MOBILE ENERGY RESOURCES

IN GRIDS OF ELECTRICITY

ACRONYM: MERGE

GRANT AGREEMENT: 241399

WP 2
TASK 2.4
DELIVERABLE D2.2

MARKET ISSUES

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SUMMARY

A massive introduction of electric vehicles (EV) in the society could have an important impact into the electric power systems, creating new challenges for the electricity sector in its structure and operation.

The conventional system expansion models and market ones will not be able to deal correctly with this integration of the electric vehicles in addition with other expected developments that will take place in Europe during the same period (integration of more renewable energy sources (RES), active demand, distributed generation, etc).

The objective of this report is to specify and explain the tools that are going to be used in order to evaluate the technical and economic impact of the electric vehicles into the medium-term system operation, for instance, system reliability, marginal costs, generation mix, CO_2 emissions.

The report has been divided in two parts, one for each tool developed. Each part explains the basics and the possible applications of their respective tool.

In order to see the effects of the presence of the electric vehicles in the system, three scenarios are examined:

- In Scenario 1 the market is simulated without EVs.
- In Scenario 2 two different levels of EV penetration are considered, while EVs act as simple loads: their owners simply define the timing and the amount of energy for charging; thus, the total load (households and EVs) grows.
- In Scenario 3 EVs can absorb or inject energy to the grid, depending on the price levels. By this way, load flexibility is achieved to a certain level.

TABLE OF CONTENTS

DELIVERABLE D2.2 – MARKET ISSUES

1 INTRODUCTION

Integration of EVs into the electrical grid will prove challenging not only for the operation of the grid, but also for the operation of the market, since EVs are seen both as a load and as a source of energy previously stored in their batteries. In order to assess the impact (technical and economical) to the market operation of different penetration levels of EVs, and the interaction of EVs with RES (analyzing the benefits and problems of this coexistence), a simulation tool is deemed necessary. Two different tools with different approaches have been developed to reach these objectives.

Such a simulation should take into account the fact that, autonomous individuals that are part of the electricity grid (e.g. consumers, EVs, distributed generation) act according to their notion of maximizing their personal profit. However, its individuals' decision inadvertently affects the optimal "state" of market equilibrium. The decisions of each individual are affected by the decisions of the other individuals because they are all part of the same market.

In order to compute the short-term system operation and evaluate the economic and technical impacts of the integration of EVs and other RES, mathematical programming and simulation is a powerful tool in order to evaluate the system operation.

In addition, in the attempt to re-produce and predict the actions of the "players" in such a complex environment, game theory has been proved to be a valuable ally.

In the following sections, a short introduction to the two tools developed is presented and then, the details of their application for the case of the EVs integration will be specified.

2 APPROACH

The first tool that is presented is the ROM Model (Reliability and Operation Model for Renewable Energy Sources). It uses the mathematical programming for optimizing (minimizing costs) the system in conjunction with a simulation process to evaluate the system in real time.

The ROM Model is able to compute reliability indices (e.g. LOLP, LOLE), marginal costs and operation results (e.g. different technologies output, emissions, primary energy surplus) resulting from the medium term system operation. Thus, by comparing results obtained with different penetration levels of EVs and RES, the impact of these technologies can be estimated.

The second tool uses the game theory as a way to solve the problem, studying the interaction of multiple players in competitive situation, trying to reach the equilibrium state at which all the players achieve the optimal gain.

PART I. ROM Model

3 MATHEMATICAL PROGRAMMING AND SIMULATION METHODOLOGIES

This section introduces the ROM Model, giving a brief overview over the structure and the characteristics of it.

3.1 Introduction

The ROM Model has been developed at the Instituto de Investigación Tecnológica (IIT), ICAI, Universidad Pontificia Comillas.

The first objective of the model is to determine technical and economic impact of the EVs and RES into the medium-term system operation, including reliability assessment.

3.2 Characteristics and structure of the model

In order to compute the short-term system operation and evaluate the EVs and other RES integration, the ROM tool follows a combined modelling approach whereby a daily optimization model [9] is followed by a sequential hourly simulation [12], with a resolution of one hour. This replicates the sequence of the markets and the decisions, reproducing the hierarchy and the chronology of the decision levels and allows representing that uncertainty is revealed over time (forecasting techniques become more accurate when the interest hour approaches). A chronological approach is used to sequentially evaluate the system operation for every day of a year. Decisions above this scope as the weekly scheduling of pumped storage hydro plants are done internally in the model by heuristic criteria. The management of hydro resources and seasonal pumped storage that exceeds the year time frame must be computed by another higher–level model and be taken as an input into the ROM. Monte Carlo simulation of many yearly scenarios is used to deal with the stochasticity of the demand and the intermittent generation.

As it will be shown in the next section, detailed operation constraints (minimum load, ramping rates…) are included into the daily unit commitment model. The hourly simulation is run afterwards to account for intermittent generation production errors and unit failures, and therefore revises the previous schedule. The differences among optimization and simulation decisions can be due to wind generation forecast errors and generation outages, and represent the value of the perfect Intermittent Generation IG forecast.

4 DESCRIPTION OF THE ROM MODEL

This section has the description of the two fundamental parts (optimization and simulation) of the model.

4.1 Formulation of the day-ahead Market Operation

In this section, the optimization model that is responsible for determining the initial daily program for the generators production is going to be described. This model calculates the daily economic dispatch, considering the demand and wind power generation forecasted one day in advance. Subsequently, these estimates may be altered by changes in the values of the random variables (electricity demand, intermittent generation, availability of the generators, etc.) that are taken into account by a simulation model that will be described in the next section.

The tables below show the main elements of the model: indexes, parameters and variables.

