between them are also presented.

Several case studies concerning the developed models are presented in Chapter 4. The presented case studies, based on a distribution network with high penetration of DG and two sets of consumers, have been chosen to cover a diversity of situations and involved players. The obtained results are presented and discussed individually for each model, and in the end of the chapter some general conclusions are taken.

Chapter 5 presents the most important conclusions that resulted from the developed work. Some perspectives of future work are also presented.

Chapter 2

Demand Response

2 DEMAND RESPONSE

Demand Response (DR) is a fast evolving topic of the planning and operation of electricity markets and of power systems in general. In the past, most of the DR programs were based on distinct electricity tariffs for different periods of the day. Recent changes in the power systems operation in the Electricity Market (EM) organization have required the development of new DR programs in order to take full advantage of DR. Some of the concepts, experiences and implementations around DR are exposed in this section.

2.1 INTRODUCTION

2.1.1 DR definition

The demand response concept is not new but it has been changed in recent years with the aim of adapting it to the new power system characteristics. Broadly defined, demand response refers to the active participation of a consumer in the EMs checking and responding to prices of electricity that change from period to period, and accounting incentive payments. This period can vary from months (when energy efficiency is studied) to a few minutes (when real-time pricing is applied). Demand response has been defined in [USDE-2006] as follows:

"Changes in electric usage by end-use customers from their normal consumption patterns in response to changes in the price of electricity over time, or to incentive payments designed to induce lower electricity use at times of high wholesale market prices or when system reliability is jeopardized."

2.1.2 Load response strategies

The participation of a consumer in a DR program corresponds to a contribution to the reduction of electricity generation need in a specific period in a specific area. This area can be seen as the whole power system or be related with the special case of transmission congestion in a small area. The cost of DR depends in part on the type of consumer strategy adopted, if the DR program design permits a choice. Consumers can respond to high prices or program events [USDE-2006] in three ways:

- Foregoing – it is a strategy of reducing electricity usage at times of high prices or DR program events, without using it later. This is the case of turning off or reducing the lights, or turning up the temperature of the thermostat in the air conditioner during an event. It always causes a temporary loss of amenity or comfort. Foregoing usage without doing it later may also cause costs due to loss of productivity.
- Shifting – it corresponds to the rescheduling of the electricity usage from periods of high prices or DR programs events to other periods. For example, for a residential consumer, it is possible to turn off a dishwasher until later in the day; an industrial consumer can reschedule a batch production process to the earlier hours of the next day. The service or amenity can be re-established in the subsequent or rescheduled period. This reschedule can have costs regarding overtime payment or productivity losses due to the required adjustments in the production process.
- Onsite generation – some consumers who have an onsite or backup emergency generator may respond by using it to satisfy some or all of their consumption needs. Requirements in the power system are reduced or satisfied with reduced impact in the load profile. Fuel and maintenance costs are incurred in this type of response.

The use of any of the referred strategies causes inconvenience, discomfort, and/or loss of productivity in the buildings occupants or in the laboring process. All these factors should be included in the cost-benefit analysis that supports DR decisions, even if some of them are not directly accounted.

2.1.3 Price elasticity of demand

The price elasticity of demand can be used by system planners and regulator entities to know how the load is expected to be changed by end customers when a change in price occurs, in order to take decisions concerning the implementation of DR programs. The price elasticity rate is a measure used in the economics to evaluate a good or service demand response to a change in its price, i.e. the percentage change in the demanded quantity in response to one percent change in price [Arnold-2008]. The formula for the price elasticity of demand is expressed in (2.1), where *Quantity* is the used quantity of the considered good or service and *Price* is the price of that good or service [Thimmapuram-2010].

$$\varepsilon = \frac{\Delta Quantity \big/ Quantity}{\Delta Price \big/ Price} \tag{2.1}$$

This quantifier has had applications like cigarettes, airline travel, car fuel, cinema, transports, drinks and rice. In electricity consumption, this is a normalized measure of the intensity of how the usage of electricity changes when its price changes by one percent. On the other hand, demand elasticity is a measure of how price changes when the usage of electricity changes.

Two types of elasticity of demand can be distinguished. The first one is the own-price elasticity which measures how customers will change the consumption due to changes in electricity price, regardless the period of variation. This rate is expected to be negative since an increase in price should cause a reduction on the load. It is useful to measure how customers adjust the satisfaction of their energy needs between the consumption of electricity and other goods. Besides this, substitution elasticity is related to the change in the period, of the day or the week, of the consumption of electricity.

Figure 2.1 represents the effect of elasticity in the electricity price. The original demand curve is represented as a vertical line when demand has no elasticity (ε=0). When the demand exhibits some elasticity, the implementation of DR programs causes changes on the demand curve. As it can be seen on the demand curve corresponding to ε = -1, a little change in demand can produce a large variation in electricity price. This can be used by DR programs in a very advantageous way, mainly in situations for which a little decrease in the demand leads to significant savings in the supply costs.

A DR approach using the price elasticity has been presented in [Albadi-2008]. This work uses an optimal power flow for economic dispatch. The market prices for each period of the next day are calculated considering the price elasticity of demand, and a new load forecast is obtained. With the new load forecast, market prices are updated to verify the positive influence of demand response in market prices. The effectiveness of DR programs in case of system contingency is demonstrated in the scope of this work.

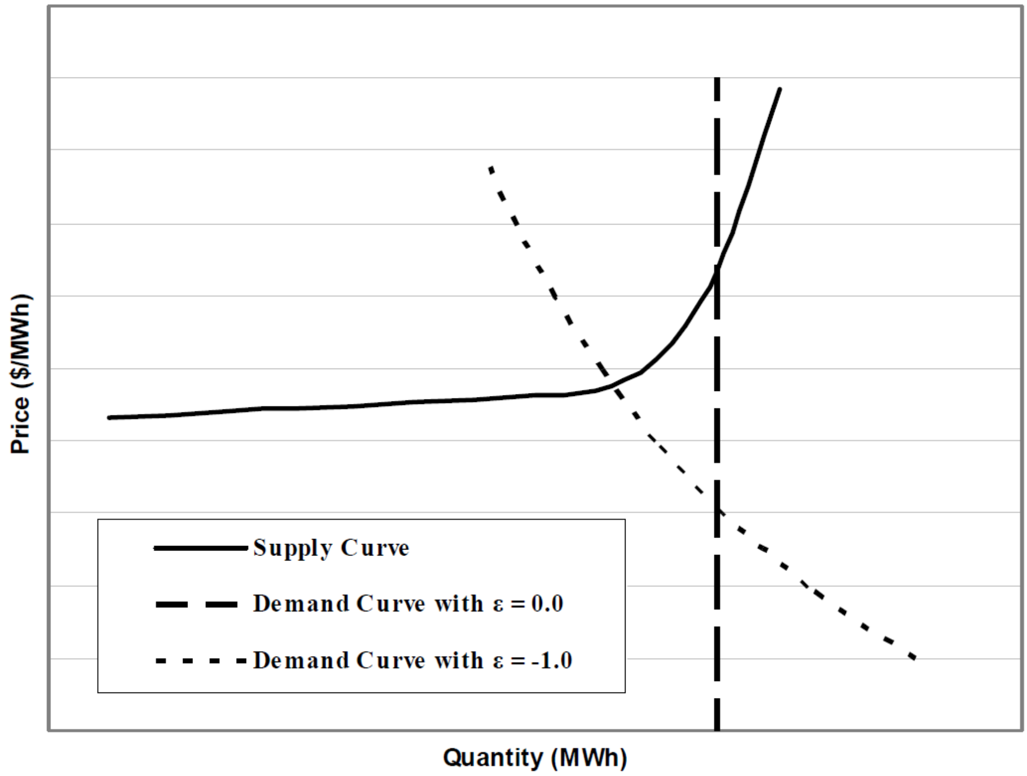

Figure 2.1. Effect of elasticity in the prices and consumption [USDE-2006]

In [Aalami-2010], price elasticity has been used to define the demand participation in several DR programs. These programs are sorted according to their priority from the point of view of the ISO, utility, customer, and regulator. Weights are associated to operation criteria and adjusted for each type of player. The authors concluded that the presented algorithm could be used as a toolbox to overcome market operation problems.

Generally, studies considering the concept of price elasticity of demand combine market conditions and consumer’s flexibility to analyze the benefits of DR whereas the present thesis uses price elasticity to determine the market signals (energy price) which are necessary for obtaining the desired response level of demand, for example in case of a supply shortage.

2.1.4 Acting players

The implementation of electricity markets gives place to the existence of several players which act in the market trying to reach individual and global goals. The basic players of an electricity market, are the consumers and the producers since the objective is to supply the consumers’ demand. Traditionally, this has often been achieved by vertically integrated companies supplying to consumers the energy provided by producers. However, in the scope of present EMs adversity of players such as DNO (Distribution Network Operator), TSO (Transmission System Operator), MO (Market Operator), VPP (Virtual Power Player), CSP (Curtailment Service Provider), and Retailers, interact to accomplish individual and common goals. Figure 2.2 shows the relationships between these players. In this figure, black thick arrows represent the physical electricity flows, and the gray arrows represent financial electricity exchanges.

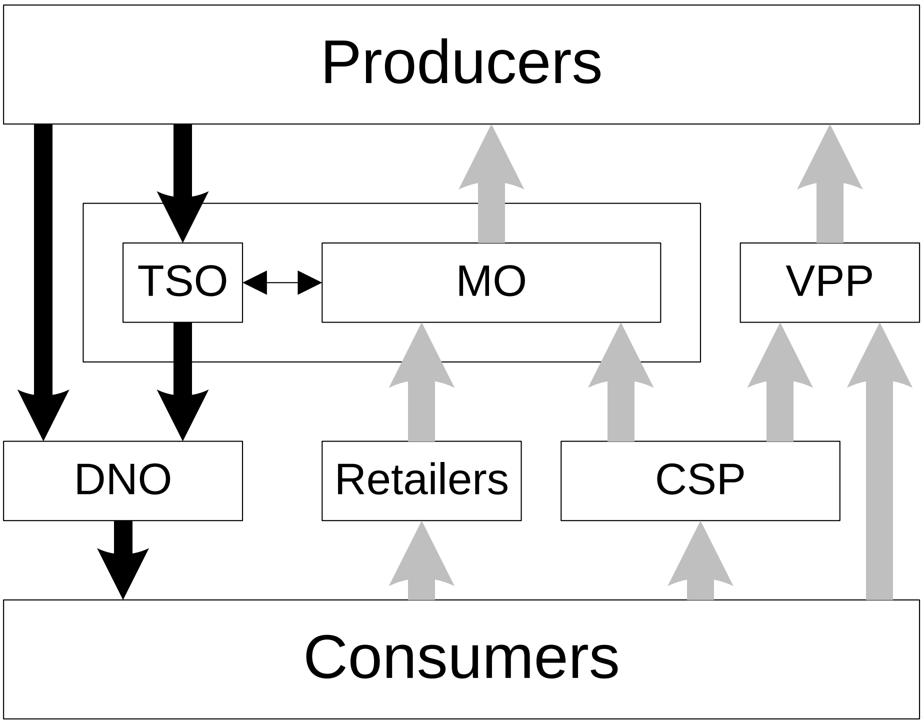

Figure 2.2. Relationships between the electricity market players (adapted from [Nguyen-2011])

Depending on the size and location of the loads, energy can be delivered to the consumers by a DNO or a TSO. For most of consumers, the TSO delivers energy to DNOs and these deliver energy to the consumers. A brief description of the players in the figure is presented in [Nguyen-2011].

Considering the participation of the new distributed resources connected to the networks in EMs, requires a new type of player. Small players owning distributed resources do not have the capability of participating in a competitive environment. VPPs can aggregate several small-scale energy resources, as DG, storage, and DR, managing these resources and making them able to participate in electricity markets.

Other special player only aggregating consumers DR participation, the CSP, is needed in order to make the small consumers able to participate in DR programs designed for large consumers. Small consumers without the reduction capacity required by the DR program managing entity (usually an ISO) make a contract with a CSP, which aggregates several small consumers DR and participates in the DR program.

2.2 DR PROGRAM IMPLEMENTATION

This section presents some important definitions concerning DR (in sub-section 2.2.1) and the explanation of the DR event timing (in sub-section 2.2.2), both based on the reference [NAESB-2008]. Sub-section 2.2.3 explains the concept of baseline, which is important for the consumer response performance evaluation [ENER-2008].

2.2.1 Definitions

- Adjustment Window - The period of time prior to a DR Event used for calculating a Baseline adjustment;
- Advance Notification(s) - One or more communications to Demand Resources of an impending DR Event in advance of the actual event;
- After-the-Fact Metering - Interval meter data separated from Telemetry that is used to measure DR. May not apply to Demand Resources under BaselineType II (Non-Interval Meter);
- Aggregated Demand Resource - A group of independent Load facilities that provide DR services as a single Demand Resource;
- Baseline Window - The window of time preceding and optionally following a DR Event over which the electricity consumption data is collected aiming the establishment of a Baseline. The applicability of this concept is limited to Meter Before/Meter After, and Baseline Type-I and Type-II;
- Demand Response Event - The time periods, deadlines and transitions during which Demand Resources are performed. The System Operator shall specify the duration and applicability of a DR Event. All deadlines, time periods and transitions may not be applicable to all DR products or services;
- Deployment - The time at which a Demand Resource begins reducing Demand on the system in response to an instruction;

- Deployment Period - The time in a DR Event beginning with the Deployment and ending with the Release/Recall;
- Ramp Period - The time between Deployment and Reduction Deadline, representing the period of time over which a Demand Resource is expected to achieve its change in consumption;
- Ramp Rate - Demand Resource ramp rate is the rate, expressed in megawatts per minute, in which a Demand Resource changes its consumption;
- Recovery Period - The time between Release/Recall and Normal Operations, representing the window over which Demand Resources are required to return to their normal Load;
- Reduction Deadline - The time at the end of the Ramp Period when a Demand Resource is required to have met its Demand Reduction Value obligation;
- Release/Recall - The time when a System Operator or Demand Response Provider notifies a Demand Resource that the Deployment Period has ended or will end;
- Sustained Response Period - The time between Reduction Deadline and Release/Recall, representing the window over which a Demand Resource is required to maintain its reduced net consumption of electricity;
- Telemetry - Real-time continuous communication between a Demand Resource or DR Provider and the System Operator;
- Validation, Editing and Estimation - The process of taking raw meter data and performing validation and, if necessary, editing and estimating corrupt or missing data, to obtain validated data.

2.2.2 DR event timing

Figure 2.3 presents the terms for timing events and time durations applicable to a Demand Response Event. The definitions of the ten elements in the illustration (already presented in sub-section 2.2.1) are the basis for describing the timing of a Demand Response Event. The applicability of these elements to a Demand Response Service is dependent on the Service type. The System Operator shall specify whether any or all of the elements illustrated in Figure 2.3 are applicable.

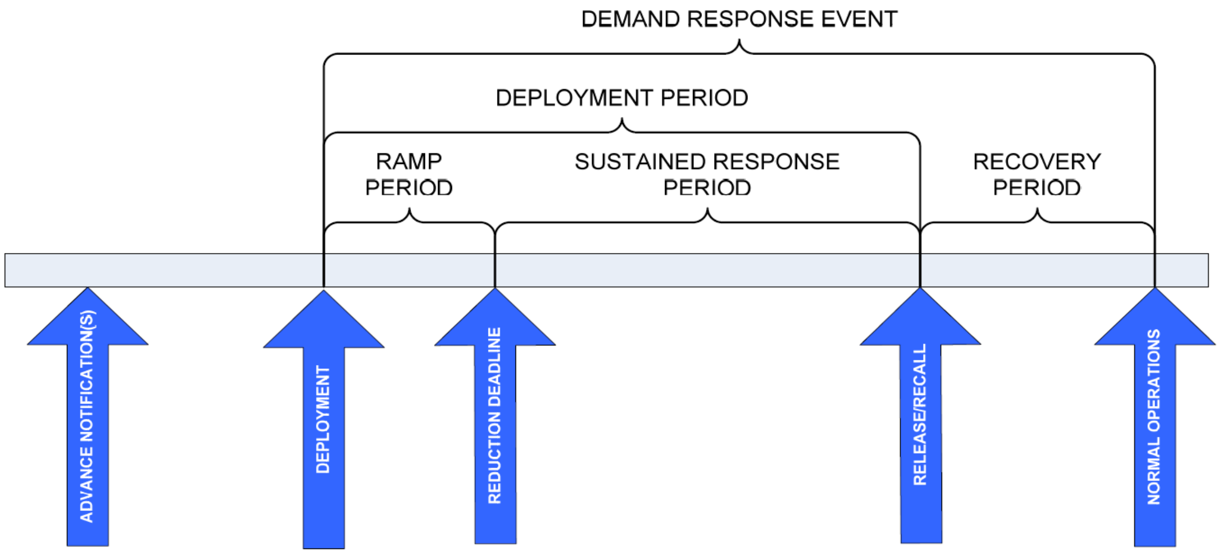

Figure 2.3. Timing of a DR Event [NAESB-2008]

2.2.3 Baseline

A Baseline is an estimate of the electricity that would have been consumed by a Demand Resource in the absence of a Demand Response Event. The Baseline is compared to the actual metered electricity consumption during the Demand Response Event to determine the Demand Reduction Value. Depending on the type of Demand Response product or service, Baseline calculations may be performed in real-time or after-the-fact. The System Operator may offer multiple Baseline models and may assign a Demand Resource to a model based on the characteristics of the Demand Resource's Load. Alternatively, it may allow the Demand Resource to choose a performance evaluation model consistent with its load characteristics from a predefined list. A baseline model is the simple or complex mathematical relationship found to exist between Baseline Window demand readings and Independent Variables. A baseline model is used to derive the Baseline Adjustments, which in turn is used to compute the Demand Reduction Value. An independent variable is a parameter that is expected to change regularly and have a measureable impact on demand. Figure 2.4 illustrates the concept of Baseline relative to a Demand Response Event.

For a given time interval t, the initial baseline b_t is calculated as the average interval demand among the 5 days with the highest energy usage out of the prior 10 non-event days (this calculation is performed for each interval during the DR event), as in equation 2.2.

$$b_t = \frac{(C_{td1} + C_{td2} + C_{td3} + C_{td4} + C_{td5})}{5} \tag{2.2}$$

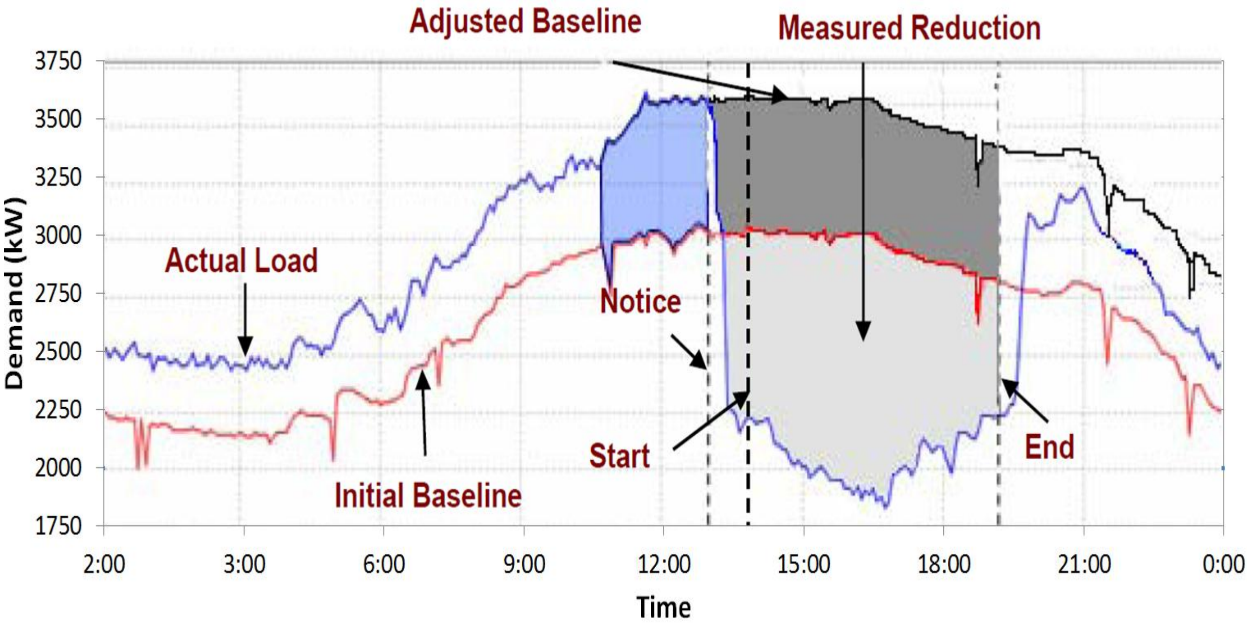

Figure 2.4. Example Baseline and Performance Measurement for Demand Response Asset [ENER-2008]

The adjustment factor *a* is calculated as the difference in observed demand and the estimated baseline, for a calibration period starting two hours before event notification, with a minimum adjustment of 0, as in equation 2.3. This factor is calculated for each time interval *t*.

$$a_t = \max\left\{\frac{\left[(C_{t-1} - b_{t-1}) + (C_{t-2} - b_{t-2})\right]}{2}, 0\right\} \tag{2.3}$$

The total performance *p* is measured as the integrated difference between the sum of the baseline *b* and the adjustment factor *a* minus the consumption *c*, for each interval *t* over an event period beginning at time *0* and ending at time *e*, as seen in equation 2.4.

$$p = \sum_{t=0}^{e} \left(b_t + a_t\right) - C_t \tag{2.4}$$

The capacity-setting performance p_{avg} is simply the average performance during all intervals of the DR event for which the program rules stipulate that performance is mandatory, as in equation 2.5.

$$p_{avg} = \frac{\sum_{t=0}^{e} \left(b_t + a\right) - C_t}{e} \tag{2.5}$$

It is important to note that the day-of load adjustment period is the two hours period prior to event notification instead of the two hours period prior to the event start.

2.3 DR PROGRAMS CHARACTERIZATION AND EVALUATION

The participation of the consumers in a DR program is always translated into a reduction in the value of the load demand (even in the cases of participating with consumers' generators, there is a reduction in the load demand from the point of view of the power system). However, a diversity of characteristics can distinguish DR programs, as described in this section. Methods for DR programs performance evaluation are also presented and discussed. The exposed concepts are detailed in [NAESB-2008].

2.3.1 Features

2.3.1.1Service Type

The participation of a consumer or of several aggregated consumers in wholesale markets can be divided into four types of services integrating the respective electricity market service. These four types are the following:

- Energy Service – In this type of DR service, only the demand reduction performance during an event is remunerated, i.e. the participants are only compensated by the energy reduction amount. The corresponding programs are generally of voluntary participation in the DR program and of voluntary response to a DR event;
- Capacity Service – The participation of DR resources in a Capacity Service is related to a mandatory response to a DR event, in spite of the participation in the DR program being voluntary. In this service, the DR capacity must be provided in a defined period of time, as scheduled/notified by the event announcer (usually the System Operator);
- Reserve Service – This service is characterized in the same way as the Capacity Service, in terms of participation of DR resources. The difference is that the reserve service is based on the reserve capacity requirements established by the System Operator to accomplish the reliability requirements;
- Regulation Service – A DR resource involved in a Regulation Service program is able to both increase and decrease load demand in response to system operator real-time signals. Since a DR resource is committed to a defined period it is continuously subjected to a dispatch, responding to changes in the system

frequency and to System Operator instructions. In this service, it is not usual to use the terms “event timeline” or “event duration”.

2.3.1.2 Trigger logic

Each DR program has a trigger logic, that is the event or signal that causes the DR event declaration. Depending on the specificity of each program, DR events can be triggered by:

- Automatic response – the loads are equipped with a frequency relay (or an equivalent capability provided in the metering device) that sheds the load when the system frequency is bellow certain levels, providing a regulation service;
- Economic dispatch / Energy price higher than offer price – loads participating in DR programs related to energy or reserve services make bids to the market. If the offer is dispatched, the load resource is used as an energy resource. Usually, the use of these programs has no regulatory constraints, just contractual ones;
- Critical peak hours – the event is declared if the real-time hourly load or if the day-ahead load forecast is higher than a certain percentage, usually 90% or 95%, of the system peak. DR programs triggered in load peak hours are normally of capacity service type;
- Day-ahead Locational Marginal Price (LMP) – there are two types of trigger logic depending on LMP values. The first is when the day-ahead LMP is higher than or equal to the price bid of the load resource. The second is when the day-ahead or the forecasted real-time LMP is higher or equal to a certain value (usually 100$/MWh) [Faria-2011c].

2.3.1.3 Overuse restriction

Despite the trigger logic signals can happen several times in a year, or in a season, limitations are applied to the number of declared events in each DR program. Limitations can also be in function of the minimum number of declared events, mainly to ensure a minimum amount of remuneration to the participants. Typically, the maximum value is expressed as the maximum number of days, with a maximum number of hours per day.

Other important constraint, which can be seen as a trigger logic, is the fact that some programs are only activated in peak hours. Moreover, limitations in the total amount of reduction caused by the participation of the consumers can be imposed.

2.3.1.4 Other

Some other characteristics, not less important than those previously referred in sub-sections 2.3.1.1 to 2.3.1.3, can be listed. These are: the period of the DR program availability (e.g., the season), determined by a begin date and by an end date; the minimum resource size and the minimum reduction amount; the possibility of an aggregated participation, through a Curtailment Service Provider (CSP); the voluntary/mandatory participation and response (even when the participation of a consumer is voluntary, after the registration in the program, the response can be mandatory); and the primary driver of the program, which can regard to reliability or economic purposes.

2.3.2 Participant roles

2.3.2.1 Deployment

There are three types of deployment applied to DR programs. The first is the "Resource-Specific Deployment", in which the system operator designates one or more discrete unique resources to provide DR capacity, through a determined communication channel. The second, the "Bulk Deployment", consists of the dispatch of a group or block of resources to provide DR capacity. Finally, the third deployment type is the "Self Deployment" and is characterized by the fact that resources are not dispatched by the system operator, but automatically, by the resource itself, or by an aggregator. Even in this case, resource participation needs to meet several signals like electrical system conditions, or economic conditions, as referred before. The use of real-time communications is optional for all these deployment types.

2.3.2.2 Communications

Communications between the consumers and the DR program managing entity need to be guaranteed in all the phases of a DR program [Cigré-2011].

In the enrollment and qualification phase, paper forms and electronic files submitted in a webpage or a user application system (e.g. the CAMS system of iso-ne) are normally used. In the forward scheduling notifications, means of communication like automated voice message, e-mail, and information posted in a webpage are used. In the deployment phase, automated voice and e-mail massage are also used. Moreover, due to the specific conditions of each program, several other means of communication can be used, such as automatic system dispatch, verbal dispatch instruction, phone, and web page post, depending on several factors, e.g. the event timings.

Alternatively, all the communications can be performed through a Supervisory Control And Data Acquisition (SCADA) system [NAESB-2008], when this is available (e.g. in NSBO area).

2.3.3 Event process

2.3.3.1 Timing

As it can be seen in the definitions section (2.2.1), DR events can be divided into four consecutive phases. The first phase is the "advance notification period" that can vary from real-time (or no advance notification) to day-ahead. This period can be specified in terms of minimum or maximum value. Usually used periods are: 5 minutes (as minimum or maximum specified period); 10 minutes; 1 hour (minimum); 2 hours (maximum); day-ahead market clearing instant; and day-ahead specified time.

The second phase, the "ramp period", which is the time between the effective event notification and the event declaration, can vary between effective instantaneous response to 2 hours. Examples of duration of this period, which depends mainly on the service type, are: 5 minutes; 7 minutes; 10 minutes (minimum / maximum); 30 minutes (minimum / maximum); 1 hour; and 2 hours.

In the "Sustained Response Period", the third phase, it is specified the minimum or maximum consecutive response time. It can vary from the resources minimum run time, to 8 hours. Moreover, this period can be defined by the participant or by the dispatch/schedule entity. In this last case, demand resources need to respond during the scheduled time, being in some cases imposed, *a priori*, a minimum response time (e.g. 1 hour or 4 hours). In the cases that the response period is not scheduled, it is usually of 5 minutes, 1 hour, 2 hours, 4 hours, and 8 hours.

The last phase, the "Recovery Period", is the time that load resources need to return to the normal conditions of operation. This phase is the one for which it is normal not to impose minimum or maximum time limits, since in many programs it is not considered / not monitored / based on resource characteristics (the time beginning imposed by the technical characteristics of the resource). However, there are cases for which limits of 5 minutes, 3 hours, and 10 hours, or a time defined in the schedule/dispatch process are imposed.

2.3.3.2 Metering

The evaluation of the DR programs participation by load resources requires adequate metering means, which can be used also for the activation or announcement of DR events, if bidirectional communications are available or required. The metering concept is intimately related to telemetry.

Telemetry use can be required under no special conditions, required over a determined resource power, or not required. Although not being applicable to all situations, usual telemetry accuracy values imposed by the system operator are ±0.2%, ±0.25%, ±0.5%, ±1%, ±2%, ±3%, ±5%. Specific time accuracy is sometimes specified, with accuracy values of 5 seconds or 5 minutes, and sometimes this accuracy value is defined per week.

Other important characteristic of telemeters is the reporting interval, that is the time distance between moments of sending meter data to the system operator or / and other intervenient, like an aggregator or a CSP. This value is usually of 2 seconds, 4 seconds, 6 seconds, 10 seconds, 1 minute, and 5 minutes, depending on the specificities of the DR program and of the load resource.

Other features are usually included as requirements for the telemetry equipment, such as information of a breaker status, base load interval, response performance, and quality status data. A special additional requirement is the capability of including on-site generation specific metering.

Finally, the metered data needs to be reported to the system operator and usually this is done several days after the event day, or at the end of the month. In rare cases it is done instantaneously. In spite of telemetry reporting interval being short, the reporting data interval is higher, usually 1minute, 5 minutes, 15 minutes, or 1 hour.

2.3.4 Performance evaluation methods

The reduction of load demand consumption is always subjective since consumers could intentionally increase consumption before a known DR event to pretend that the load demand was reduced during the DR event. To avoid these cases, performance evaluation methods have been developed.

The evaluation of DR programs participation by load resources is based on five main methods, as detailed below [NAESB-2008]:

- Maximum Base Load – it is a performance evaluation method used for the load resource response evaluation, regarding its electricity consumption at the deployment phase. This method is obviously used in cases for which the advance notification period is very short or non-applicable, or, otherwise, when the load resources are remunerated by the availability and not only by the proper response. This is the case of DR programs of capacity type, for which even if the reduction is not verified, it is considered as available to be used;
- Baseline Type-I – it is a baseline performance evaluation method that uses load resources' historical metered data. It can also include other variables such as weather and calendar data. This method is characterized by all the features of the baseline information, as described in sub-section 2.2.3;
- Baseline Type-II – it is a baseline performance evaluation method for aggregated loads. It estimates the electricity consumption of an aggregated demand response resource for which interval metering is not available for all of the consumers.
- Meter before / meter after – it makes a comparison between the electricity consumption over a predefined period of time prior to DR event deployment phase and readings during the sustained response period;
- Meter generator output – it is the simplest and more accurate method for evaluating demand resource participation but it can only be used for generation resources. It is based on a meter installed near to a generation resource participating as a DR source, for which the demand reduction value corresponds to the generated power.

2.4 RELATED WORK

DR studies can be grouped in three major classes [USDE-2006], namely illustrative studies, integrated resource planning studies, and program evaluation studies. Illustrative studies, which aim to quantify the economic impacts of DR, are most of the published studies and have better results for DR benefits since they consider larger flexibility of loads. Integrated resource planning studies can report good results for DR benefits too, considering regional impacts over a long period and considering it as part of long-term resource planning. Program evaluation studies are implemented by independent system operators to determine the actual value of DR programs implemented in practice. These studies report lower benefits of DR in part because they do not consider the full range of DR market opportunities or the long-term DR.

In [USDE-2006], several experiences and facts about the United States are reported. A core point is that Load Management (LM) decreased 32% between 1996 and 2006 due to weak load management services offered by utilities. A reduction of 10% on money spent in load management programs since 1990 can explain the reduction in LM results and, consequently, the reduced customers' participation. Between 1996 and 2004, 32% of utilities stopped providing LM programs.

In response to this, recent initiatives were conducted by grid operators and utilities recognizing the value of DR for grid reliability and the enhancement of organized spot markets efficiency [FERC-2010]. ERCOT (Electric Reliability Council of Texas) is working on the use of metering equipment for improvement and implementation of DR and reports the need to have new load profiles. However, creating a new model can take years before it is ready to be implemented in wholesale settlements [ERCOT-2007]. PJM interconnection estimates, for 2012/2013, a reduction of $162.32/MW per day in unconstrained zones, in market clearing price, through the participation of demand-side resources. Both PJM and New England's Independent System Operator (ISO-NE) consider existing and new demand-side resources for eligible capacity resources [Gottstein-2010]. China has implemented a large load control system through which customers are told when they may or may not operate. The system operator uses the interruptible price to interrupt the desired loads. This system is applied to large industrial customers and is used in periods of energy shortage and when energy prices are very high. Presently, the interruptible prices program is being extended to the overall level of demand [RAP-2008].

In 2001, California's electricity market has exhibited very high prices for electricity and threats of shortages. In [Borenstein-2001], it is argued that the problems that appeared in California and other markets are intrinsic to the market design and DR is indicated as a possible solution. [Heffner-2001] presents the study of five cases corresponding to five different organizations: a Federal Agency, two utility investors, an independent system operator and a rural electric cooperative. These programs include interruptible load programs, emergency and economic options and residential load control. The last one is designed for domestic consumers and the others are for large commercial and industrial customers. This work [Heffner-2001], published in 2001, reports a rapid proliferation of load management programs and the fact that voluntary interruptible programs seem to be applicable in situations in which end users could reduce high prices. The authors of [Borenstein-2002] consider that dynamic pricing should be assumed as default for large customers since the use of forward contracts can reduce their exposure to real-time prices. [Boisvert-2003] discusses the consideration of load curtailment by retail customers as resources that compete in energy supply bids and concludes that the participation of customers in wholesale markets can give substantial benefits for all stakeholders.

A study of long-run of efficiency of Real Time Pricing (RTP) is conducted in [Borenstein-2005] being demonstrated that efficiency gains from RTP are significant even if the price elasticity of demand is very little. In addition, it is demonstrated that the Time Of Use (TOU) tariff, that is a simple peak and off-peak pricing tariff, enables very small efficiency gains when compared with RTP.

An evaluation of automated demand response in large facilities is performed in [Piette-2004] with the main goal of evaluating the performance of automated DR systems in commercial buildings and secondary goals that include the evaluation of size of demand shedding capabilities, identification of technology gaps, and development and test of real-time signal for automated DR. Authors concluded that automated DR is technically feasible, in spite of reporting several items to develop in future work, as well as the need to gain more knowledge concerning DR strategies implementation.

Recently, advanced building control systems have been designed to improve control for energy efficiency and new studies about how to use existing controls in commercial buildings to integrate energy efficiency and demand response were undertaken [Kili-2006]. Representing an evolution to the traditional works that only consider state of art controllable equipment, simulations about DR and future DR programs participation strategies in a commercial building are performed in [Kili-2006].

The American Council for an Energy-Efficient Economy published a report [Elliott-2007] about the potential capabilities of energy efficiency, demand response, and onsite renewable energy to satisfy the Texas's electric energy needs. It was concluded that investments in energy efficiency and renewable energy resources created more jobs than the ones that could be created by investing in conventional generation. Moreover, it has concluded that the identified resources can meet the increasing demand in Texas over the next 15 years.

Some difficulties in the transition from a traditionally regulated industry to a competitive environment can be justified by the lack of retail demand response. However, it is accepted that time-dependent pricing (e.g. RTP) can benefit the sector's operation and investment [Woo-2010].

2.5 PRACTICAL EXPERIENCES

This section briefly reports some of the most important DR practical experiences, which are cases of real implementation. Both electricity markets and small scale cases are exposed.

2.5.1 Electricity markets implementation

The current state of DR around the world is summarized in [Woo-2010]. Experiences of DR in the wholesale market are taking place in Europe [Torriti-2010], in the United States [Cappers-2010], in China [Wang-2010] and also in other places around the world [Charles-2010].

CIGRÉ[2] is an Organization that covers power system technical, economic, environmental, organizational, and regulatory aspects. This non-profit and non-governmental organization aims at facilitating the exchange of information synthetized in state-of-art world practices. In [Cigré-2011], the most important aspects concerning the integration of DG and storage in the network and the impact of the DR on network planning are summarized. A review of DR initiatives is also provided in the same document.

The specific case of Portugal, in convergence with Spain, is regulated by Decree No. 592/2010 [Economia-2010]. Consumers have a base remuneration depending on the value of interruptible power varying in several steps. The minimum interruptible power is 0.25 MW.

[2] International Council on Large Electric Systems. http://www.cigre.org

The maximum base remuneration is paid to consumers with an interruptible power higher than 4 MW. This base remuneration is a fixed monthly paid rate and depends on the value of the interruptible power, for the consumer. An additional is also defined for the use remuneration. It depends on the medium market price in the periods of the declared event, on the interruptible power, and on the total number of hours of interruption in a certain month. Penalizations to the consumers who fail the response to an event are defined. The smallest penalization corresponds to the charge of four months of base remuneration. The worst case leads to the ceasing of the contract.

FERC’s order 719, issued on October 2008, aims at improving the electricity markets by increasing the role of DR [FERC-2008]. The main directive is the comparable treatment between generation sources and DR. This document is of large importance in what concerns the regulatory impositions to the development of DR initiatives. Due to its importance as a result of the application of the referred document, some examples must be listed. Table 2.1 presents some market DR implementations in the area of FERC, based on [Rahimi-2010]. This is not an exhaustive list of the DR programs implementations in the area of FERC. However, the presented cases are some of the most relevant in the field of this thesis. For each ISO or RTO the products offered to consumers interested in participating in DR programs are listed.

Table 2.1. FERC market DR implementations

ISO/RTO	Product	Description		
		Markets	***Compensations***	***Observations***
NYISO	EDRP	- Emergency energy market	$500/MWh or the LMP	- Only is possible the subscription of 1 CSP
	DADRP	- Day-ahead energy market	Day-ahead market-clearing price	- Mandatory response - In case of fail response is charged the higher of the day-ahead and the real-time price
	ICAP	- Emergency energy market	As installed capacity resources	- Mandatory response
	DSASP	- Ancillary services	Day-ahead market-clearing price	- Real-time telemetry required
ERCOT	VLR	-	-	- Consumption reduction in response to prices
	BUL	- Regulation AS	- Ancillary services market-clearing price	-
	LaaR	- Reserve markets		- Telemetry required

ISO/RTO	Product	Description		
		Markets	***Compensations***	***Observations***
ISONE	RDR	- Emergency energy market	- Maximum of $500/MWh or the LMP - Capacity credit	- Mandatory response - Trigger: extreme emergency - Minimum reduction: 100 kW
	RPR	-	Maximum of $100/MWh or the LMP	- Trigger: high real-time prices
	DALR	- Day-ahead energy market	Maximum of Day-ahead LMP or Bid Price	- Optional for RDR and RPR participants - Minimum reduction: 100 kW - Bid price: minimum $50/MWh; maximum $1000/MWh
Midwest ISO	DDRI	- Ancillary services	Ancillary services market-clearing price	- Can participate in reserve but not in regulation - Resources committed (ON /OFF) but not dispatched - Can include shut-down cost ($) and hourly curtailment cost ($/h)
	DDRII			- Committable and dispatchable - Can supply energy, reserve, and regulation - Can include shut-down cost ($) and hourly curtailment cost ($/h)
CAISO	EDR	- Emergency energy market	-	- Reliability-based - Can't participate in AS - Can't participate in real-time market
	PLP	- Day-ahead energy market		- Can participate in Energy and NS reserve market - Telemetry required for NS reserve - Mandatory response
PJM	ELR	- Capacity market	- Retail rate for LSEs - Zonal LMP minus Retail rate for CSPs	- Trigger: LMP>=$75/MWh
	-	- Synchronized reserve market	Day-ahead market-clearing price	- Meter scan rate > 1 minute - Participant power must be lower than 25% of the required reserve
		- Regulation market		- Real-time metering required - Reduction must be <25% of the required regulation power

The information is organized in what concerns the market component in which the market component is integrated, the way the consumers are compensated and / or remunerated, and other diverse information labeled as observations.

2.5.2 Small scale experiences

Before being actually implemented in the scope of EMs, several types of DR programs have been put in practice by small-scale companies. These experiences are currently being developed. This section presents some of those small-scale experiences.

In [Taqqali-2010], the focus is turned to the development of a smart grid in Dubai. In spite of the special importance of the smart grid implementation, this project follows the concept of DR. The authors conclude that the annual peak demand can be reduced in 8.5% by using DR. One can conclude that TOU program is economically viable for both electricity suppliers and consumers.

A study about DR in China is presented in [Zhong-2010]. DR participation can be obtained by three means - load shifting, by encouraging the use of more efficient consumption and network resources, and by having more efficient generation resources. This study was applied in three places – Beijing, Jiangsu province, and Guangdong province. In the first case, the use of seasonal prices caused the shifting of 42MW from the peak load in the summer of 2004. Otherwise, 497 energy storage projects were implemented, with the capability of storing heat or ice for air conditioning during the peak hours. This made possible the shifting of 200 MW from the peak hours. A CPP program that proposes an increase of 10% in the peaking hours of workdays in the summer is presently under implementation.

The Jiangsu province, which is an area with a large amount of industrial consumers, has experienced serious electricity shortages in the recent years. The investments in the end users equipment efficiency made possible to save, in two years, the equivalent to a 579MW thermal power plant.

At last, Guangdong province is an important load center in the southern China. The demand side management systems implemented by three cities has made the controllable load to reach 60% of the total load. For the commercial consumers who move the working hours one or two hours ahead, the electricity prices were reduced in 10-20% of the regular prices. For the industrial consumers, the night electricity prices can be reduced about 50% of the regular price. The authors comment that low investments in the distribution network have caused several blackouts and made difficult the implementation of more elaborated DR programs.

The authors of [Wang-2011] summarize the smart grid DR programs in six companies of North America. The Cape Light Compact company conducted, in 2009, a residential smart home energy monitoring pilot that tested the importance of residential energy monitoring systems. The used equipment provides real-time viewing of energy usage and savings in kWh, monetary, and CO_2 emissions. The study was based in 100 qualifying households. A 9.3% (2.9 kWh/day) average daily energy consumption reduction was achieved. Consumers were classified in three groups regarding the average level of reduction. The consumers with higher energy savings reviewed house monitor graphs more frequently. This fact shows the importance of the home display from the point of view of the consumers and of the program implementation responsible entity. However, when questioned about the possibility of paying a monthly charge for the system, the consumers lost the interest in the program.

A similar study was conducted by Hydro One company. For this case study 400 consumers were enrolled and the study was conducted during 2.5 years. An average overall demand reduction of 6.5% was reported. Consumers were then divided into two groups – electric and non-electric space heating. The first group showed a reduction of 1.2% whereas the second group had a reduction of 8.2%.

In 2009, the Salt River Project enrolled 100000 consumers in a scheme of prepaid energy. In this scheme, the consumer has a smart card that is charged at pay centers and is inserted in a home smart meter. This makes the consumer able to know the credit amount and days available and make the management of the energy consumption. As a result of this program, consumers reduced the annual consumption by 12%, the system peak was reduced by 31.2MW, and in a decade of implementation 375GWh were saved.