Table 1. Sets

Name	Meaning
p	Periods (hours)
g	Generators
t	Thermal units ($\{t\} \subset \{g\}$)
h	Hydro plants (reservoirs) ($\{h\} \subset \{g\}$)
b	Pumped storage hydro plants (reservoirs) ($\{b\} \subset \{h\}$)
i	Concentrated solar power (CSP) plants ($\{i\} \subset \{g\}$)

Table 2. Parameters

Name	Meaning	Unit
D_p	Demand for period p	MW
WG_p	Wind and other RES generation for period p	MW
UR_p, DR_p	Upward and downward reserve in period p	MW
$\overline{GP}_p^g$	Maximum output of generator g in period p	MW
RU^t, RD^t	Ramp-up and ramp-down of thermal unit t	MW/h
$\overline{GC}_p^h$	Maximum consumption of pumped storage hydro plant $h \in b$ in period p	MW
I_p^h	Inflows in reservoir h for period p	MWh

In_p^i	Irradiation in CSP plant i for period p	MWh
IRC^i, IRD^i	Charging and discharging ramp of storage of CSP plant i	MWh/h
URC, DRC	Upward and downward reserve deficiency cost	€/MWh
$NSEC$	Non-supplied energy cost	€/MWh
FC^t	Fixed cost of thermal unit t	€/h
VC^g	Variable cost of thermal unit g including fuel cost and O&M	€/MWh
SC^t	Start-up cost of thermal unit t	€

Table 3. Variables

Name	Meaning	Unit
$opcost$	Total system operation cost	€
nse_p	Non-supplied energy in period p	MW
sp_p	Energy spillage in period p	MW
$urdef_p, drdef_p$	Upward and downward reserve deficiency in period p	MW
st_p^t, sh_p^t	Start-up and shut-down of thermal unit t in period p	[0,1]
c_p^t	Commitment of thermal unit t in period p	[0,1]
ih_p^h	Indicator of pumping or generation of hydro plant h in period p	[0, 1]
gp_p^g	Output of generator g in period p	MW
gc_p^h	Consumption of pumped storage hydro plant $h \in b$ in period p	MW
r_p^h, s_p^h	Reservoir level and spillage of hydro reservoir h in period p	MWh
gur_p^g, gdr_p^g	Upward and downward power reserve of generator $g \notin b$ in period p	MW
pur_p^h, pdr_p^h	Upward and downward power reserve of pumped storage hydro plant $h \in b$ in period p	MW
ie_p^i, is_p^i	Energy stored and spilled in CSP plant i in period p	MWh
ic_p^i, id_p^i	Power output and power consumption of CSP plant i in period p	MW

4.1.1 Objective function

The operations costs minimization of the electric system is expressed as follows:

$$opcost = \sum_p \left[\begin{array}{l} \sum_t \left(FC^t c_p^t + SC_t st_p^t + VC^g gp_p^g \right) + \\ NSEC\, nse_p + URC\, urdef_p + DRC\, drdef_p \end{array} \right] \quad (1)$$

Model constraints are described in the following sections. Note that the duration of all periods is one hour and therefore the formulation becomes simplified.

4.1.2 Demand and reserve constraints

- The equation that controls the balance of generation and demand by the generation units for each period is (2). The set of generators g includes thermal units, hydro plants and CSP plants as well. The wind generation considers its forecasted production:

$$D_p - WG_p - nse_p + sp_p = \sum_g gp_p^g \quad \forall p \qquad \textbf{(3)}$$

- The total upward and downward reserve for each period p:

$$\left. \begin{array}{l} \sum_{g \notin b} gur_p^g + \sum_{h \in b} pur_p^h + urdef_p \geq UR_p \\ \sum_{g \notin b} gdr_p^g + \sum_{h \in b} pdr_p^h + drdef_p \geq DR_p \end{array} \right. \quad \forall p \qquad \textbf{(4)}$$

4.1.3 Thermal unit constraints

- The commitment, start-up and shut-down of thermal units is controlled by these variables, with the following logical relation. Only commitment variable needs to be defined as binary.

$$c_p^t - c_{p-1}^t = st_p^t - sh_p^t \quad \forall p,t \qquad \textbf{(5)}$$

- The output plus the power reserve of each thermal unit is bounded by the maximum output of the unit, given by the parameter $\overline{GP}_p^g$.

$$gp_p^g + gur_p^g \leq \overline{GP}_p^g \quad \forall p, g \in t \qquad \textbf{(6)}$$

- The generators could have a minimum time that, once the generator has been switched on (respectively switched off), it must be kept running (respectively stopped).The up and down ramps limit the variation of the thermal unit output including the up and down power reserves in consecutive hours:

$$\begin{aligned} &\left(gp_p^g + gur_p^g\right) - \left(gp_{p-1}^g - gdr_{p-1}^g\right) \le RU^g \\ &\left(gp_{p-1}^g + gur_{p-1}^g\right) - \left(gp_p^g - gdr_p^g\right) \le RD^g \end{aligned} \qquad \forall p, g \in t \qquad \textbf{(7)}$$

4.1.4 Hydro plant constraints

- The model considers and equation that ensures that if a unit is pumping, it cannot be generating at the same time.

$$\begin{aligned} &gp_p^h \le ih_p^h \overline{GP}_p^h \\ &gc_p^h \le \left(1 - ih_p^h\right) \overline{GC}_p^h \end{aligned} \qquad \forall p, h \qquad \textbf{(8)}$$

- The maximum output (pumping) of the hydro units is bounded by technical limitations of the unit.

$$gp_p^g + gur_p^g \le \overline{GP}_p^g \quad \forall p, g \in h \qquad \textbf{(9)}$$

- The account of the hydro reservoir is controlled by the following hourly constraint:

$$r_p^h - r_{p-1}^h = -gp_p^h + gc_p^h - s_p^h + I_p^h \quad \forall p, h \qquad \textbf{(10)}$$

4.1.5 CSP plant constraints

- The equation that controls the energy balance in the CSP plant:

$$In_p^i - gp_p^i - ic_p^i + id_p^i = 0 \quad \forall p, i \qquad \textbf{(11)}$$

- The balance of the CSP plant storage is given by the following equation:

$$ie_p^i - ie_{p-1}^i = ic_p^i - id_p^i - is_p^i \quad \forall p, i \qquad \textbf{(12)}$$

- The constraints in the charge and discharge of the CSP plants:

$$\begin{aligned} &ie_p^i - ie_{p-1}^i \le IRC^i \\ &ie_{p-1}^i - ie_p^i \le IRD^i \end{aligned} \qquad \forall p, i \qquad \textbf{(13)}$$

4.2 Real Time Simulation

The correction of the deviations identified previous to the hour 14 (this is the hour when the daily programming is sent to the System Operator [10]) of the day before the operation has been modelled in the optimization module. After the 14 h, the adjustments that have to be done in the commitment of the units, the program of the units and the level of the different loads of the system are computed by a simulation module. This module is divided in two steps:

- In the first step, the simulation module performs **corrections to the commitment specified by the daily optimization module**, applying them in the 24 h of the day before the operation (D-1). The Midnight is assumed to be the last time where the commitment decision of a group would allow this group to reach the ramping hours in the morning (7-12 am). These deviations could be produced by an error in the forecast of the intermittent generation or the failure of the generation units. The corresponding corrective actions are the commitment of new generation units or the shutting down of others, whose objective is to reduce the deviation into safe margins that can later be handled by the use of reserve (for instance reducing error to less than 1 GW).
- The second step deals with the **monitoring of each hour of the interest day and it takes the adequate decisions in order to correct the error** in the forecasting of the wind production, the demand or failure of the thermal units. Once the hour 24 of the day D-1 has gone by, these corrective actions cannot be the commitment or shutting down of any unit (except the fast peaking units). The actions that can be selected to achieve this objective are the use of the reserves, the commitment of the fast start-up peaking units and finally load shedding.

Table 4. Daily Operation chronological resume

Time	Action
Hour 14 of day D-1	Estimation of intermittent generation for each hour of day D (errors for 10 to 34 h in advance)
	Daily dispatch of day D using the optimization module
Hour 24 of day D-1	Estimation of the intermittent generation for each hour of day D (errors for 1 to 24 h in advance)
	Commitment (disconnection) correction of units related to the error estimation for peak (low consumption) periods
Each hour of day D	Knowledge of actual intermittent generation
	Selection of adequate decisions for forecast deviations correction according to priorities (as can be seen in Figure 1)
Last hour of day D	Data regarding the commitment of the different units, production and the reservoir level is stored to be used in the unit commitment of the next day

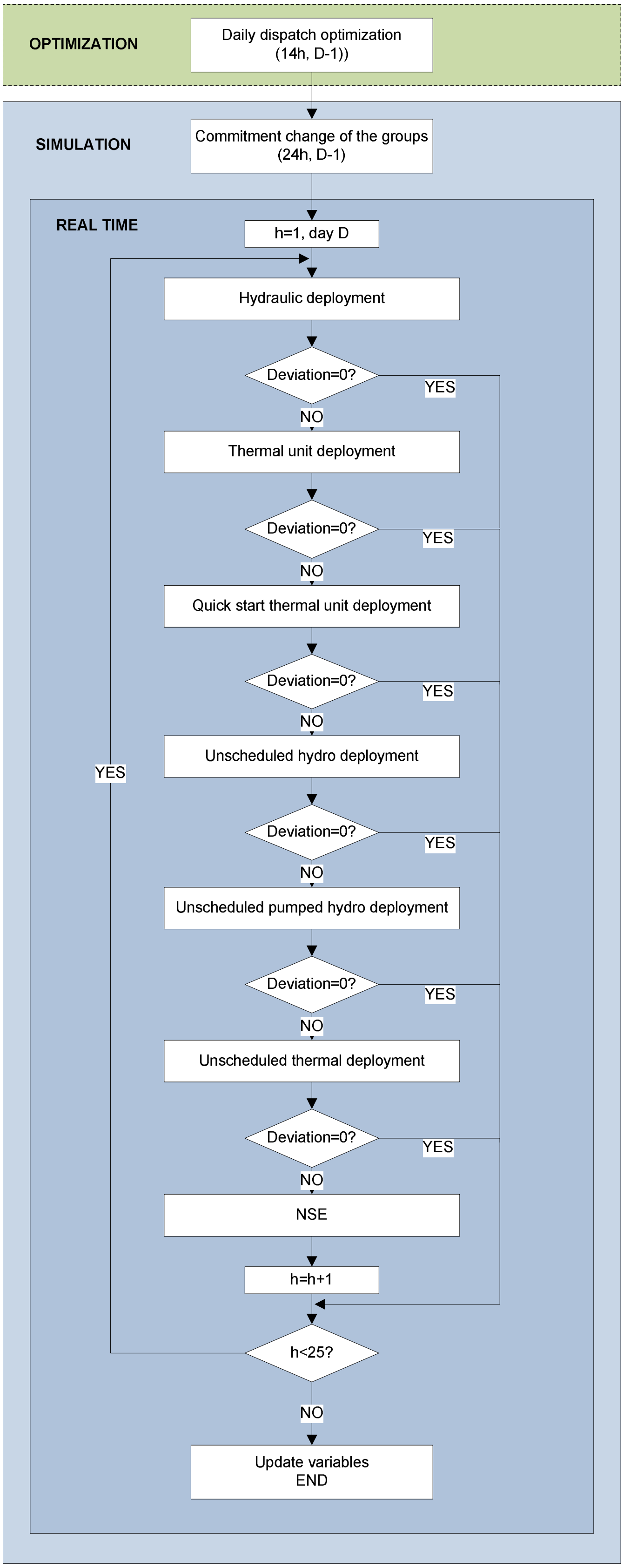

Figure 1. Simulation scheme

5 DEVELOPMENTS FOR THE CONSIDERATION OF THE EVs

This section describes the adaptations that have been done to the ROM Model in order to accomplish with the objectives of the MERGE project.