A communicating thermostat based program has been implemented in the Sacramento Municipal Utility District. Two different programs – CPP and Air-Conditioning Control (ACC) – were applied to 35 offices, 31 retail stores, and 12 restaurants. Around two-thirds chose CPP. On event days, the company achieved 20% peak load reductions and the participants in the program reduced by 20% to 30% their bills. Thermostat data showed that restaurants were the lower participating consumers.

An air-conditioning DLC program was implemented in 2003 by the New York Independent System Operator (NYISO) and the Consolidated Edison company. Residential consumers with central air conditioning received a free smart thermostat in order to allow the company to control the air conditioning in the high demand days. 17200 smart thermostats were distributed to consumers, and the load reductions have totalized almost 19 MW. A similar program was created for small business consumers: 7200 equipment were distributed and 10MW reductions were reached.

The Austin Energy company has implemented a program similar to the one above. 86000 smart thermostats were installed, and load was reduced by 90MW in the peak periods.

The same authors published in reference [Wang-2011a] two specially interesting studies concerning other two programs. PEPCo company installed smart meters and smart thermostats (for consumers with air-conditioning) in 900 consumers installations. CPP program consumers with smart thermostat reduced the summer peak by 49% whereas the consumers without smart thermostat only reduced the summer peak by 29%.

In Commonwealth Edison company, a DR program has been applied to 110000 consumers, that must be regular internet users and understand and accept RTP. Consumers can check the day-ahead prices of electricity via multiple interfaces. When those prices are higher than a determined value, consumers are required to participate in the load reduction, within the contract conditions. The consumers participating in this program, in the year of 2009, saw their annual electricity bill decreased between 11% and 21%.

2.6 CONCLUSION

The demand response concept is a fast evolving topic of crucial importance for the planning and operation of future electricity markets and of power systems in general. Most of DR programs in the past were based on distinct electricity tariffs for different periods of the day. Presently, DR is evolving to more flexible approaches, able to benefit from the participation of the involved players. The ability of the demand side to play a dynamic, active, and strategic role is especially important under this context.

The present chapter exposed the most important concepts, experiences and implementations concerning DR. A brief description of the proposed DR programs and of actual DR experiences, involving several consumer group sizes implementations has been made.

Several DR programs implementation characteristics, including the event timing, trigger logic, overuse restriction, communications, deployment, and the baseline are explained. Consumer performance evaluation methods are also addressed.

Chapter 3

DemSi – A DR program simulator

3 DEMSI – A DR PROGRAM SIMULATOR

3.1 INTRODUCTION

The design and development of simulation models and tools for DR programs are becoming more and more important for adequately taking the maximum advantages of DR programs use. This chapter presents the developed DR simulator – DemSi – and the designed/implemented models of DR programs, which have been conceived and implemented in the scope of this thesis.

This introductory section gives an explanation of the designed models while comparing and characterizing them. The other sections, before the concluding one, detail each one of the developed and implemented models, which are summarized in table 3.1.

The first column of table 3.1 lists several parameters that characterize the models and make the distinction between them. The entity that manages the distribution network (VPP, DNO, etc.) aims at minimizing operation costs or maximizing profits. A distribution network is usually connected to a larger upstream network, from where it can acquire extra power to supply the demand, jointly with existing distributed resources. In this thesis, the power from the upstream network is considered to be acquired to one or several suppliers acting in that connection point.

Some models consider the existence of DG. DG units can be distinguished regarding the generation cost functions and taking into account the way that a resource is scheduled. For a certain type of DG technology it can be both considered the schedule of each unit or the schedule of each generation type aggregating the DG units of the same type.

An important characteristic of a DR program/model is the event trigger. It determines when the program is activated, and can be due to economic or technical conditions of the system. Some programs simply consider the DR capacity as a resource, at the same level as DG and other resources.

In a similar way of the generators, DR resources can be characterized in different manners. This characterization depends on the type of cost function and on the quantity or quantities that can be used and in what conditions. To conclude, depending on the temporal horizon, the cost/remuneration of DR use can be contracted, regulated, and can be made by a set of bids that consumers and/or generators submit to the managing entity. The models in the columns of the table 3.1 are ordered as in the next sections.

Table 3.1. Characterization of DR developed models

Characteristic	Model						
	DNO_VOLL	VPP_ST	DNO_RTP	VPP_CSP_LMP	VPP_CSP_ST	VPP_LMP_VAR	VPP_BID
DG	Costs of DG not considered	5 groups of generators - quadratic and linear costs	-	DG units aggregated by generation type	DG units aggregated by generation type	Each unit considered individually with linear costs	Each unit considered individually with quadratic costs
Suppliers	Larger public distribution network	1 supplier (electricity market)	1 supplier (electricity market)	2 amounts: day-ahead and real-time	1 Supplier	1 Supplier	Several suppliers
Resource management goal	Minimization of DNO operation costs	Minimization of VPP operation costs	Maximization of DNO Profits	Minimization of VPP operation costs	Minimization of VPP operation costs	Minimization of VPP operation costs	Minimization of VPP operation costs
Trigger	Fault occurrence	As scheduled	As scheduled	LMP>0.1$/kWh	LMP increase	Use for validation	As scheduled
Response characterization	2 types of flexible supply contracts	3 steps – curtailment and reduction	Elasticity values for each load type	2 amounts: DR-event and DR-contract	3 curtailment steps	3 steps – curtailment and reduction	Participation With quadratic costs
Bids	-	-	-	-	-	-	Bids by generators and loads for energy and reserve

The first model (DNO_VOLL) considers the minimization of operation costs in a network managed by a DNO. The operated network area is connected to a larger network. The existence of a fault in the connection line between the operated area and the larger network causes the operation in isolated mode. With the aim of supplying the loads in a way that the Value Of Lost Load (VOLL) is minimized, the capacity from DG and DR contracts is scheduled.

In the VPP_ST model, a VPP minimizes the operation costs in a network supplied by DG, a Supplier, and considering DR. DG resources are grouped into five Source Types (ST), with linear or quadratic cost functions. Three steps of DR use are considered in the same way as other resources. DR resources are triggered as scheduled, i.e. they are used regarding their use costs.

DNO_RTP is a model for the maximization of the DNO profits through the application of Real-Time Pricing (RTP). The DNO buys energy to a supplier and makes use of consumers' elasticity to determine the optimal price to be applied to a consumer or type of consumers in order to manage its consumption value. This method can be applied to the consumption increase and reduction, depending on the actual operating conditions of the network.

The VPP_CSP_LMP model considers a VPP managing a network, where DG units are grouped and scheduled regarding the DG unit type, aiming at minimizing the operation costs. The energy bought to a supplier is divided into two quantities prevenient from the day-ahead and real-time markets. DR participation is also divided into two quantities. The first one is an ordinary resource used like DG, as scheduled. The second quantity is used when an event triggered by the value of LMP is declared. If the LMP value at which the energy is bought in the real-time is higher than a specified value (usually $0.1/kWh), the DR event is declared. Large consumers can participate in the DR event directly delivering power to the VPP. Small consumers need to be aggregated by a Curtailment Service Provider (CSP), in order to totalize the minimum power to be delivered to the VPP in the presence of an event.

VPP_CSP_ST model is similar to the VPP_CSP_LMP model. The characteristics that distinguish this model from the previous one are the external energy bought in a singular way to a supplier, and the use of DR only in case of declaration of an event. DR capacity is divided into three different steps, with distinct prices, and it is activated when the increment in the value of load consumption causes an increase in the LMP value of energy. The participation of consumers can be done directly, similarly to the previous model, with the VPP or through a CSP.

For the VPP_LMP_VAR, when comparing it with the two previous models, each DG unit is considered individually and with linear costs. Three steps of reduction/curtailment of consumption are considered in the scheduling problem. The model compares the same conditions of operation with and without the use of DR. If the use of DR causes a positive impact in the operation costs minimization, the VPP acquires information confirming that in the specified operation conditions, DR is an important resource to be considered. This model includes an AC power flow to consider the network constraints.

Finally, the VPP_BID model considers a VPP receiving bids of both consumers and generators for the acquisition of energy and reserve required quantities. Several Suppliers make bids too, in the same way as the other referred participants. All the participants are able to submit bids with quadratic costs.

After this introduction section, section 3.2 presents the developed simulator architecture and explains its implementation.

3.2 DEMSI ARCHITECTURE AND IMPLEMENTATION

The designed and proposed DR models were implemented in the Demand Simulator (DemSi), which is one of the main results of this thesis, combining the use of GAMS optimization software and of MATLAB, which has been used to program some of the models. The other models have been programmed in GAMS. PSCAD is used for the electrical network simulation and is connected with the other two software tools.

This section presents a brief description of each one of the used software tools and a general view of DemSi.

DemSi is an important tool for DR programs and models analysis and validation, both in what concerns the business and economic aspects and the technical validation of their impacts in the network. DemSi considers the players involved in the DR actions and the results can be analyzed from each specific player point of view. This includes five types of players: electricity consumers, electricity retailers (suppliers), distribution network operator (DNO), Curtailment Service Providers (CSPs), and VPPs.

PSCAD is used as the basis platform for the network simulation. The used network can be chosen by a set of networks already available. As an alternative, the user may introduce a new network from scratch. DemSi also provides the user with functionalities that allow modifying already existing networks.

Consumers can be characterized individually or in an aggregated basis. The simulation requires knowledge about load data and about the contracts between clients and their electricity suppliers. These contracts may include flexibility clauses that allow the network operator to reduce or cut the load of specific clients and circuits. On the other hand, the response of each client to the used tariff scheme is also characterized, allowing the analysis of the impact of alternative DR schemes.

Figure 3.1 presents the DemSi functional diagram. The simulation of a scenario requires information concerning network characterization, consumers' profile, and DR programs models. The gray blocks in figure 3.1 are the ones that do not change when the conditions of simulation (models, network, etc.) change.

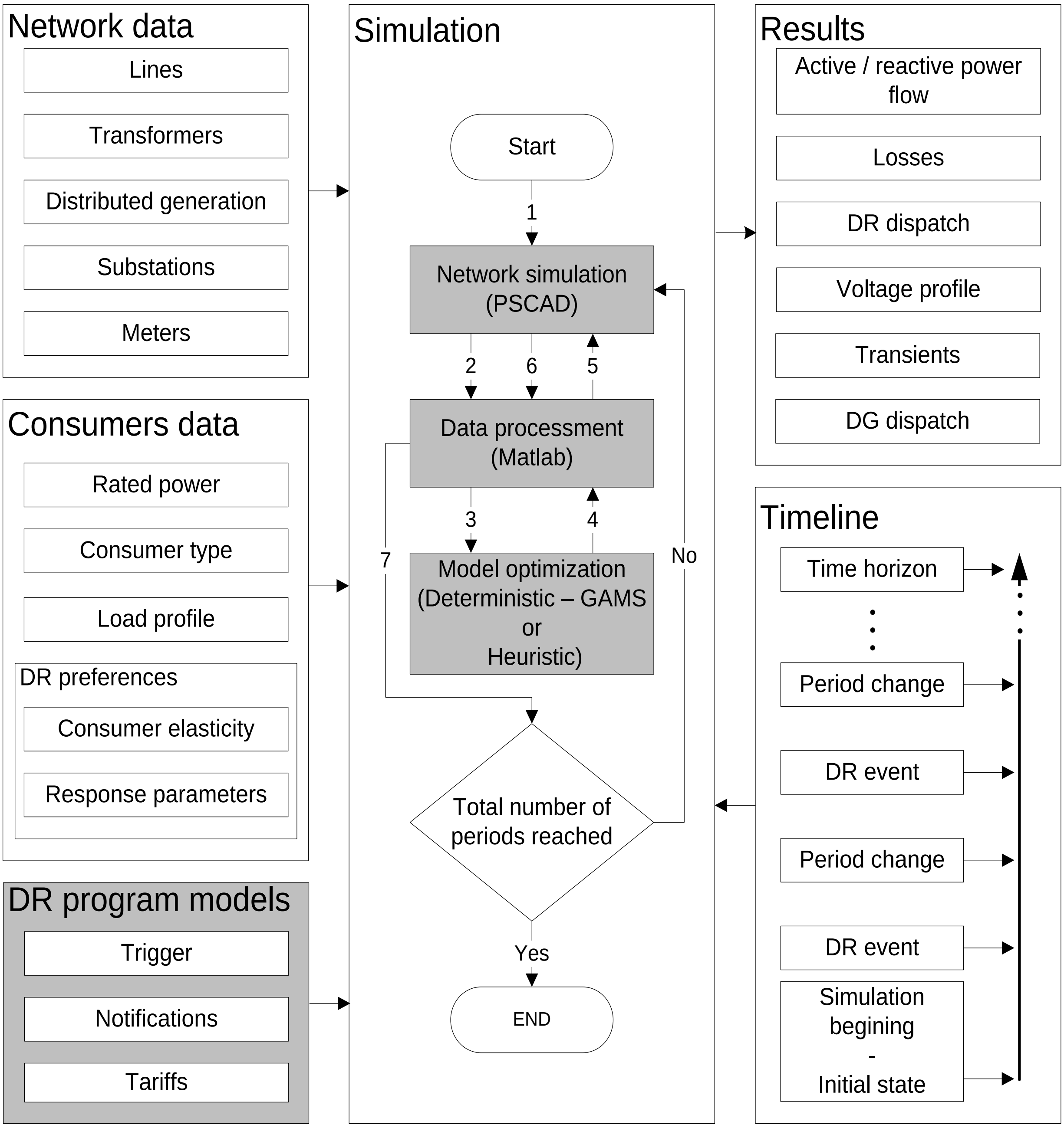

Figure 3.1. DemSi functional diagram

The realistic network simulation performed by PSCAD requires a large amount of parameters for the modeling of the network elements and for the resources connected to it. In this way, the network data (including DG and loads' electrical characteristics) are an important basis for the success of the simulations to be run. The data concerning load response characterization, as well as the event data, are necessary for the DR programs and models simulation.

Considering the power system area to be simulated, the power that is available to supply the loads is equal to the total power available minus the required reserves and the power loss. The value of the power loss is estimated for each run. In fact, this value is obtained from PSCAD simulation before the implementation of demand response but, after this implementation, load flow changes, resulting in a slightly different power loss value.

The simulation timeline is composed by a sequence of periods with a single event or multiple events occurring over time. In the beginning of the simulation, all the variable parameters, including the system voltage, are defined according to the considered initial state. Every change in the system causes instability in the simulation, and therefore some simulation time is given for the system to be in a stable state. After this stabilization time, the network state is saved and the first DR event is simulated. A stabilization period succeeds the DR event trigger; after this, the new state of the system, seen as the results of the event, is saved. This sequence is repeated for the number of periods of the simulation. After saving the results of an event, the network state for the next period is charged.

During the simulation, the different software tools used communicate and transfer data among them. The simulation starts in PSCAD and every time a new network state needs to be charged and/or saved this is done using the MATLAB connection to save/use data to/from Microsoft Excel datasheets. The optimization (resources schedule) is performed using the connection with MATLAB. This optimization can be deterministic (performed in GAMS), or heuristic (Using PSO implemented in MATLAB). The sequence of software data transferences is represented by numbers in the middle block of figure 3.1.

3.2.1 Computational tools used in DemSi implementation

The development of DemSi has been based on three simulation tools. A brief presentation of them is done in this section.

GAMS – General Algebraic Modeling System – is a computational tool developed to implement linear optimization problems, as well as non-linear and mixed-integer ones [GAMS-2008]. With GAMS the user is concerned only with the formulation of the problem / model. In this way, the difficulties around the modeling of the solving method are suppressed. It is simple to choose from several available numeric methods and then comparing the obtained results [GAMS-2009]. The diverse solvers make possible to solve a large variety of problems. The optimization problems related with the proposed models are solved using DICOPT[3], CPLEX[4], and CONOPT[5].

MATLAB (MATrix LABoratory) is a powerful software of numeric computation that was developed in 1978 by Cleve Moler and is nowadays a property of MathWorks[6]. The main characteristic of MATLAB is the use of matrixes as the basic data structure [Graham-2005]. As it is an interactive software of high performance, MATLAB is used in several applications in the industry, as well as in academic activities, and has been applied to several problems of science and engineering. MATLAB has toolboxes that allow obtaining the solution for several types of problems such as the ones related with numerical analysis, data analysis, matrix calculus, and signal processing. The user can use the available toolboxes or program functions and routines to solve the envisaged problem.

PSCAD/EMTDC is a simulation tool developed by the Manitoba-HVDC Corporation[7], dedicated to the system analysis and having electric power systems as the main application area. PSCAD is the graphical interface to the user, while EMTDC is the simulation software. The graphical interface of PSCAD considerably improves the EMTDC usability. It makes possible for the user to build the circuit schematically, to process the simulation, to analyze the results, and to manage the data in a completely integrated environment. The control systems can be agglomerated in modules improving the organization of the simulation. An important advantage of PSCAD, which is crucial for DemSi, is the possibility of linking it with MATLAB software.

3.3 MODEL – DNO_VOLL

This section presents a simple DR model intended to illustrate the importance of the use of demand response to reduce the Value Of Lost Load (VOLL) in case of generation shortage. This model, published in [Faria-2010], is applied to a situation in which a fault in the network originates a lack of supply.

[3] DIscrete and Continuous OPTimizer.

[4] Simplex and C programming.

[5] CONtinuous global OPTimizer

[6] The MathWorks, Inc., Natick, United States, 2010, www.mathworks.com

[7] Manitoba HVDC Research Centre, Manitoba, Canada, 2010, www.pscad.com

3.3.1 Introduction

The growing use of Distributed Generation (DG) has changed the way that electricity networks are operated. A fault originating a lack of supply that causes the existence of an island can be a good opportunity for both DR and DG to be used, evidencing their real value. Figure 3.2 shows an example of a distribution network connected to a larger upstream network through line 0-1. When a fault occurs in this line, there will be a lack of supply from the upstream network, and the envisaged distribution network will operate in island mode.

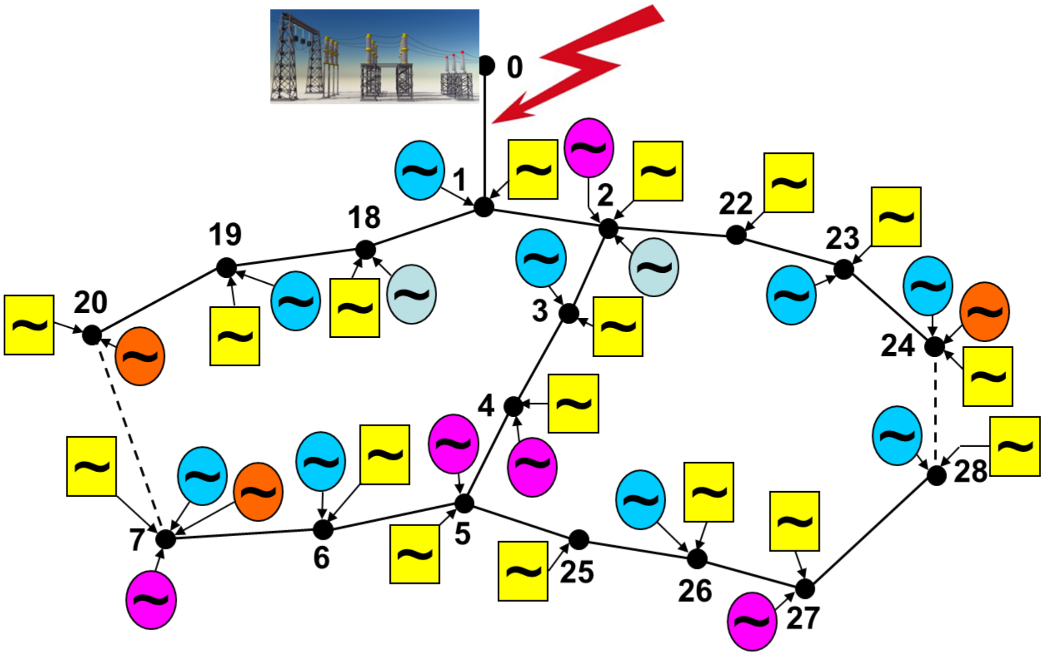

Figure 3.2. Example of network islanding operation

An adequate use of the available resources can make possible to supply some important loads and reduce the economic impact of the fault.

When facing a generation shortage (e.g. in case of an incident), the DNO makes use of flexible contracts and/or Real-Time Pricing (RTP) to condition consumers' behavior. When such situation occurs, the solution can be found in two phases:

- Phase I – The available energy production is evaluated and it is analyzed if it is sufficient to supply the critical loads. These loads should never be shed, unless it is absolutely impossible to supply them, due to security and/or economic reasons. The critical load status should be adequately addressed in the contracts between these loads owners and their suppliers. If all critical loads can be satisfied and there is a surplus of energy, the way this energy should be used, is determined in phase II;

- Phase II – The remaining loads that should be completely or partially supplied are determined using an optimization approach. This aims at minimizing the costs of the incident, from the suppliers and the DNO point of view.

Figure 3.3 shows the representation of this model.

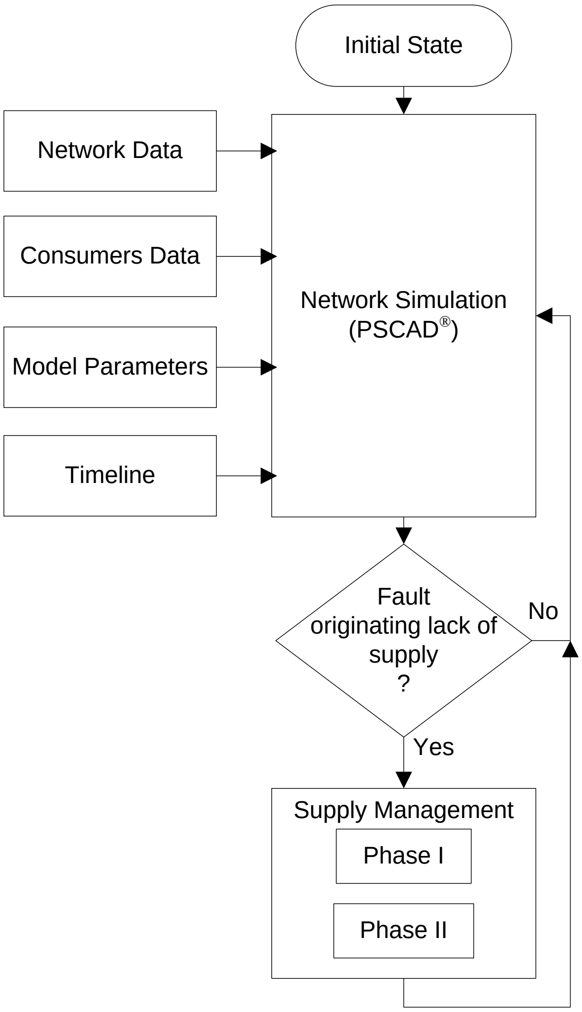

Figure 3.3. DNO_VOLL model

From the point of view of the demand response, loads differ mainly on the conditions they impose for eventually being curtailed or reduced under specific situations. This determines if each load must be considered in Phase I or in Phase II, as well as the Value Of Lost Load (VOLL) established in the contract. By default, DemSi considers three different typical load profiles, as follows:

- Critical Loads (CL) which should be supplied in every situation. When not supplied, these loads receive high compensation values, as determined by the contracts between their owners and their suppliers;

- Clients with Flexible Supply contracts (FS), which have hired the priority of their circuits and/or loads in case of supply shortage. The DNO can control each of these clients' overall load or some of its circuits. Financial terms for this supply flexibility are established in the supply contracts;
- All other loads, which are considered Regular Loads (RL).

3.3.2 Mathematical formulation

As mentioned above, Phase II aims at minimizing the costs of a generation shortage situation. After completing Phase I with all the critical loads supplied, this can be modeled as an optimization problem. Problem characteristics lead to a mixed-integer linear model. The objective function, in (3.1), is formulated with the aim of minimizing the total cost that the DNO and the suppliers have to pay for non-supplied loads (VOLL). It is important to note that Phase II always corresponds to a situation for which there is a lack of supply.

Minimize

$$OC = \sum_{c=1}^{Nc}\left(P_{Red(c)} \times C_{Red(c)} + P_{Cut(c)} \times C_{Cut(c)} \right) \tag{3.1}$$

The constraints of the problem are the power balance (3.2); the maximum curtailment for each consumer (3.3); and the maximum reduction for each consumer. The difference between reduction and curtailment is that the curtailment is the decrease of the total amount of power, whereas the reduction can be of any value between zero and the total considered load. In a technical point of view, the reduction corresponds to the changes, for example, in the lighting power, in function of the specified luminance needs. Otherwise, the curtailment method corresponds to the elimination of the consumption in a determined consumer, circuit of loads, or load. Both methods require adequate technological means. A certain consumer could have both methods of consumption decrease, or only one of them.

$$P_{DG} = \sum_{c=1}^{Nc}\left(P_{Load(c)} - P_{Red(c)} - P_{Cut(c)} \right) \tag{3.2}$$

$$P_{Cut(c)} = P_{MaxCut(c)} * X_{Cut(c)}, \forall c \in \{1,\ldots,Nc\}, X_{Cut(c)} \in \{0,1\} \tag{3.3}$$

$$P_{Red(c)} = P_{MaxRed(c)}, \forall c \in \{1,\ldots,Nc\} \tag{3.4}$$

Using this approach and its knowledge about load profiles, the DNO can determine the better way to define and establish supply contracts, at the same time that situations of lack of supply are solved by the use of those contracts.

3.4 MODEL – VPP_ST

The model VPP_ST presented in this section was published in [Faria-2011] and includes the scheduling of multiple types of generation resources and DR. This schedule is performed by a VPP and considers several Source Types (ST) in which generation sources are grouped.

3.4.1 Introduction

This model is designed to perform the optimal scheduling of diverse generation resources (DG units), a supplier that sells energy, and DR (considering three steps of power reduction). Figure 3.4 shows the schematic architecture of the model.

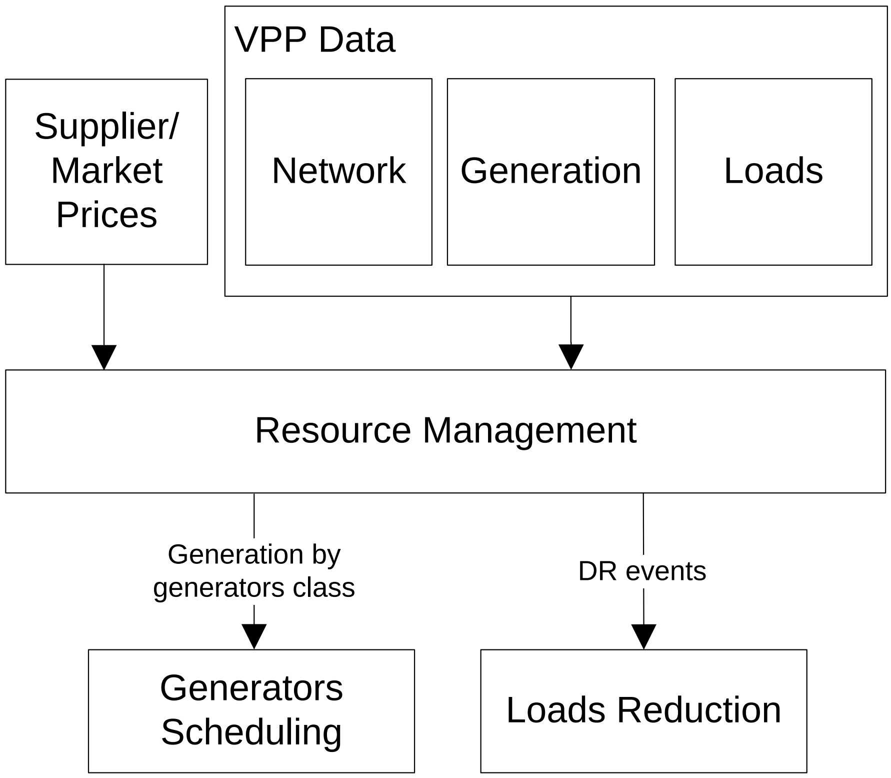

Figure 3.4. VPP_ST management diagram

It considers the resources managed by the VPP and the market information for the optimal scheduling of generators and loads (DR events). The "DR Management" module addresses the problem presented in 3.4.2 to solve the formulated optimization problems. Each simulation begins with a scenario that specifies what are the generation resources and load demand for the simulation horizon. When a DR event is declared, the VPP can make use of flexible supply contracts.

3.4.2 Mathematical formulation

The proposed problem aims at minimizing the VPP costs and can be modeled as an optimization problem. Problem characteristics lead to a mixed-integer non-linear model and consist on the minimization of a multimodal function usually with many local minima and a global optimum.

The objective function can be expressed as in (3.5). This objective function leads to the minimization of the costs considering the reduction of loads in three different and successive steps (RedA, RedB, and RedC), the costs of the energy provided by the electricity supplier, and the energy generated by photovoltaic, wind, Combined Heat and Power (CHP), and by two other groups of distributed generation units - waste-to-energy, biomass, fuel cell and hydro. These distributed generation units and the CHP have quadratic energy cost functions. The binary variables related to the units quadratic cost functions are due to the fact that the fixed costs only have to be considered when the resource is actually used.

Minimize

$$OC = \begin{bmatrix} \sum_{c=1}^{Nc}\left(P_{RedA(c)} \times C_{RedA(c)}\right) + \sum_{c=1}^{Nc}\left(P_{RedB(c)} \times C_{RedB(c)}\right) \\ + \sum_{c=1}^{Nc}\left(P_{RedC(c)} \times C_{RedC(c)}\right) + P_{Supplier} \times C_{Supplier} \\ + P_{PV} \times C_{PV} + P_{Wind} \times C_{Wind} \\ + Ca_{CHP} \times X_{CHP} + Cb_{CHP} \times P_{CHP} + Cc_{CHP} \times P_{CHP}^{2} \\ + Ca_{O1} \times X_{O1} + Cb_{O1} \times P_{O1} + Cc_{O1} \times P_{O1}^{2} \\ + Ca_{O2} \times X_{O2} + Cb_{O2} \times P_{O2} + Cc_{O2} \times P_{O2}^{2} \end{bmatrix} \tag{3.5}$$

As the constraints of the problem, one has to guarantee the power balance as seen in (3.6) and the use of resources below their upper limits (3.7 – 3.14), i.e. the maximum load curtailment of and maximum production of distributed generation units.

$$\sum_{c=1}^{Nc}\left(P_{Load(c)} - P_{RedA(c)} - P_{RedB(c)} - P_{RedC(c)}\right) = P_{Supplier} + P_{PV} + P_{Wind} + P_{CHP} + P_{O1} + P_{O2} \tag{3.6}$$

$$P_{RedA(c)} \leq P_{MaxRedA(c)}, \forall c \in \{1, ..., Nc\} \tag{3.7}$$

$$P_{RedB(c)} \leq P_{MaxRedB(c)}, \forall c \in \{1, ..., Nc\} \tag{3.8}$$

$$P_{RedC(c)} \leq P_{MaxRedC(c)}, \forall c \in \{1, ..., Nc\} \tag{3.9}$$

$$P_{PV} \leq P_{MaxPV} \tag{3.10}$$

$$P_{Wind} \leq P_{MaxWind} \tag{3.11}$$

$$P_{CHP} \leq P_{MaxCHP} \tag{3.12}$$

$$P_{O1} \leq P_{MaxO1} \tag{3.13}$$

$$P_{O2} \leq P_{MaxO2} \tag{3.14}$$

3.5 MODEL – DNO_RTP

The model DNO_RTP is divided into two distinct parts – the consumption reduction and the consumption increase. The first part was published in [Faria, 2011b]. This model was designed for the maximization of the DNO profit by the use of RTP. Another similar study, aiming at minimizing the consumers' costs, was published by the author of this thesis in [Faria, 2011a] and corresponds to the second part of the model.

3.5.1 Introduction

Real Time Pricing (RTP) is one of the price-based response programs and is based on the response of the consumers demand to the real-time variations in the real-time electricity prices. RTP can be used in order to reduce or to increase the consumption when electricity price increases or decreases, respectively. In this way, the mathematical formulation of this problem is divided into two parts, one aiming at the reduction and other aiming at the increase of the demand. The response of the consumers to the variations in the electricity price is modeled through the price elasticity of demand, commonly called elasticity, as explained in sub-section 2.1.3.

3.5.2 Mathematical formulation

The mathematical formulation of the problem, in both demand reduction and increase approaches, is formulated aiming the maximization of DNO's profits.

3.5.2.1 Consumption reduction

Let us consider the DNO point of view, aiming at maximizing the retailers profit when there is a need of consumption reduction. This problem's characteristics lead to a non-linear model. The objective function can be expressed by (3.15) and expresses the aim of maximizing the profit of the retailer who provides energy to the set of considered customers. This profit is the difference between the earnings of the retailer due to selling energy to consumers and the costs that it bears (electricity acquisition costs and other operational costs).

$$\begin{aligned} & \textit{Maximize} \\ & \textit{Profit} = \sum_{c=1}^{Nc} \left[\left(P_{Load(c)} - P_{Red(c)} \right) \times \left(C_{Initial(c)} + C_{Var(c)} \right) \right] \\ & \qquad - P_{Supplier} \times C_{Supplier} - C_{Other} \end{aligned} \tag{3.15}$$

The consumers' response to price variation cannot be assumed as totally flexible; therefore, the following constraints are considered in this optimization problem. Maximum limits have to be imposed for load reduction (3.16) and price caps are also considered (3.17). The balance between load and generation has to be guaranteed (3.18). The consideration of load response is formulated based on price elasticity of demand (3.19), therefore the elasticity should be included in the formulation, since it shows the relation between power and price variation and makes them mutually dependent. Assuming a constant value for each consumer's elasticity, changes on price imply a corresponding change in the load consumption. Solving the optimization problem corresponds to finding the optimal values for load reduction and price variation for all the considered loads.

$$P_{Red(c)} \le P_{MaxRed(c)}, \forall c \in \{1, \ldots, Nc\} \tag{3.16}$$

$$C_{Var(c)} \le C_{MaxVar(c)}, \forall c \in \{1, \ldots, Nc\} \tag{3.17}$$

$$P_{Supplier} = \sum_{c=1}^{Nc} P_{Load(c)} - \sum_{c=1}^{Nc} P_{Red(c)} \tag{3.18}$$

$$Elasticity_{(c)} = -\frac{P_{Red(c)} \times C_{Initial(c)}}{P_{Load(c)} \times C_{Var(c)}}, \forall c \in \{1, \ldots, Nc\} \tag{3.19}$$

Using this approach and having knowledge on load profile the DNO can manage the loads in order to optimize its operation. The optimized individual load reductions and the electricity price variations for each consumer are obtained solving the formulated optimization problem. Some case studies consider the obligation of having the same price variation for the loads of the same type as formulated in (3.20), where T is the consumer type.

$$C_{Var(c)} = C_{Var(T)}, \forall c \in T \tag{3.20}$$

3.5.2.2 Consumption increase

In a second approach, let us consider the Distribution Network Operator (DNO) aiming the same objective (profit maximization) and applying the same consumers management method (price variations based on the elasticity values). The difference is that, in this approach, there is a certain amount of available energy acquired by the DNO and its objective is to increase the consumers' demand reducing the electricity price. The difference in the mathematical formulation, in the two approaches, is in the balance equation. For the consumption increase approach, the balance equation is as in (3.18), although the power reduction in each load becomes negative.

3.6 MODEL – VPP_CSP_LMP

The model VPP_CSP_LMP considers a VPP managing the network where the consumers response can be contracted directly with the VPP or through a Curtailment Service Provider (CSP). The specificity of the model when comparing with other developed models is the event trigger which is activated regarding the LMP value of electricity. This model was published in [Faria, 2011c].

3.6.1 Introduction

The Locational Marginal Price (LMP) is an important market signal since it can give the ability to analyze market conditions in distinct zones where LMPs are also distinct. This is the basis for the calculation of the charges/incomes of a player located in a specific node of the network. The LMP is also a signal that players can use to decide on the way they participate in the market. Several electricity markets use the LMP values to declare and remunerate DR events [Cappers, 2010].

This model proposes a DR event declaration performed by a VPP (Virtual Power Player) who manages a distribution network, when the energy component of the LMP that results from the schedule of the resources, including the electricity market, is higher than a specified value (figure 3.5). A currently used value is 100USD/MWh. In this condition, the VPP uses of the DR-Event participants' capacity trying to reduce the LMP value.

The proposed model considers that the VPP manages several distributed energy resources including Distributed Generation (DG) units, storage, and DR opportunities, and two ways of obtaining energy in the electricity market (day-ahead market and real-time market).

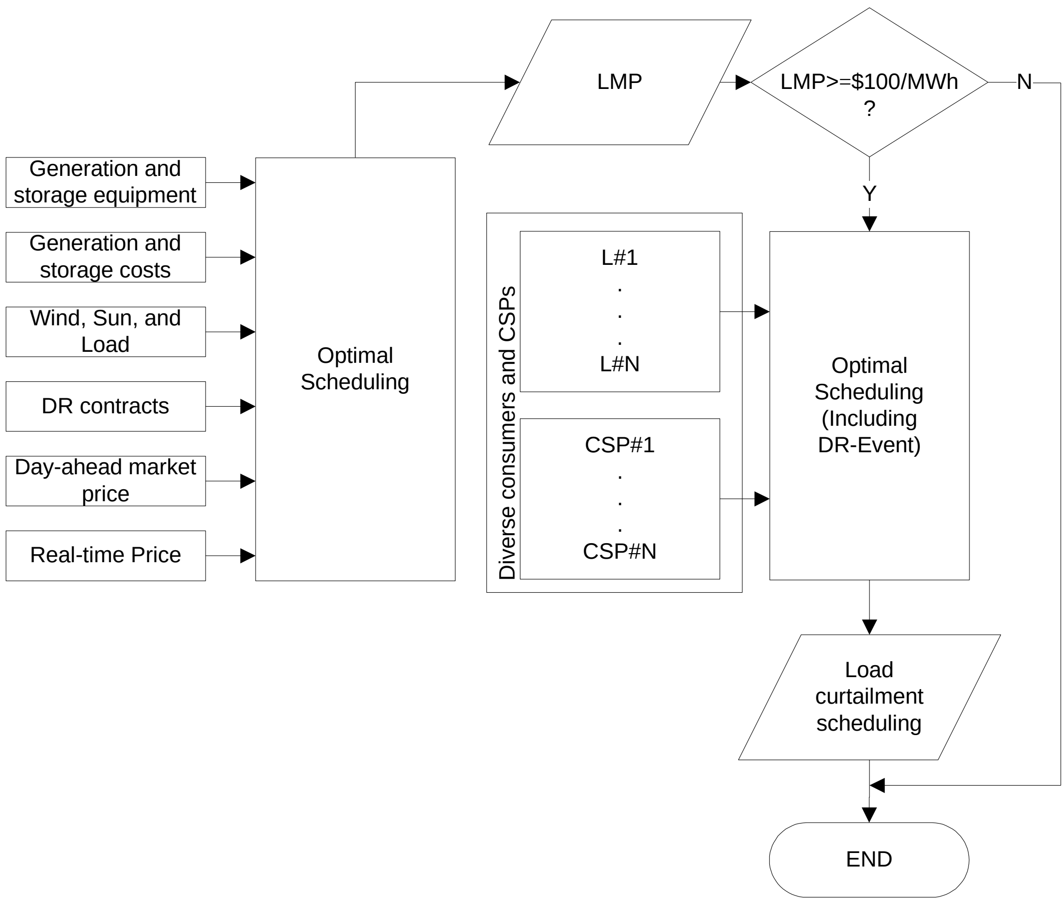

Figure 3.5. VPP_CSP_LMP method diagram

Every time the VPP receives the values of real-time market prices, and knowing about the day-ahead market results and about its own resources, an optimal scheduling is run to obtain the LMP value. It is important to note that the VPP should decide on how to obtain the energy that it is lacking, whether buying it in the real-time market and/or obtaining it from its available resources and eventually reducing the LMP in the managed network. At this phase, DR contracts are considered as an ordinary resource, since customers have contracted with the VPP an amount of load curtailment in specified conditions. If the LMP of a certain period is higher than the specified value, additional DR capacity (DR-Event) can be used trying to minimize the value of the LMP. This additional DR capacity is obtained from entities providing at least a defined amount of curtailment (usually 100 kW). Therefore, large consumers can participate directly in the event and small consumers need to be managed by a CSP in order to participate.

3.6.2 Mathematical formulation

The objective function (3.21) of this mixed-integer non-linear model is formulated with the aim of finding the total minimal cost to supply the demand. The energy component value of the LMP is obtained as a result of the optimization method.

$$\text{Minimize}$$

$$OC = \begin{pmatrix} P_{Day-ahead} \times C_{Day-ahead} + P_{Real-time} \times C_{Real-time} \\ + \sum_{gt=1}^{Ngt} (P_{Gen(gt)} \times C_{Gen(gt)}) + P_{NSP} \times C_{NSP} \\ - P_{StorageCharge} \times C_{StorageCharge} + P_{StorageDischarge} \times C_{StorageDischarge} \\ + \sum_{c=1}^{Nc} \left(P_{DR-Event(c)} \times C_{DR-Event(c)} + P_{DR-Contract(c)} \times C_{DR-Contract(c)} \right) \end{pmatrix} \tag{3.21}$$

As referred before, two types of DR capacity are considered - DR-Contract, and DR-Event. DR-Event capacity is only considered if the LMP-triggered event is activated. The existence of storage units and several generation types, as well as the energy supplied by the electricity market (day-ahead and real-time markets) are also considered.

Equations (3.22) to (3.34) refer to the constraints that are considered. Equation (3.22) refers to the power balance constraint.

$$\begin{aligned} P_{StorageCharge} + P_{EGP} + P_{Loss} = P_{Day-ahead} + P_{Real-time} + \sum_{gt=1}^{Ngt} P_{Gen(gt)} \\ + P_{StorageDischarge} + P_{NSP} + \sum_{c=1}^{Nc} \left(P_{DR-Event(c)} + P_{DR-Contract(c)} - P_{Load(c)} \right) \end{aligned} \tag{3.22}$$

Equations (3.23) to (3.28) represent the constraints concerning the maximum capacity considering the available resources, for generation (3.23, 3.24), day-ahead market (3.25), load response (3.26, 3.27), and storage units (3.28). DR-Event capacity is used in the total amount available; the DR-Contract can be used in the desired amount.

$$P_{Gen(gt)} \leq P_{MaxGen(gt)} \times X_{Gen(gt)}, X_{Gen(gt)} \in \{0,1\}, \forall gt \in \{1,...,Ngt\} \tag{3.23}$$

$$P_{Gen(gt)} \geq P_{MinGen(gt)} \times X_{Gen(gt)}, \; X_{Gen(gt)} \in \{0,1\}, \forall gt \in \{1,...,Ngt\} \tag{3.24}$$

$$P_{Day-ahead} \leq P_{MaxDay-ahead} \tag{3.25}$$

$$P_{DR-Contract(c)} \leq P_{MaxDR-Contract(c)}, \forall c \in \{1,...,Nc\} \tag{3.26}$$

$$P_{DR-Event(c)} = P_{MaxDR-Event(c)} \times X_{Event}, X_{Event} \in \{0,1\}, \forall c \in \{1,...,Nc\} \tag{3.27}$$

$$P_{Storage} \leq P_{MaxStorage} \tag{3.28}$$

Storage resources require a special treatment due to specific operation constraints. The discharge capacity is considered in equation (3.29) and the charge capacity in equation (3.30). In each instant, the battery only can be charged or discharged, as imposed by equation (3.31).

$$P_{StorageDischarge} \leq P_{MaxStorageDischarge} \times X_{Storage}, \; X_{Storage} \in \{0,1\} \tag{3.29}$$

$$P_{StorageCharge} \leq P_{MaxStorageCharge} \times Y_{Storage}, Y_{Storage} \in \{0,1\} \tag{3.30}$$

$$X_{Storage} + Y_{Storage} \leq 1, \; X_{Storage} \; and \; Y_{Storage} \in \{0,1\} \tag{3.31}$$

It is also necessary to impose that it is not possible to discharge more than the stored energy (3.32). Similarly, the power to be charged plus the power stored cannot be higher than the total storage unit capacity (3.33). Finally, the storage state is obtained considering the initial stored energy, the charge, and the discharge in each time period (3.34).

$$P_{StorageDischarge} - P_{StorageInitial} \leq 0 \tag{3.32}$$

$$P_{StorageCharge} + P_{StorageInitial} \leq P_{MaxStorage} \tag{3.33}$$

$$P_{Storage} = P_{StorageInitial} - P_{StorageDischarge} + P_{StorageCharge} \tag{3.34}$$

3.7 MODEL – VPP_CSP_ST

In the VPP_CSP_ST model, the LMP curves are generated for the VPP resources scheduling taking into account the LMP values. The objective is to minimize the VPP operation costs. The DG and Supplier energy costs are considered. If an increase in the load demand value causes an increase in the energy component of the LMP, the declaration of a DR event is simulated in order to evaluate the influence of the DR event in the LMP value. This method is expected to provide the VPP a tool to support decisions on DR event declaration.

3.7.1 Introduction

This model corresponds to a methodology that aims at supporting decisions concerning DR programs use, based on the impact that this use has on the energy component of the LMP. This methodology is divided into two main phases, the first one that generates several LMP curves and the second one that includes the analysis of those LMP curves, illustrated respectively in figure 3.6 and in figure 3.7.

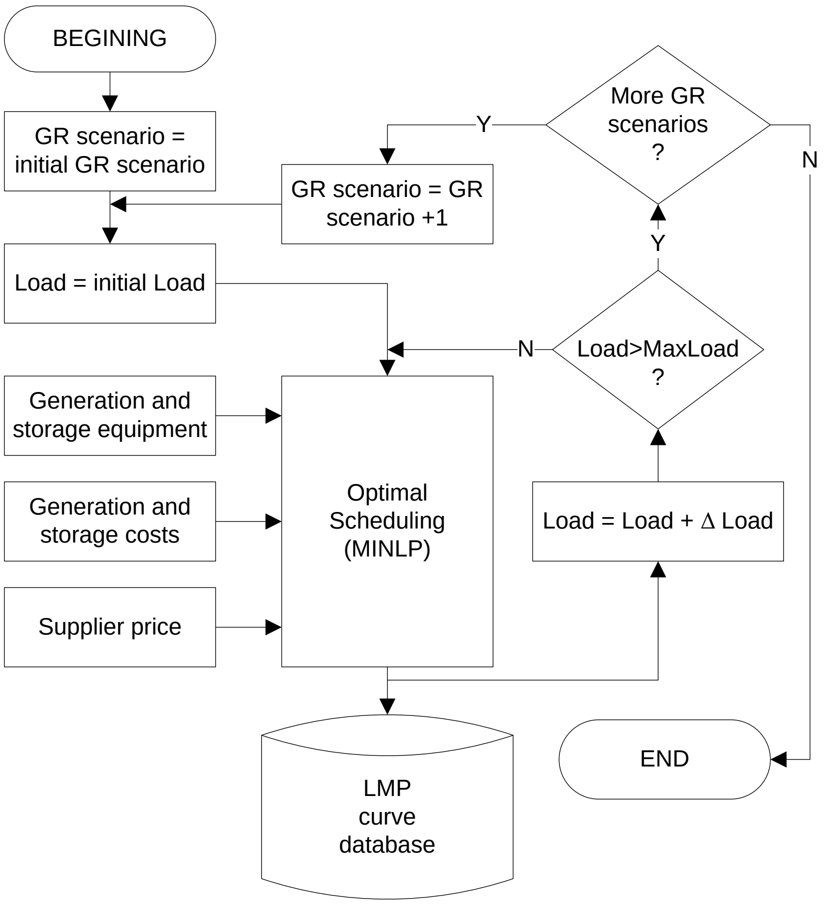

Figure 3.6. VPP_CSP - Generation of LMP curves

The first phase (seen in figure 3.6) uses an optimal scheduling based on a mixed integer non-linear algorithm, which manages the optimal use of generation resources and the DR, to minimize the operation costs. The LMP values are obtained as a result of the optimization problem.

The diversification of the LMP generated curves is obtained with the variation of total load demand value for each considered generation resource availability scenario (represented in figure 3.6 as “GR”). Every time a simulation is performed, including the information about generation and storage units technical characteristics and costs, and the Supplier energy price, the results are updated in a LMP curve data base.

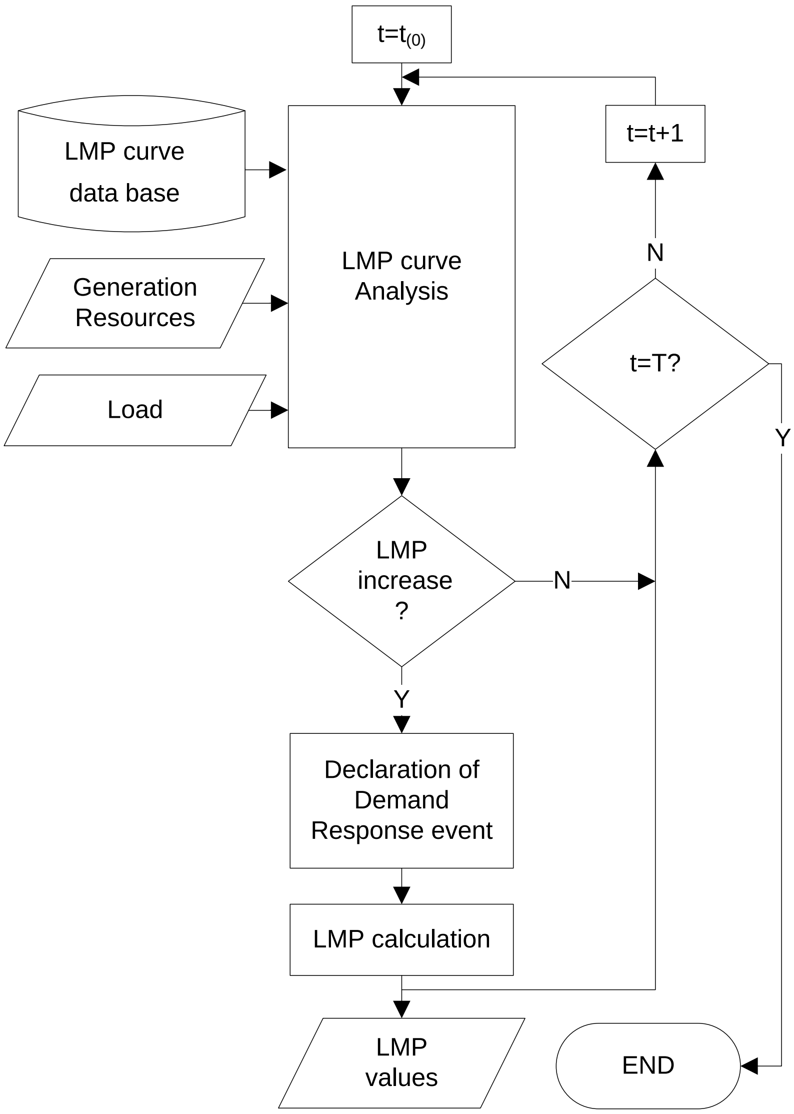

Figure 3.7. VPP_CSP - Analyses of LMP curves and DR management

The second phase (seen in figure 3.7) makes use of the LMP curves data base previously generated in an operation context, for each time period.

- In each period a LMP curve is selected, considering the referred database information, the resource availability, and the actual value of load demand. The LMP evolution from the previous period to the present one is analyzed and the use of DR programs is evaluated when there is an LMP increase. This evaluation is undertaken considering the new LMP value computed assuming that the DR event takes place.

3.7.2 Mathematical formulation

This problem is classified as mixed-integer non-linear. The objective function (3.36) of this mixed-integer non-linear model is formulated with the aim of finding the total minimal cost of supplying the demand. The energy component value of the LMP (Locational Marginal Price) is obtained as a result of the optimization method.

Three load curtailment steps are considered as a resource to obtain a better solution in the studies in which the LMP value determines the use of this resource. The existence of storage units and several generation types, as well as the energy supplied trough a supplier, are also considered.

Equations (3.37) to (3.43) refer to the constraints that are considered. Equation (3.37) refers to the power balance constraint.

$$
\begin{aligned}
&Minimize\\
&OC = \left(\begin{array}{l}
P_{Supplier} \times C_{Supplier} + \sum_{gt=1}^{Ngt} (P_{Gen(gt)} \times C_{Gen(gt)}) + P_{NSP} \times C_{NSP} \\
- P_{StorageCharge} \times C_{StorageCharge} + P_{StorageDischarge} \times C_{StorageDischarge} \\
+ \sum_{c=1}^{Nc} \left(P_{CutA(c)} \times C_{CutA(c)} + P_{CutB(c)} \times C_{CutB(c)} + P_{CutC(c)} \times C_{CutC(c)} \right)
\end{array}\right)
\end{aligned}
\tag{3.36}
$$

$$
\begin{aligned}
&P_{StorageCharge} + P_{EGP} = P_{Supplier} + \sum_{gt=1}^{Ngt} P_{Gen(gt)} + P_{NSP} \\
&+ P_{StorageDischarge} + \sum_{c=1}^{Nc} \left(P_{CutA(c)} + P_{CutB(c)} + P_{CutC(c)} - P_{Load(c)} \right)
\end{aligned}
\tag{3.37}
$$

Equations (3.38) to (3.43) represent the constraints concerning the maximum capacity regarding the available resources, for both generation (3.38, 3.39) and load response (3.40, 3.41, and 3.42), and for storage units (3.43). In this formulation, the participation of each load, in each load curtailment level, can only be by its total curtailment power in that level.

$$P_{Gen(gt)} \leq P_{MaxGen(gt)} \times X_{Gen(gt)}, X_{Gen(gt)} \in \{0,1\}, \forall gt \in \{1,...,Ngt\} \quad (3.38)$$

$$P_{Gen(gt)} \geq P_{MinGen(gt)} \times X_{Gen(gt)}, X_{Gen(gt)} \in \{0,1\}, \forall gt \in \{1,...,Ngt\} \quad (3.39)$$

$$P_{CutA(c)} = P_{MaxCutA(c)} \times X_{CutA(c)}, X_{CutA(c)} \in \{0,1\}, \forall gt \in \{1,...,Ngt\} \quad (3.40)$$

$$P_{CutB(c)} = P_{MaxCutB(c)} \times X_{CutB(c)}, X_{CutB(c)} \in \{0,1\}, \forall c \in \{1,...,Nc\} \quad (3.41)$$

$$P_{CutC(c)} = P_{MaxCutC(c)} \times X_{CutC(c)}, X_{CutC(c)} \in \{0,1\}, \forall c \in \{1,...,Nc\} \quad (3.42)$$

$$P_{Storage} \leq P_{MaxStorage} \quad (3.43)$$

Storage resources require a special treatment due to specific operation constraints. The constraints related to the storage units, included in this model, are the same that were used in the model VPP_CSP_LMP (3.29 – 3.34).

3.8 MODEL – VPP_LMP_VAR

The VPP_LMP_VAR is a DR program activated when the use of DR capacities causes important variations in the LMP value. When compared with the previous model (VPP_CST_ST), each DG unit is considered individually and with linear costs. An AC power flow is included for network constraints consideration.

Three steps of reduction/curtailment of consumption are considered in the scheduling problem. The model compares the same conditions of operation, with and without the use of DR. If the use of DR causes a positive impact in the operation cost minimization, the VPP acquires information confirming that in the specified operation conditions, the DR is an important resource to be considered.

3.8.1 Introduction

This model implements a methodology that aims at supporting decision making concerning DR program and contract design and use. This methodology is mainly based on the impact that the DR use has on the LMP of the network bus. It also analyses the DR impact on the operation costs.

This method includes two main phases seen on figure 3.8. The first phase (scenario set generation) consists on the definition of the increments to consider for the variables, based on their range and importance to the problem. With these values, it is possible to determine the number of scenarios (Sc) and the scenarios to be analyzed.

The second phase (LMP Curve Generation) uses an optimal scheduling based on the mixed integer non-linear programming approach which manages the optimal use of energy resources, including DR, to minimize the operation costs. The LMP values are obtained as a result of solving the optimization problem considering two distinct situations for each scenario: using DR and not using DR.

The number and diversity of the obtained LMP curves depend on the decisions made to generate the scenario set, namely in what concerns the defined increments and ranges for each problem variable. In practice, special care should be taken defining the load range and increment as it determines the load range applicability and the accuracy of the study conclusions. Other variables that should be considered are the resources present in the considered system and information concerning suppliers and the electricity market.

The proposed model allows to take conclusions concerning the adequate DR program design and use in regard to these intermittent non-dispatchable resources availability and to the load. Every time that a simulation is performed, including the constant data, the results are added to the LMP curve database.

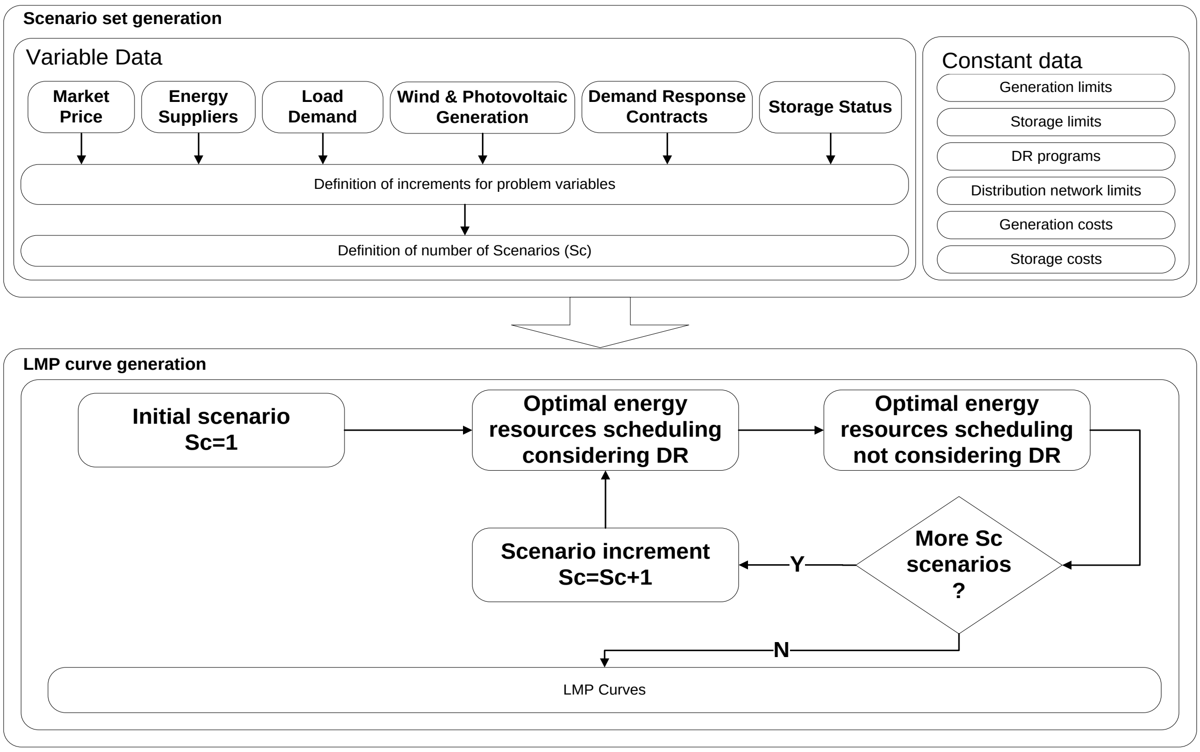

Figure 3.8. VPP_ST_LMP_VAR - analyses of LMP curves

Once obtained the LMP curve set for each bus, with DR and without DR, it is possible to define where and when DR use is advantageous. The obtained results allow supporting decisions both on DR use and design.

Decisions concerning DR program and contract design require alternative DR programs and contracts to be considered in the second phase of the method. For instance, if the full DR capacity is used and priority loads have to be curtailed in a relevant sub-set of the studied scenarios, it can be concluded that the considered DR programs and contracts are not enough. In such case, it is necessary to consider new contracts, providing the VPP additional DR capacity, which value should be based on the LMP results. Once DR programs and contracts are considered settled, the corresponding data is considered unchanged. Considering other variables changing within adequate ranges, according to strategically chosen increments, allows to take conclusions to support DR program and contract use.

3.8.2 Mathematical formulation

The objective function (3.44) of this mixed-integer non-linear model is formulated with the aim of finding the total minimal cost of supplying the demand, considering all the available resources, including DR. The bus LMP values are obtained as a result of the optimization method. In order to obtain the total LMP values, considering all the involved components (used energy resources, losses, congestion, bus voltage limits, and the penalty values due to the non-supplied energy to priority loads), it was necessary to implement an AC power flow in the problem formulation.

Minimize

$$OC = \begin{pmatrix} \sum_{sp=1}^{Nsp}\left(P_{Supplier(sp)} \times C_{Supplier(sp)}\right) + \sum_{g=1}^{Ng}\left(P_{Gen(g)} \times C_{Gen(g)}\right) \\ + \sum_{s=1}^{Ns}\begin{pmatrix} P_{StorageDischarge(s)} \times C_{StorageDischarge(s)} \\ -P_{StorageCharge(s)} \times C_{StorageCharge(s)} \end{pmatrix} \\ + \sum_{c=1}^{Nc}\begin{pmatrix} P_{Red(c)} \times C_{Red(c)} + P_{CutA(c)} \times C_{CutA(c)} \\ +P_{CutB(c)} \times C_{CutB(c)} + P_{NSP(c)} \times C_{NSP(c)} \end{pmatrix} \end{pmatrix} \quad (3.44)$$

Load demand must be matched with adequate energy generation. The present formulation considers generation and storage units, DR contracts, and the energy supplied through a defined set of contracts with external Suppliers, which represent the energy bought in the electricity market. The existence of non-supplied power is also considered for each consumer.

DR programs are formulated as a capacity that the VPP or other management entity can use in two different DR program types to satisfy the demand. The first one, referred as Red program, is a reduction in power consumption for which the management entity is able to manage the involved loads. The second DR program type corresponds to load curtailment contracts for an installation or for some of its circuits. The following formulation considers the use of two programs of this type - CutA and CutB.

The constraints of this problem are the same of the VPP_CSP_ST model, but they also include AC power flow constraints, obtained from the reference [Morais-2010a]. These constraints, related to the network technical limits, consider the active and reactive power flows, the line thermal limits, voltage amplitude and angle limits. Contemplating distribution networks with reconfiguration capability, a constraint for radial operation is included.

3.9 MODEL – VPP_BID

The VPP_BID model considers the bids of DR resources competing with the bids of generators and suppliers, and it has been inspired by [Behrangrad-2010].

3.9.1 Introduction

The electrical energy negotiated in an electricity market can be divided into two distinct products – energy and reserve [Behrangrad-2008]. Generators traditionally ensured both products and recently DR programs have also been used to ensure them. The use of DR for reserve requirement fulfillment is very interesting due to the adequacy of the DR fast response. Moreover, the reserve is mostly important in periods of peak power, when a contingency can cause increased effects. Consumers are able to participate with load curtailment in those periods, with several advantages when comparing with traditional generation resources [Jazayeri-2005].

The VPP_BID model considers that generators and consumers can participate in both energy and reserve products fulfillment (figure 3.9). The schedule of the resources used in these products is performed by a VPP aiming at minimizing the operation costs of supplying the demand and ensuring the adequate reserve. External suppliers that can supply electricity through the connections between the VPP owned network and the larger distribution network can also present bids for participation in the energy resources schedule.

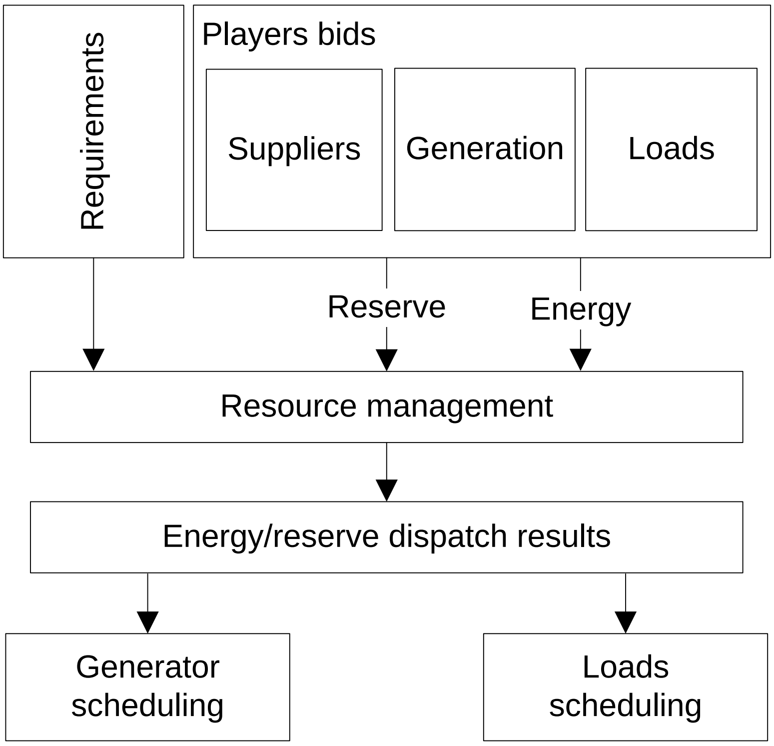

Figure 3.9. VPP_BID - DR management diagram

Figure 3.9 shows the schematic architecture of the model. It considers the resources managed by the VPP (generation and loads) and the suppliers' information for the optimal scheduling of generators and loads. The "Resource management" module addresses the formulated optimization problem considering also the requirements for each product.

3.9.2 Mathematical formulation

The proposed problem aims at minimizing the VPP costs and can be modeled as an optimization problem. Problem characteristics lead to a mixed-integer non-linear model and the problem consists on the minimization of a multimodal function with many local minima and a global optimum.

The objective function can be expressed as in (3.45). This objective function leads to the minimization of the costs considering the bids for energy and reserve products, made by suppliers, generators, and DR. All the bids are made with quadratic cost functions.

In the planning phase is not possible to know the effective use of the determined required power for reserve, therefore the probability of the use of the reserve is included. The binary variables related to the units quadratic cost functions are due to the fact that the fixed costs only have to be considered when the resource is actually used. The linear costs related to the non-contracted load shed and to the excess generated power are also included.

Minimize

$$OC = \left[\begin{array}{l} \sum_{sp=1}^{Nsp} \left[\begin{array}{l} X_{Supplier(sp)} \times Ca^{e}_{Supplier(sp)} + P^{e}_{Supplier(sp)} \\ \times Cb^{e}_{Supplier(sp)} + P^{e}_{Supplier(sp)}{}^{2} \times Cc^{e}_{Supplier(sp)} \\ + X_{Supplier(sp)} \times Ca^{r}_{Supplier(sp)} \\ + \left[\begin{array}{l} P^{r}_{Supplier(sp)} \times Cb^{r}_{Supplier(sp)} \\ + P^{r}_{Supplier(sp)}{}^{2} \times Cc^{r}_{Supplier(sp)} \end{array} \right] \times pr \end{array} \right] \\ + \sum_{g=1}^{Ng} \left[\begin{array}{l} X_{Gen(g)} \times Ca^{e}_{Gen(g)} + P^{e}_{Gen(g)} \times Cb^{e}_{Gen(g)} \\ + P^{e}_{Gen(g)}{}^{2} \times Cc^{e}_{Gen(g)} + X_{Gen(g)} \times Ca^{r}_{Gen(g)} \\ + \left[P^{r}_{Gen(g)} \times Cb^{r}_{Gen(g)} + P^{r}_{Gen(g)}{}^{2} \times Cc^{r}_{Gen(g)} \right] \times pr \end{array} \right] \\ + \sum_{c=1}^{Nc} \left[\begin{array}{l} X_{Red(c)} \times Ca^{e}_{Red(c)} + P^{e}_{Red(c)} \times Cb^{e}_{Red(c)} \\ + P^{e}_{Red(c)}{}^{2} \times Cc^{e}_{Red(c)} + X_{Red(c)} \times Ca^{r}_{Red(c)} \\ + \left[P^{r}_{Red(c)} \times Cb^{r}_{Red(c)} + P^{r}_{Red(c)}{}^{2} \times Cc^{r}_{Red(c)} \right] \times pr \\ + P_{NSP(c)} \times C_{NSP(c)} \end{array} \right] \end{array} \right] \quad (3.45)$$

Regarding the constraints of the problem, one has to guarantee the use of resources below their upper limits (3.46 – 3.55) i.e. the maximum curtailment of loads and the maximum production of distributed generation units and suppliers, and the power balance as seen in (3.55 – 3.57). For each resource, there is a maximum quantity for participating in each product and a total capacity. These maximums are defined as a parameter of the bid submitted by the resource.

$$P^{e}_{Supplier(sp)} \le P^{e}_{MaxSupplier(sp)}, \forall sp \in \{1, ..., Nsp\} \quad (3.46)$$

$$P^{r}_{Supplier(sp)} \le P^{r}_{MaxSupplier(sp)}, \forall sp \in \{1,...,Nsp\} \quad (3.47)$$

$$P^{r}_{Supplier(sp)} + P^{e}_{Supplier(sp)} \le P_{MaxSupplier(sp)}, \forall sp \in \{1,...,Nsp\} \quad (3.48)$$

$$P^{e}_{Gen(g)} \le P^{e}_{MaxGen(g)}, \forall g \in \{1,...,Ng\} \quad (3.49)$$

$$P^{r}_{Gen(g)} \le P^{r}_{MaxGen(g)}, \forall g \in \{1,...,Ng\} \quad (3.50)$$

$$P^{r}_{Gen(g)} + P^{e}_{Gen(g)} \le P_{MaxGen(g)}, \forall g \in \{1,...,Ng\} \quad (3.51)$$

$$P^{e}_{Red(c)} \le P^{e}_{MaxRed(c)}, \forall c \in \{1,...,Nc\} \quad (3.52)$$

$$P^{r}_{Red(c)} \le P^{r}_{MaxRed(c)}, \forall c \in \{1,...,Nc\} \quad (3.53)$$

$$P^{r}_{Red(c)} + P^{e}_{Red(c)} \le P_{MaxRed(c)}, \forall c \in \{1,...,Nc\} \quad (3.54)$$

$$P^{r}_{Red(c)} + P^{e}_{Red(c)} + P_{NSP(c)} \le P_{Load(c)}, \forall c \in \{1,...,Nc\} \quad (3.55)$$

$$\sum_{sp=1}^{Nsp} P^{r}_{Supplier(sp)} + \sum_{g=1}^{Ng} P^{r}_{Gen(g)} + \sum_{c=1}^{Nc} P^{r}_{Red(c)} = P^{r}_{Required} \quad (3.56)$$

$$\begin{aligned} &\sum_{sp=1}^{Nsp} \left[P^{e}_{Supplier(sp)} \right] + \sum_{g=1}^{Ng} \left[P^{e}_{Gen(g)} + P_{EGP(g)} \right] \\ &+ \sum_{c=1}^{Nc} \left[P^{e}_{Red(c)} + P_{NSP(c)} \right] = \sum_{c=1}^{Nc} P_{Load(c)} \end{aligned} \quad (3.57)$$

Regarding the balance equations, there are three. The first one (3.55) is the balance of each consumer' power. The second one (3.56) is the balance of all the resources participating in the reserve product, which need to guarantee the required power for this product. The last one (3.57) is the load-generation balance in the system.

3.10 CONCLUSIONS

The success of DR programs strongly depends on their adequate design and use. The entities responsible for DR programs need to use simulation tools in order to validate and redesign DR programs. This chapter presented DemSi, the DR simulator developed in the scope of this thesis. DemSi allows the analysis and validation of DR programs and models, both in what concerns the business and economic aspects and the technical validation of their impacts in the network.

The models of DR programs that have been designed and implemented in the scope of this thesis were also presented. The used software tools were briefly described. The parameters that characterize the models and make the distinction between them have also been presented. The consideration of DG, in what concerns the generation cost function, the costs themselves, and the individual/grouped unit schedule led us to multiple possibilities on how to operate this resource. This gave place to a diversity of models that have been designed and implemented.

The way the energy provided by one or more suppliers is considered also varies from model to model. This energy can be obtained in distinct periods (day-ahead and real-time markets for example) and one or more supplier prices can be considered.

A specific DR program can also differ in the resource management goal, which can be the minimization of the operation costs or the maximization of profits. This goal comes from the managing entity or the consumers' point of view.

The DR program event trigger determines the system or market conditions in which the DR event is declared. The developed models consider DR programs in which the trigger is the occurrence of a fault, the LMP being equal or higher than *a priori* specified value, or DR can simply be used because its price is lower than those of the remaining available resources.

The last parameter is the response characterization. Consumers' DR capacity can be divided into a single or several steps of curtailment and/or reduction of consumption. It can also be defined by the bid that the consumer or group of consumers submit to the participation in the DR program. In the RTP model, the participation of consumers, which depends on the price of electricity, is modeled by the consumer elasticity.

The aggregated participation of consumers is useful when single consumer participation has not the required minimum participation reduction capacity. The curtailment aggregation entity is generally called a Curtailment Service Provider (CSP).

Chapter 4

Case Studies

4 CASE STUDIES

This chapter presents several case studies that illustrate the application of the proposed models and DemSi performance. Although it is not possible to demonstrate DemSi models and functionalities in their full extent in this written document, the presented case studies have been chosen to cover a diversity of situations and involved players. The results obtained are presented and discussed individually for each model. In the end of the chapter some general conclusions are taken.

4.1 INTRODUCTION

The diversity in the characteristics of the developed/implemented models leads to the need of creating several individual case studies. After this introduction section, which explains the organization of the present chapter, section 4.2 presents the most relevant data concerning the consumer sets and the network used for the case studies. Each subsequent section from 4.3 to 4.9 corresponds to a case study concerning each one of the models presented in chapter 3. Finally, a conclusion section presents the main conclusions that can be drawn from this chapter contents.

Table 4.1 summarizes the characteristics of the considered case studies. The relevant information concerning the application of the models are the number of consumers and the use of a Particle Swarm Optimization (PSO) approach to solve the optimization problem. The other information included in this table, and that characterizes the model and not the case study application, has already been presented in chapter 3 and is repeated here to allow a better understanding of the differences between the case studies. The models in the columns of table 4.1 are ordered as in the next sections.

In the first column of table 4.1, are presented several parameters that characterize the models and make the distinction between them. As already explained in chapter 3, the distinction between the models can be made regarding the number of consumers, the existence of DG, the considered suppliers, the resource management goal, the use of PSO, the DR event trigger, the consumer response characterization, and the possibility of consumers presenting bids.

The acronym that identifies each model starts with the acronym of the entity that manages the distribution network (VPP, DNO, etc.) aims at minimizing operation costs or maximizing profits. The remaining part of the model acronym identifies the most relevant and unique characteristics of each model.

The case studies presented in this section were implemented in DemSi, the DR simulator presented in chapter 3.

Table 4.1. Characterization of models and scenarios

Characteristic	Model						
	DNO_VOLL	VPP_ST	DNO_RTP	VPP_CSP_LMP	VPP_CSP_ST	VPP_LMP_VAR	VPP_BID
No. of consumers	32	218	218	32	32	32	218
DG	Costs of DG not considered	5 groups of generators - quadratic and linear costs	-	DG units aggregated by generation type	DG units aggregated by generation type	Each unit considered individually with linear costs	Each unit considered individually with quadratic costs
Suppliers	Larger public distribution network	1 supplier (electricity market)	1 supplier (electricity market)	2 amounts: day-ahead and real-time	1 Supplier	1 Supplier	Several suppliers
Resource management goal	Minimization of DNO operation costs	Minimization of VPP operation costs	Maximization of DNO Profits	Minimization of VPP operation costs	Minimization of VPP operation costs	Minimization of VPP operation costs	Minimization of VPP operation costs
PSO	-	Classic PSO and mutated PSO	-	-	-	-	-
Trigger	Fault occurrence	As scheduled	As scheduled	LMP>0.1$/kWh	LMP increase	Use for validation	As scheduled
Response characterization	2 types of flexible supply contracts	3 steps – curtailment and reduction	Elasticity values for each load type	2 amounts: DR-event and DR-contract	3 curtailment steps	3 steps – curtailment and reduction	Participation With quadratic costs
Bids	-	-	-	-	-	-	Bids by generators and loads for energy and reserve

4.2 NETWORK AND CONSUMER SETS

The case studies to be presented in sections 4.3 to 4.9 use a distribution network with 33 buses, 32 of them load buses, based on [Baran-1989]. This network considered initially 32 consumers corresponding one consumer to each bus. The used network was adapted from the original by a study of the evolution of the DG and demand. Section 4.2.1 describes in detail the network description in terms of DG. Consumers' characteristics are presented in section 4.2.2.

4.2.1 33-bus test system

The distribution network used in [Baran-1989] has been object of a study that considers the evolution of the demand and the integration of Distributed Generation (DG) in several future scenarios, for years 2008, 2010, 2015, 2020, 2030, and 2040, as presented in [Vale-2009a]. Figure 4.1 presents the network in its original state, as in [Baran-1989], and figure 4.2 presents it in the state that includes the integration of DG, in a scenario that corresponds to the year 2040, as in [Vale-2009]. A connection to the upstream network is established in bus number 0.

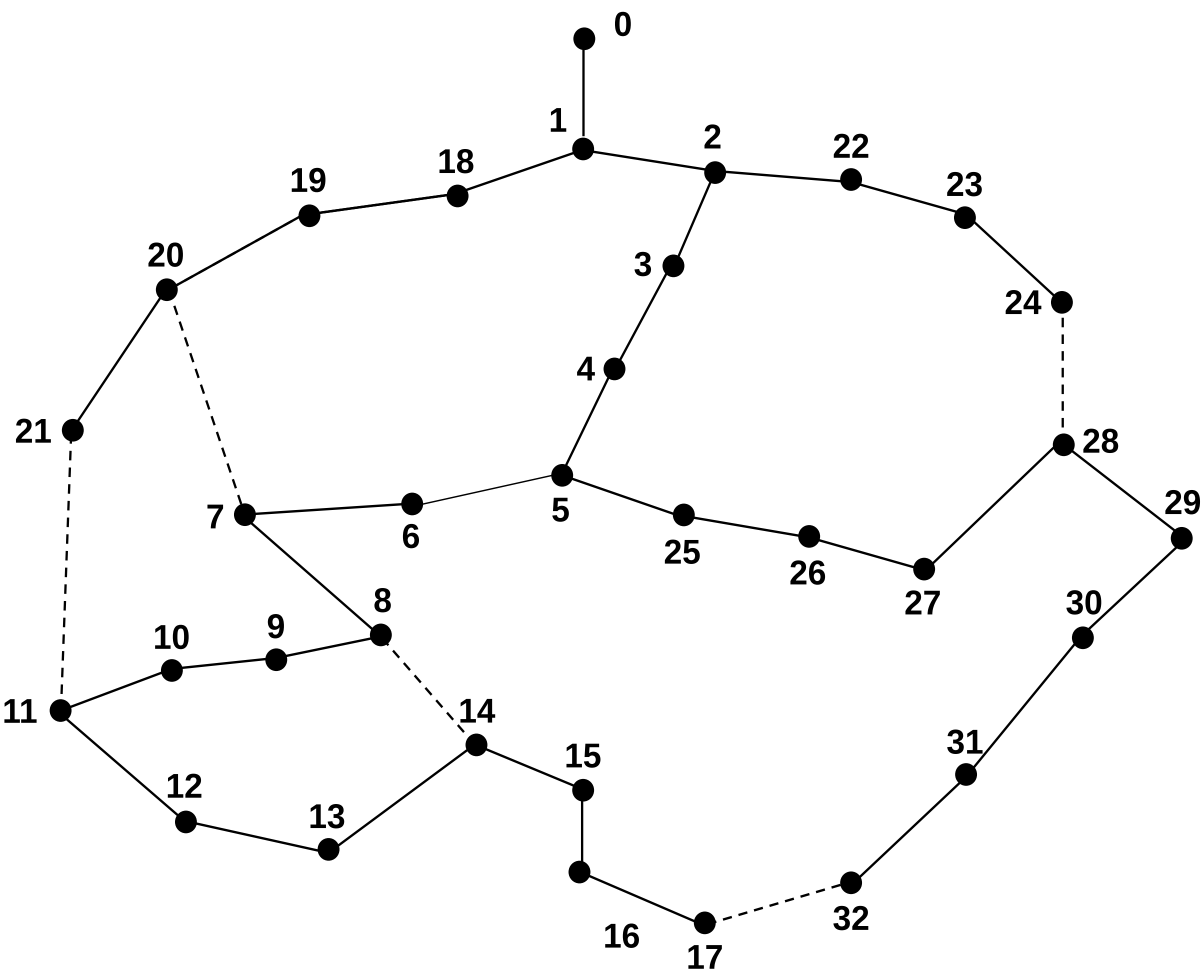

Figure 4.1. 33 bus original distribution network

The performed studies concerned the determination of DG units, type of technology (photovoltaic, wind, etc.), and size for each scenario. The allocation of units in the buses of the network has been done randomly to reproduce the real conditions in what concerns the localization. For the 2040 scenario, the network comprises 66 DG units.

Some of the case studies presented in this chapter consider several suppliers connected to bus 0, which connects the considered distribution network to the upstream network.

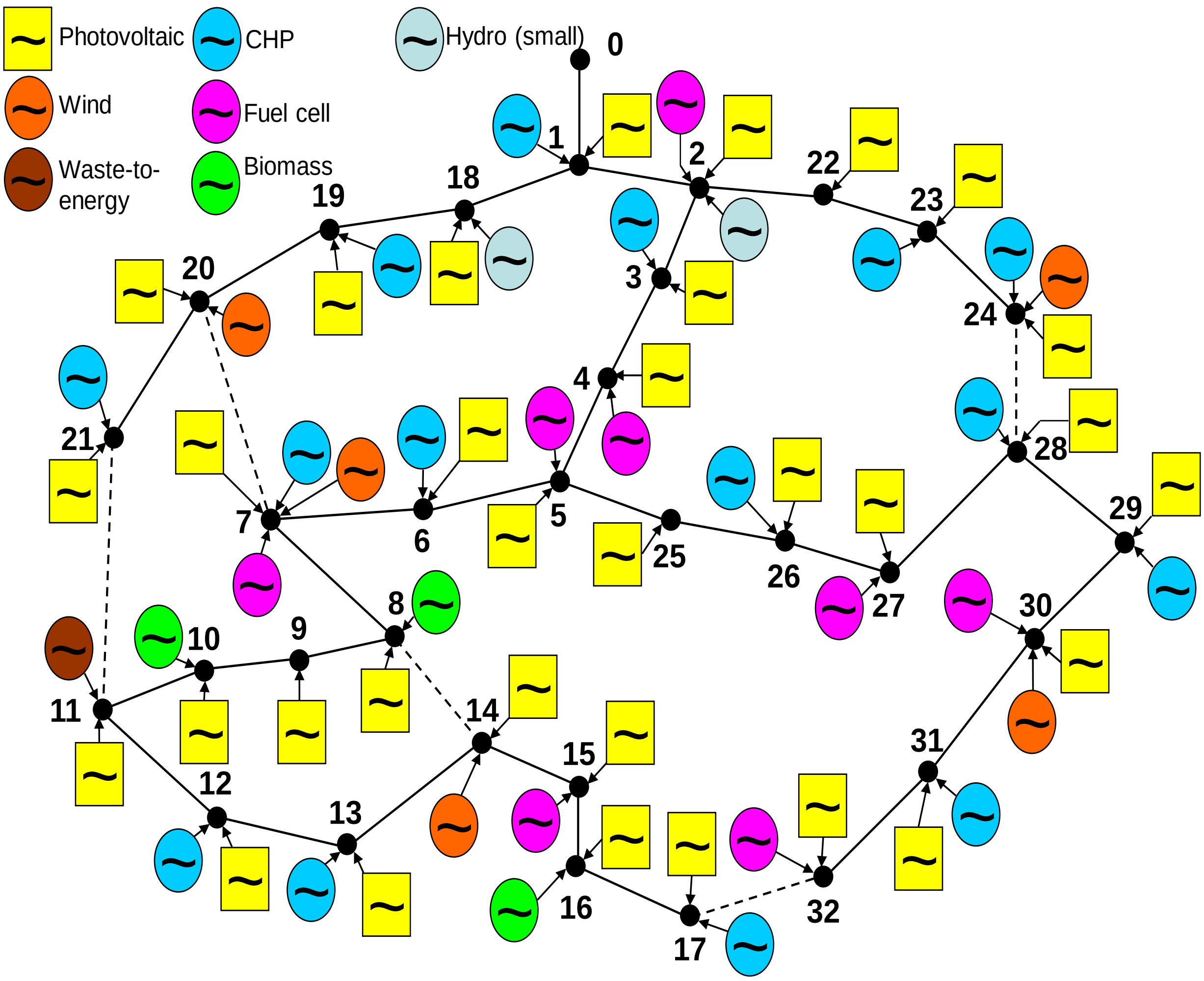

Figure 4.2. 33 bus modified distribution network, with DG, for 2040

Table 4.2 presents the most relevant data for the 2040 scenario DG units. For each DG unit type, it presents the number of units, the size of the smaller unit, the size of the larger unit, and the total installed capacity.

The costs of using each one of the DG units depend on the specific characteristics of each case study. Therefore, this information concerning DG costs is presented in the section concerning each case study.

Table 4.2. DG characterization

DG Type	Number of units	Minimum size (kW)	Maximum size (kW)	Total capacity (kW)
Photovoltaic	32	3	30	558
Wind	5	100	200	700
Waste-to-energy	1	10	10	10
CHP	15	10	100	740
Fuel cell	8	10	50	235
Biomass	3	100	150	350
Hydro	2	30	40	70

4.2.2 Consumer sets characterization

Depending on the case study, two different consumer sets have been considered for the used distribution network. In the first one, a single consumer is allocated in each bus of the network (with the exception of bus 0), as considered in its initial state in [Baran-1989], and updated according to the undertaken demand evolution study as referred above. The second one considers a larger amount of consumers connected along the 32 consumption buses, making a total of 218 consumers in the network.

Each consumer is classified in one of six types:

- DM – Domestic;
- SC – Small Commerce;
- MC – Medium Commerce;
- LC – Large Commerce;
- MI – Medium Industrial;
- LI – Large Industrial.