First of all, the new sets, parameters and variables that have been necessary to include the EV in the model are shown. Afterwards, the new constraints that are included in the model are described.

In order to model the EV behaviour two sets have been added: the type of EV (technical characteristics and traffic patterns) that can exist in the system (which are defined in tasks 1.5 [11] and 2.1 [6]) and the state in which these EVs can be.

The EV state can be: parked and connected to the grid (sc), parked and disconnected from the grid (su) and moving (sm).

These states make possible three different situations in the use of the batteries of the EVs, depending if the vehicle is connected, disconnected or moving:

- The connected ones can be charging/ discharging their batteries or be in a neutral state (neither charging nor discharging). It has to be considered that the charging and discharging process have different efficiencies.
- It is assumed that the disconnected vehicles, as has been mentioned previously, are parked and their batteries do not have losses.
- The moving EVs have a pattern of distance and time of the movement (in fact, the energy consumed) given by a parameter. The transformation of energy to mechanic movement has a different efficiency than the charging and discharging processes.

It has to be stressed that the model decides the best way to charge/discharge the batteries of the EVs in order to satisfy the needs of the users (use the EVs according to their usage pattern) and to improve the operation of the system. So when doing smart charging the system decides when and how much to either charge or discharge the EV or just not doing anything with the EV.

5.1 Adaptations in the formulation of the day-ahead Market Operation

This section will describe the new sets, parameters, variables and equations introduced in the model described in section 4 in order to include the characteristics and behaviour of the EV.

Table 5. New sets

Name	Meaning
e	Types of EV
s, s'	State of the EV (sc, su and sm)

Table 6. New parameters

Name	Meaning	Unit

$\overline{EC}^e_p, \overline{ED}^e_p$	Maximum power charged and discharged by EV e in the period p	MWh
$\underline{EE}^e, \overline{EE}^e$	Minimum and maximum energy charged by EV e	MWh
ERC^e, ERD^e	Battery charge and discharge ramp of EV e within a period	MWh/h
$EP^{e,s}_p$	Percentage of EVs of type e and in the state s for each period p	p.u.
$EPT^{e,s,s'}_p$	Percentage of EVs of type e and in the state s' that move to the state s for each period p	p.u.
$ET^{e,s}_p$	Use of the battery energy in transport of each type of EV e in each state s for each period p	MWh
$EEfGtB^e$	Grid to battery efficiency for each type of EV e	p.u.
$EEfBtG^e$	Battery to grid efficiency for each type of EV e	p.u.
$EEfBtW^e$	Battery to wheel efficiency for each type of EV e	p.u.

Table 7. New variables

Name	Meaning	Unit
$ee^{e,s}_p$	State of charge (SOC) of the battery of EV e at the end of period p in each state in state s	MWh
$ep^{e,s}_p, ec^{e,s}_p$	Generation and consumption of EV e in state s in period p	MW
eur^e_p, edr^e_p	Upward and downward power reserve available for EV e in period p	MW
$eurc^e_p, eurd^e_p, edrc^e_p, edrd^e_p$	Upward and downward power reserve of charging and discharging available for EV e in period p	MW
ch^e_p	EV e discharging or charging in period p	{0,1}

5.1.1 Objective function

The objective function of the optimization model is the same one than the model described in section 4. EVs affect the objective function indirectly, by demand and reserve constraints.

5.1.2 Demand and reserve constraints

- The equation that controls the balance of generation and demand for each period has to include the production and consumption of the EV:

$$D_p - WG_p - nse_p + sp_p = \sum_{g} gp_p^g + \sum_{e,s}\left(ep_p^{e,s} - ec_p^{e,s}\right) \quad \forall p \tag{14}$$

- Furthermore, the total upward and downward reserve for each period p also takes into consideration the contribution of the EV to the reserves:

$$\left.\begin{array}{l} \sum_{g \notin b} gur_p^g + \sum_{g \in b} pur_p^g + \sum_{e} eur_p^e + urdef_p \geq UR_p \\ \sum_{g \notin b} gdr_p^g + \sum_{g \in b} pdr_p^g + \sum_{e} edr_p^e + drdef_p \geq DR_p \end{array}\right. \quad \forall p \tag{15}$$

5.1.3 EVs constraints

- The battery energy inventory keeps track of the SOC at any period p each EV e and each state s as a function of the energy charged into the battery, the energy discharged from the battery and the SOC at the end of the previous hour.

$$ee_p^{e,s} - ee_{p\text{-}1}^{e,s} = ec_p^{e,s} EEfGtB^e - \frac{ep_p^{e,s}}{EEfBtG^e} - \frac{ET_p^{e,s}}{EEfBtW^e} + \sum_{s' \neq s} ee_{p\text{-}1}^{e,s'} EPT_{p\text{-}1}^{e,s,s'} \quad \forall p,e,s \tag{16}$$

- The logical constraints of the charge, discharge and the movement of the EVs e in the period p is as follows:

$$\begin{array}{ll} ec_p^{e,s} = 0 & \forall s \notin sc \\ ep_p^{e,s} = 0 & \forall s \notin sc \\ ET_p^{e,s} = 0 & \forall s \notin sm \end{array} \quad \forall p,e,s \tag{17}$$