Table 4.3 summarizes the characteristics of the two consumer sets (32 and 218 consumers). The values of demand in each bus are presented in the second column of table 4.3. The percentage of that value and the number of consumers of each consumer type are presented in the remaining columns.

For the 32 consumers scenario, the consumer type is the one that corresponds to the numbers in bold green in the table. In this scenario, the power consumption in the bus is obviously equal to 100% for the consumer type corresponding to the one in bold green.

Each of the used and presented consumer sets totalizes a demand of 5827 kW. Regarding the 218 consumers scenario, most of the consumers (120) are domestic (DM), and the consumer type with less consumers (7) is Medium Industrial (MI).

Table 4.3. Consumer sets characterization

Bus	Demand (kW)	Power consumption (%)						Number of consumers					
		DM	SC	MC	LC	MI	LI	DM	SC	MC	LC	MI	LI
1	169.0	-	20	**40**	40	-	-	-	2	2	1	-	-
2	148.0	25	**75**	-	-	-	-	2	5	-	-	-	-
3	147.0	40	**60**	-	-	-	-	4	4	-	-	-	-
4	145.0	70	**30**	-	-	-	-	7	2	-	-	-	-
5	94.0	**100**	-	-	-	-	-	8	-	-	-	-	-
6	311.0	20	10	-	**70**	-	-	4	1	-	2	-	-
7	309.0	-	10	20	**70**	-	-	-	1	1	2	-	-
8	89.0	**85**	15	-	-	-	-	9	1	-	-	-	-
9	91.0	**100**	-	-	-	-	-	10	-	-	-	-	-
10	67.0	**60**	40	-	-	-	-	4	2	-	-	-	-
11	91.0	**80**	20	-	-	-	-	6	1	-	-	-	-
12	91.0	**100**	-	-	-	-	-	7	-	-	-	-	-
13	181.0	30	20	**50**	-	-	-	5	2	2	-	-	-
14	91.0	**100**	-	-	-	-	-	6	-	-	-	-	-
15	91.0	**80**	20	-	-	-	-	7	1	-	-	-	-
16	92.0	**65**	35	-	-	-	-	5	2	-	-	-	-
17	135.0	15	**60**	25	-	-	-	2	4	1	-	-	-
18	152.0	-	-	**30**	70	-	-	-	-	2	2	-	-
19	152.0	15	-	**50**	35	-	-	3	-	3	1	-	-
20	152.0	-	40	**60**	-	-	-	-	4	4	-	-	-
21	151.0	-	20	**40**	40	-	-	-	2	2	1	-	-
22	147.0	20	**80**	-	-	-	-	2	5	-	-	-	-
23	675.0	5	5	-	-	-	**90**	2	1	-	-	-	4
24	669.0	-	5	-	-	10	**85**	-	1	-	-	1	4
25	94.0	**100**	-	-	-	-	-	7	-	-	-	-	-
26	93.0	**75**	25	-	-	-	-	5	1	-	-	-	-
27	92.0	**100**	-	-	-	-	-	8	-	-	-	-	-
28	183.0	15	25	**60**	-	-	-	2	2	3	-	-	-
29	295.0	-	10	**15**	-	75	-	-	1	1	-	3	-
30	225.0	-	**10**	-	-	60	30	-	1	-	-	3	1
31	315.0	-	-	20	**80**	-	-	-	-	2	4	-	-
32	90.0	**100**	-	-	-	-	-	5	-	-	-	-	-
Total	5827.0	-	-	-	-	-	-	120	46	23	13	7	9

4.3 CASE STUDY – DNO_VOLL

As referred in section 3.5, which explains DNO_VOLL model, this work was published by the author of this thesis in [Faria-2010]. After a brief introduction to the considered scenarios, results are presented and some conclusions are indicated.

4.3.1 Outline

Let us consider the 33 bus distribution network of figure 4.2 and the 32 consumers set. As previously referred, this network is connected to the larger distribution public network through bus number 0. Considering a fault in line 0-1 that connects bus 0 to the upstream larger distribution network, we will have:

- The considered network turns to an island where DG is the only mean of electricity generation;
- The available DG is not enough to supply all the demand but is enough to supply Critical Loads (CL) and to ensure an adequate amount of reserve;
- The remaining DG must be optimally used to supply additional loads, according to their profiles and contract clauses.

DemSi has been used to find the optimization results, and to perform the network simulation. A complete day has been simulated for this case study.

4.3.2 Results

Figure 4.3 presents the value of the total load and total DG for this period.

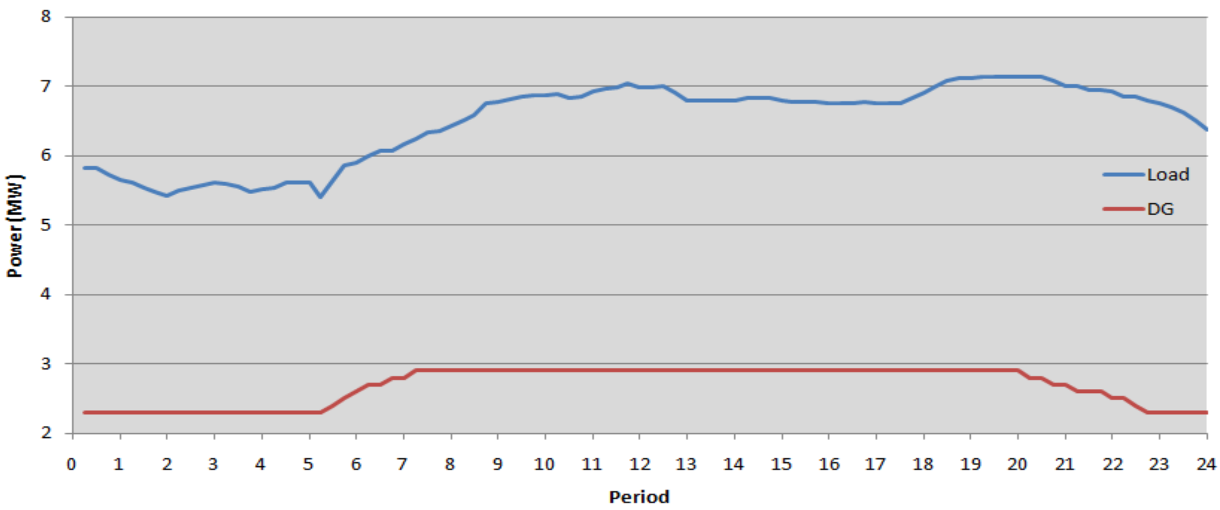

Figure 4.3. Load and DG diagram

The load diagram corresponds to the consumers demand. After the occurrence of the above referred fault, DG is the only generation means so only a part of this demand can be supplied. The considered fault keeps line 0-1 out of service, starting in instant 0 and lasting the whole day. The value of the estimated power losses is discounted in the value of the available generation power that is considered to supply the demand.

Table 4.4 shows the results obtained for the considered scenario, with and without demand response use for the first period of 15 minutes. In this period, the total generation is 2300kW. Table 4.4 also indicates for the total load connected to each bus the value in kW of the Non-Supplied Load (NSL) and the monetary Value Of Lost Load (VOLL).

Table 4.4. Results for the first period

Bus	Demand (kW)	Without DR			With DR			
		NSL (kW)	*Unitary VOLL (€/kWh)*	*VOLL (€)*	*Supply Contract*	*NSL (kW)*	*Unitary VOLL (€/kWh)*	*VOLL (€)*
1	169.0	169.0	7	295.8	FS1	135.3	0	0.0
2	148.0	148.0	5	185.0	RL	148.0	5	185.0
3	147.0	0.0	40	0.0	CL	0.0	40	0.0
4	145.0	0.0	9	0.0	FS2	72.8	0	0.0
5	94.0	94.0	7	164.5	RL	0.0	7	0.0
6	311.0	311.0	5	388.8	FS1	248.9	0	0.0
7	309.0	309.0	6	463.5	FS2	154.3	0	0.0
8	89.0	89.0	6	133.5	RL	89.0	6	133.5
9	91.0	91.0	5	113.8	RL	91.0	5	113.8
10	67.0	0.0	30	0.0	CL	0.0	30	0.0
11	91.0	91.0	8	182.0	FS1	72.9	0	0.0
12	91.0	91.0	7	159.3	FS2	45.7	0	0.0
13	181.0	0.0	30	0.0	CL	0.0	30	0.0
14	91.0	91.0	8	182.0	RL	0.0	8	0.0
15	91.0	91.0	5	113.8	RL	91.0	5	113.8
16	92.0	0.0	50	0.0	CL	0.0	50	0.0
17	135.0	135.0	3	101.3	RL	135.0	3	101.3
18	152.0	152.0	6	228.0	FS1	121.9	0	0.0
19	152.0	152.0	5	190.0	RL	0.0	5	0.0
20	152.0	152.0	5	190.0	RL	75.8	0	0.0
21	151.0	151.0	3	113.3	RL	151.0	3	113.3
22	147.0	0.0	7	0.0	FS1	117.8	0	0.0
23	675.0	0.0	9	0.0	RL	675.0	9	1518.3
24	669.0	669.0	7	1170.8	RL	669.0	7	1171.3
25	94.0	94.0	5	117.5	RL	94.0	5	117.2
26	93.0	0.0	25	0.0	CL	0.0	25	0.0
27	92.0	92.0	4	92.0	RL	92.0	4	92.2

Bus	Demand (kW)	Without DR			With DR			
		NSL (kW)	*Unitary VOLL (€/kWh)*	*VOLL (€)*	*Supply Contract*	*NSL (kW)*	*Unitary VOLL (€/kWh)*	*VOLL (€)*
28	183.0	183.0	8	366.0	FS2	91.5	0	0.0
29	295.0	0.0	50	0.0	CL	0.0	50	0.0
30	225.0	0.0	20	0.0	CL	0.0	20	0.0
31	315.0	315.0	3	236.3	RL	315.0	3	236.3
32	90.0	90.0	5	112.5	RL	90.0	5	112.3
Total	5827.0	3760.0	-	5299.3	-	3776.9	-	4010.1

FS1 – Flexible Contracts type 1
FS2 – Flexible Contracts type 2
RL – Regular Loads
CL – Critical Loads

The case study considers two different situations: with and without demand response. Without DR, the VOLL is calculated according to the value of the unitary VOLL attributed to each individual load. With DR, the VOLL is calculated using the clauses of each load contract; these clauses determine the conditions under which a part of the load may be curtailed. These values are calculated for each individual load; the total value for the load connected to each bus is presented in Table 4.4.

This scenario considers two types of flexible contracts (FS1 and FS2), that represents the use of DR, which only differ on the specific contract clauses (percentage of load that the clients accept to be curtailed and contract tariffs). The loads that have not any type of supply contract are indicated as RL (Regular Loads).

From the presented results, we can conclude that the total VOLL is substantially decreased when considering DR with a part of the loads with types CL and FS contracts. It is important to note that the values presented in this table only refer to the VOLL concerning a 15 minutes period. The total annual decrease in the VOLL value depends on the number, duration and characteristics of the faults that cause a lack of supply.

Figure 4.4 shows the amount of non-supplied load considering and not considering DR for the whole day concerning the fault of this case study. These two curves are very similar because they correspond to the use of the amount of DG available (minus losses, as explained in sub-section 3.2) along the day.

In spite of this similarity, the VOLL presents very different values in the two situations as shown in figure 4.5. The results presented in this figure clearly show that an adequate use of DR, through flexible contracts can significantly decrease the VOLL.

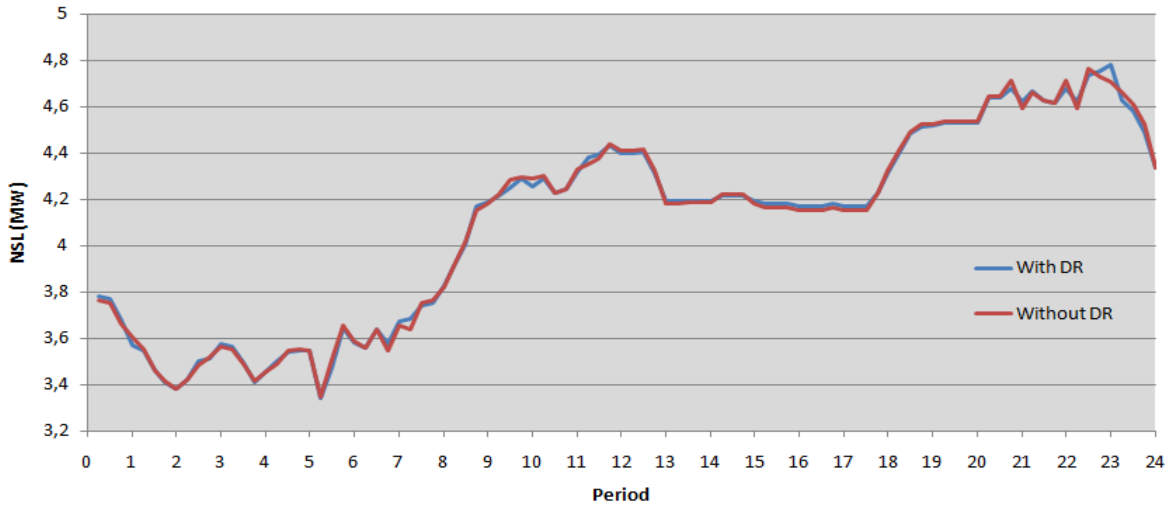

Figure 4.4. NSL with and without DR

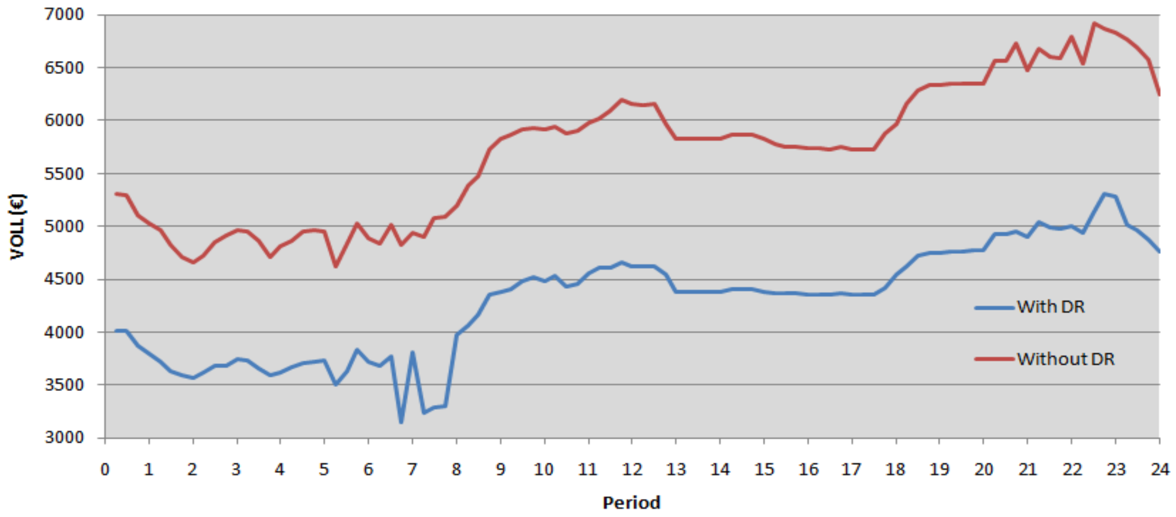

Figure 4.5. VOLL with and without DR

4.3.3 Results analysis

Future power systems should accommodate an intensive use of distributed generation which requires to adequately address technical problems that this use arises. Moreover, distributed generation brings new possibilities of increasing service quality, namely in case of incidents. Some incidents may cause an islanded operation, which can also occur in a normal operation of the system. In these future scenarios, demand response must be considered a relevant energy resource that can be used by consumers to take advantage of their elasticity and by suppliers and distribution operators to increase service quality and/or decrease costs. A case study considering a fault, which cause an islanded operation of the network, evidences the advantages of using adequate methodologies to manage demand response in this kind of situation.

4.4 CASE STUDY – VPP_ST

As referred in the explanation of the model presented in section 3.4, this work was published in [Faria-2011]. The results obtained in this case study are divided into three scenarios – fixed supplier price; variable supplier price; and supplier price steps.

4.4.1 Outline

The first of the three scenarios presented in this case study consider a fixed supplier price for electricity, as well as to the other resources. In the second scenario, results are analyzed regarding variations in the supplier price of electricity. Finally, in the third scenario, the energy provided by the supplier is dived into three steps of available power, with a different price for each step. In this way, in the three scenarios is acting one supplier. However, its power and respective price are considered in three different ways.

All the three scenarios are solved by Mixed Integer Non-Linear Programming (MINLP) as the formulated problem is non-linear and include both discrete and continuous variables; the first scenario is also solved by two Particle Swarm Optimization (PSO) methods - classic PSO and an improved PSO that considers mutation (PSO-MUT). The implementation of the PSO methods and the obtained results were done with the authors of [Faria, 2011].

This case study considers 218 consumers and 6 types of power sources, as defined in the VPP_ST model description presented in the section 3.6. Table 4.5 presents the costs of load reduction for each consumer type. The three steps of load reduction are successive, i.e. "RedC" only can be used when "RedA" and "RedB" have been already fully used. For this case study, it is considered that each reduction step is limited to 20% of the total rated load power in each bus.

Table 4.5. Load reduction costs

Type of consumer		Values of reduction cost (m.u./kWh)		
		RedA	***RedB***	***RedC***
Domestic	DM	0.16	0.20	0.24
Small Commerce	SC	0.15	0.19	0.22
Medium Commerce	MC	0.18	0.20	0.26
Large Commerce	LC	0.17	0.24	0.26
Medium Industrial	MI	0.17	0.25	0.27
Large Industrial	LI	0.17	0.26	0.28

The generation costs and the maximum capacity of each generation resource type are presented in table 4.6. These costs are modeled considering fixed (a), linear (b), and quadratic (c) components of cost function. Some generation resource costs only have the linear component (b).

Table 4.6. Generation resources costs

Source	Price			*Capacity (kW)*
	***a* (m.u./h)**	***b* (m.u./kWh)**	***c* (m.u./kWh^2)**	
Wind	-	0.020	-	700
PV	-	0.010	-	558
Other1	0.001	0.080	0.00002300	305
Other2	0.000	0.043	0.00000125	400
CHP	0.006	0.200	0.00005300	700
Supplier	-	0.250	-	-

4.4.2 Results

4.4.2.1Scenario 1

The participation of the energy resources (including DG, market energy, and DR) to satisfy the load needs is evaluated according to each resource costs. Results are obtained with the three methods already referred and compared. This comparison is done in terms of the obtained solution global costs and also of the execution time of each method for each scenario. The number of particles assigned to PSO and PSO-MUT methods was 20. The number of iterations was 100 for both versions in order to allow comparing the obtained results.

The results for power reduction, for the three highest power demand consumers' types (LC – Large Commerce; MI – Medium Industrial; and LI – Large Industrial) are presented in figures 4.6, 4.7, and 4.8, respectively for steps RedA, RedB, and RedC, and for the three proposed methods. The curve of maximum permitted load reduction is also presented in these figures. The results for other consumers' types are included in Annex A.

Taking as reference the MINLP results, one can see that in all reduction uses the reduction values equal the upper limits. Looking at the results provided by the PSO-MUT, in RedA reduction step, the maximum allowed reduction is used for all but one load whereas classical PSO solution does not fully use the maximum allowed reductions for several loads. In RedB step, this tendency is more evident with the PSO-MUT using the maximum reduction for less loads and the classical PSO solution staying far from using the maximum reduction for most of the loads. These two methods solutions do not reduce any load in RedC step what leads to the use of other energy resources as can be seen in figure 4.9 and, consequently, to higher costs.

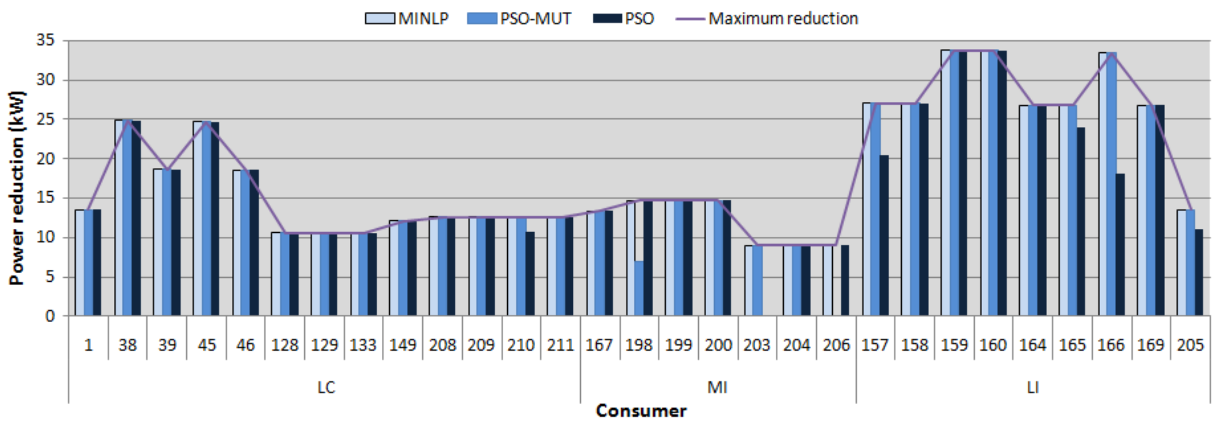

Figure 4.6. Power reduction for reduction step RedA, in scenario 1 of VPP_ST, for LC, MI, and LI consumers

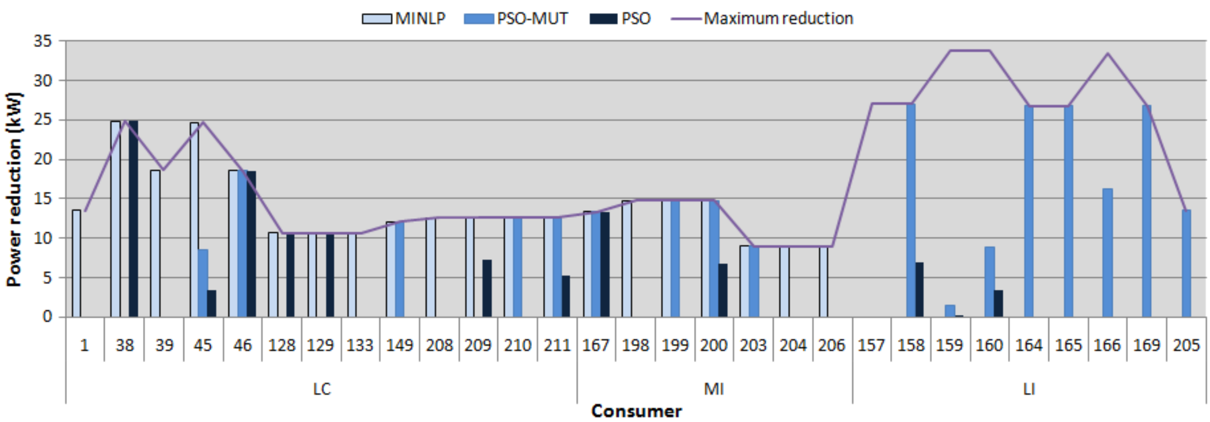

Figure 4.7. Power reduction for reduction step RedB, in scenario 1 of VPP_ST, for LC, MI, and LI consumers

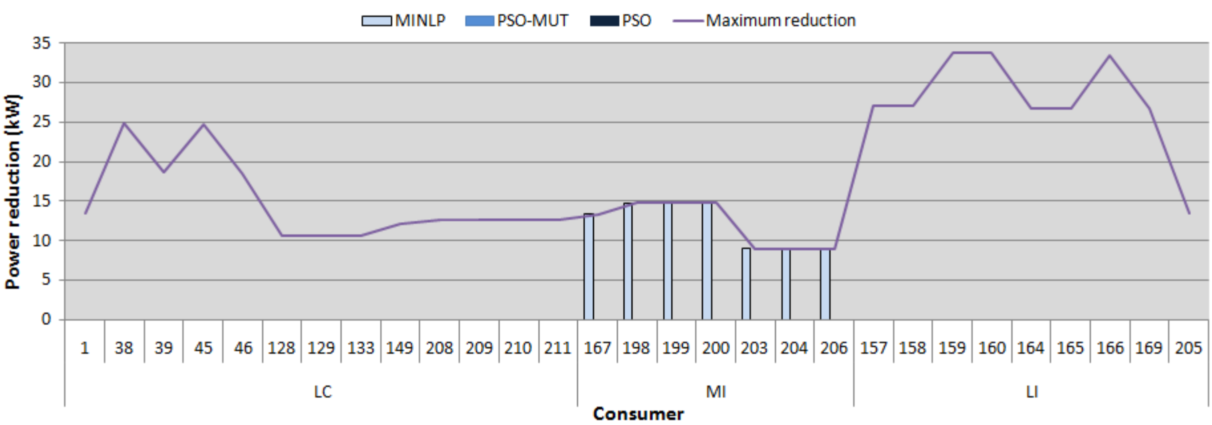

Figure 4.8. Power reduction for reduction step RedC, in scenario 1 of VPP_ST, for LC, MI, and LI consumers

Figure 4.9 presents the results of energy resources usage considering the solutions obtained by the three methods. As concluded above, PSO and PSO-MUT result in lower values of consumption reductions, therefore causing the use of other resources. This effect is more evident in the classic PSO approach, showing the importance of mutation to obtain better results. PSO solutions use more energy from the market, which is one of the resources with higher price.

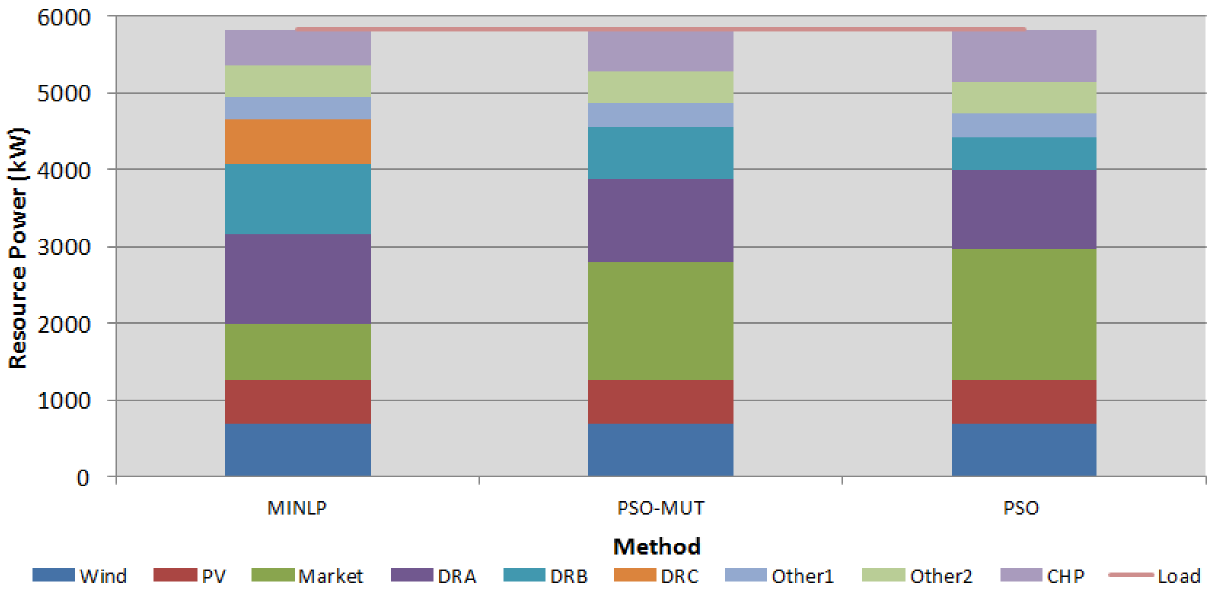

Figure 4.9. Resources scheduling in scenario 1 of VPP_ST

The values of the objective function (i.e. the total cost of supplying the demand) and the time necessary to obtain the results by each method in each scenario are presented in table 4.7. Swarm optimization based methods are much faster than the reference method. This is true even for a very demanding situation evidencing the advantage of PSO approaches in terms of processing time (about 83% time reduction). In terms of cost solution, PSO-MUT shows better performance than the classic PSO approach, only with slightly higher execution times.

Table 4.7. VPP_ST Time and costs comparison

Method	Results			
	Time (s)	*Time reduction (%)*	*Costs (m.u.)*	*Cost increase (%)*
Reference	0.7962	-	870.48	-
PSO	0.1304	83.60	914.00	4.50
PSO-MUT	0.1351	83.03	902.00	3.62

4.4.2.2Scenario 2

In the second scenario, all the characteristics of the problem are the same, except for the supplier energy price. In this scenario, the supplier energy price varies from 0.1 to 0.5

m.u./kWh. Figures 4.10 and 4.11 show the scheduled use of resources for both generation and DR, with regards to the supplier price. The results of the operation costs are also shown. One can conclude that for lower supplier energy prices, its power is all used causing lower values of the objective function (operation costs).

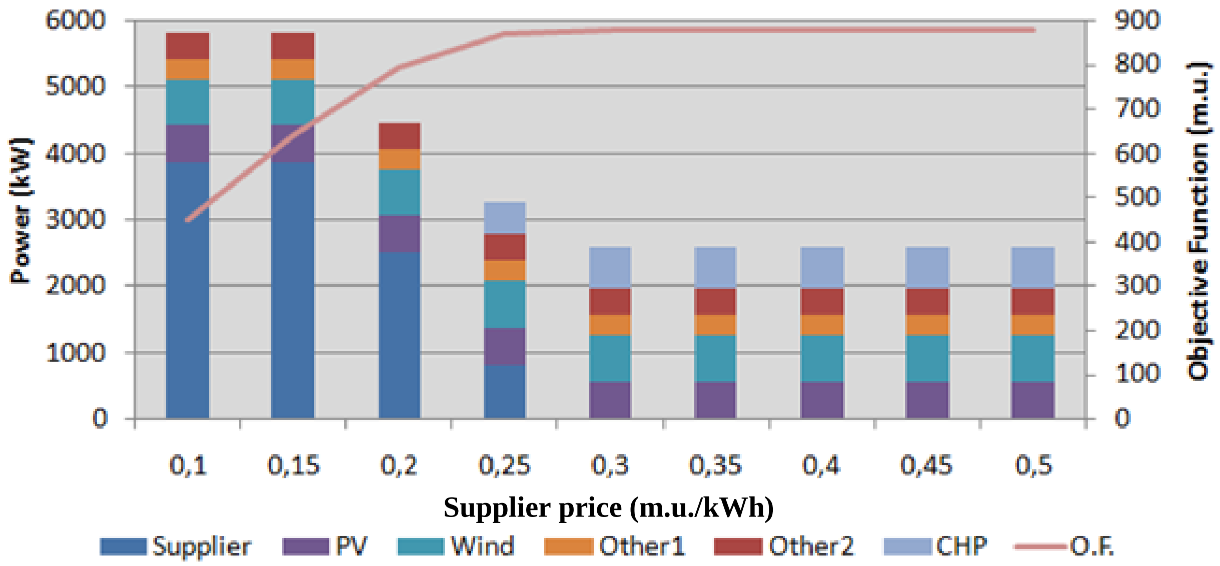

Figure 4.10. Resources scheduling in scenario 2 of VPP_ST

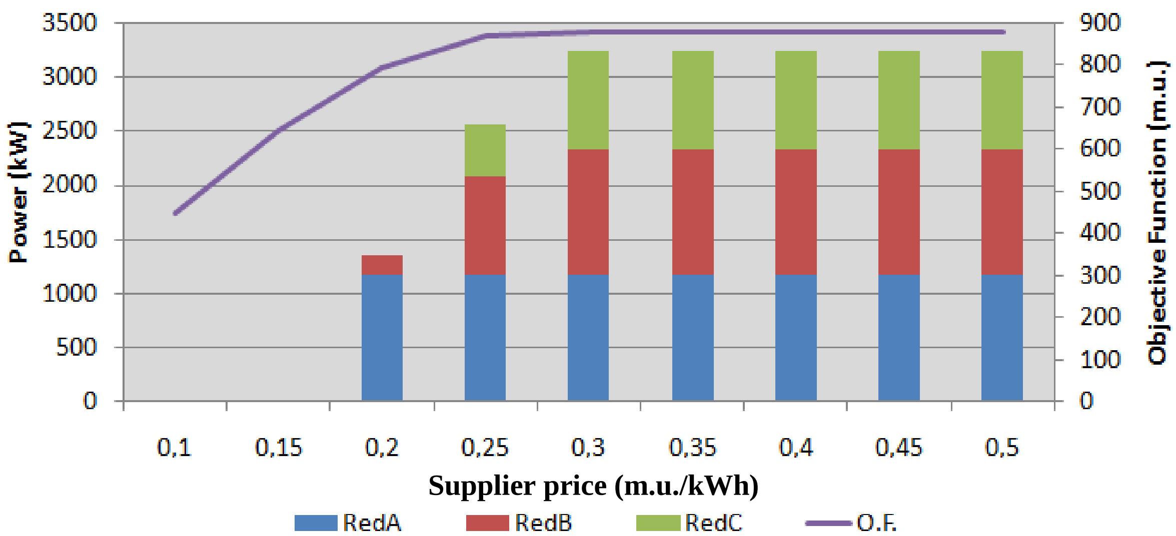

Figure 4.11. DR use in scenario 2 of VPP_ST

Generally, all the generation sources, apart from CHP, are used for all the considered supplier prices. CHP is used for higher supplier prices, jointly with DR. With the increase of the supplier price, DR resources are gradually more used. One can see that for higher supplier prices, DR use allows the VPP to keep the operation costs below a certain level, in spite of the increase of the supplier price.

Figures 4.12 to 4.14 present the results of DR resources use regarding the supplier price and the consumer type. For all the prices for which RedA is used, all the consumers' types are used almost with all the capacity. RedB and RedC are used only with the increase in the supplier price.

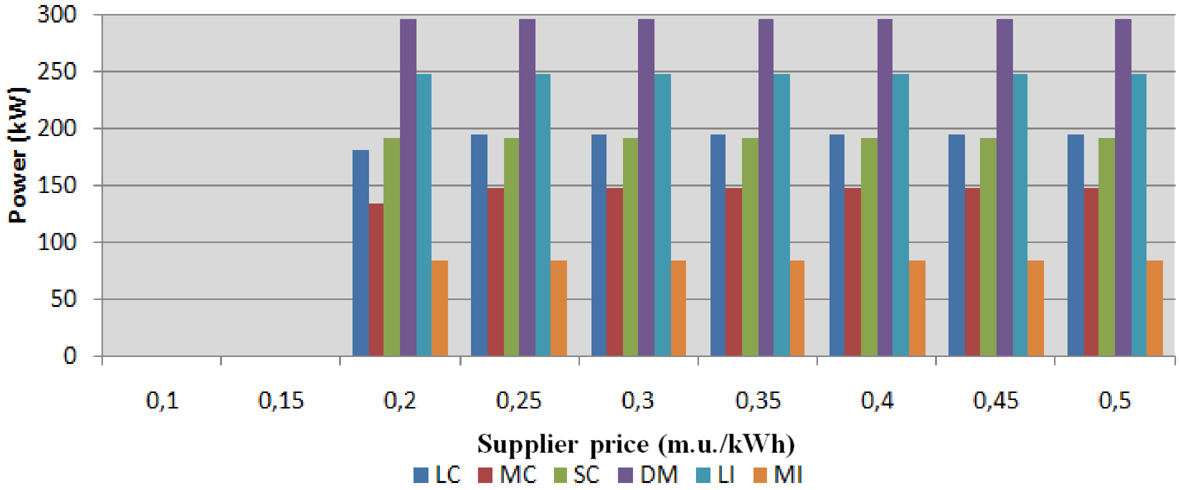

Figure 4.12. RedA use, in each consumer type, in scenario 2 of VPP_ST

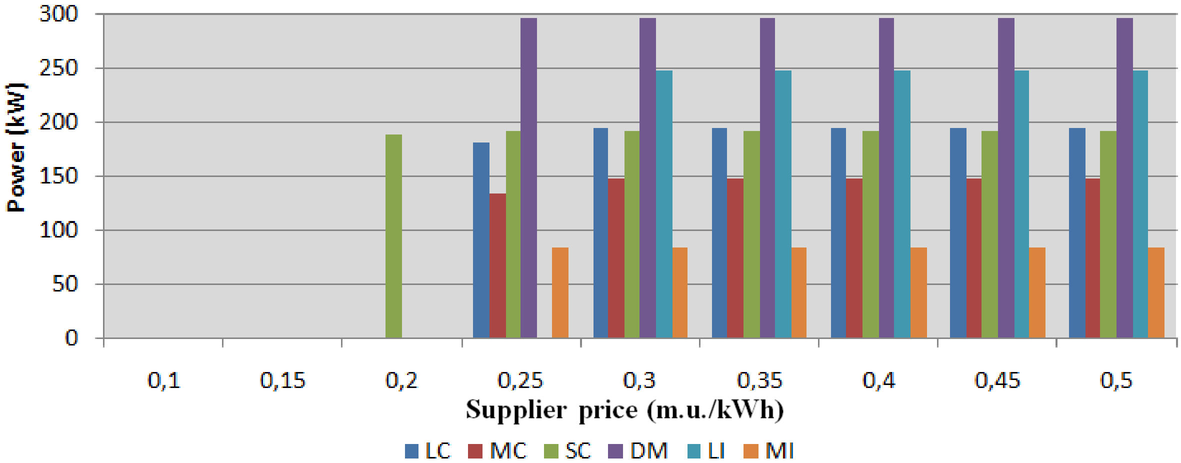

Figure 4.13. RedB use, in each consumer type, in scenario 2 of VPP_ST

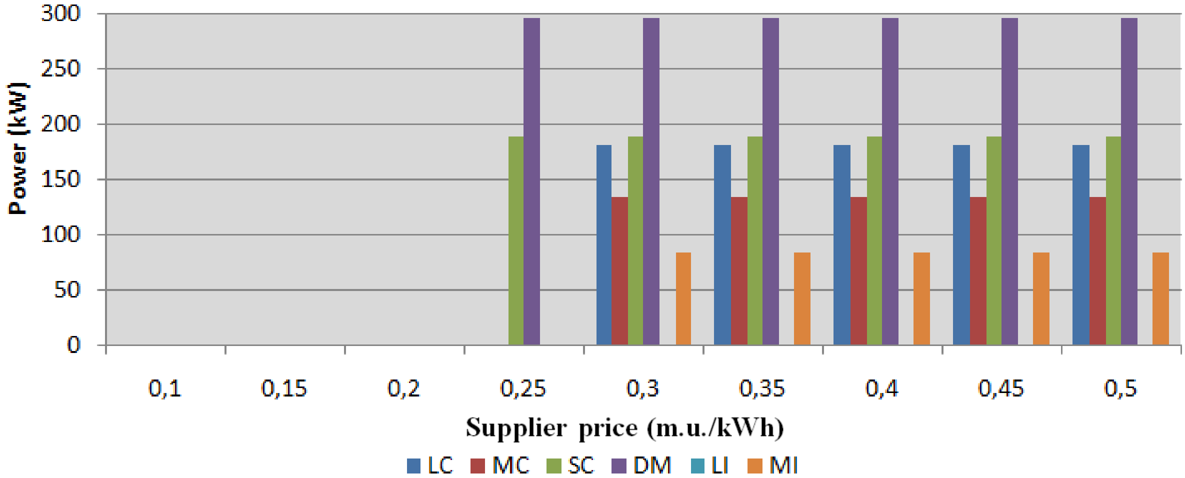

Figure 4.14. RedC use, in each consumer type, in scenario 2 of VPP_ST

Consumers of type SC are the most participating (as they participate even for reduced supplier prices of RedB and RedC) and consumers of type LI are the least participating, since they don't participate in any supplier price for RedC.

4.4.2.3Scenario 3

Scenario 3 also considers variations in the supplier price. The difference from the previous scenario is that this time the supplier' energy is bought according to the price steps offered by the supplier. These steps definition includes the aggregation of several available business opportunities.

The initial prices are 0.1, 0.15, and 0.2 m.u./kWh respectively for supplier steps A, B, and C. The power available in the three steps is respectively 900, 1600, and 2000 kW. Figures 4.15 and 4.16 show the scheduled use of resources for both generation and DR, regarding the percentual variation in the initial supplier step prices. The results of the operation costs are also shown.

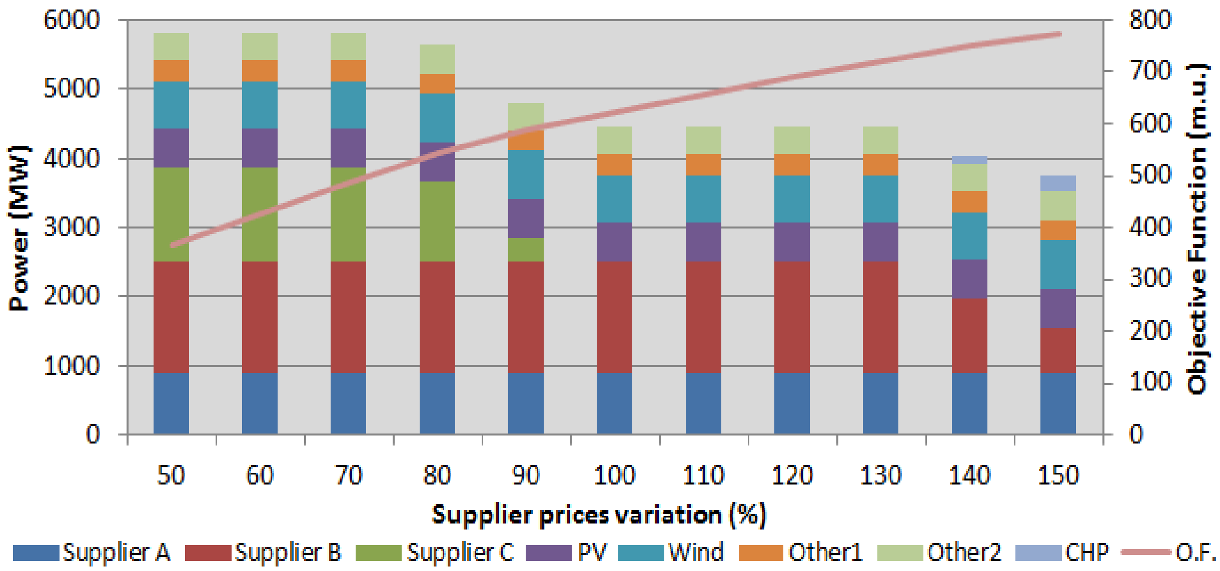

Figure 4.15. Resources scheduling in scenario 3 of VPP_ST

It is important to note that the use of the three supplier price steps of this scenario caused a decrease in the maximum operation costs value comparing to scenario 1 and scenario 2. The increase of the supplier energy price reflects an increase in the objective function value.

Figures 4.17 to 4.19 present the results of DR resources use regarding the supplier price and the consumer type. In what concerns the use of DR, its use was considerably reduced in RedB and RedC capacities; RedC is almost unused.

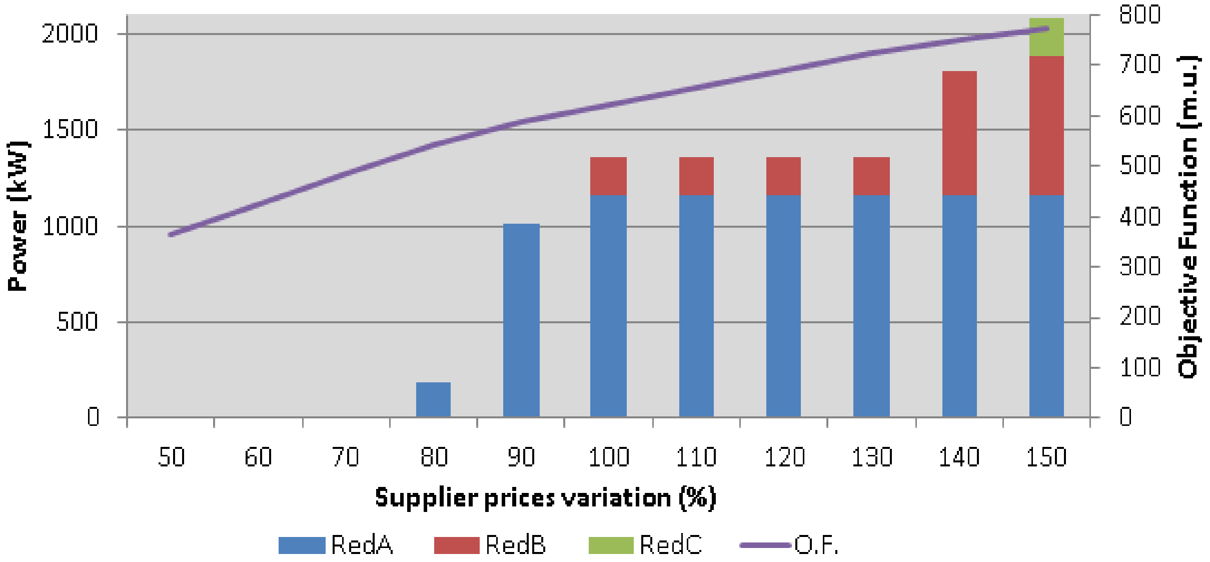

Figure 4.16. DR use in scenario 3 of VPP_ST

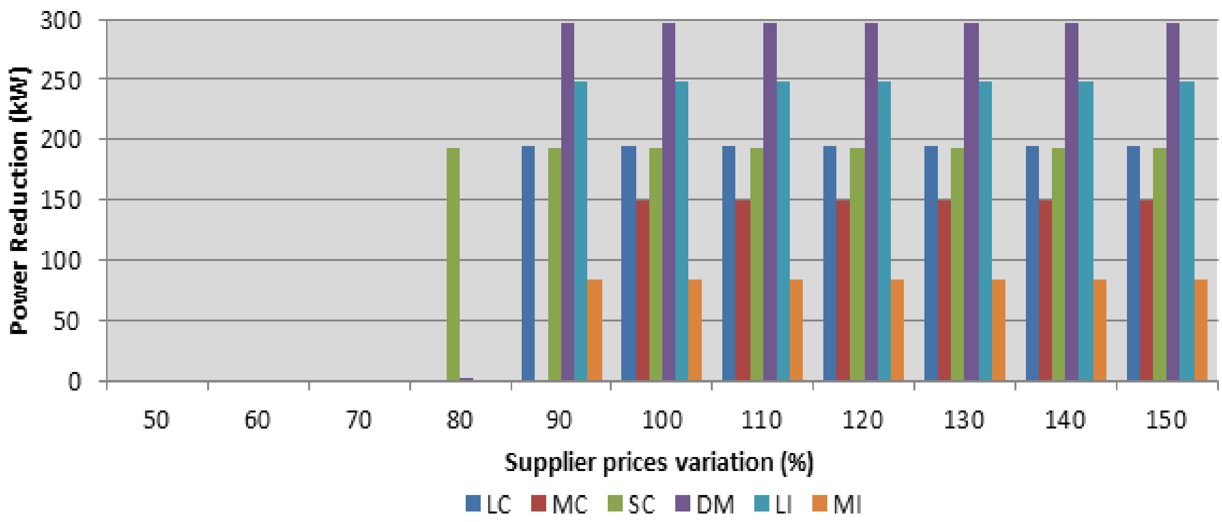

Figure 4.17. RedA use, in each consumer type, in scenario 3 of VPP_ST

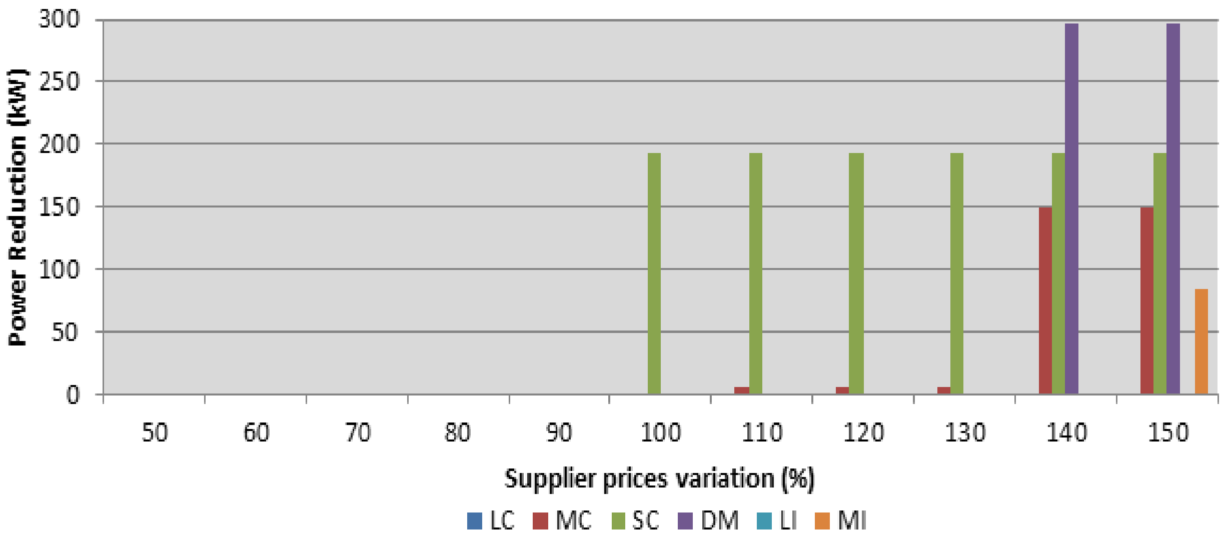

Figure 4.18. RedB use, in each consumer type, in scenario 3 of VPP_ST

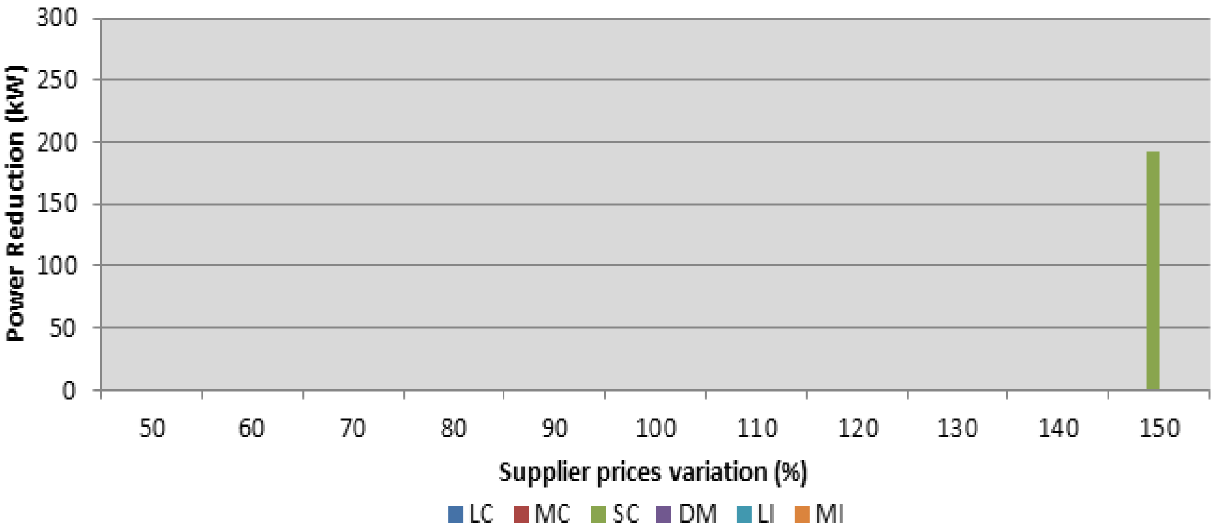

Figure 4.19. RedC use, in each consumer type, in scenario 3 of VPP_ST

One can conclude that for the lower supplier price, its power is all used causing lower values of the objective function (operation costs). In this scenario, the use of DR capacity was lower than its use in scenario 1 and scenario 2. This reduction increases the flexibility concerning scenarios with even higher prices from the supplier and from other resources.

4.4.3 Results analysis

In this case study, related to the VPP_ST model, PSO was applied to the schedule of several energy resources, including DR, several generation resources and energy bought in the scope of the electricity market, minimizing the operation costs of a VPP. PSO is used in its classic form and in an improved approach, which considers mutation.

In this case study, three scenarios were presented. In the first scenario, PSO is used in its classic form and in an improved model that considers mutation. PSO approaches are compared with the MINLP approach obtained in GAMS software using deterministic approach. Results show the best performance of the PSO with mutation approach in terms of the objective function value, with only a slightly higher execution time than the classic PSO approach and with much lower times than the deterministic approach.

In the second and third scenarios, variations in the supplier energy price were introduced. For lower supplier energy prices, the power is entirely used, causing lower values of objective function (operation costs). For higher supplier prices, DR allows the VPP to keep the operation costs in a determined level.

In the third scenario, the use of the three supplier price steps caused a decrease in the maximum value of operation costs. In this scenario, DR capacity' use was reduced. This reduction increases the flexibility concerning scenarios with even higher prices from the supplier and from other resources.

4.5 CASE STUDY – DNO_RTP

The DNO_RTP model, described in section 3.5, considers the application of RTP to maximize the profit of a DNO. It is divided into two approaches – consumption reduction (published in [Faria, 2011b]) and consumption increase. Three different scenarios are considered for each approach. These scenarios are characterized by the price of energy bought by the DNO. The developed scenarios can also be distinguished by considering or not the application of the same price variation for the consumers of the same type. This case study also includes the results of a sensitivity analysis.

4.5.1 Outline

For the present case study, in each one of the referred scenarios, four situations based on consumer response capability have been considered. The differences between the situations arise from the following aspects:

- Limits imposed for the maximum price and power variations (power and price caps);
- Imposition or not of the same price variation for consumers of the same type.

Table 4.8 summarizes the characteristics of these four scenarios. The power cap is the same for all the situations and corresponds to the variation of 15% in the power consumption value of each customer. Reference [USDE-2006] reports values of potential load reduction, in percentage, depending on the classification of the consumer. Using the results published in [USDE-2006], the value of 15% is a prudently weighted value which has been chosen for this case study. The load reduction value is assumed as equal for all consumer types, to simplify the results' analysis. 218 consumers were used in this case study.

In what concerns the price variation limits (price cap), two different values are considered: a maximum increase of 50% and 150% in the value of energy price for each customer (labeled as *A* and *B* data, respectively).

The other variation in the situations characteristics is the fact of considering or not equal price variations for all the customers of the same type. Approach *C* considers individual price variations for each customer whereas approach *T* imposes the same price variation for every customer of each customer type. "*A*" and "*B*" indices are related to *A* data and *B* data, respectively, and "*C*" and "*T*" indices are used for approaches *C* and *T* respectively. In total, we have four situations that combine the above referred characteristics: *AC*, *BC*, *AT*, and *BT* situations.

Table 4.8. DNO_RTP scenarios characterization

	AC	BC	AT	BT
Price cap	0.5	1.5	0.5	1.5
Price variation	Individual price variation, independent from the customers type		Same price variation for every customer of the same type	
Power cap	15%			

Table 4.9 shows both elasticity and electricity price (the default values of the electricity price, which correspond to the values of flat-rate tariffs), regarding each consumer type. Additionally, this table includes the supplier electricity price. This means that a fixed value of elasticity is used for all the customers of the same type.

The consumer types are usually strongly related to the activity sector, and depend on the used studies. A report concerning some of these studies is presented in [Fan-2010]. The data presented in table 4.9, concerning the consumer classification (type) and the corresponding elasticity values, is derived from [Fan-2010] and [USDE-2006]. The values in tables 4.8 and 4.9 are considered for both consumption reduction and consumption increase approaches.

Table 4.9. DNO_RTP elasticity and electricity prices

Consumer type	Elasticity	Electricity price (m.u./kWh)
Domestic	- 0.14	0.18
Small Commerce	- 0.12	0.19
Medium Commerce	- 0.20	0.20
Large Commerce	- 0.28	0.16
Medium Industrial	- 0.30	0.12
Large Industrial	- 0.38	0.12
Supplier	-	0.15

All the achieved results consider a load reduction or a load increase requirement. The load reduction requirement can be evaluated as the total initial load demand level, minus the available generation amount, and corresponds to the quantity of load that the retailer wants to reduce, which should be obtained through the use of DR.

4.5.2 Results

The results of this case study are based on the referred scenarios and approaches. The consumption reduction scenario is used as reference for the analysis of the multiple situations in what concerns a fixed price scenario. The results regarding the other scenarios and the consumption increase approach are shown only for *BT* situation. For a better understanding of the influence of the required variation in power consumption, nine reduction need values are considered (from 1 to 831 kW).

4.5.2.1 Consumption reduction

This first approach studies the use of RTP by a DNO, aiming at inferring demand reduction and maximizing the DNO profit.

4.5.2.1.1 Fixed price

In this scenario, the price of the energy bought by the DNO is defined. Figure 4.20 presents the values of the objective function, which represent the profits of the DNO, in each situation.

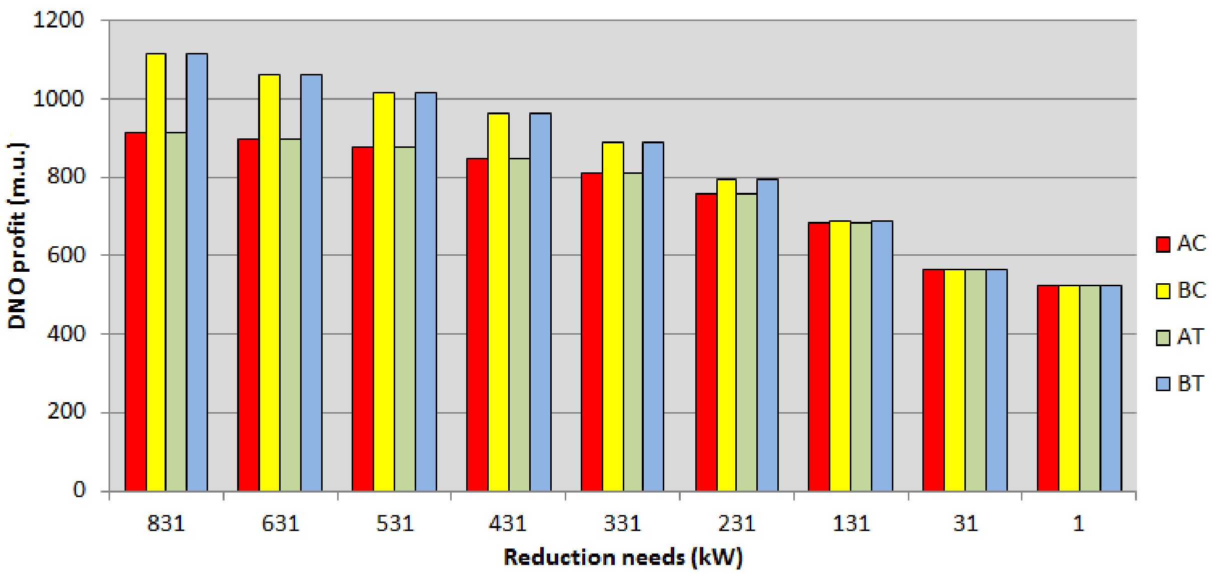

Figure 4.20. Values of the objective function for each situation, in reduction approach, and fixed price, of DNO_RTP

From the results shown in figure 4.20, is possible to conclude that when there is load flexibility to respond to higher reduction needs, the retailers benefit from this characteristic and various opportunities of higher profits will occur.

Analyzing figure 4.20, one can see that for lower load reduction needs, the differences between the results for the four analyzed scenarios are insignificant. For higher reduction needs, it is clear that the values of the objective function are lower for the scenarios using *A* data, indicating lower profits for the retailer. This means that the retailer's profit can be increased with the increase of the price variation limit. If the retailer uses a part of this additional profit as an incentive for consumers, additional DR can be obtained.

The comparison of the results obtained by the optimization algorithm for scenarios considering a normalized tariff for each consumer type with the results of the corresponding scenario, considering individual consumer tariffs (i.e. comparing the results of *AC* with *AT* and of *BC* with *BT*) shows that the normalization of tariffs by consumer type does not significantly affect the maximum retailer profit (the maximum difference is below 26 Euros, in this case study).

Considering normalized tariffs for each consumer type is a fairer strategy in comparison to the application of different tariffs for consumers of a same type, being more prone to be well accepted by the consumers, this is an important conclusion to be taken into account for retailers' decision making.

An important aspect to be analyzed for the use of DR programs is the optimal variation on the energy tariff to encourage customers to reduce their power consumption so that the retailer's profit is maximized. Figures 4.21 and 4.22 present the maximum variations in the energy price obtained respectively for *A* and *B* situations.

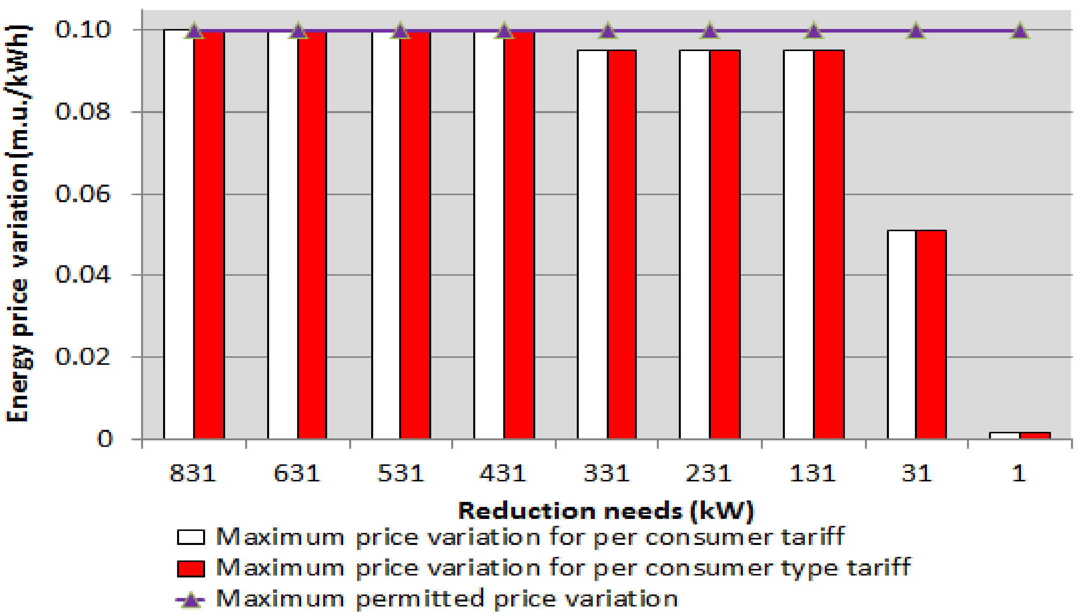

Figure 4.21. Maximum price variations for *A* situation and for each reduction need

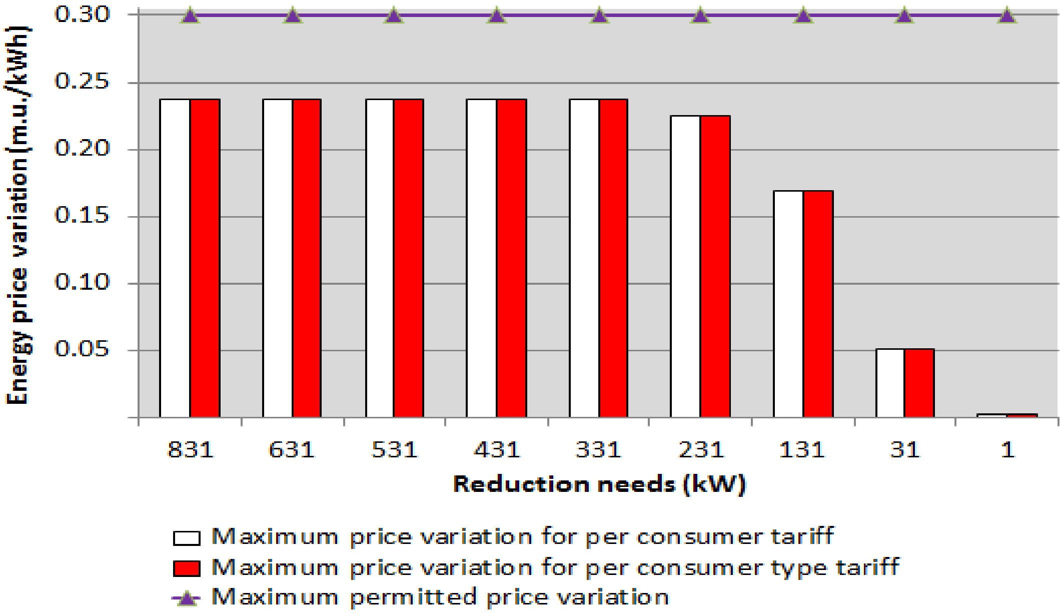

Figure 4.22. Maximum price variations for *B* situation and for each reduction need

As mentioned, *A* and *B* data have as major distinction the predominant cap parameter (price for *A* and power for *B*). Thus, figures 4.23 and 4.24 present, for each reduction need, the number of loads that reached the limit of price and power variations, for *A* and *B* situations, respectively.

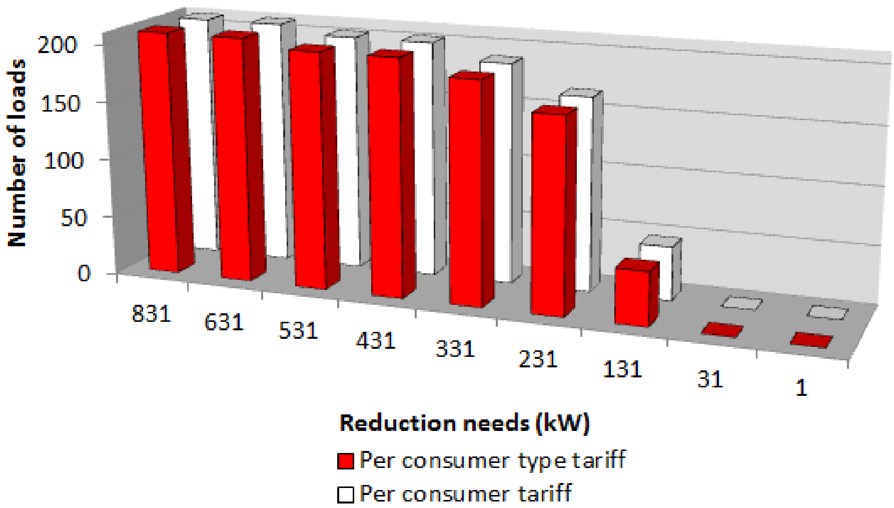

Figure 4.23. Number of loads that reached the price limit, for *A* situation

From the results presented in figure 4.22, it can be concluded that, for *B* data (i.e. when larger load reduction margins are allowed), the highest price variation never reaches the maximum permitted value. On the other hand, the results presented in figure 4.21 show that for *A* data the load response is limited by the price cap, for the highest load reduction needs.

For the scenarios using *A* data, the maximum energy price variation is generally lower for the normalized tariff for each consumer type. For this situation, the reduction need tends to be divided by all the customers of the same type, while the approach applying different tariffs for consumers of the same type obtains the required load reduction from a smaller number of customers (those with lower reduction tariffs).

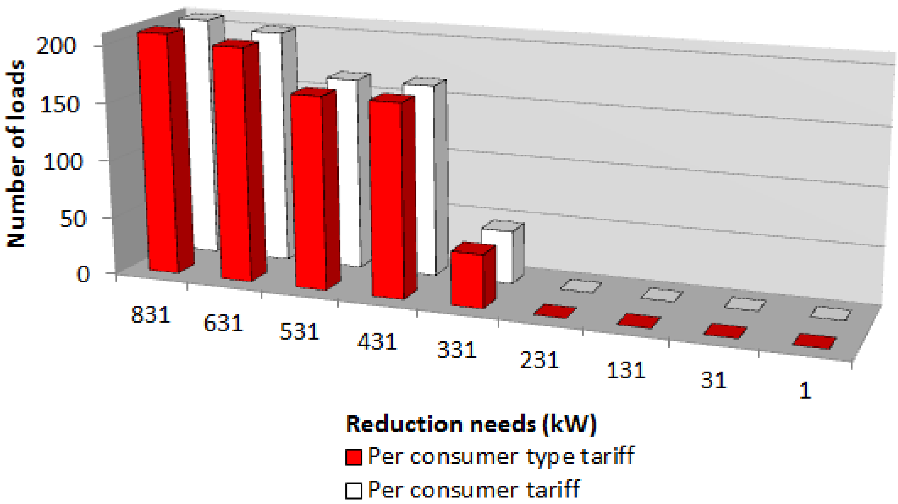

Figure 4.24. Number of loads that reached the power reduction limit, for *B* situation

For other situations, namely price variation for *B* data and power variation for *A* data, it has been concluded that there are no loads reaching the variation limits. For lower reduction needs, there are no loads reaching any variation limit. As we increase the reduction needs, more loads reach the variation limits and it can be seen that for the higher reduction needs there are not any differences in the results obtained for *A* and *B* data.

Envisaging a more detailed analysis, let us focus on the lowest and highest reduction needs. Figures 4.25 and 4.26 present the results for the price and power variations for *A* data, respectively, for the lowest and highest reduction needs. The results are presented only for *AT*, since *AC* results are similar. Note that buses are grouped into type of customers and are ordered from lower to higher elasticity values.

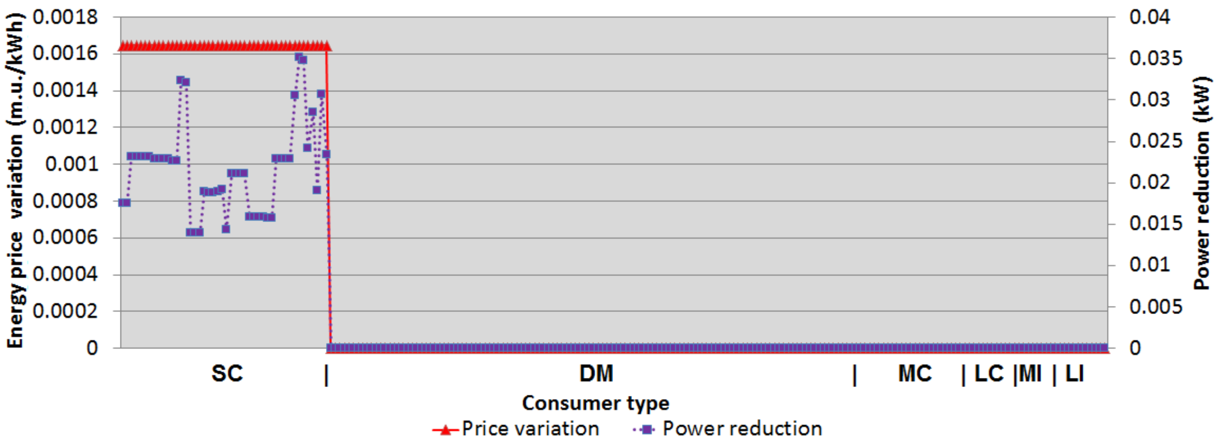

Figure 4.25. Price and power variations for AT situation for the lowest reduction need

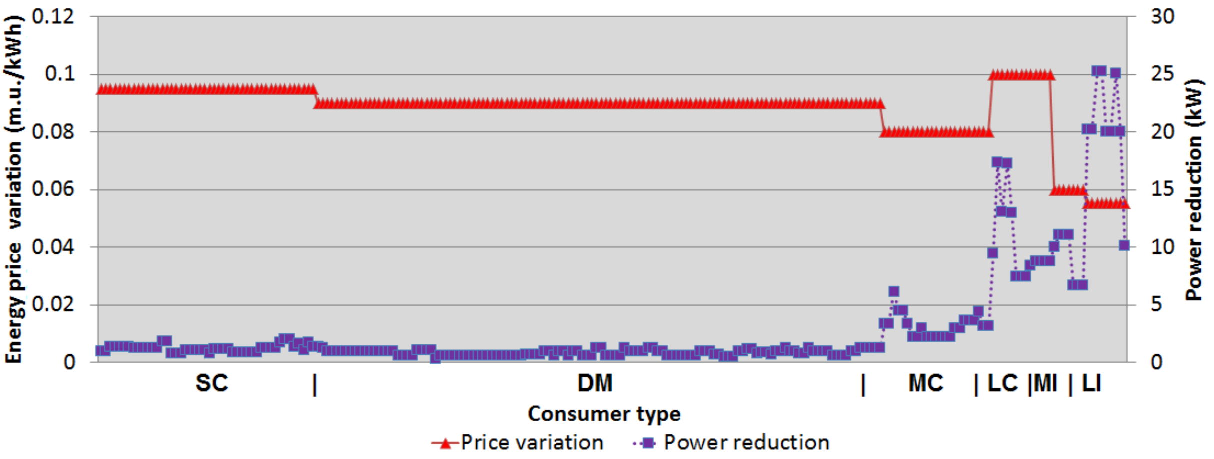

Figure 4.26. Price and power variations for AT situation for the highest reduction need

For the lowest reduction need, only small commerce consumers participate since they have the minor elasticity value and therefore they are the first choice for the profit maximization. On the contrary, industrial customers, who have the highest elasticity values, only participate in higher reduction needs if the retailer's profit maximization approach is used. If a consumers' cost minimization approach is used, industrial customers would be preferably chosen to satisfy lower reduction needs due to their high elasticity values.

Figures 4.27 and 4.28 are similar to figures 4.25 and 4.26, concerning the results for *B* data.

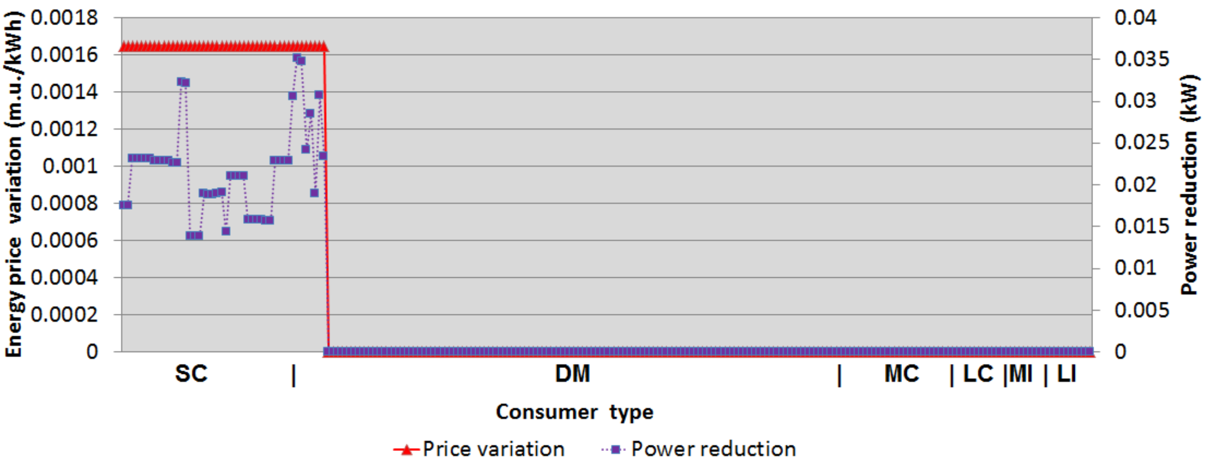

Figure 4.27. Price and power variations for BT situation for the lowest reduction need

For the lowest reduction need, results are similar to those obtained with *A* data. In what concerns the highest reduction need, the absolute power reduction is not the same for *A* and for *B* data, what makes the comparison of figures 4.26 and 4.28 less interesting. As the power cap in B data has been increased, the highest price variation now happens for SC consumers and not for LC consumers, as before.

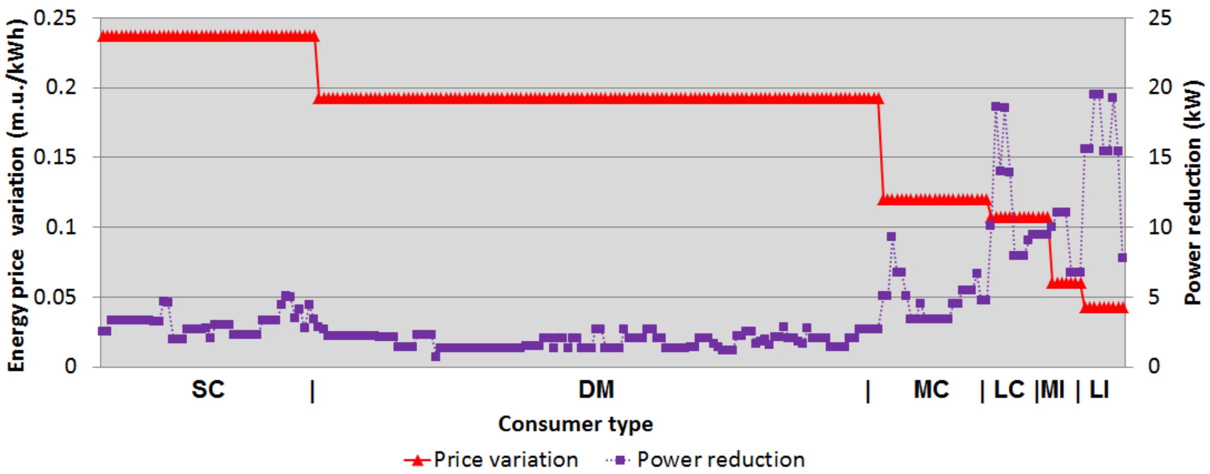

Figure 4.28. Price and power variations for BT situation for the highest reduction need

4.5.2.1.2 Variable price

In this second scenario, the price at which the DNO buys energy varies from 0.12 to 0.22 m.u./kWh. Only the results of the objective function for the BT situation are presented since the other results would not add any conclusion. It can be seen from figure 4.29 that the increase of the energy price causes a large reduction in the DNO profit. In the highest reduction need, an increase of 0.05 m.u./kWh in the energy price causes a reduction of more than 200 m.u. in the DNO profit. For lower reduction needs this value is even higher. For reduction needs below 231, retailer's profit is null.

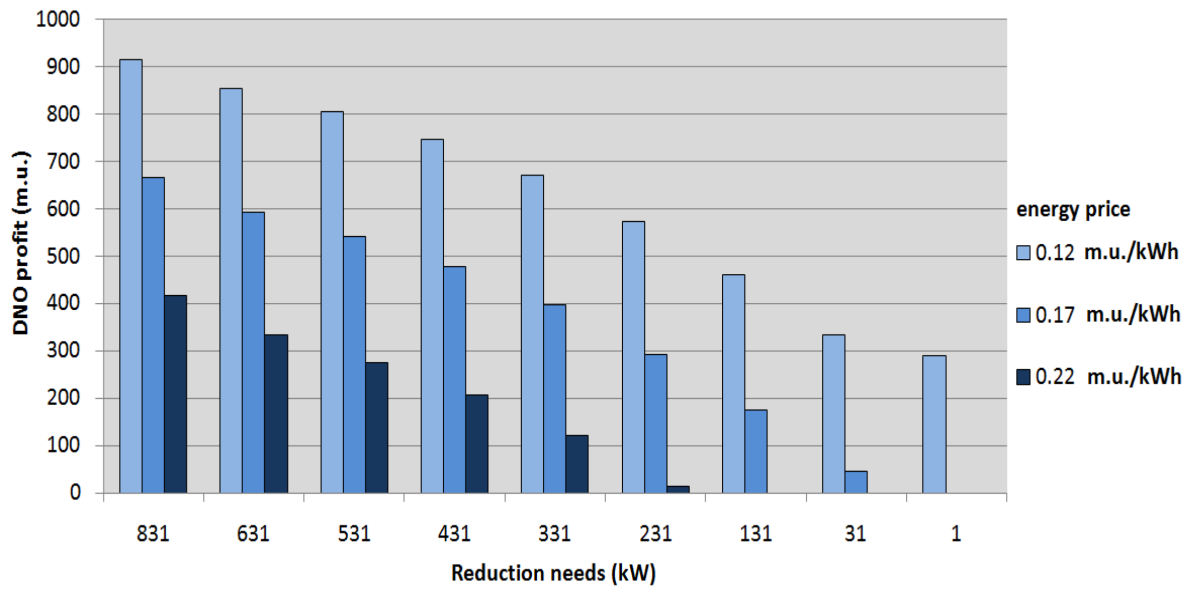

Figure 4.29. Values of the objective function for BT situation, in reduction approach, and variable price, of DNO_RTP

Some incentives given to the consumers to increase their power and price caps could make the present model to help DNO to increase the profit for higher energy prices.

4.5.2.1.3 Price steps

The last scenario considers that the prices at which the energy is bought by the DNO correspond to three price steps, which depend on the required amount of power. The prices are 0.11 and 0.19 m.u./kWh respectively for the first and the third steps. For the price of the second step, several values are considered: 0.11, 0.13, and 0.15 m.u./kWh. In fact, considering the price of the second step equal to 0.11 m.u./kWh, which is equal to the first step price, corresponds to consider only two steps.

Figure 4.30 shows the values of the objective function for each reduction need, in BT situation. It is possible to conclude that higher prices of energy still cause reductions in the DNO profit.

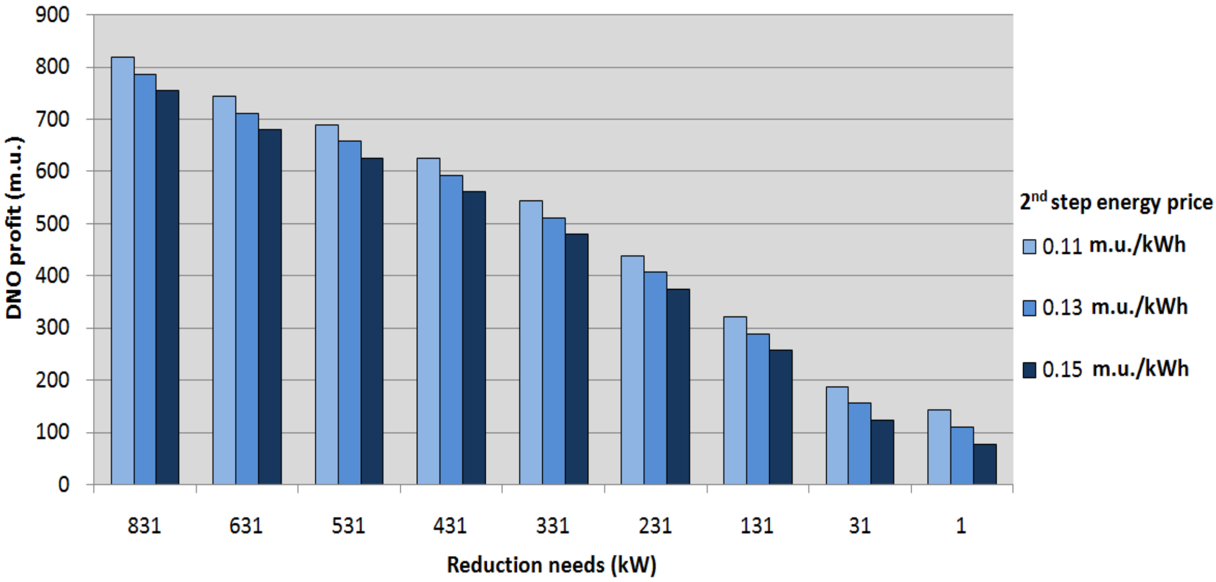

Figure 4.30. Values of the objective function for BT situation, in reduction approach, and price steps, of DNO_RTP

4.5.2.2 Consumption increase

In the consumption increase approach, DNO reduces the energy price for consumers in order to increase their consumption. The case study results were obtained for the referred three scenarios. For simplification in the results exposition, only the analysis of the objective function values is included for this approach.

Figure 4.31 shows the results of the objective function in each situation, with fixed price, according to the reduction need. The analysis of this figure leads to the same conclusions already taken for the reduction approach. In what refers to the objective function value, it can be concluded that, for the same situation and for the same amount of reduction need and of increase, the DNO profit is lower for the consumption increase situation than for the consumption reduction situation.

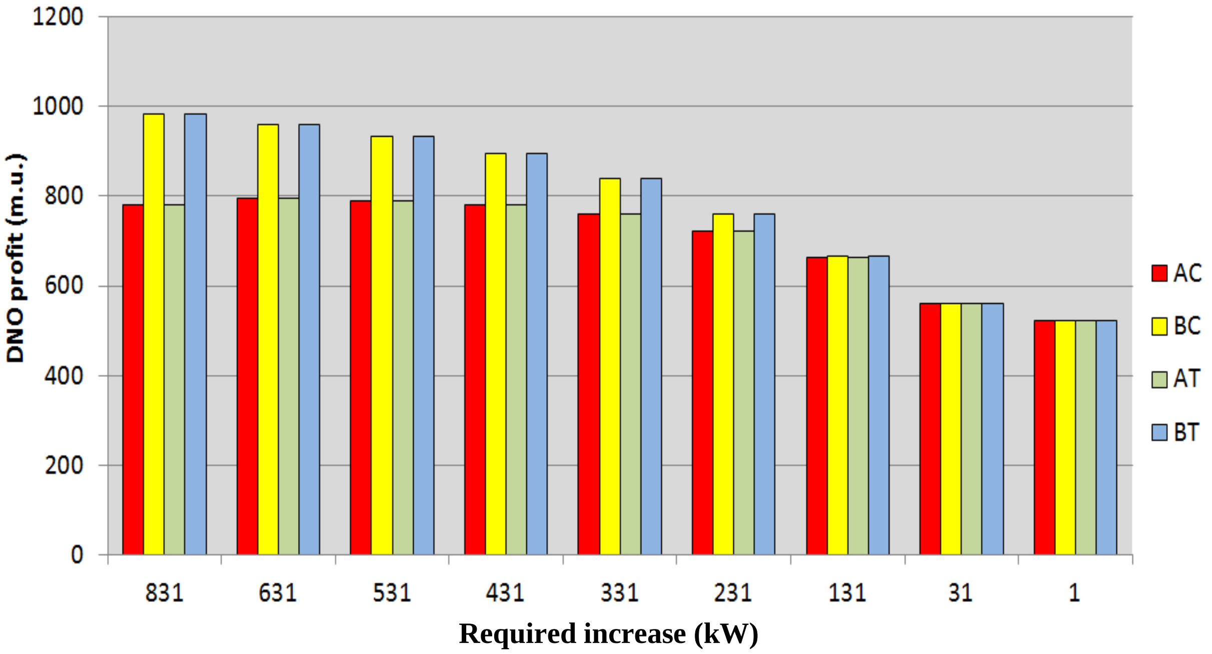

Figure 4.31. Values of the objective function for each situation, in increase approach, and fixed price, of DNO_RTP

The values of the objective function for variable energy price, as described for the same scenario in the reduction approach, are presented in figure 4.32. As before, in this scenario, the DNO profit is also higher for the reduction situation.