- The maximum power that the EV e can charge and discharge in each state s for each period p is limited by the maximum charge and discharge of a individual battery times the number of EVs in that state, and taking into account the logical condition that an EV cannot charge and discharge at the same period:

$$\left.\begin{array}{l} ec_p^{e,s} \leq \left(1 - ch_p^e\right) \overline{EC}^e EP_p^{e,s} \\ ep_p^{e,s} \leq ch_p^e \overline{ED}^e EP_p^{e,s} \end{array}\right. \quad \forall p,e,s \tag{18}$$

- The maximum power the EVs e can consume and generate in each state s and for each period p is constrained by the amount of energy stored in the battery:

$$\begin{aligned} ec_p^{e,s} &\le EP_p^{e,s}\left(\overline{EE}^e - ee_p^{e,s}\right) \\ ep_p^{e,s} &\le EP_p^{e,s}\left(ee_p^{e,s} - \underline{EE}^e\right) \end{aligned} \qquad \forall p,e,s \quad \textbf{(19)}$$

- The charging and discharging ramps of the batteries the EV e (affect the battery, not the energy stored in it) have to perform in each state s and for each period p:

$$\begin{aligned} ec_p^{e,s} - ec_{p\text{-}1}^{e,s} &\le RC^e \\ ep_{p\text{-}1}^{e,s} - ep_p^{e,s} &\le RD^e \end{aligned} \qquad \forall p,e,s \qquad \textbf{(20)}$$

- The provision of battery energy for the mobilization of power reserves. If EVs e are providing (up and down) power reserves in period p some energy has to be kept in the battery in case this energy will be actually required by the system:

$$\begin{aligned} ee_p^{e,s} &\ge \underline{EE}^e + \sum_{p'\le p}\left(\frac{eurd_{p'}^e}{EEfBtG^e} + eurc_{p'}^e EEfGtB^e\right) \\ ee_p^{e,s} &\le \overline{EE}^e - \sum_{p'\le p}\left(\frac{edrd_{p'}^e}{EEfBtW^e} + edrc_{p'}^e EEfGtB^e\right) \end{aligned} \qquad \forall p,e,s \qquad \textbf{(21)}$$

- The upward and downward power reserve of an EV e in period p is the amount of upward and downward power reserve of charging and discharging available for EV e in period p:

$$\begin{aligned} eur_p^e &= eurc_p^e + eurd_p^e \\ edr_p^e &= edrc_p^e + edrd_p^e \end{aligned} \qquad \forall p,e \qquad \textbf{(22)}$$

- The maximum amount of power that can be provided to the upward and downward power reserves for an EV e in period p:

$$\begin{aligned} eur_p^e &\le EP_p^{e,s}\left(\overline{EC}_p^e + \overline{ED}_p^e\right) \\ edr_p^e &\le EP_p^{e,s}\left(\overline{EC}_p^e + \overline{ED}_p^e\right) \end{aligned} \qquad \forall p,e,s \in sc \qquad \textbf{(23)}$$

6 ROM MODEL RESULTS

In this section, a preliminary analysis has been carried out to give a quick show of the type of results that could be obtained by the ROM.

In order to examine the influence in the system and the market of the EVs, three scenarios were considered:

Scenario 1: there is no existence of EVs.

Scenario 2: EVs are added acting only as a load.

Scenario 3: as in Scenario 2, considering the extra capability of the EVs to offer energy to the grid.

For the cases where EVs are present, the penetration level considered is as much as EVs as the 25% of the peak demand.

The technical characteristics of the type of EV considered are shown in Table 8, and their use pattern is similar to Figure 9.

Table 8. Technical characteristics of the EV considered

Capacity of the batteries	24 kWh
Battery to wheel efficiency	0.15 kWh/km
Charge and discharge efficiency	89.44 %
Charge and discharge rate	3.43 kWh/h
Range	160 km

The generation results for the different cases simulated are shown in Table 9 and Table 10.

Table 9. Energy sources distribution without EV

% of peak demand	**0%**	
Source	**GWh**	**%**
Nuclear	16466	35,8%
Coal	18832	40,9%
Oil	1545	3,4%
Hydro	6030	13,1%
Wind	3128	6,8%
OtherRES	0	0,0%
BEV	0	0,0%

Table 10. Energy sources distribution with EV

% of peak demand	**25%**			
	Smart		**No V2G**	
Source	**GWh**	**%**	**GWh**	**%**
Nuclear	16466	35,8%	16466	35,8%
Coal	19985	43,5%	19467	42,3%
Oil	1273	2,8%	1567	3,4%

Hydro	6056	13,2%	6045	13,1%
Wind	3128	6,8%	3128	6,8%
OtherRES	0	0,0%	0	0,0%
BEV	890	1,9%	0	0,0%

The marginal price of the system and the Non-Served Energy (NSE) for the different cases of study are shown in Table 11 and Table 12.

Table 11. Marginal price and NSE without EV

% peak demand	NSE		Cost
	GWh	%	€/MWh
0%	2,7	0,0%	62

Table 12. Marginal price and NSE with EV

% peak demand	No V2G			Smart		
	NSE		Cost	NSE		Cost
	GWh	%	€/MWh	GWh	%	€/MWh
25%	2,7	0,0%	64	0,6	0,0%	56

A comparison of the prices between the different case studies, is presented in the Figure 2.

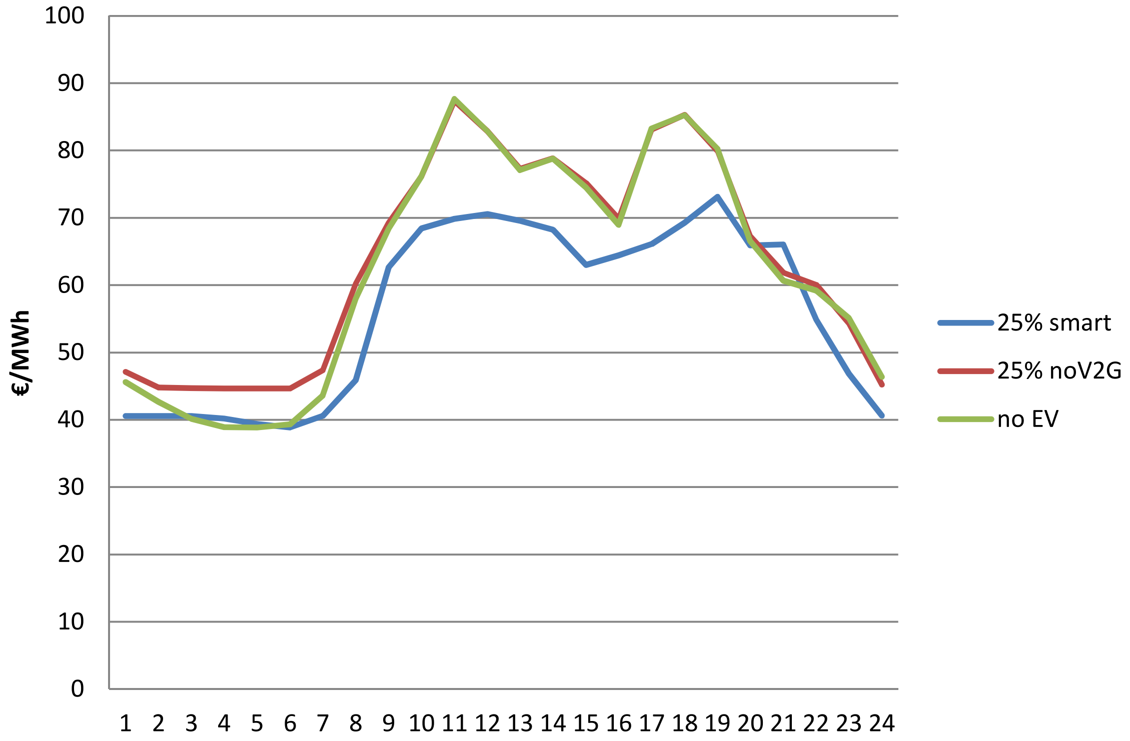

Figure 2. Marginal price for the study cases.

The previews results given in Table 11 and Table 12 show that the introduction of EVs, that are able to introduce energy into the system, improve its reliability (NSE is reduced almost a 78%) and reduce the costs of energy (almost a 10%). Figure 2 shows a graphical view of the evolution of the cost during a day, so that it can be appreciated the major reduction of cost is during the peak hours.

PART II. Game theory model

7 GAME THEORY METHODOLOGY

Game theory is a branch of applied mathematics that studies the interaction of multiple players in competitive situations. Its goal is the determination of the equilibrium state at which the optimal gain for each individual is achieved. More specifically, the theory of non-cooperative games studies the behaviour of agents in any situation where each agent's optimal choice may depend on his forecast of the choices of his opponents [1].

Various categories of games exist depending on the assumptions regarding the timing of the game; the knowledge associated with the payoff functions; and last but not least the knowledge regarding the sequence of the previously made choices. More specifically, the games can be categorized as follows:

- Static/dynamic games: the players choose actions either simultaneously or consecutively.
- Complete/incomplete information: each player’s payoff function is common knowledge among all the players/at least one player is uncertain about another player’s payoff function.
- Perfect/imperfect information (defined only for dynamic games): at each move in the game the player with the move knows or does not know the full history of the game thus far [2].

7.1 Static games

One of the most fundamental definitions in game theory is that of the Nash equilibrium which applies to *static games*. In the n-player normal-form game $G=\{S_1,\ldots,S_n;u_1,\ldots u_n\}$ (where $S_1,\ldots,S_n$ are the players’ strategy spaces and $u_1,\ldots,u_n$ are their payoff functions), the strategies $\left(s_1^*,\ldots,s_n^*\right)$ are a *Nash equilibrium* if, for each player i, s_i^* is player i’s best response to the strategies specified for the n-1 other players, $\left(s_1^*,\ldots,s_{i-1}^*,s_{i+1}^*,\ldots s_n^*\right)$:

$$u_i\left(s_1^*,\ldots,s_{i-1}^*,s_i^*,s_{i+1}^*,\ldots s_n^*\right)\geq u_i\left(s_1^*,\ldots,s_{i-1}^*,s_i,s_{i+1}^*,\ldots s_n^*\right)$$

for every feasible strategy s_i in S_i; that is, s_i^* solves

$$\max_{s_i\in S_i} u_i\left(s_1^*,\ldots,s_{i-1}^*,s_i^*,s_{i+1}^*,\ldots s_n^*\right)$$

Such a game-theoretic problem is solved by what is called *iterated elimination of strictly dominated strategies*. Firstly, it is necessary to define what a strictly dominated strategy is:

In the normal-form game $G=\{S_1,\ldots,S_n;u_1,\ldots u_n\}$, let s_i' and s_i'' be feasible strategies for player I (i.e., s_i' and s_i'' are members of S_i). Strategy s_i' is strictly dominated by strategy s_i'' if for each feasible combination of the other player's strategies, i's payoff from playing s_i' is strictly less that i's payoff from playing s_i'':

$$u_i\left(s_1,...,s_{i-1},s_i',s_{i+1},...s_n\right) < u_i\left(s_1,...,s_{i-1},s_i'',s_{i+1},...s_n\right)$$

for each $\left(s_1,...,s_{i-1},s_{i+1},...s_n\right)$ that can be constructed from the other players' strategy spaces $S_1,\dots,S_{i-1},S_{i+1},\dots,S_n$.