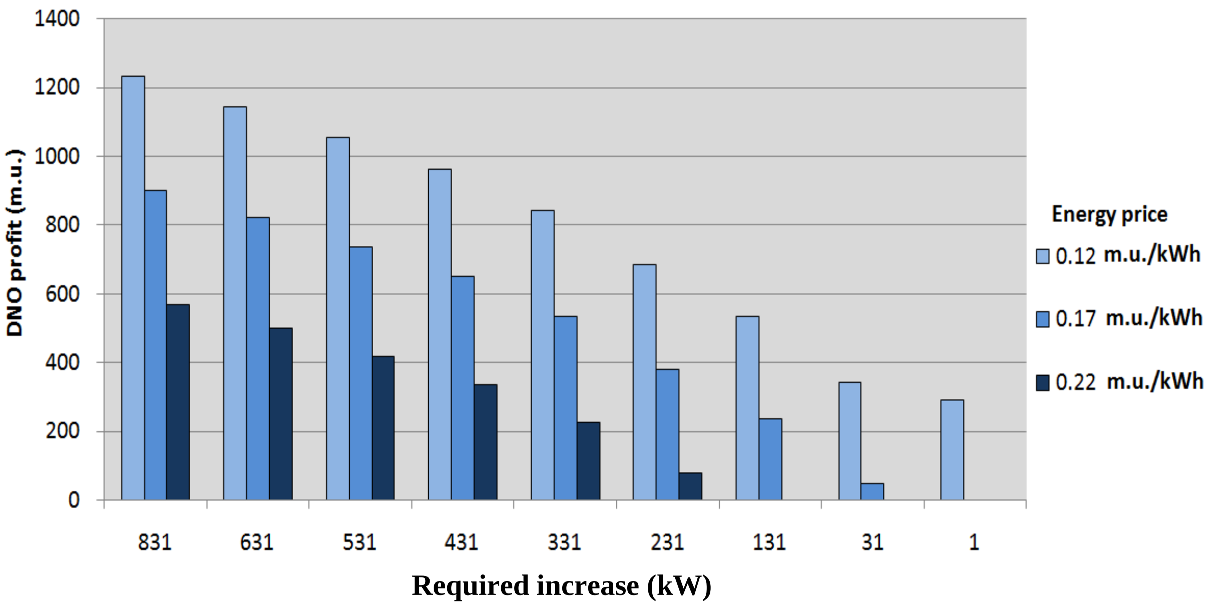

Figure 4.32. Values of the objective function for each situation, in increase approach, and variable price, of DNO_RTP

For the scenario with price steps, results are presented in figure 4.33, maintaining the trend to lower DNO profits when compared with the consumption reduction situation.

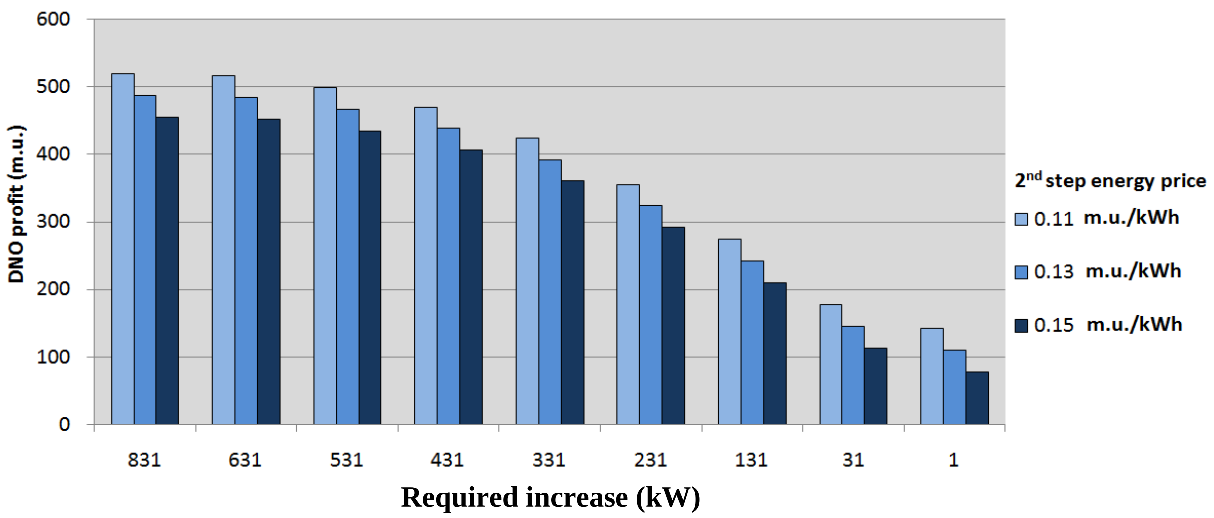

Figure 4.33. Values of the objective function for each situation, in increase approach, and price steps, of DNO_RTP

4.5.2.3Sensitivity analysis

A sensitivity analysis has been performed in order to reach conclusions concerning the impact of changes in the study input parameters on the obtained solutions. These conclusions are relevant so that decision agents are aware of the risk involved when considering, for each input, values that may differ from the real ones in a smaller or higher extent.

The sensitivity study considered the influence of three different input variables in the results of the objective function (that represents the profit obtained by the DNO), according to the reduction need. Therefore, the reduction need can be seen as the 4th variable of this study. The results of the sensitivity study are shown in table 4.10 for the load reduction approach and in table 4.11 for the consumption increase approach. The discrete values of changes in these variables, in percentage or absolute values, are displayed in the second column. These changes are applied equally to all the consumers.

The first input variable is the power cap, for which increasing and decreasing percentage changes are considered. For the second input, the electricity price, positive and negative increments of 0.02 m.u./kWh are considered.

For the simulations considering the changes in the electricity price, the values of price caps, which were considered as a percentage of the electricity price, were also updated. For the last considered input, the value of elasticity, positive and negative increments of 0.05 are considered.

From the analysis of the results shown in tables 4.10 and 4.11, it can be seen that the solutions are highly sensitive to the elasticity value. For this variable, the sensitivity increases with the increase of the reduction need. The power cap is the input to which the solutions are less sensitive. Changes increase with the increase of reduction needs, and present lower absolute values.

Table 4.10. Sensitivity analysis of the objective function value (in m.u.) with respect to the variable parameters' values, in the reduction approach

Input variable	Value change	Reduction need (kW)								
		1	*31*	*131*	*231*	*331*	*431*	*531*	*631*	*831*
Power cap (%)	-10	523.24	565.89	688.67	796.52	888.76	950.95	1001.86	1036.57	1079.36
	-5	523.24	565.89	688.67	796.65	890.28	957.27	1010.22	1049.66	1100.93
	0	523.24	565.89	688.67	796.65	891.40	962.91	1017.47	1061.48	1116.27
	5	523.24	565.89	688.67	796.65	892.26	967.77	1024.03	1070.92	1130.29
	10	523.24	565.89	688.67	796.65	892.85	971.55	1029.91	1078.91	1143.28
Electricity price (m.u./kWh)	-0.04	289.87	324.05	422.34	508.51	584.06	640.65	684.93	721.20	764.35
	-0.02	406.56	444.97	555.50	652.58	737.73	801.75	851.18	891.34	940.31
	0.00	523.24	565.89	688.67	796.65	891.40	962.91	1017.47	1061.48	1116.27
	0.02	639.93	686.81	821.85	940.73	1045.07	1124.11	1183.80	1231.62	1292.23
	0.04	756.62	807.73	955.03	1084.81	1198.74	1285.34	1350.14	1401.76	1468.19
Elasticity	-0.10	531.16	793.92	1171.37	1296.12	1383.45	1441.84	1481.87	1513.25	1529.25
	-0.05	524.37	599.83	811.92	980.39	1110.46	1188.16	1250.63	1292.03	1346.01
	0.00	523.24	565.89	688.67	796.65	891.40	962.91	1017.47	1061.48	1116.27
	0.05	522.78	551.91	636.78	712.32	779.03	832.62	876.08	911.41	958.06
	0.10	522.52	544.28	608.22	665.27	715.64	758.06	793.67	822.65	862.97

Table 4.11. Sensitivity analysis of the objective function value (in m.u.) with respect to the variable parameters' values, in the increase approach

Input variable	Value change	Reduction need (kW)								
		1	*31*	*131*	*231*	*331*	*431*	*531*	*631*	*831*
Power cap (%)	-10	523.08	560.93	667.71	759.56	835.80	881.99	916.90	935.61	946.40
	-5	523.08	560.93	667.71	759.69	837.32	888.31	925.26	948.70	967.97
	0	523.08	560.93	667.71	759.69	838.44	893.95	932.51	960.52	983.31
	5	523.08	560.93	667.71	759.69	839.30	898.81	939.07	969.96	997.33
	10	523.08	560.93	667.71	759.69	839.89	902.59	944.95	977.95	1010.32
Electricity price (m.u./kWh)	-0.04	289.71	319.09	401.38	471.55	531.10	571.69	599.97	620.24	631.39
	-0.02	406.40	440.01	534.54	615.62	684.77	732.79	766.22	790.38	807.35
	0.00	523.08	560.93	667.71	759.69	838.44	893.95	932.51	960.52	983.31
	0.02	639.77	681.85	800.89	903.77	992.11	1055.15	1098.84	1130.66	1159.27
	0.04	756.46	802.77	934.07	1047.85	1145.78	1216.38	1265.18	1300.80	1335.23
Elasticity	-0.10	531.00	788.96	1150.41	1259.16	1330.49	1372.88	1396.91	1412.29	1396.29
	-0.05	524.21	594.87	790.96	943.43	1057.50	1119.20	1165.67	1191.07	1213.05
	0.00	523.08	560.93	667.71	759.69	838.44	893.95	932.51	960.52	983.31
	0.05	522.62	546.95	615.82	675.36	726.07	763.66	791.12	810.45	825.10
	0.10	522.36	539.32	587.26	628.31	662.68	689.10	708.71	721.69	730.01

These results allow concluding that an erroneous evaluation of consumer elasticity may result in significant errors in the identified optimal solutions. On the other hand, variations in the allowed power caps do not bring significant changes to the objective function value.

4.5.3 Results analysis

This case study is based on the DNO perspective and includes a set of events with a load reduction/increase level being envisaged for each one. The study considers both price and load variation caps for each consumer. For each envisaged consumption variation, the optimal demand response solution was determined using a non-linear programming approach. Results show that customer's demand depends on price elasticity of demand, and on the real-time pricing tariff. The optimal solution also depends on the imposed price caps according to the concerned DR programs.

The study includes simulations considering a normalized tariff for each consumer type and considering individual consumer tariffs. When comparing the results obtained imposing the use of a normalized tariff and those resulting from the consideration of individual consumer tariffs, it can be concluded that the DNO benefits are almost the same. The use of normalized tariffs for each consumer type is a fairer strategy in comparison with the application of different tariffs for consumers of a same type, being more prone to be well accepted by the consumers. This is an important conclusion to be taken into account when DR programs are designed. Two different approaches were considered – consumption reduction and consumption increase. It was concluded that the consumption reduction can give higher profits to the DNO.

4.6 CASE STUDY – VPP_CSP_LMP

As described in section 3.6, the model VPP_CSP_LMP, which was published in [Faria, 2011c], considers a VPP managing the network where the consumers response can be contracted directly with the VPP or through a Curtailment Service Provider (CSP).

4.6.1 Outline

Let us consider a Virtual Power Player (VPP) that manages a distribution network using all the available resources to supply the required demand and aiming at the minimum operation costs. The focused resources are DG units, a quantity of energy acquired in the day-ahead market, the energy acquired in the real-time market and two options of DR capacity. The first option is managed like the remaining resources, with a contract (DG as an example) and is labeled as "*DR-Contract*". The second DR resource can be used when the LMP (Locational Marginal Price) value reaches a specified value (0.1 m.u./kWh), and is labeled as "*DR-Event*".

The total demand and available DG resources are the ones specified in the description of the network and consumers in section 4.2. The case study applying the model VPP_CSP_LMP is tested with the 32 consumers' scenario. The capacity bought in the day-ahead market is 4000 kW and the total capacity of DR contracts is 330 kW. Table 4.12 shows the average prices of each resource.

Table 4.12. Resources costs in VPP_CSP_LMP

Generation resource	Average Price (m.u./kWh)
Photovoltaic	0.200
Wind	0.045
Wast-to-energy	0.110
CHP	0.080
Fuel cell	0.300
Biomass	0.150
Small hydro	0.030
Real-time market	0.073
Day-head market	0.070
DR Contracts	0.300

In the present case study the storage units are not considered. The proposed model focuses on *DR-Event* capacity which is used in the specified condition. The remuneration of the LMP triggered program considered in this case study is 0.5 m.u./kWh. Table 4.13 includes information about the consumers that participate in this program.

Table 4.13. LMP triggered program participants

Type of aggregation	CSP#1	CSP#2	VPP	Non-participants
Number of consumers	10	5	3	14
Consumers	5, 8, 10, 11, 12, 14, 15, 16, 25, 27	20, 21, 28, 29, 30	23, 24, 31	1, 2, 3, 4, 6, 7, 9, 13, 17, 18, 19, 22, 26, 32

There are three loads that respond directly to the VPP event declaration, since their curtailment capacity is higher than 100 kW. These loads are considered under the label “VPP”. The remaining participant loads, which have reduced curtailment capacity, need to participate in the event through a Curtailment Service Provider (CSP). CSPs need to obtain more than 100 kW to participate in the event announced by the VPP. In this case study, two CSPs are considered.

4.6.2 Results

Figure 4.34 shows the values of the day-ahead LMP and real-time LMP, in the considered 24 hours scenario. The DR-Event trigger value of LMP is also shown.

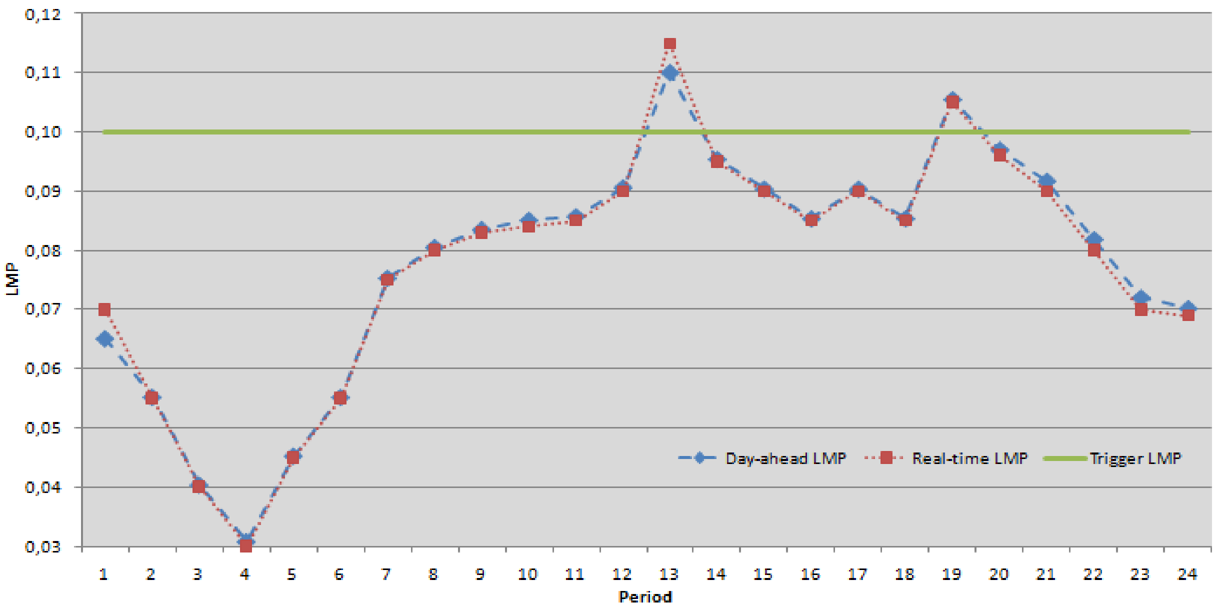

Figure 4.34. LMP values for real-time and day-ahead markets

As explained, the VPP manages the available resources making a scheduling, and if the LMP is in the referred conditions, a new scheduling including *DR-Event* capacity is performed. Looking at figure 4.34, one can see that a DR event is declared in periods 13 and 19. It is not usual, as referred in chapter 1, to have more than one of these events in the same day. However, this case study considers two events in different peak periods to better illustrate the application of the proposed method.

After determining the periods when the events are declared, four scenarios are compared (two periods, after and before the application of DR events). Figure 4.35 shows the utilization of the resources in each scenario. For better understanding this figure, DG resources utilization is shown as a whole. Obviously, *DR-Event* capacity is only used in the scenarios after the declaration of the DR event. The use of this DR resource causes the non-utilization of *DR-Contracts*, mainly because all the available capacity for DR events is mandatorily paid. Specific characteristics of each period, mainly the load demand value, make the real-time market capacity only needed in period 19.

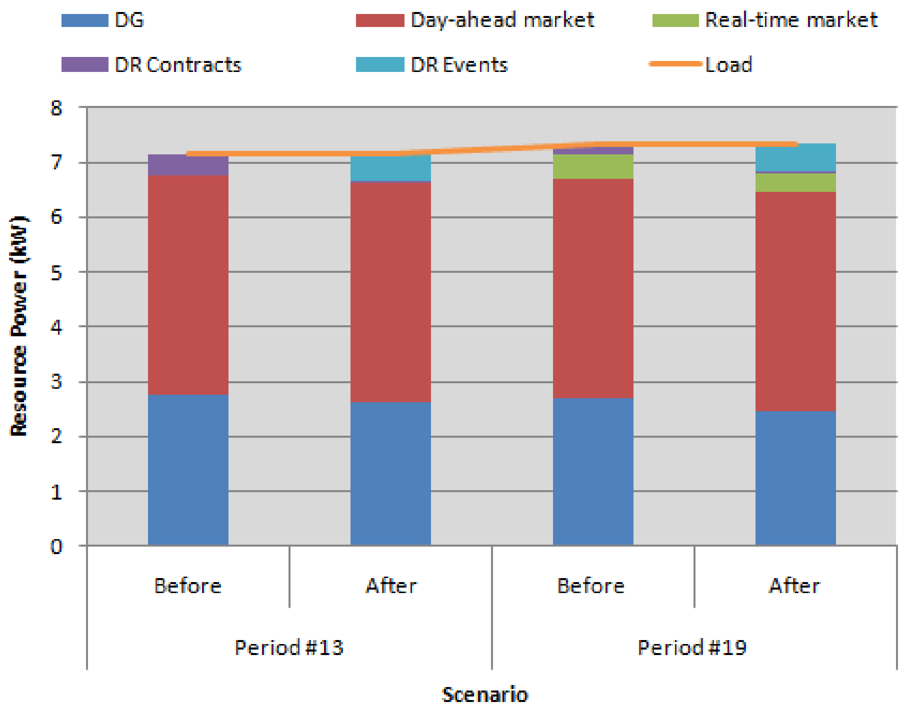

Figure 4.35. Resources utilization in the four focused scenarios

Figure 4.36 presents the LMP values for each scenario. In spite of having higher load demand, LMPs in period 19 are lower than the ones in period 13, for both "*after*" and "*before*" DR event scenarios.

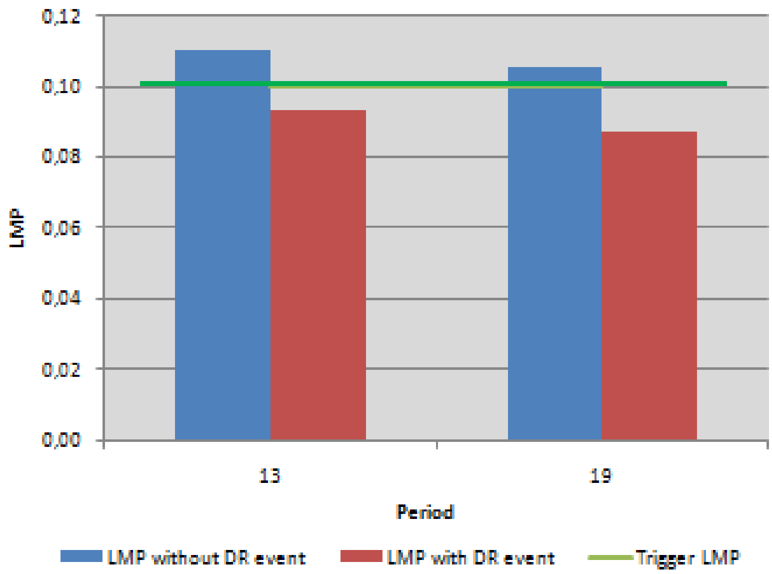

Figure 4.36. LMP values in the four scenarios

The load profile and DR capacity characterization, for each one of the 32 consumers, in period 13, taken as an example, is presented in Figure 4.37. In the present case-study, the DR-Event capacity is considered equal for all day periods, in opposition to the load demand level which depends on the period. The loads that have no participation in the LMP triggered program appear in the left side of Figure 4.37. On the right side, the participants in the program are presented. *DR-Contracts* capacity, although not used in this period, is also shown; however, it is difficult to see since this capacity is much lower than DR-Event capacity and load demand.

It is important to remember that once a customer subscribes the LMP triggered program, his participation on a declared event is mandatory. This fact makes the *DR-Event* capacity shown equal to the actual curtailment, since participation failure is not considered in the present case study.

In this case study, LMP triggered events of DR are proved to have advantages for the VPP area energy price, in spite of the high cost of remunerating the participation of customers.

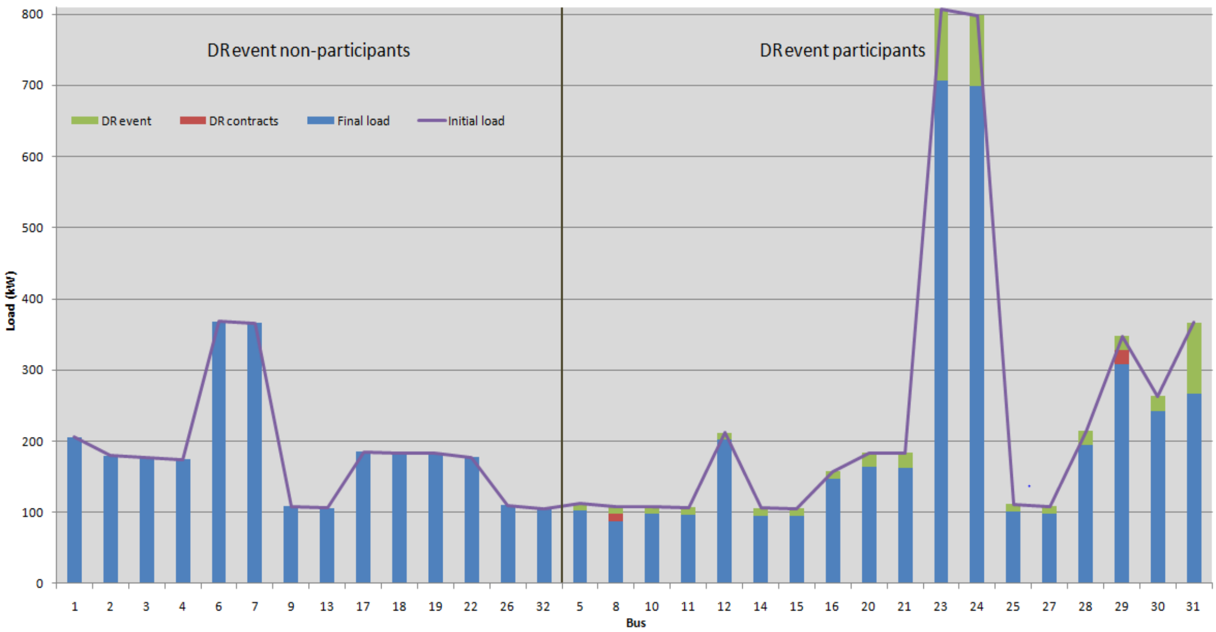

Figure 4.37. Values Load profile and DR capacity characterization, for each load, in period 13

4.6.3 Results analysis

The VPP_CSP_LMP model proposes an approach where a VPP manages all the available resources. These include demand response programs – based on load curtailment contracts (DR contracts) and based on locational marginal price event trigger (DR events).

Customers can participate in these DR events either individually (if they can offer 100 kW of more of load curtailment) or through a curtailment service provider, which is the only possible way of participation for smaller consumers.

The proposed method optimizes resource management aiming at achieving the lower possible energy price, considering all the involved costs, including the remuneration of DR programs' participation, and the cost of the energy bought in the day-ahead and real-time markets.

The proposed method was computationally implemented and its application was illustrated with a case study that considers a 32 bus network with intensive use of distributed generation. In this case study, LMP triggered events of DR proved to have advantages lowering the energy price in the VPP area, in spite of the high cost of remunerating the participation of customers in the considered DR events.

4.7 CASE STUDY – VPP_CSP_ST

The VPP_CSP_ST model, described in section 3.7, considers the generation of LMP curves for the VPP resources scheduling, taking into account the LMP values. The objective is to minimize the VPP operation costs. The scenario of 32 consumers is used to validate this model. In the present case study, the storage units are not considered.

4.7.1 Outline

The proposed model considers that each consumer has contracted 3 load curtailment levels – curtailment steps *CutA*, *CutB*, and *CutC* – to be managed by the VPP. The VPP manages all available resources determining the conditions in which load curtailment can reduce the LMP (Locational Marginal Price) energy component value.

The total DG resources available and their energy price, as well as the price of energy bought by the VPP to the supplier are presented in table 4.14.

The implementation of the proposed methodology requires adequate knowledge about consumers' characteristics. This characterization is presented in table 4.15, where one can see that the cost of the curtailment, for each curtailment step, depends on the consumer type (only 5 consumer types are considered in this case study). The maximum power to be considered in each curtailment step corresponds to 5% of the total power demand of the consumer.

Table 4.14. Generation resources availability and costs in VPP_CSP

Generation resource	Capacity (kW)	Price (m.u./kWh)
Photovoltaic	1400	0.200
Wind	1000	0.045
Wast-to-energy	150	0.110
CHP	1500	0.080
Fuel cell	500	0.300
Biomass	700	0.150
Small hydro	250	0.030
Supplier	-	0.300

Table 4.15. Consumers characterization in VPP_CSP

Type of consumer		Consumers	Curtailment costs (m.u./kWh)		
			CutA	***CutB***	***CutC***
Domestic	DM	5, 8, 9, 10, 11, 12, 14, 15, 16, 25, 26, 27, 32	0.16	0.20	0.24
Small Commerce	SC	2, 3, 4, 17, 22	0.15	0.19	0.22
Medium Commerce	MC	1, 13, 18, 19, 20, 21, 28, 29, 30	0.18	0.20	0.26
Large Commerce	LC	6, 7, 31	0.17	0.24	0.26
Industrial	IN	23, 24	0.17	0.26	0.28

LMP calculation has been performed for several values of total load demand between 2000 kW and 7000 kW, considering the existence of the resources presented in table 4.14 to supply this load demand.

4.7.2 Results

When an increase in load demand causes an increase in the LMP value, the activation of curtailment programs is considered to determine its impact on the LMP value. This is used to support the decision about the use of these programs and the way they are used (the consumers and the steps to be used).

Figure 4.38 shows the LMP values, with and without DR, for each value of total load demand. Each step of the "Without DR" curve is due to the scheduling of a new generation resource type. For each of these steps, the use of DR curtailment programs is studied. Due to the involved prices, DR programs are only useful for high load demand values. For high values of demand (but before the use of all curtailment capacity), DR programs are very effective.

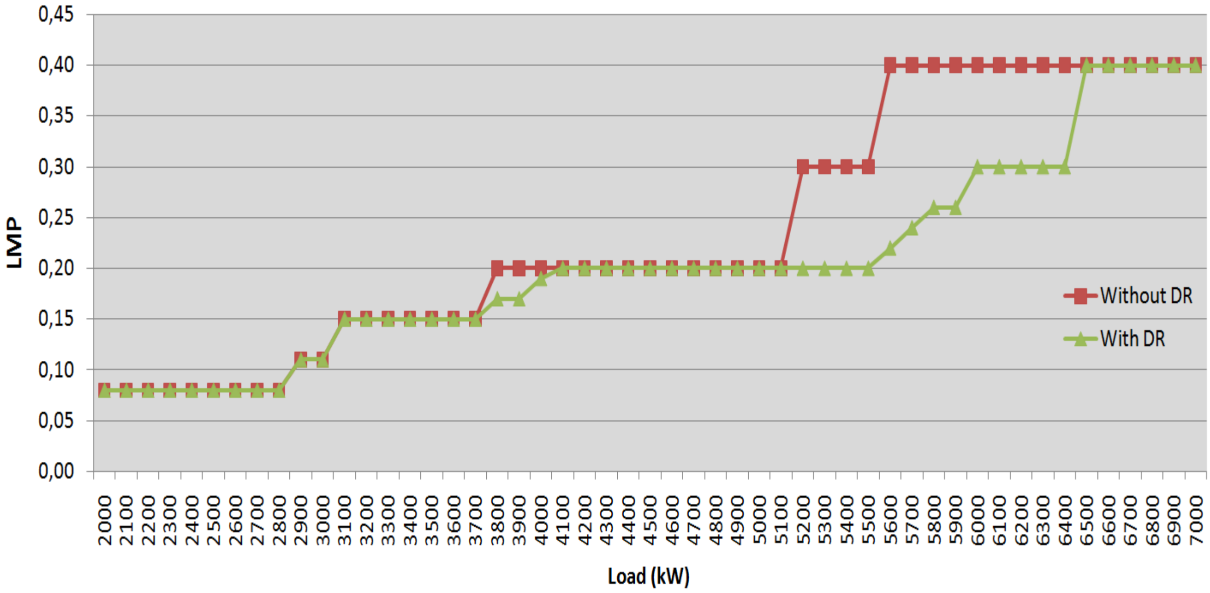

Figure 4.38. LMP values in function of the total load value, with and without DR

This study originates a large amount of result data for all the considered load demand, which is not possible to present in a concise way. Due to this, this and the following sub-sections comment only some of the obtained results. Figure 4.39 shows the detailed load curtailment in each bus, for the three curtailment steps, when the total load is equal to 5800 kW. Results are grouped by consumer type. The horizontal axis shows the bus numbers, ordered according to the load type.

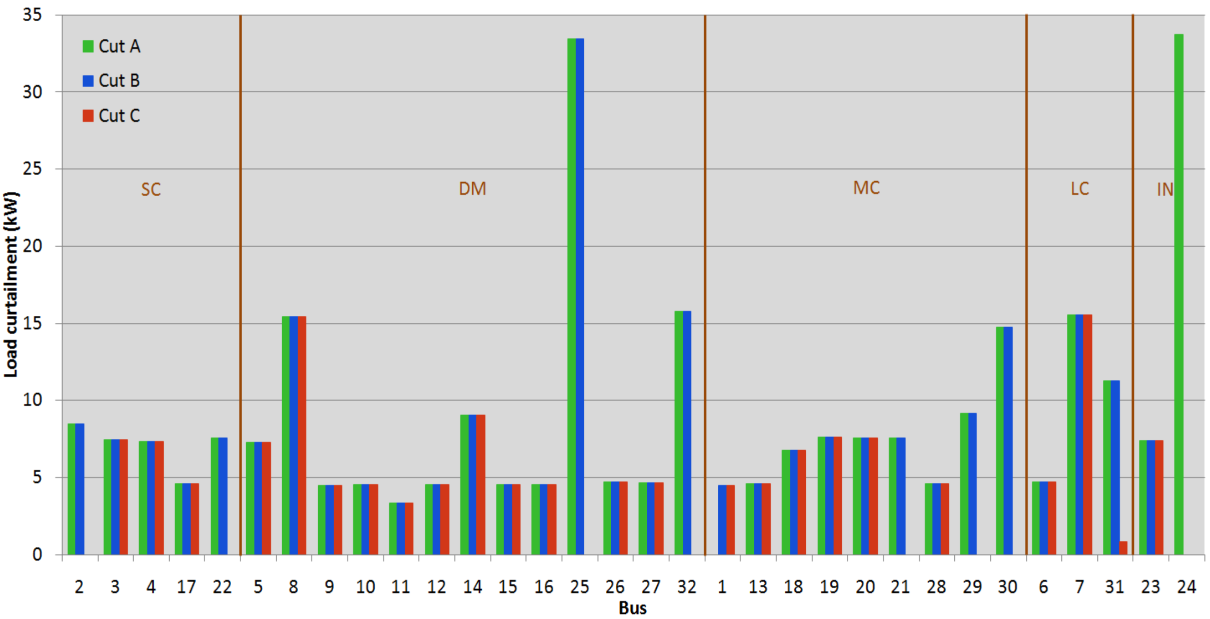

Figure 4.39. Load curtailment in each bus, for three curtailment steps, for total load equal to 5800 kW

In this load scenario, load curtailment is near the limit; therefore, almost all curtailment capacity is used. The remaining capacity is in curtailment step *CutC*, with the exception of the load in bus number 24 which has high load demand and high curtailment prices. For the interpretation of this figure, it is important to note that the consumers' response is a load curtailment, i.e. the load of a consumer is shed in the total load value of a curtailment step.

Figure 4.40 shows the total load curtailment regarding the total load for each curtailment step. For load demand values lower than the ones represented in the horizontal axis, there is no load curtailment. The progressive use of each curtailment step with the increase of load demand value can be observed in this figure. Near to the 3900 kW load scenario, there is a usage of *CutA* and *CutB* curtailment steps. After this and before the 5100 kW load demand scenario, the use of DR programs brings no advantages to the LMP reduction.

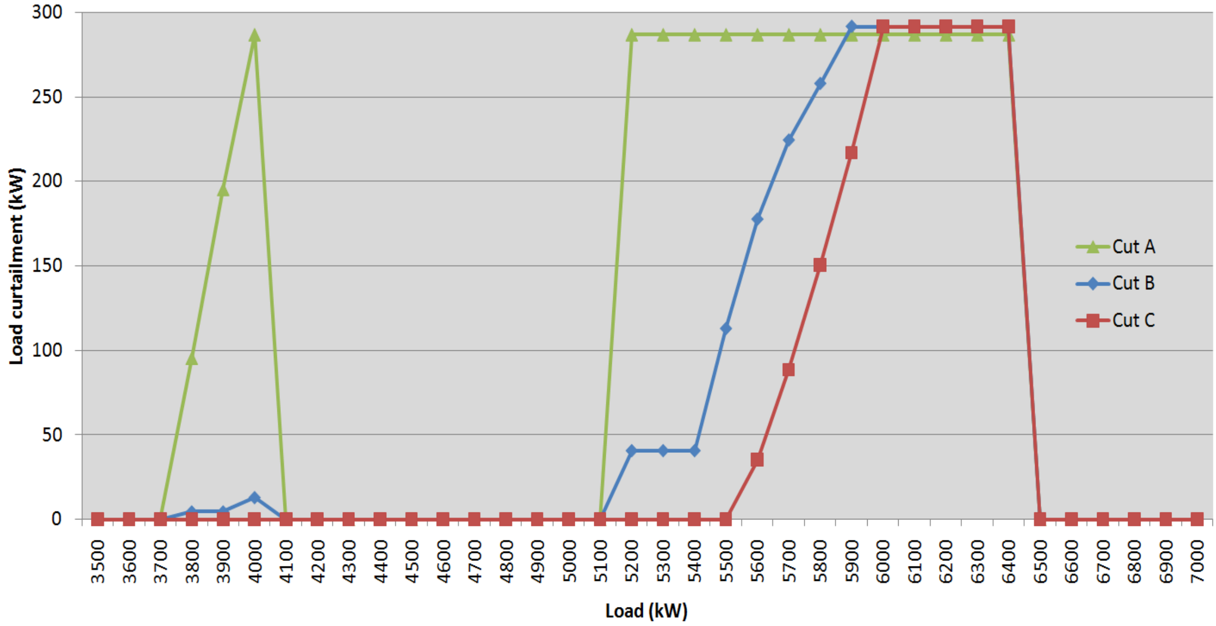

Figure 4.40. Total load curtailment in function of the total load and grouped by curtailment step

In Annex B, figures illustrate, regarding the total load demand, the total load curtailment for each load type, for curtailment steps *CutA* , *CutB*, and *CutC*. Analyzing these figures, it is possible to evaluate the importance of an adequate design of DR programs for each consumer type.

4.7.3 Results analysis

In the scope of future power systems, operating in the context of intensive use of distributed generation, energy resource management is of upmost importance.

The presented model proposes an approach to manage demand response programs, based on locational marginal prices computation. The proposed method has been computationally implemented and its application is illustrated with a case study that considers a 33 bus network with intensive use of distributed generation.

The proposed methodology proved to be computationally efficient and adequate to be used by VPPs, even if of small size. Moreover, the method is flexible enough to be able to cope with diverse players characteristics, in terms of the managed resources and in terms of the specific used demand response programs.

4.8 CASE STUDY – VPP_LMP_VAR

The VPP_LMP_VAR model, described in section 3.8, presents a DR program activated when the use of DR capacities causes important variations in the LMP value. An AC power flow is included for network constraints consideration. The scenario of 32 consumers is used to validate the VPP_LMP_VAR model.

4.8.1 Outline

This case study illustrates the application of the proposed method to a distribution network managed by a Virtual Power Player (VPP). For the construction of the database, were considered all resources, some of them with variable values (aiming at LMP curves diversification) and the other with fixed values. Both variable and fixed data are presented in table 4.16.

Table 4.16. Generation resources availability and costs in VPP_ST_LMP_VAR

Generation resource	Minimum Active Power (kW)	Maximum Active Power (kW)	Price (m.u. / kWh)
Load	820	8200	-
Hydro	-	70	0.037
CHP	-	740	0.04
Wind	0	700	0.065
Fuel cell	-	235	0.10
Biomass	-	350	0.165
Photovoltaic	0	558	0.19
Storage	-	1200	0.55
Supplier1	-	3000	0.05
Supplier2	-	2000	0.075
Supplier3	-	2000	0.10

The variation of the wind and photovoltaic generation power was considered, as well as the total load demand power. The other resources are considered as fixed values. Three suppliers connected to bus 0 are also considered as fixed. The table shows the minimum and the maximum values that each variable assumes. Prices are fixed for each resource.

Table 4.17 presents the DR contract data, for each consumer type. DR capacities are divided into three groups (Red, CutA, CutB); the values of reduction price are shown in table 4.17. The prices of Non-Supplied Power (NSP) are also presented for each consumer type. DR power limit value is a percentage of the consumers demand in a specific scenario, and is 3, 5, and 7% respectively in Red, CutA, and CutB. This case study considers that all available photovoltaic generation must be used by the VPP.

Table 4.17. Consumers characterization in VPP_ST_LMP_VAR

Type of consumer		Consumers	Curtailment costs (m.u./kWh)			
			Red	***CutA***	***CutB***	***NSP***
Domestic	DM	5, 8, 9, 10, 11, 12, 14, 15, 16, 25, 26, 27, 32	0.16	0.20	0.24	2
Small Commerce	SC	2, 3, 4, 17, 22	0.15	0.19	0.22	2.5
Medium Commerce	MC	1, 13, 18, 19, 20, 21, 28, 29, 30	0.18	0.20	0.26	3
Large Commerce	LC	6, 7, 31	0.17	0.24	0.26	3.5
Industrial	IN	23, 24	0.17	0.26	0.28	4.5

All studied scenarios consider the situation of using and not using DR programs. The application of the proposed method with this data makes possible to build the LMP curve database.

4.8.2 Results

After the construction of the LMP curve database, it is possible for a VPP to evaluate the need and/or the usefulness of DR programs in the presence of a specific scenario.

This case study considers four scenarios, listed below (in all scenarios, the load demand is at its maximum value):

- Scenario 1 – there is no wind nor photovoltaic generation available;
- Scenario 2 – the photovoltaic generation is at the maximum value, and the wind generation is not available;
- Scenario 3 – the wind generation is at the maximum value, and the photovoltaic generation is not available;

- Scenario 4 – both wind and photovoltaic generation are at their maximum value.

Figure 4.41 presents results for Scenario 1. Figure 4.41 a) presents the values of the operation costs according to the total load demand value with and without the use of DR capacities. It can be seen that, for lower values of load demand, the existence of DR does not affect the value of operation costs. Figure 4.41 b) presents the value corresponding to the difference between the maximum and minimum LMP values in the 33 buses of the network, for each value of load demand power. One can conclude that for lower values of load demand the LMP values are homogeneous along the network buses, even without DR use. The use of DR capacities make possible to make the LMP values more homogeneous for higher load demand values.

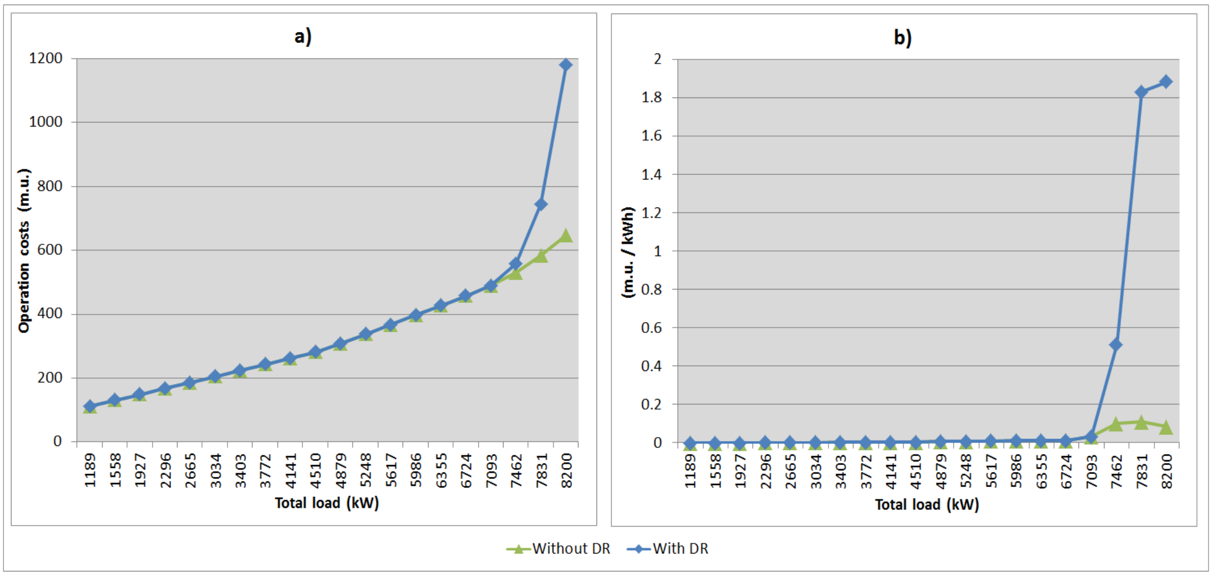

Figure 4.41. Values in function of the total load demand value, with and without DR use, in Scenario 1: a) operation costs (objective function); b) bus LMP amplitudes

One can conclude that the use of DR is more interesting for higher values of load demand power. Thus, the results obtained and commented below are related to the maximum value of load demand.