Rational players do not play strictly dominated strategies. Assuming that it is a common knowledge that all the players are rational, it is to be expected that in any case the strategies of the players will be such that the Nash equilibrium will be reached.

7.2 Dynamic games

For the case of *dynamic games* of complete and perfect information the state of equilibrium is no longer the Nash equilibrium; the *backwards-induction outcome* directly refers to the fact that the play is now sequential. In such a game the timing is as follows:

1) Player 1 chooses an action a_1 from the feasible set A_1.
2) Player 2 observes a_1 and then chooses an action a_2 from the feasible set A_2.
3) Payoffs are $u_1(a_1, a_2)$ and $u_2(a_1, a_2)$.

We solve the previously described game using *backwards induction*. At the second stage of the game, player 2 will solve the following problem, given the action a_1 previously chosen by player 1:

$$\max_{a_2 \in A_2} u_2\left(a_1,a_2\right)$$

It is assumed that for each a_1 in A_1, player 2's optimization problem has a unique solution, denoted by $R_2\left(a_1\right)$. This is player 2's best response to player 1's action. Since player 1 can solve player 2's problem as well as player 2 can, player 1 should anticipate player 2's reaction to each action a_1 that player 1 might take, so player 1's problem at the first stage amounts to:

$$\max_{a_1 \in A_1} u_1\left(a_1,R_2\left(a_1\right)\right)$$

It is assumed that this optimization problem for player 1 also has a unique solution, denoted by a_1^*. $\left(a_1^*,R_2\left(a_1^*\right)\right)$ is the backwards-induction outcome of the game.

8 DESCRIPTION OF THE GAME THEORY MODEL

As will become clear later on, when the rules of the game will be defined, the most appropriate class of games for the task at hand is the dynamic game of complete and perfect information, while the solution of such a game is determined as the backwards-induction outcome.

In order to define the game, it is necessary to define the following:

1) The players
2) The rules of the game
3) The payoff functions of each player

8.1 The players

For the case of the integration of EVs and their affect in the operation of the retail market, the following players are defined:

- Household consumers
- Distributed generation units (DG)
- EVs
- Aggregator

8.2 The rules of the game

In our dynamic game of complete and perfect information the timing is as follows:

1) The aggregator chooses price levels for buying and selling electric energy for the next hour.
2) According to these prices, household consumers select their load level, DG units select their production levels, while EVs choose whether to absorb or give electricity to the grid depending on the state of charge of the batteries.
3) At the final step, the payoff of each player is calculated.

Figure 3 depicts the game previously described in its extensive form representation. This procedure is repeated consecutively for each hour of one day at which point the payoff of each participant is settled according to the choices made by each and every one of them.

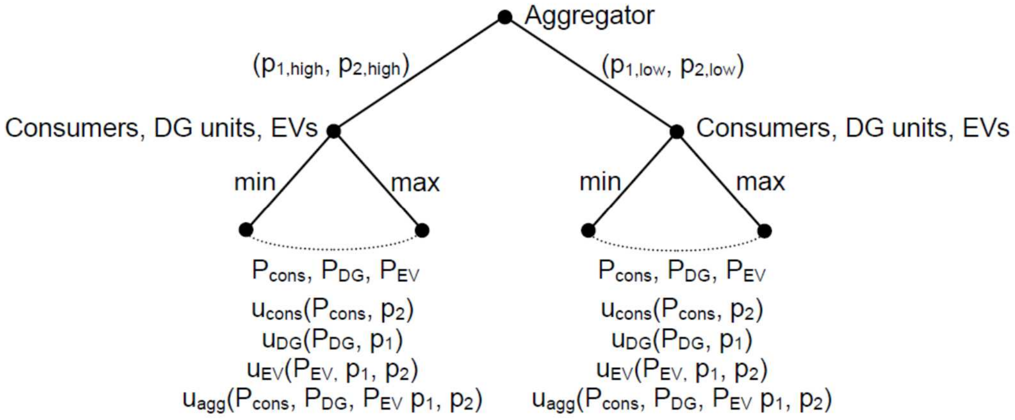

Figure 3: Extensive form representation of the game

As game theory suggests, each player's predicted strategy must be the best response to the predicted strategies of the other players (that is, each participant chooses the strategy that maximizes his or her payoff). Such a prediction is called strategically stable of self-enforcing, because no single player wants to deviate from his or her predicted strategy. In order to determine each player's optimal strategy, backwards-induction is applied as follows:

1) t =24
2) For all possible strategies of the aggregator s_i^t , i = 1,…,N, the optimal response of each player is computed ($P_{con,i}^t\left(s_i^t\right)$, $P_{DG,i}^t\left(s_i^t\right)$, $P_{EV,i}^t\left(s_i^t\right)$).
3) For each combination of strategies the payoff of each player is calculated.
4) Selection of the optimal combination for the tth hour is done by maximizing the payoff of the aggregator.
5) t = t-1
6) If $t \geq 1$ return to step 2.
7) End.

Figure 4 gives an overview of the above described procedure.