Figure 4.42 shows, for each scenario, the LMP value in each bus, with and without the use of DR. It is concluded that the use of DR has no influence in the LMP value if both photovoltaic and wind generations are available. If only one of these resources is available, the use of DR reduces the impact. Moreover, if there is neither photovoltaic generation nor wind generation, the use of DR has an important impact in reducing the LMP value in certain busses. This is due to the congestion in the power flow in the line linking busses 3 and 4.

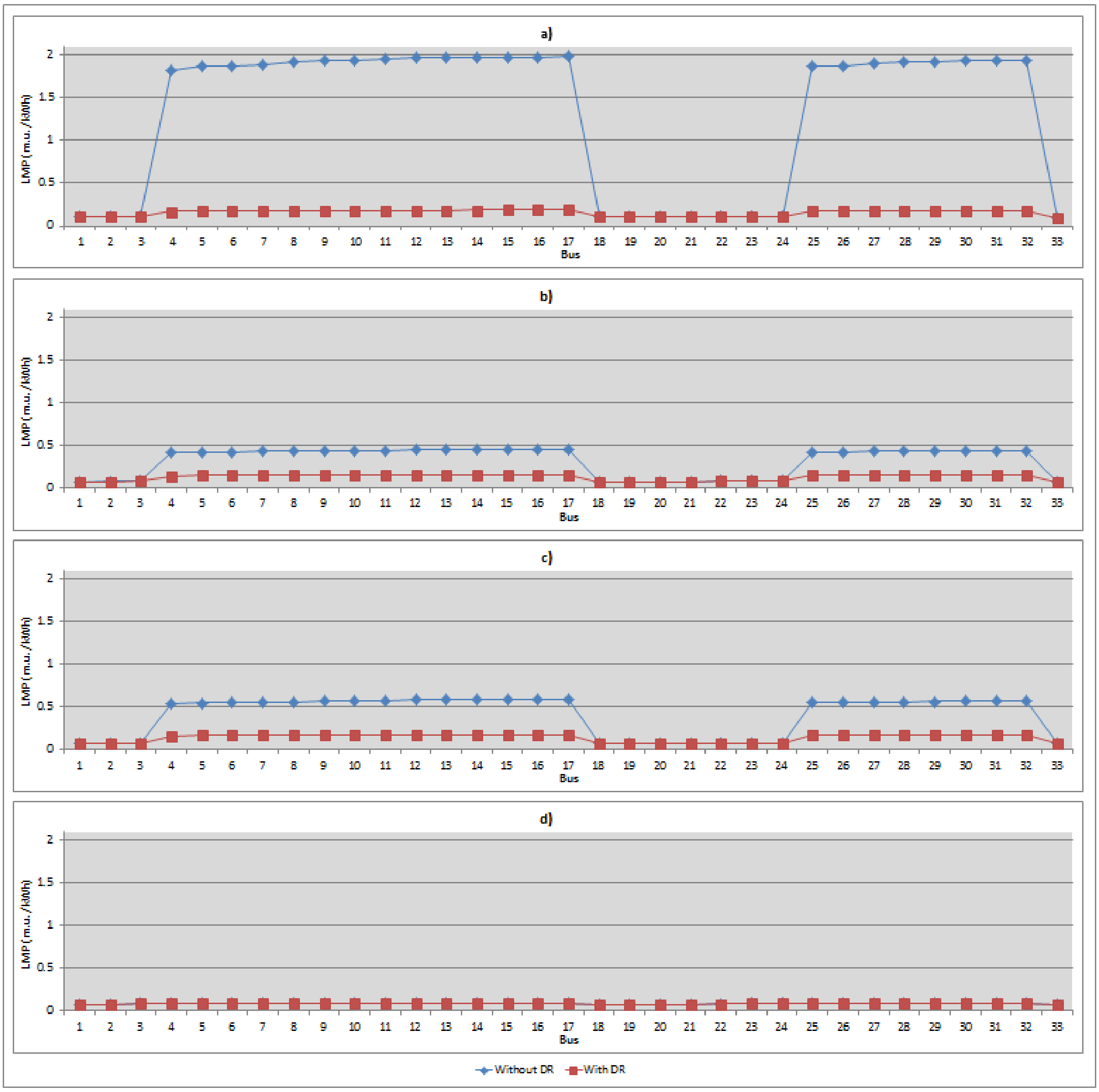

Figure 4.42. LMP values, with and without DR, in the four scenarios: a) Scenario 1; b) Scenario 2; c) Scenario 3; d) Scenario 4

Figure 4.43 shows the use of DR capacity, in each bus, in the first three scenarios, since DR capacity is not scheduled for use in the fourth scenario. It can be seen that DR is only scheduled for use in the busses located in a downstream position in relation to line 3 – 4. The major use of DR capacity occurs in Scenario 1, with the use of all the three available DR programs. In the other two scenarios, only Red is used.

Finally, figure 4.44 shows the resource scheduling, with and without DR use, for Scenario 1. Due to the reduced use of DR in Scenarios 2, 3, and 4, the corresponding resource scheduling is not presented. For Scenario 1, one can see that for higher values of load demand power, if DR is not available, it appears an amount of NSP, making the operation costs very high, as it has already been seen in figure 4.41.

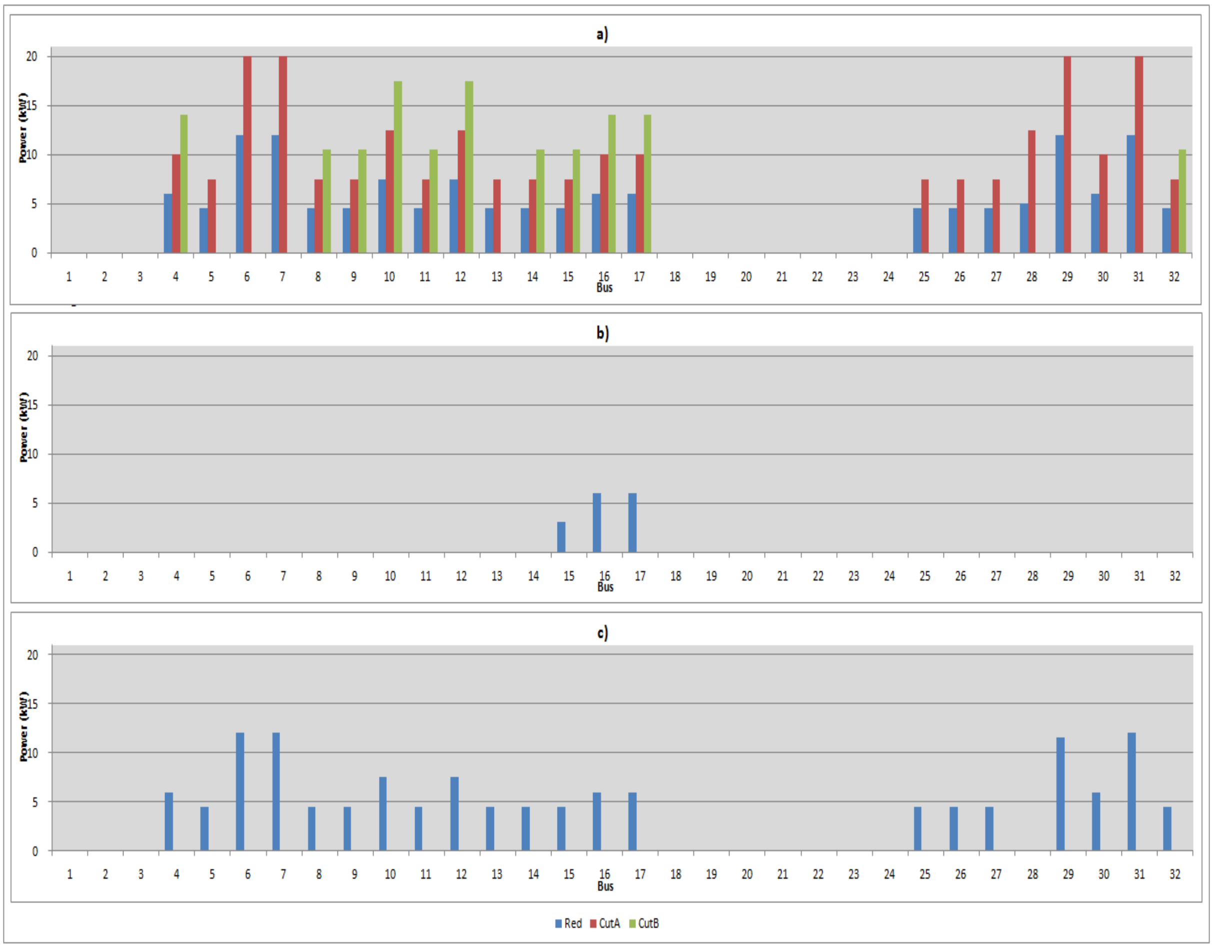

Figure 4.43.Use of DR capacity, in each level, for 3 scenarios: a) Scenario 1; b) Scenario 2; c) Scenario 3

Due to the relative lower price of DR programs usage, one can see that this resource can have an important role in keeping LMP values within acceptable levels. In a scenario with unavailability of wind and photovoltaic generation, like Scenario 1, without the use of DR programs, the LMP value is very high due to the high value of the total load and to the limited available resources. This limitation in the resources availability causes the existence of NSP, which is highly priced. At this point, one can conclude that the application of DR incentives to increase the use of DR programs can be very advantageous for the VPP that manages the network, as well as for all the other involved players.

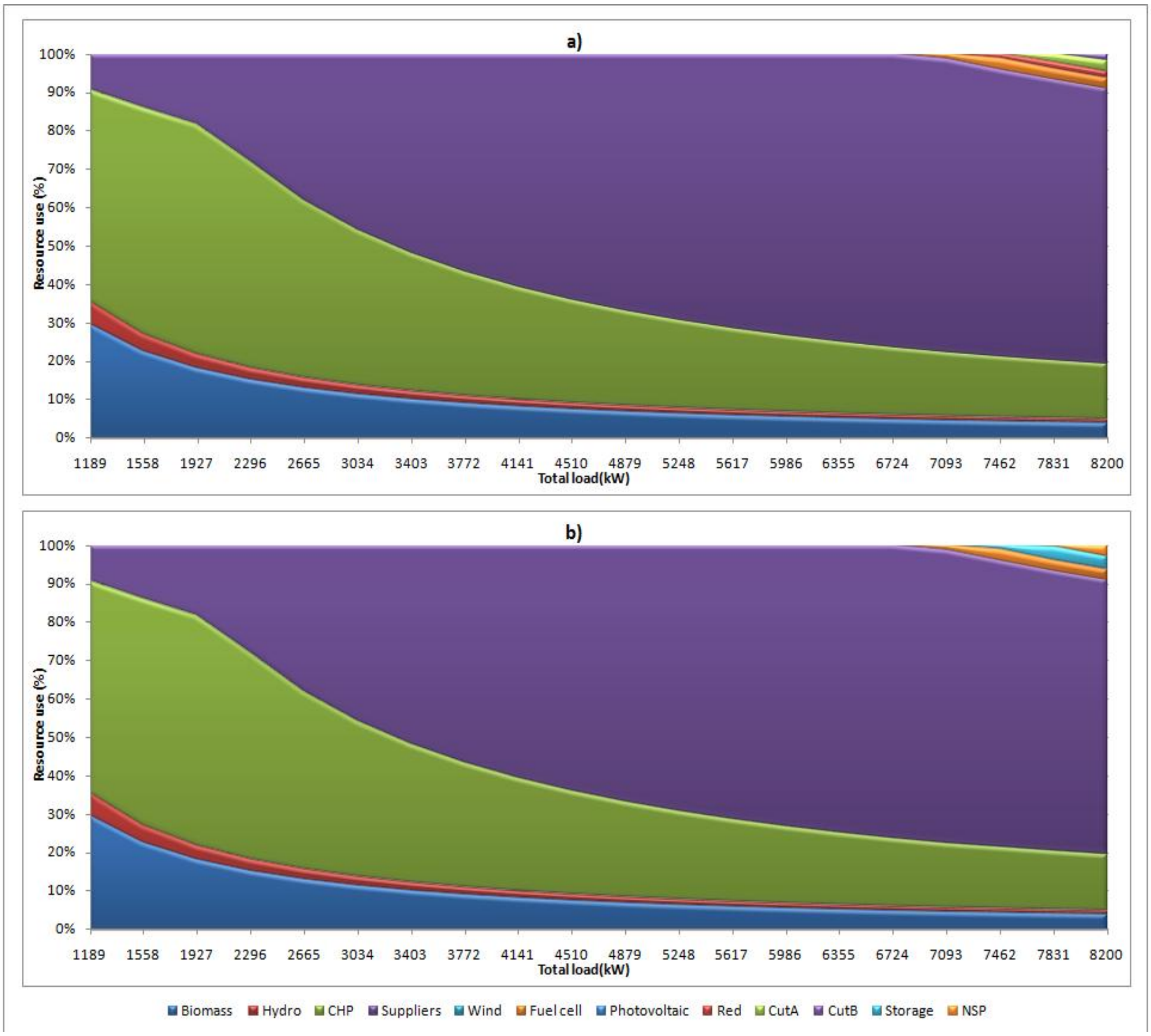

Figure 4.44. Percent use of resources, in Scenario 1: a) with DR; b) without DR

4.8.3 Results analysis

This case study presented the achieved results when applying the proposed model. This model is characterized as an approach that supports demand response programs and contracts, based on locational marginal prices computation. The proposed method has been computationally implemented and its application is illustrated with a case study considering a 33 bus network with intensive use of distributed generation.

The proposed methodology has proved to be computationally efficient and adequate to be used by VPPs, even when their size is small. Moreover, one can conclude that the method is flexible enough to be able to cope with diverse player characteristics, both concerning the managed resources, and also in what regards the considered specific demand response programs.

4.9 CASE STUDY – VPP_BID

As described in section 3.9, the VPP_BID model, inspired by [Behrangrad-2010], considers the bids of DR resources competing with the bids of generators and suppliers. The case study applying this model is tested with the 218 consumers scenario. After presenting the results of the developed scenarios, this case study includes also the consumer performance evaluation.

4.9.1 Outline

The electrical energy negotiated in an electricity market can be divided into two distinct products – energy and reserve. The VPP_BID model considers that generators and consumers can participate in both energy and reserve products fulfillment. The proposed problem aims at minimizing the VPP operation costs.

All the generators are offering the total available or installed capacity (values presented in table 4.2, section 4.2). 70% of this capacity is offered to the energy product. The remaining 30% regards the participation in the reserve product. The bid price of generators is considered equal for all the generators of the same type, for both energy and reserve products. These values and the bid prices for the five considered suppliers are shown in table 4.18.

Table 4.18. Generator bid prices

Type of generator	Energy			Reserve		
	***a* (m.u./h)**	***b* (m.u./kWh)**	***c* (m.u./kWh^2)**	***a* (m.u./h)**	***b* (m.u./kWh)**	***c* (m.u./kWh^2)**
Photovoltaic	0	0.15	0	0	0.165	0
CHP	0.000151	0.001062	0.001006	0.000166	0.001168	0.001106
Fuel cell	0	0.098	0	0	0.1078	0
Hydro	0	0.042	0	0	0.0462	0
Wind	0	0.071	0	0	0.0781	0
Biomass	0	0.086	0	0	0.0946	0
RSU	0	0.056	0	0	0.0616	0
Suplier1	0	0.23	0	0	0.286	0
Suplier2	0	0.24	0	0	0.264	0
Suplier3	0	0.25	0	0	0.275	0
Suplier4	0	0.26	0	0	0.253	0
Suplier5	0	0.27	0	0	0.297	0

In what concerns the consumers participation, the power considered for DR participation is 40% of the consumer consumption (presented in table 4.3, section 4.2). This capacity is divided in two parts: 60% for the participation in the energy product bid, and the remaining 40% for the reserve product. Table 4.19 presents the values of consumer bid prices. Those were considered equal for the consumers of the same type, for both energy and reserve products. For both products, consumer bids consider quadratic energy cost functions. The consumers scheduled for participation in one or both products are remunerated at the price they bid.

Table 4.19. Consumers bid prices

Type of consumer		Energy			Reserve		
		***a* (m.u./h)**	***b* (m.u./kWh)**	***c* (m.u./kWh^2)**	***a* (m.u./h)**	***b* (m.u./kWh)**	***c* (m.u./kWh^2)**
Domestic	DM	0.0020	0.20	0.000020	0.0021	0.21	0.000021
Small Commerce	SC	0.0016	0.16	0.000016	0.0018	0.18	0.000018
Medium Commerce	MC	0.0019	0.19	0.000019	0.0020	0.20	0.000020
Large Commerce	LC	0.0018	0.18	0.000018	0.0019	0.19	0.000019
Medium Industrial	MI	0.0012	0.12	0.000012	0.0008	0.08	0.000008
Large Industrial	LI	0.0014	0.14	0.000014	0.0007	0.07	0.000007

In order to make possible the participation of small consumers, three consumer aggregators are considered (CSP1, CSP2, and VPP). Table 4.20 shows the consumers aggregated to each one of two CSPs and to one VPP. In the case of VPP aggregated consumers, some of them (with higher response capability) are directly participating in the DR program; the other are small consumers that participate in the DR program in an aggregated way.

Table 4.20. Consumers aggregation

DR Provider	Consumers
CSP1	1-136; 150-156; 170-190; 214-218
CSP2	137-149; 191-207
VPP	157-169; 208-213

4.9.2 Results

The VPP_BID model includes several parameters that affect the conditions of the problem. The VPP operation costs in a specific situation depend on the quantity required for reserve product, on using or not the reserve power, on the price of resources.

The present results sub-section presents firstly the results for the situation of probability of reserve use equal to 1. Then the results regarding a variable probability of reserve use are shown. Some results concerning the remuneration and participation of the aggregation players (CSP1, CSP2 and VPP) are presented in Annex C.

4.9.2.1 Probability of reserve use equal to 1

Let us assume that the probability of using the reserve is equal to 1. Bidding resource use and the VPP operation costs are analyzed regarding the variations in the amount of power required for the reserve product and the variations in the price of electricity provided by the suppliers.

Figure 4.45 presents the values of the objective function regarding the required reserve amount and the supplier price. The basis for the price of the energy provided by each supplier is the one presented in table 4.18. Taking as reference those values, several steps of supplier prices were defined (for example, the “0.6” step corresponds to a reduction of 40% in the basis price; the “1” step is the basis price; and the “1.4” step corresponds to an increase of 40% in the suppliers price).

One can see that both increases in the supplier price step and in the required reserve cause an increase in the operation costs. The supplier price step significantly influences the operation costs.

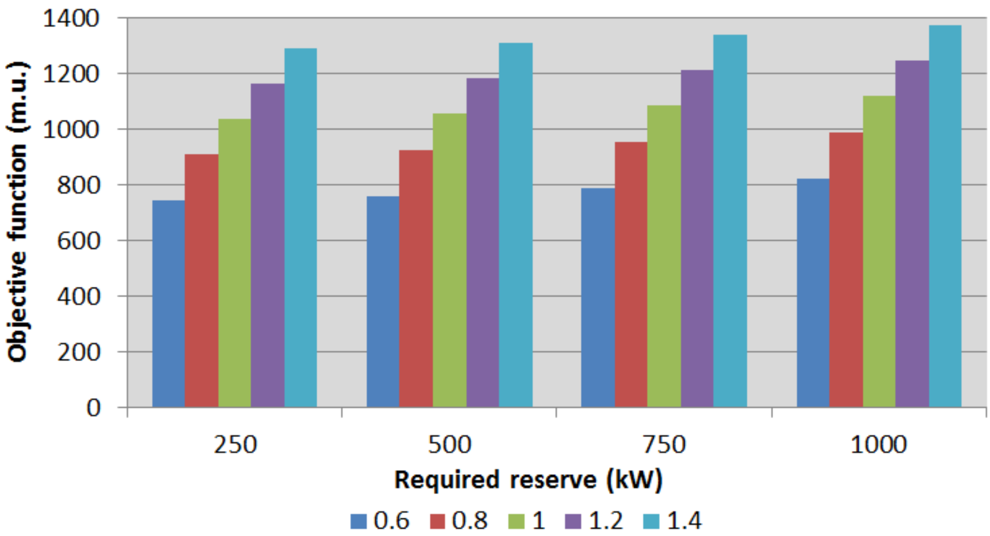

Figure 4.45. Values of the objective function regarding the required reserve and the supplier price step.

Figures 4.46 and 4.47 present the values of DR use regarding the variations in the supplier price, respectively for the energy and reserve products. Results are organized by consumer types. The results presented in the figures 4.46 to 4.49 assume a value of 750 kW for the amount of required reserve.

Regarding the participation of DR in the energy product, one can say that MI and LI consumers always participate, independently from the supplier price step. The consumers of other types do not participate when the supplier prices are reduced in 40%.

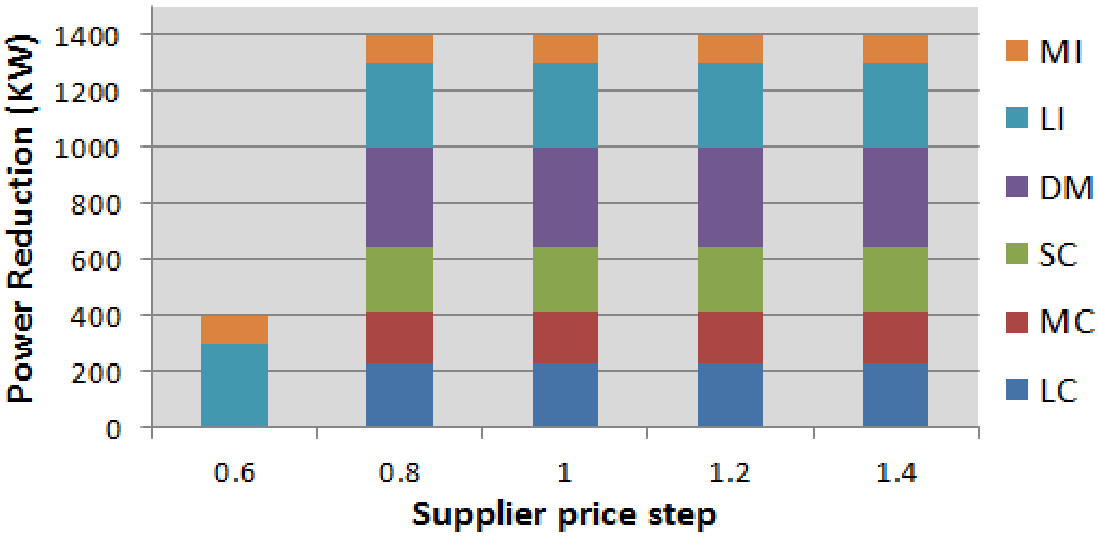

Figure 4.46. DR use regarding the supplier price step and the type of consumer, for the energy product.

In the case of the reserve product, only MI and LI consumers participate. This participation is independent of the supplier price step. In the results presented in figure 4.47, the total amount of DR participation is constant because the required reserve power is constant and equal to 750 kW.

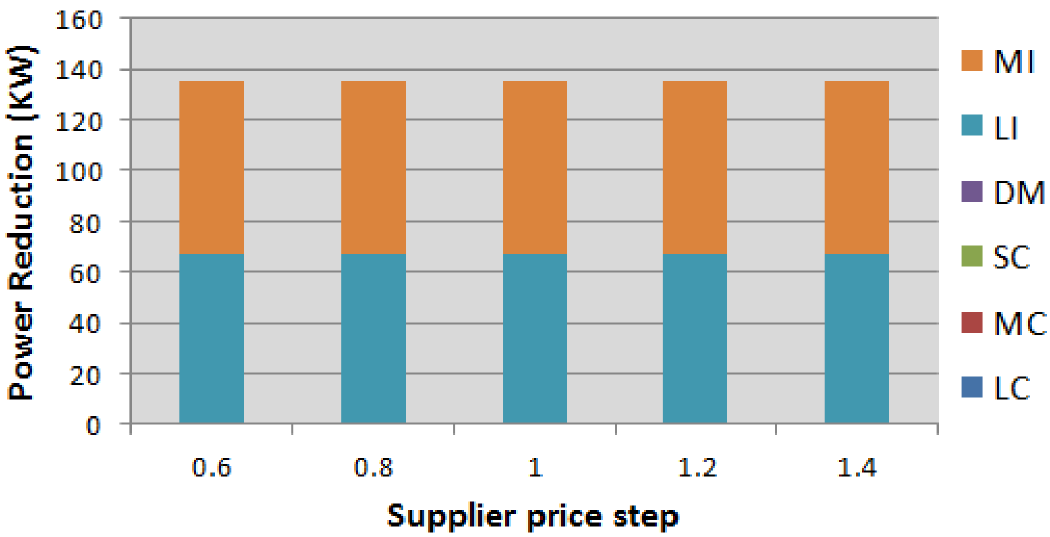

Figure 4.47. DR use regarding the supplier price step and the type of consumer, for the reserve product

Figures 4.48 and 4.49 present the values of generation use regarding the variations in the supplier price, respectively for the energy and reserve products. Results are organized by generation types.

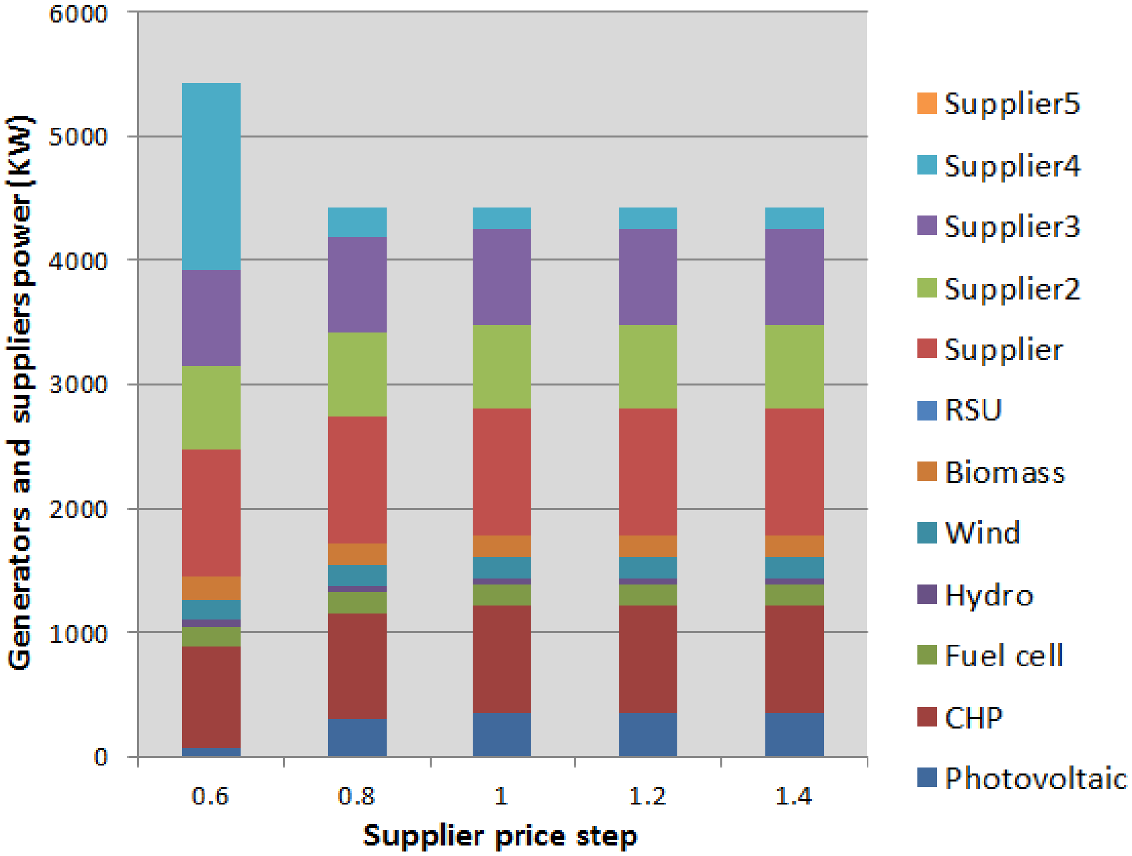

Figure 4.48. Generation use regarding the supplier price step for the energy product

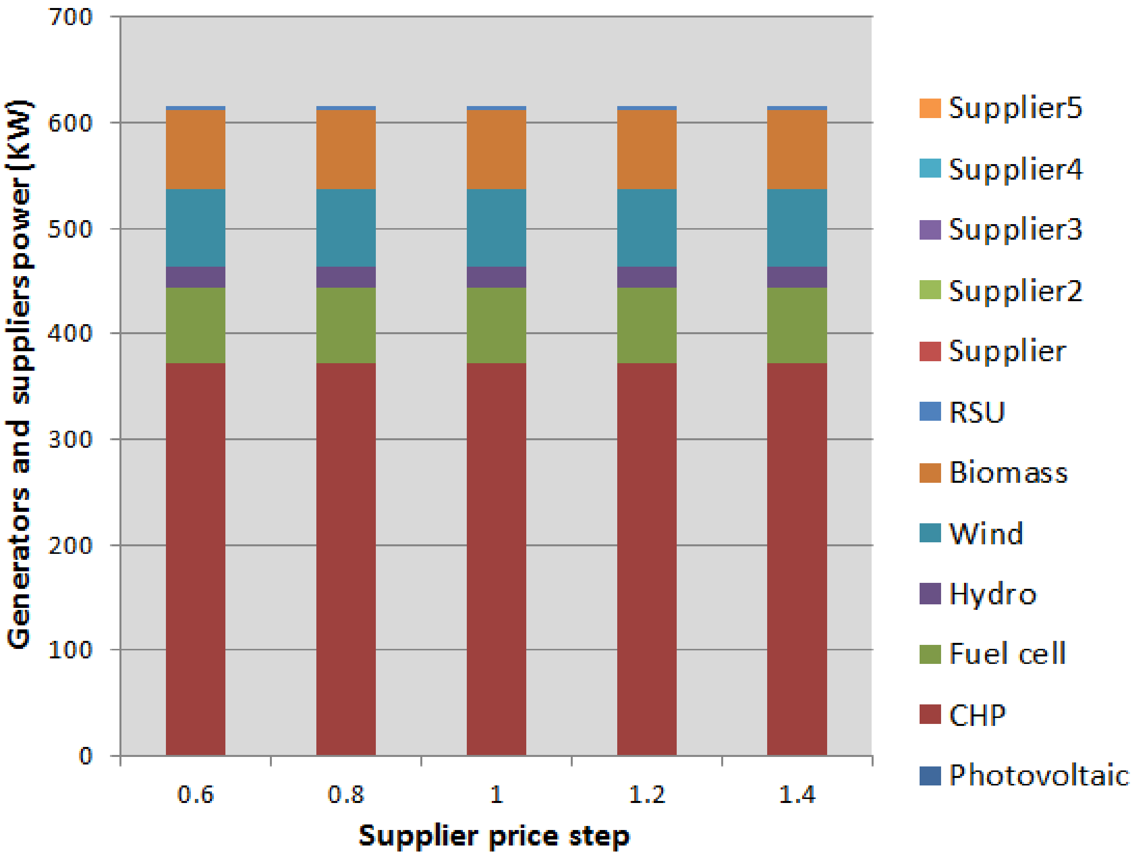

Figure 4.49. Generation use regarding the supplier price step for the reserve product

Concerning the energy product, only RSU and supplier5 do not participate. Depending on the supplier price step, the amounts of power used in each resource can vary. The special case of supplier4 should be noted; its participation significantly increases when the supplier price is reduced in 40%.

In the case of the reserve product, as the required amount is always the same, independently from the supplier price step, the total amount of use is always the same. In this product, for the specified conditions, only the suppliers are scheduled.

4.9.2.2 Variable probability of reserve use

In order to evaluate the influence of the reserve use probability, some results are herein analyzed. The required reserve power is assumed to be equal to 750 kW. Figure 4.50 presents the values of the objective function regarding the variations in the reserve probability of use and the variations in the supplier price step.

One can see that both increases in the supplier price step and in the reserve probability of use cause an increase in the operation costs. The supplier price step significantly influences the operation costs, also in this situation.

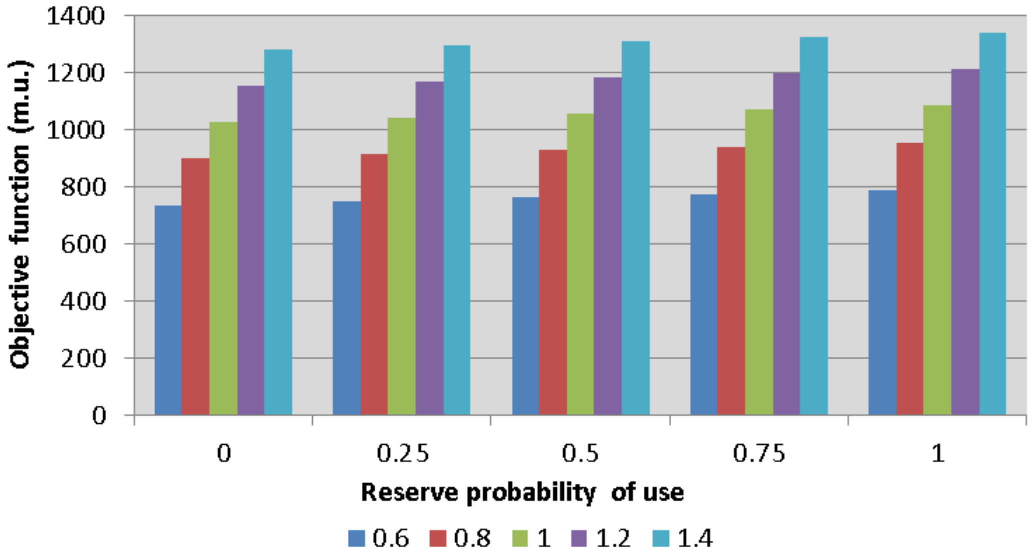

Figure 4.50. Values of the objective function regarding the reserve probability of use and the supplier price step.

Figures 4.51 and 4.52 show the use of both power generation and reduction, respectively for generation resources and for the consumers' response, regarding the variations in the supplier price step and in the reserve probability of use.

Figure 4.51 shows the results of the generation and supplier use for the reserve product. The value of the supplier price step does not influence the total quantity of generator and supplier resources usage. The value of probability of reserve use only affects the amount of resources usage when that probability is zero.

Figure 4.52 shows the results of DR usage in the same conditions used for figure 4.51. As concluded for the use of generator and supplier resources, the value of the supplier price step does not influence the quantity of resource usage. Also, for the value of probability of reserve use, it only affects the amount of resources usage when that probability is zero.

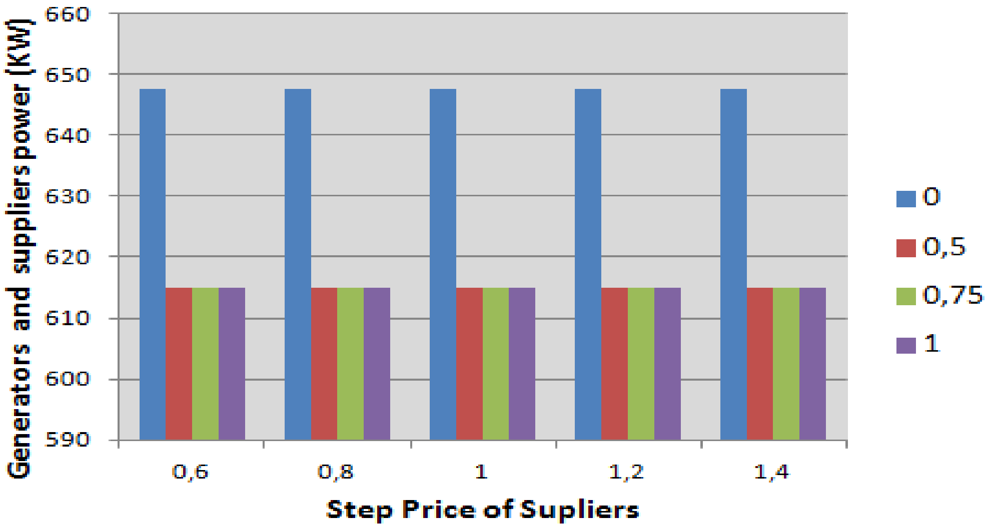

Figure 4.51. Generation use regarding the supplier price step and the reserve probability of use, for the reserve product

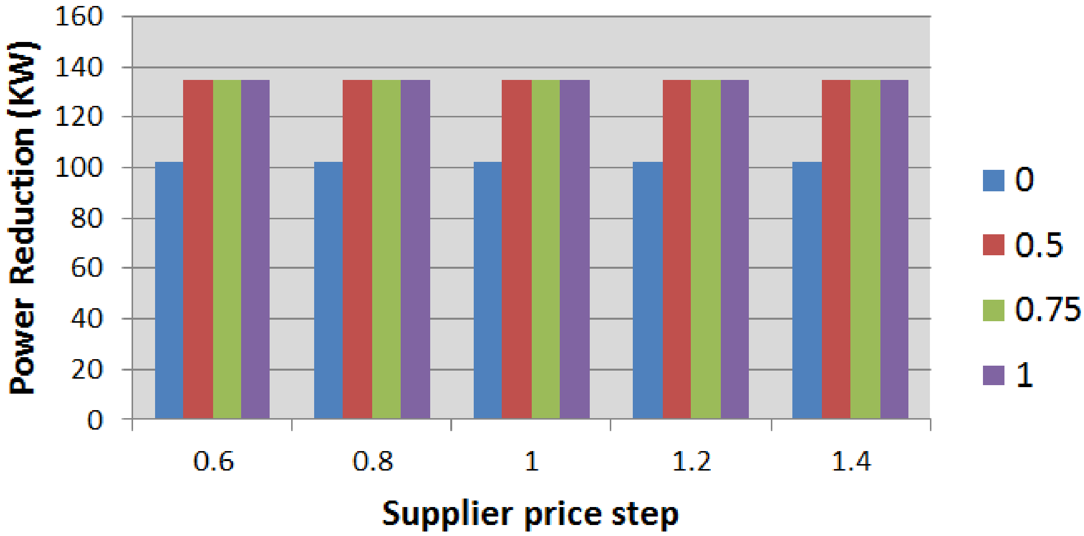

Figure 4.52. DR use regarding the supplier price step and the reserve probability of use, for the reserve product

4.9.3 Consumer performance evaluation

The participation of a consumer in a DR program event implies a reduction in his/her consumption. In order to determine the effective consumption reduction it is necessary to use a consumer performance evaluation method since the metering equipment data gives us only the value of the consumption in a specified period. The present sub-section presents the application of the consumer performance evaluation method explained in sub-section 2.2.3 to the VPP_BID case study. Six consumers, one of each type, randomly selected, were chosen to illustrate the application of the method. The used results concern the reserve probability of use equal to 1, a reserve requirement of 750 kW, and the basis energy supplier prices.

Table 4.21 presents metered consumptions concerning the consumers demand historic and event day data required for the application of the referred consumer performance evaluation method. For each of the six selected consumers, this table shows the values of consumption for the past ten non-event days, regarding the time interval under analysis and the two preceding periods. As required by the method, the five highest consumption days (the ones marked in purple color in the table) are selected. In the case of the event day consumption, the values of the two periods preceding the event are also required.

Table 4.21. Consumers demand metered data

Consumer ID	***Time interval***	**10 Past non-event days consumption (kW)**										***Event day consumption (kW)***
		td10	***td9***	***td8***	***td7***	***td6***	***td5***	***td4***	***td3***	***td2***	***td1***	
1	t-2	46.14	69.56	73.11	70.27	72.40	68.85	56.78	42.59	71.69	68.14	70.98
	t-1	41.74	62.94	66.15	63.58	65.50	62.29	51.38	38.53	64.86	61.65	64.22
	t	43.94	66.25	69.63	66.92	68.95	65.57	54.08	40.56	68.28	64.90	51.38
2	t-2	34.78	36.55	35.14	36.20	34.43	28.39	21.29	35.84	34.07	35.49	34.78
	t-1	31.47	33.07	31.79	32.75	31.15	25.69	19.27	32.43	30.83	32.11	31.47
	t	33.12	34.81	33.46	34.48	32.79	27.04	20.28	34.14	32.45	33.80	22.98
4	t-2	17.39	18.19	17.05	17.90	17.21	14.20	10.65	17.71	17.04	17.75	17.39
	t-1	15.12	15.87	15.89	16.00	15.57	12.84	9.63	16.02	15.41	16.06	15.12
	t	15.02	16.00	16.01	15.00	16.39	13.52	10.14	17.07	16.22	16.90	12.84
11	t-2	19.80	20.81	20.00	20.61	19.60	16.16	12.12	20.40	19.39	20.20	19.80
	t-1	17.91	18.83	18.10	18.64	17.73	14.62	10.97	18.46	17.55	18.28	17.91
	t	18.86	19.82	19.05	19.62	18.66	15.39	11.54	19.43	18.47	19.24	14.62
157	t-2	138.92	146.00	140.33	144.59	137.50	113.40	85.05	143.17	136.08	141.75	138.92
	t-1	125.69	132.10	126.97	130.82	124.40	102.60	76.95	129.53	123.12	128.25	125.69
	t	132.30	139.05	133.65	137.70	130.95	108.00	81.00	136.35	129.60	135.00	98.28
167	t-2	68.84	72.35	69.54	71.65	68.14	56.20	42.15	70.95	67.44	70.25	68.84
	t-1	62.28	65.46	62.92	64.83	61.65	50.84	38.13	64.19	61.01	63.56	62.28
	t	65.56	68.91	66.23	68.24	64.89	53.52	40.14	67.57	64.22	66.90	40.14

Table 4.22 presents the results concerning the event response parameters for each of the six selected consumers. The scheduled reduction corresponds to the amount of power expected to be reduced for a determined consumer and for a specific DR event, as scheduled

by the DR program managing entity. The actual value of the consumption is the value registered in the metering equipment for the event period (the one shown in table 4.21 for time interval t in the event day). In the presence of a DR event, each consumer can have several consumption reduction responses. The consumer participation factor can be computed with the consumer baseline, the scheduled reduction and the actual value of the consumption (registered in the metering equipment).

Table 4.22.Consumers response

Consumer		**Response**		
ID	***Type***	***Scheduled reduction (kW)***	***Actual consumption (kW)***	***Participation factor***
1	DM	16.22	51.38	1.00
2	SC	13.52	22.98	0.80
4	MC	4.06	12.84	1.00
11	LC	4.62	14.62	1.00
157	MI	54.00	98.28	0.68
167	LI	26.76	40.14	1.00

Table 4.23 presents the results of the calculations regarding the updated baseline and performance characterization. The baseline variables were calculated using equations (2.2) and (2.3) presented in sub-section 2.2.3. The performance calculation used equation (2.4) presented in the same sub-section.

Table 4.23. Baseline and consumers performance parameters

Consumer		**Baseline variables**				**Performance**	
ID	***Type***	b_t (kW)	b_{t-1} (kW)	b_{t-2} (kW)	a_t (kW)	***Power (kW)***	***Remuneration (m.u.)***
1	DM	16.22	51.38	1.00	51.38	16.63	3.34
2	SC	13.52	20.28	0.80	22.98	11.02	1.71
4	MC	4.06	12.84	1.00	12.84	3.16	0.60
11	LC	4.62	14.62	1.00	14.62	4.73	0.86
157	MI	54.00	81.00	0.68	98.28	37.53	5.05
167	LI	26.76	40.14	1.00	40.14	27.16	3.27

Regarding the consumer performance results, both power reduction amount and remuneration values are provided. Let us first consider the consumers with participation factor equal to 1, i.e. consumers 1, 4, 11 and 167. In the specific case of consumer 1, from the performance evaluation method resulted a power reduction higher than the scheduled reduction. The same was verified for consumers 11 and 167. In the case of consumer 4, the remaining one for which the participation factor is equal to 1, the method determined a performance power lower than the scheduled. For consumers 2 and 157, both with participation factor below 1, the method determined that the power reduction amount was below the scheduled, for both consumers.

The remuneration of the consumers is presented in figure 4.53. It compares the values of each consumer's remuneration resulting from the performance evaluation method (blue bars) and the remuneration that would be applied if this method was not used (red bars). The performance evaluation method allows remunerating the consumers participation based on their recent consumption behavior.

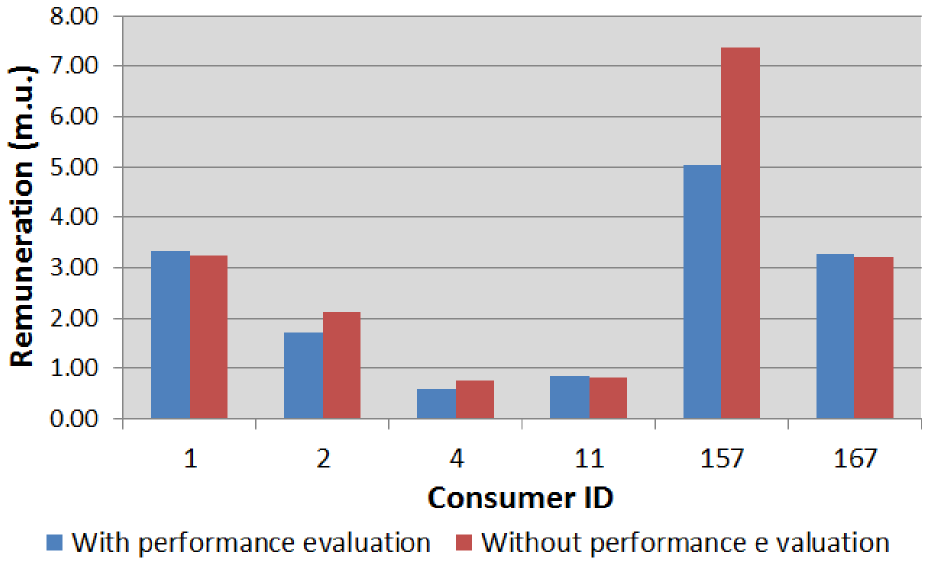

Figure 4.53. Consumers' remuneration with and without performance evaluation

4.9.4 Results analysis

The electrical energy negotiated in an electricity market can be divided into two distinct products – energy and reserve. The VPP_BID model considers the bids of DR resources competing with the bids of generators and suppliers for both products, aiming at minimizing the VPP operation costs. The case study applying this model was tested with the 218 consumers set.

In order to make the participation of small consumers possible, three consumer aggregators were considered (CSP1, CSP2, and VPP). In the case of VPP aggregated consumers, some of them (with higher response capacity) were participating directly in the DR program; the others, small consumers, participate in the DR program in an aggregated way through the VPP.

The VPP operation costs in a specific situation depend on the quantity required for the reserve product and whether the reserve power is actually used or not. The results considered several values for the probability of reserve use (0; 0.25; 0.50; 0.75 and 1).

It was possible to conclude that the increase of the three varying parameters (the reserve probability of use, the supplier price, and the required reserve amount) have a direct impact on the VPP operation costs. The highest relevance is given has been found for the impact of the supplier energy price. In what concerns the probability of using the reserve, in the considered case study, it only affects the amount of resources usage when that probability is zero.

After presenting the results of the developed scenarios, this case study also included the consumer performance evaluation, in order to determine the effective consumption reduction, since the metering equipment data give us only the value of the consumption in a specified period. Six consumers, one of each type, were chosen to illustrate the application of the method.

4.10 CONCLUSIONS

This chapter presented several case studies that illustrate the application of the proposed models and DemSi performance. Although it is not possible to demonstrate DemSi models and functionalities in their full extent in this written document, the presented case studies have been chosen to cover a diversity of situations and involved players.

The presented case studies used a distribution network with 33 buses, 32 of them load buses. Several DR programs characteristics, such as the DR event trigger logic, the way that the consumers reduction is achieved, the way that the suppliers are considered, and the existence of bids, were implemented in order to ensure diversity in the simulated models.

Several case studies were created corresponding to each one of the developed models. These cases cover the maximization of the profits, the minimization of the operation costs and also the point of view of two distinct managing entities (VPP and DNO).

The consideration of LMPs as DR event trigger, together with the simulation of large set of scenarios allowed to illustrate the use of the methodology proposed for supporting decision making concerning DR program design and use.

A PSO approach was used in one of the simulated models in comparison with the MINLP approach obtained in GAMS software using a deterministic approach. The obtained results have shown the best performance of the PSO with mutation approach in terms of the objective function value, with only a slightly higher execution time than the classic PSO approach and with much lower times than the deterministic approach.

Chapter 5

Conclusions and future work

5 CONCLUSIONS AND FUTURE WORK

This chapter begins, in section 5.1, presenting the most important conclusions that resulted from the work developed in the scope of this thesis. An analysis on how the objectives of the work were achieved is also included. Some perspectives of future work are presented in section 5.2.

5.1 MAIN CONCLUSIONS AND CONTRIBUTIONS

The demand response concept is a fast evolving topic of crucial importance for the planning and operation of future electricity markets and of power systems in general. Presently, DR is evolving towards more flexible approaches, able to benefit from the participation of the involved players.

This thesis work focused on demand response contributing to the development and implementation of several models and tools able to support the involved players in DR program design and use. The developed work is part of a larger vision, which main objective is to develop, implement and validate several DR program models and a methodology to support decision making concerning Demand Response (DR) program and contract design and use, as already introduced in chapter 1 (see figure 1.1). In the context of this decision-support based vision of DR, some specific objectives were defined for this thesis. In order to adequately address this problem, DR programs, and opportunities of DR in present and future power systems were identified.

The most important concepts, experiences and implementations concerning DR were exposed in this dissertation. Several consumer group sizes actual implementations, several DR programs implementation characteristics, and consumer performance evaluation methods have also been addressed.

The success of DR programs is strongly dependent on their adequate design and use. Considering the complex and dynamic environment in which these programs have to be implemented, the existence of a DR program simulator is highly important in what regards supporting decision players in taking the adequate decisions concerning DR program design and use. This has been the main focus of the present thesis, which resulted in the design and implementation of DemSi, a DR program simulator. This simulator has a wide range of application, providing users with and economic and technical analysis of DR program use. DemSi is of crucial importance to enable decision-support by the players acting in DR programs.

DemSI presents characteristics that distinguish it from the already existing DR tools, what makes it a valuable contribution to the DR field. It allows a flexible use of a diversity of DR models, electricity networks and consumers sets. One of its unique features is the optimization of the DR program use, given the specific conditions for its application. Another very relevant feature is the realistic technical validation of DR solutions, based on PSCAD, which ensures DemSi applicability to real world problems. Moreover, DemSI provides the means for this analysis to be undertaken from different points of view, making it useful for consumers, retailers/suppliers, DNOs, CSPs, and VPPs.

Several DR programs have been modeled, establishing the basis for a DR program model module that is used by DemSi and that can be enlarged over the time, with new DR program models.

The use of LMPs as DR event trigger and the simulation of a large set of scenarios are the basis of a specific methodology proposed for supporting decision making concerning DR programs.

Regarding the consumers' response characterization, DR capacity can be divided into a single or several steps of curtailment and/or reduction of consumption. It can also be defined by the bid that the consumer or group of consumers submit to the participation in the DR program or modeled by the consumer elasticity. The aggregated participation of consumers (usually performed by a Curtailment Service Provider) is useful when single consumer participation does not present the required minimum participation reduction capacity.

Several case study scenarios regarding the simulation of the developed DR program models were implemented. These scenarios included several future power systems characteristics such as the intensive us of DG, the consideration of diverse suppliers, etc. The set of case studies included in the thesis illustrate the use of the proposed methodologies and demonstrate the applicability and the advantages of the proposed models. Analysis undertaken from VPPs and DNOs points of view are included in the presented set of case studies. Diverse event trigger and optimization goals are also addressed. A bid based energy and ancillary service market in which DR offers compete with generators and suppliers offers is also presented. In this case, the use of a consumer performance evaluation method is illustrated.

PSO has been used in its classic form and in an improved approach, which considers mutation. It was implemented in a case study concerning the energy resources management. PSO approaches were compared with a deterministic approach in which MINLP is used making use of GAMS software. Results have shown the best performance of the PSO with mutation approach in terms of the objective function value, with only a slightly higher execution time than the classic PSO approach and with much lower times than the deterministic approach.

The work developed in the scope of this thesis has resulted in the publication of seven papers, two of them published in SCI journals. The unpublished work is presently either under review or being prepared to be submitted for publication.

5.2 PERSPECTIVES OF FUTURE WORK

The continuous development of this work is a relevant part of the core of some recently approved FCT projects, which come to give continuity to the projects already mentioned in the introductory chapter, namely the following:

- IMaDER – Intelligent Short Term Management of Distributed Energy Resources in a Multi-Player Competitive Environment (PTDC/SEN-ENR/122174/2010);
- MAN-REM – Multi-Agent Negotiation and Risk Management in Electricity Markets (PTDC/EEA-EEI/122988/2010). This project will be developed in joint endeavour between GECAD – Knowledge Engineering and Decision Support Research Centre, LNEG – National Laboratory of Energy and Geology, and ISEL – Institute of Engineering of the Polytechnic of Lisbon.

Among the many advances that the development of this work gave opportunity to, allowing future works and scientific findings, some future developments can be referred:

- Improving the DR programs and contracts optimization module with more extensive application of metaheuristic approaches;

- Developing and implementing a machine learning (ML) based methodology to support DR programs use. This methodology will be based on clustering and classification techniques, resulting in a rule base concerning DR programs and contracts use. Creating a large set of simulation results will be used as the basis data for the application of the proposed ML method;
- Including the consideration of DR-Event participants' failure in responding to the declared events;
- Modeling DR business models in a detailed way. As an example, these models must consider the remuneration of CSPs in the optimization of the DR program;
- Including single consumer's goals in the objective function;
- Considering the social impact of the consumers chosen to participate in each DR event, when this choice is done by a managing entity. In this context, the participation of each participating consumer must be considered over time;
- Designing and implementing an agent based architecture for the entities participating in DR, in the context of a smart grid. Agent negotiation will be used to respond to DR announced opportunities.

The majority of these suggestions has been considered not only for the future development of this thesis work in the scope of the previously mentioned projects, but also as basis for the already granted PhD scholarship.

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Annexes

Annex A. VPP_ST

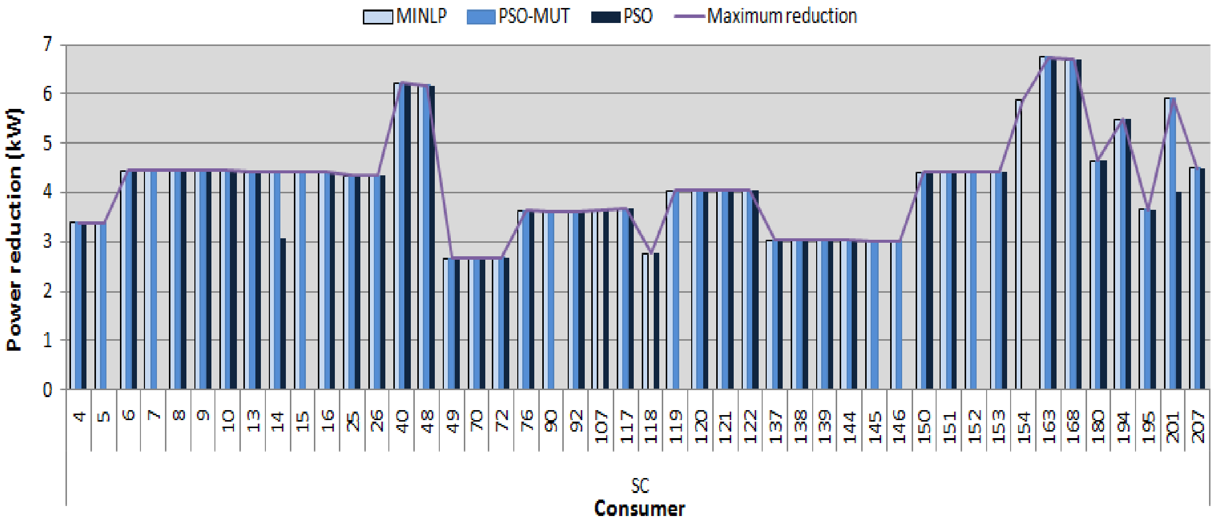

Figure A. 1. Power reduction for reduction step RedA, in scenario 1 of VPP_ST, for SC consumers.

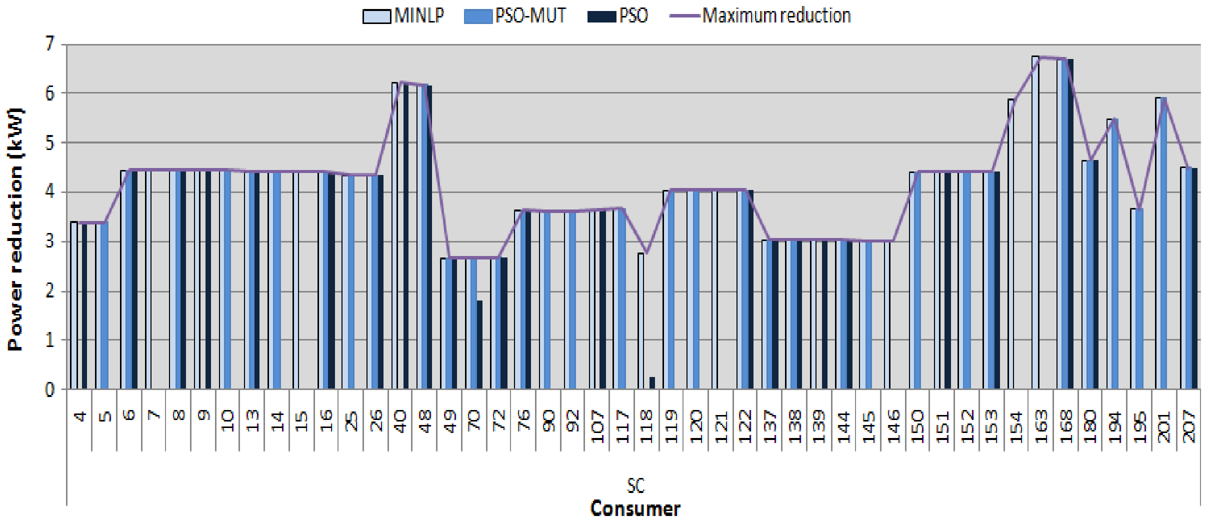

Figure A. 2. Power reduction for reduction step RedB, in scenario 1 of VPP_ST, for SC consumers.

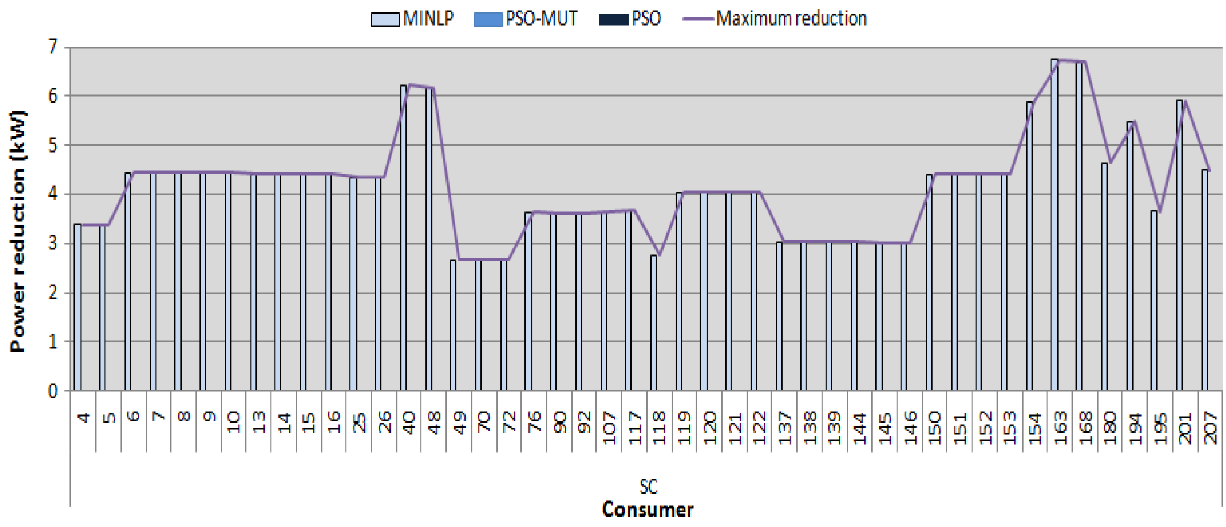

Figure A. 3. Power reduction for reduction step RedC, in scenario 1 of VPP_ST, for SC consumers.

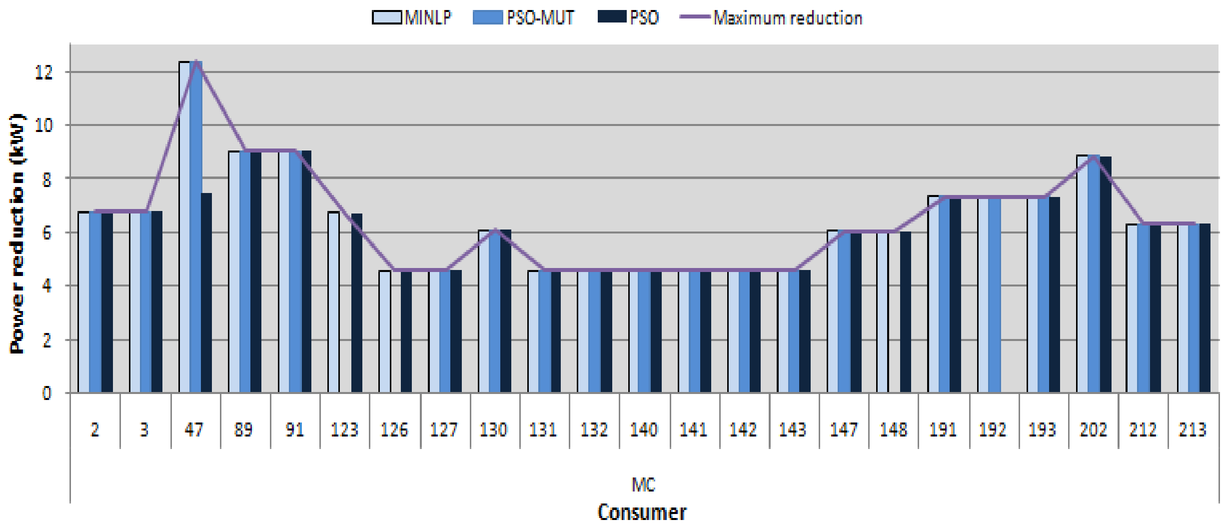

Figure A. 4. Power reduction for reduction step RedA, in scenario 1 of VPP_ST, for MC consumers.

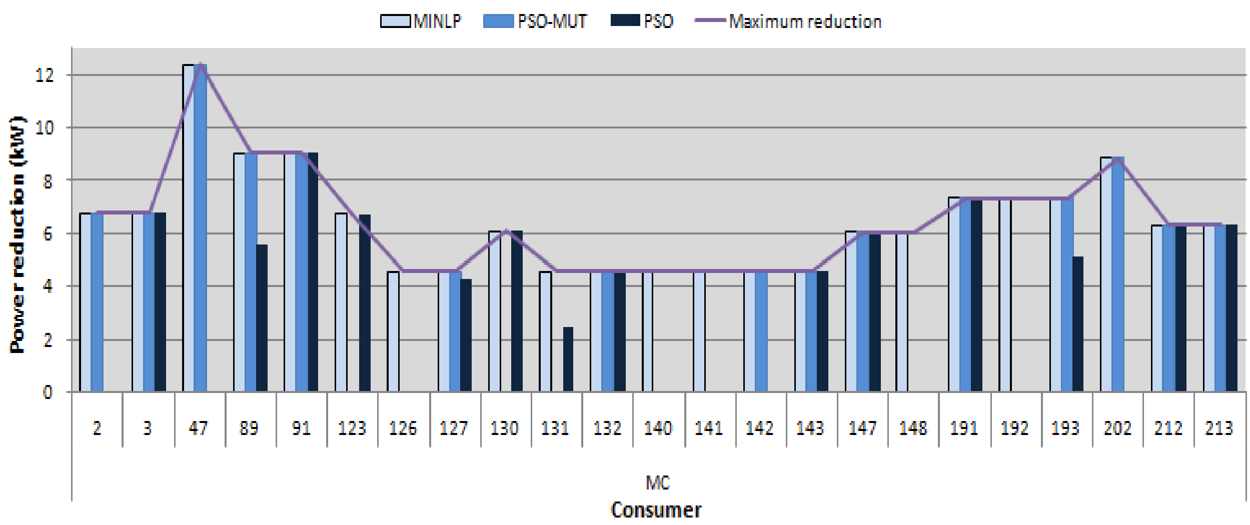

Figure A. 5. Power reduction for reduction step RedB, in scenario 1 of VPP_ST, for MC consumers.

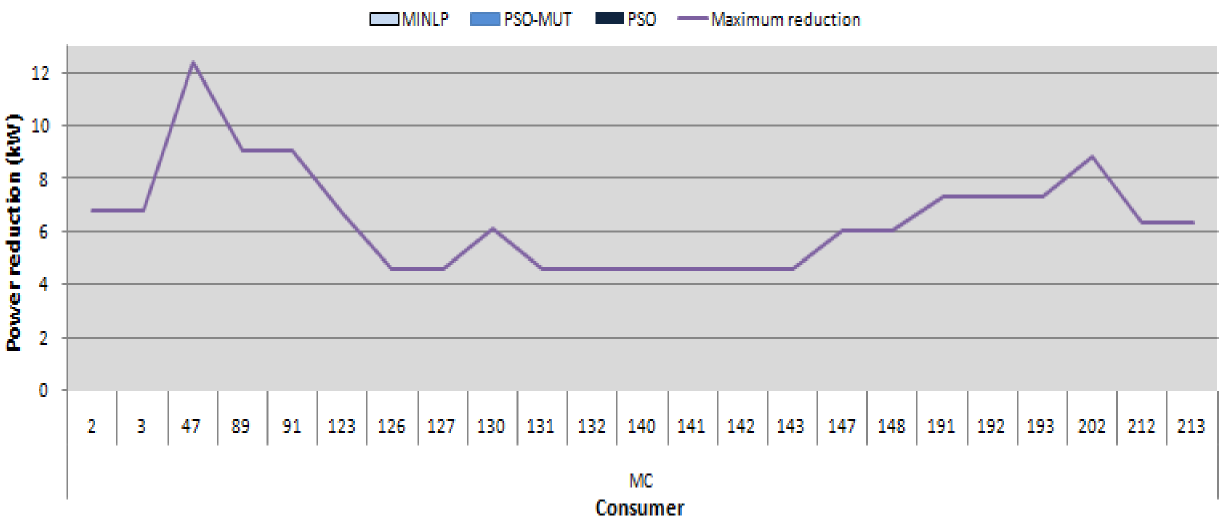

Figure A. 6. Power reduction for reduction step RedC, in scenario 1 of VPP_ST, for MC consumers.

Annex B. VPP_CSP_ST

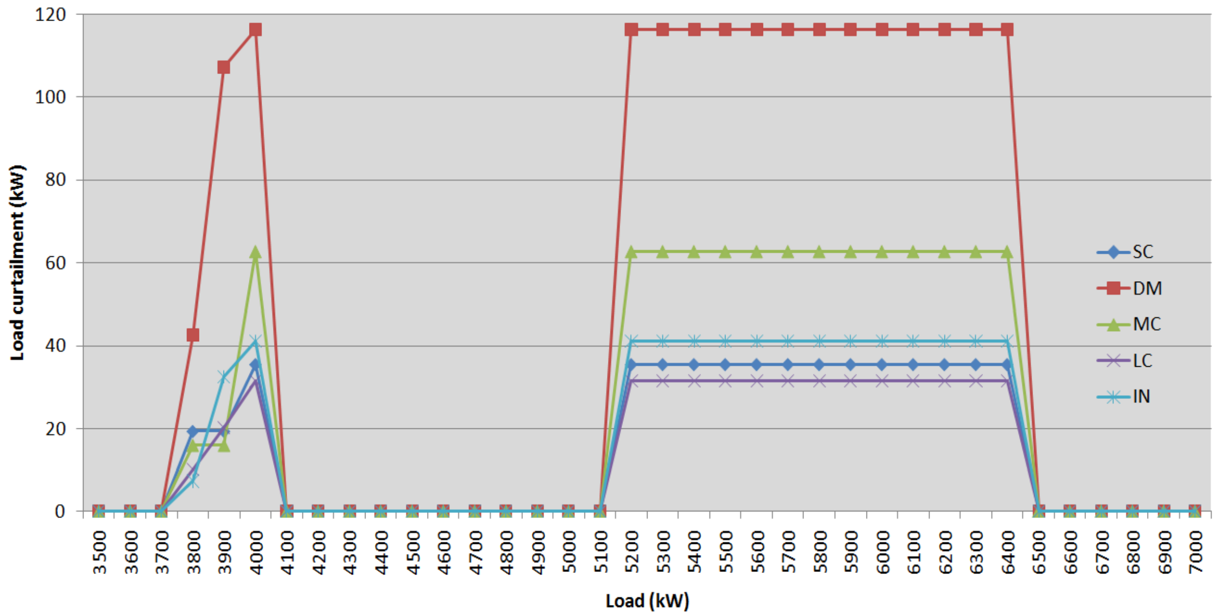

Figure B. 1. Load curtailment regarding the total load and grouped by consumer type, for curtailment step CutA.

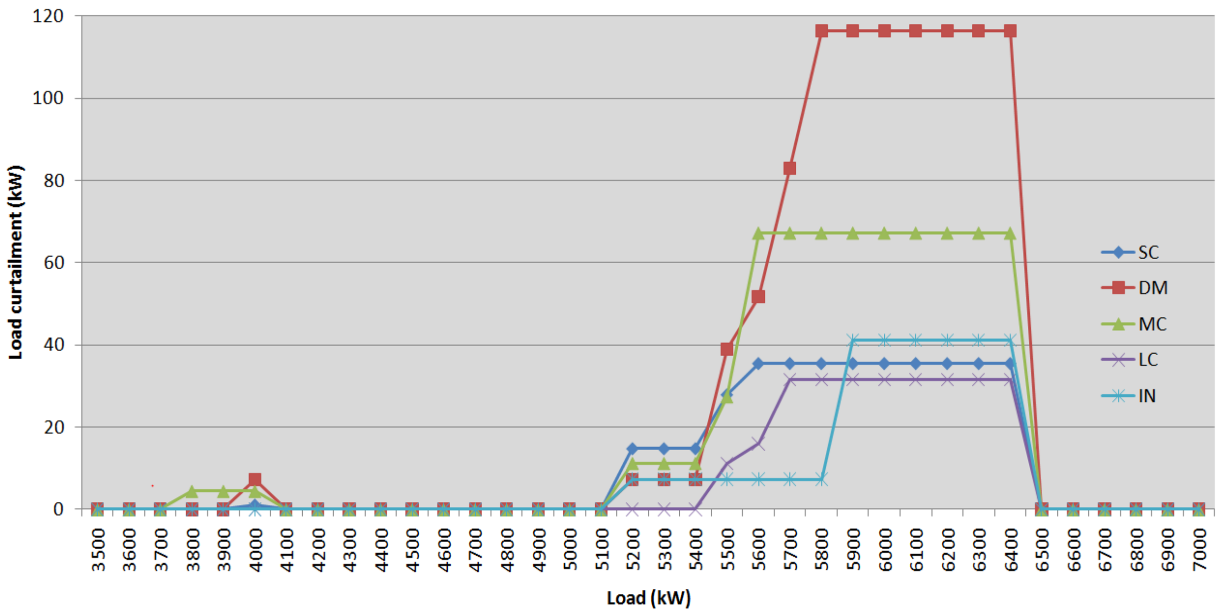

Figure B. 2. Load curtailment regarding the total load and grouped by consumer type, for curtailment step CutB.

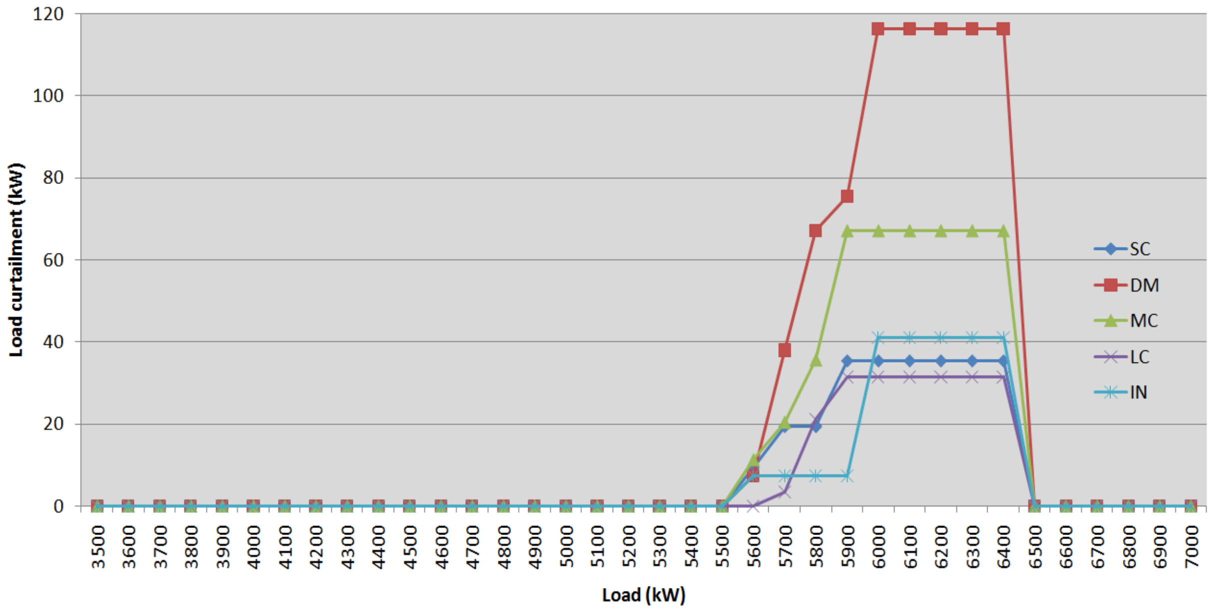

Figure B. 3. Load curtailment regarding the total load and grouped by consumer type, for curtailment step CutC.

Annex C. VPP_BID aggregation players

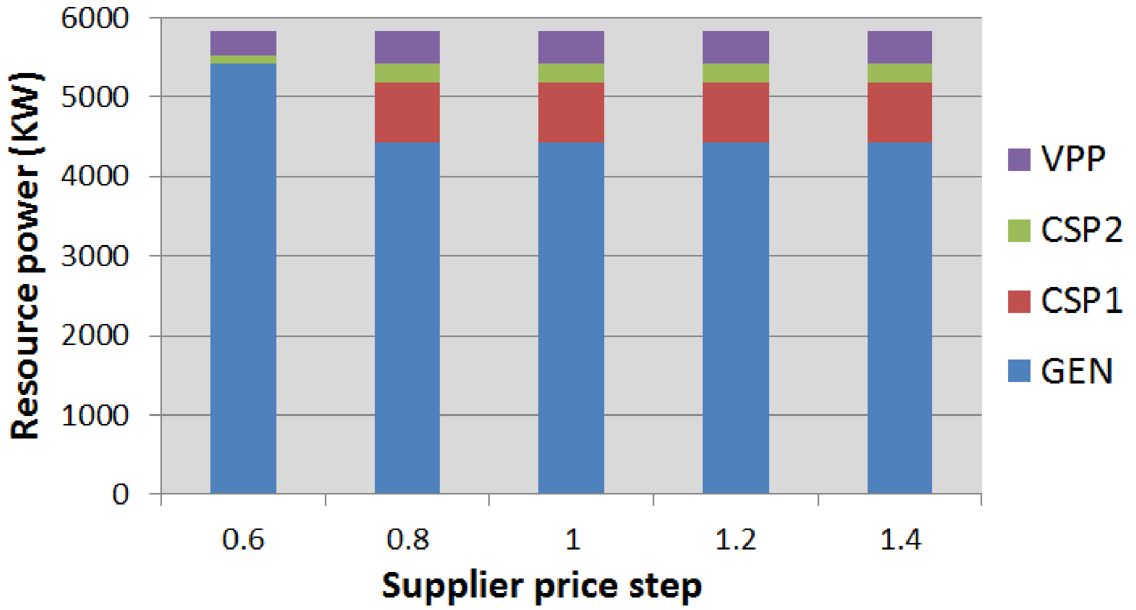

Figure C. 1. Resource use regarding the supplier price step, for energy product.

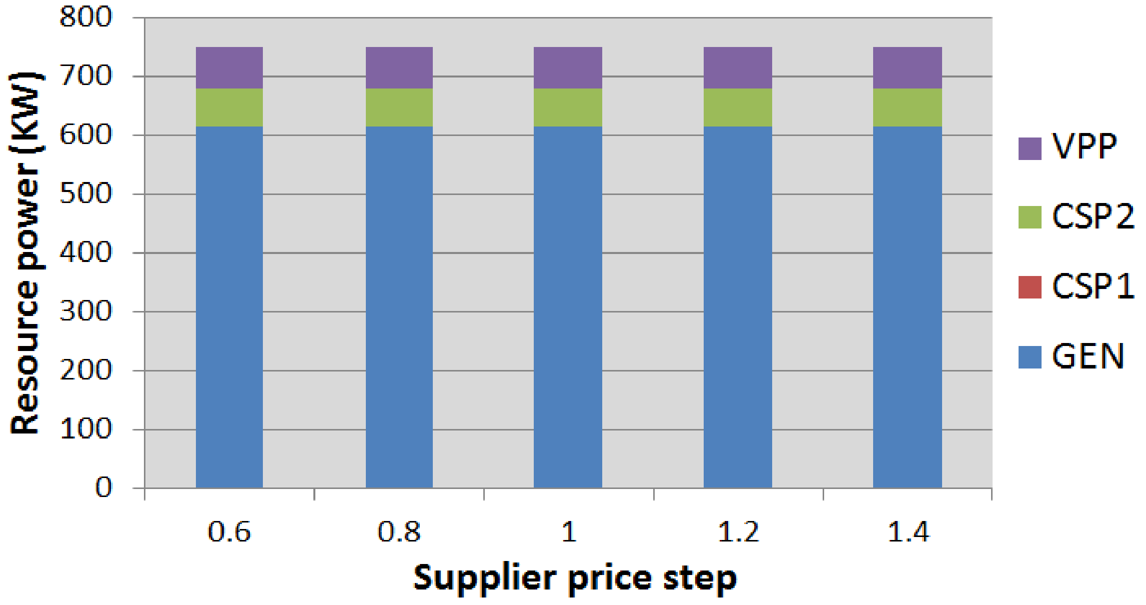

Figure C. 2. Resource use regarding the supplier price step, for reserve product.

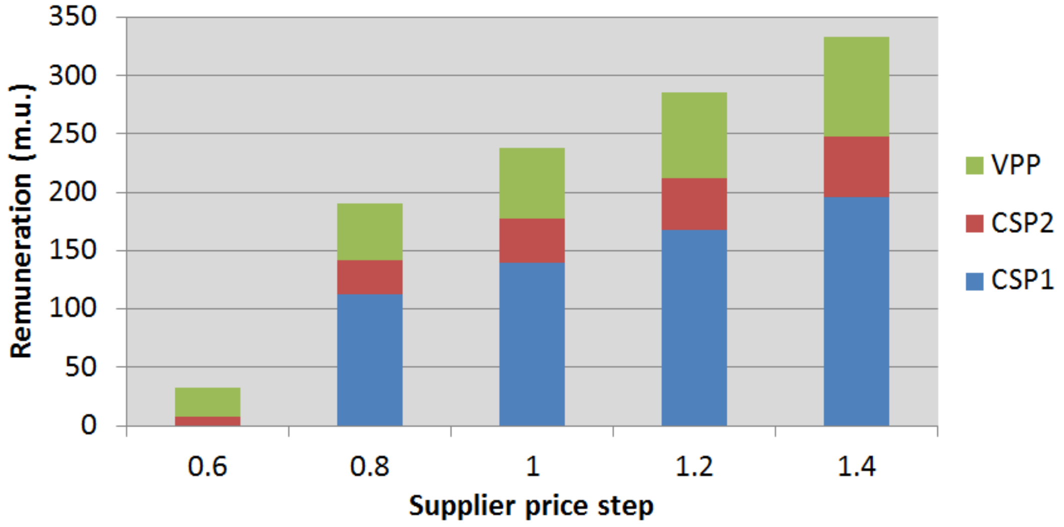

Figure C. 3. DR players' remuneration regarding the supplier price step for energy product.

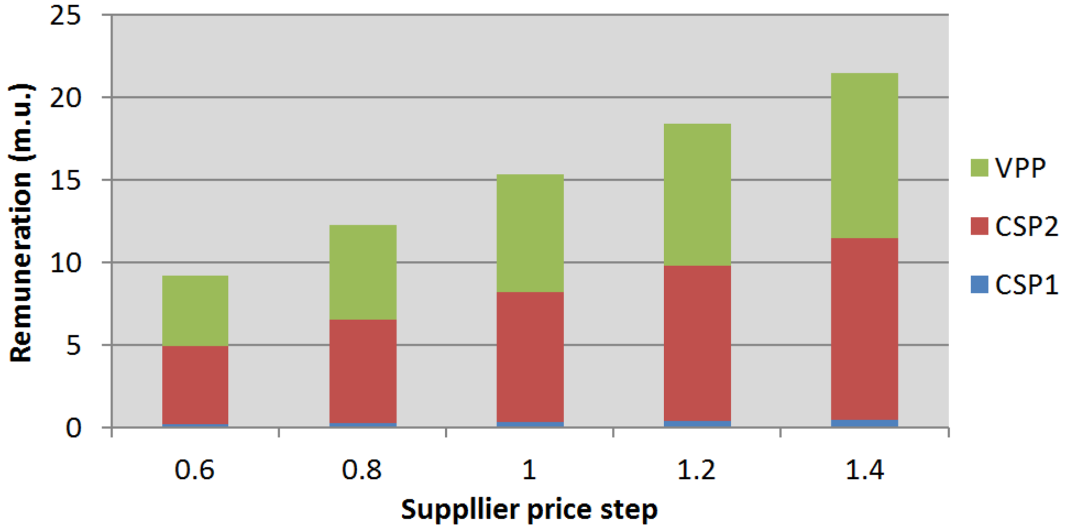

Figure C. 4. DR players' remuneration regarding the supplier price step for energy product.

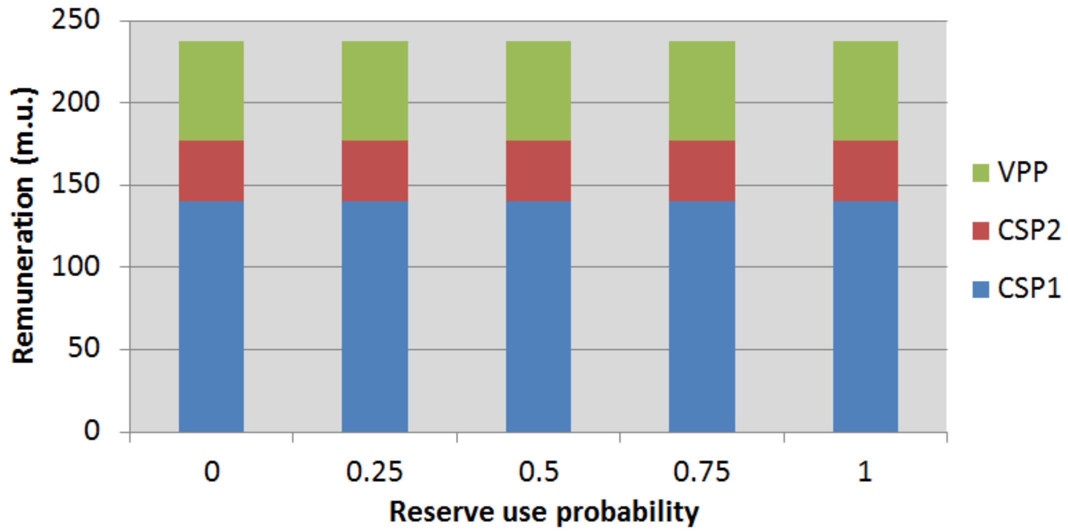

Figure C. 5. DR players' remuneration regarding the reserve probability of use, for energy product.

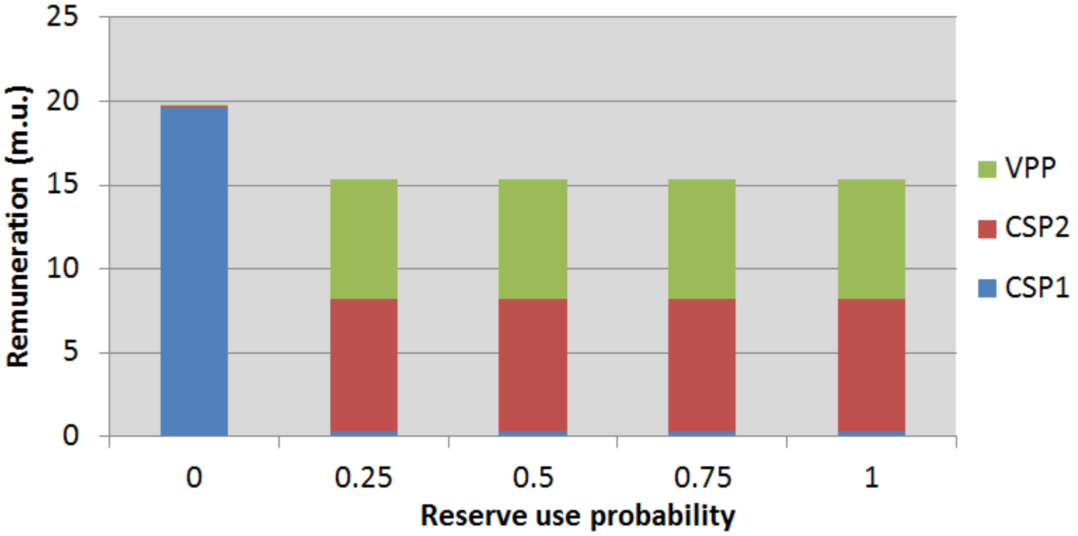

Figure C. 6. DR players' remuneration regarding the reserve probability of use, for reserve product.