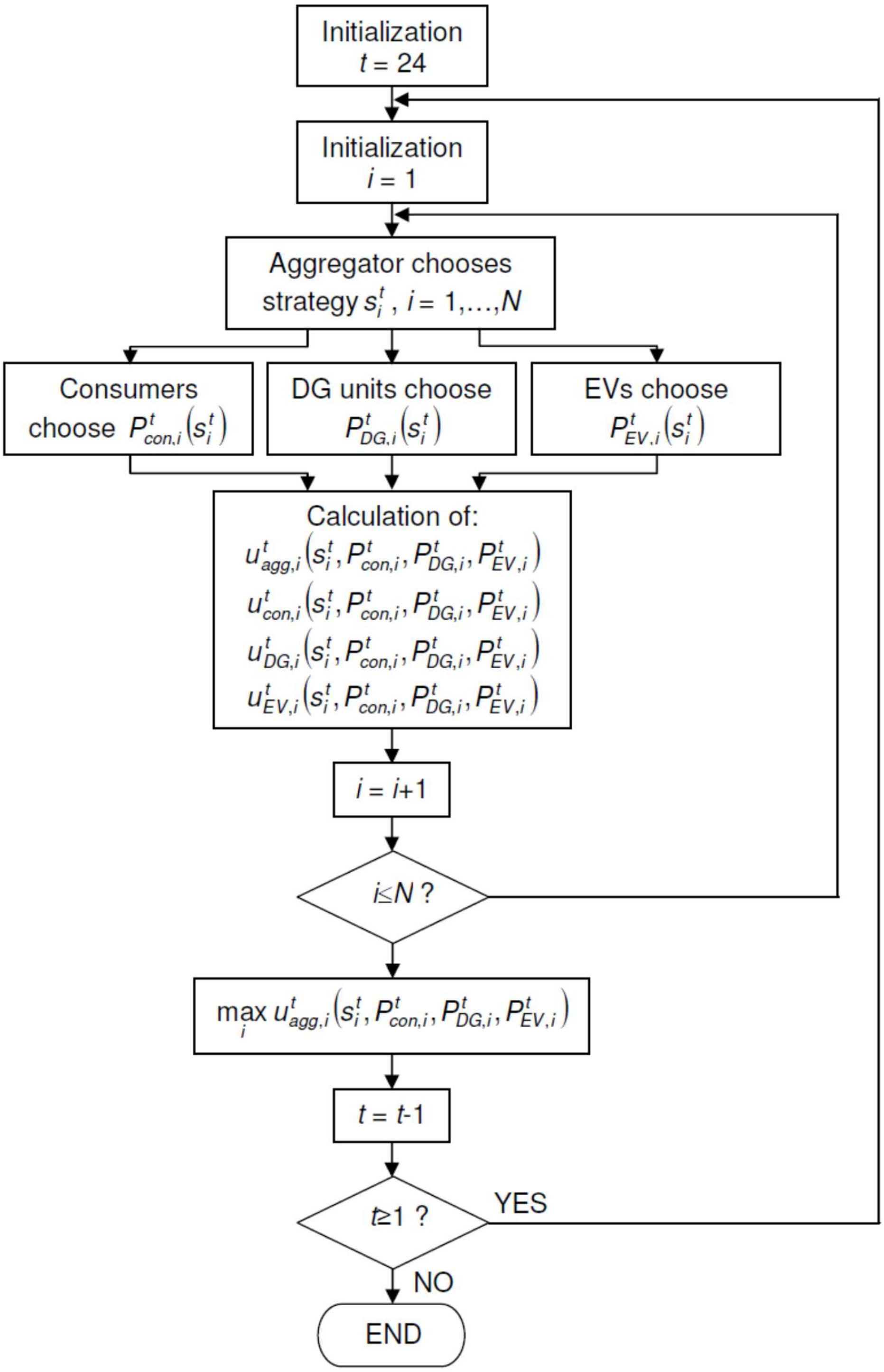

Figure 4: Flow chart of the procedure for determining the optimal strategies of each participant, using the backwards induction method

8.3 The payoff function of each player

8.3.1 Household consumers

Household consumers select their consumption level (which is their strategy space) according to the price announced by the aggregator. In order to describe/model that kind of behaviour, the demand curve is the most appropriate. Such a curve depicts the relationship between the amount of electricity and the price the consumers are willing to pay for it. Ideally such a curve is as the one presented in Figure 5.

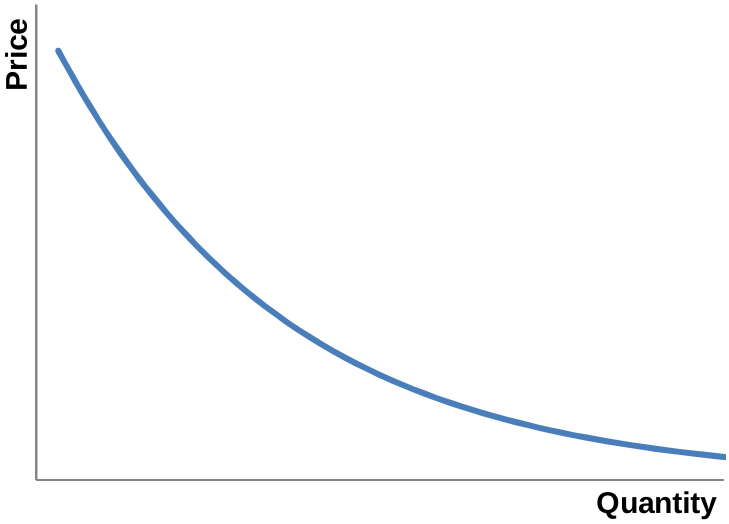

Figure 5: Demand curve describing the consumer behavior.

For the sake of simplification, the demand curve is approximated by a linear function of the form Quantity = a – b·Price. In fact the inverse demand curve is being used: Price = a – b· Quantity that describes the linear part of the graph in Figure 6. Two priority levels were considered for the load: high and low priority. The first category includes the refrigerator and lighting, which are inflexible, while the rest of the loads are characterized as low-priority, and can be influenced by the price levels. The linear part of the graph is parameterized as follows:

$$p(P_{con}) = p_m \left(1 - \frac{1}{\varepsilon_m}\right) + \frac{p_m}{P_m \cdot \varepsilon_m} \cdot P_{con}$$

where ε_m: is the price elasticity of demand and $(p_m, P_m) \in p(P_{con})$ (see Table 13).

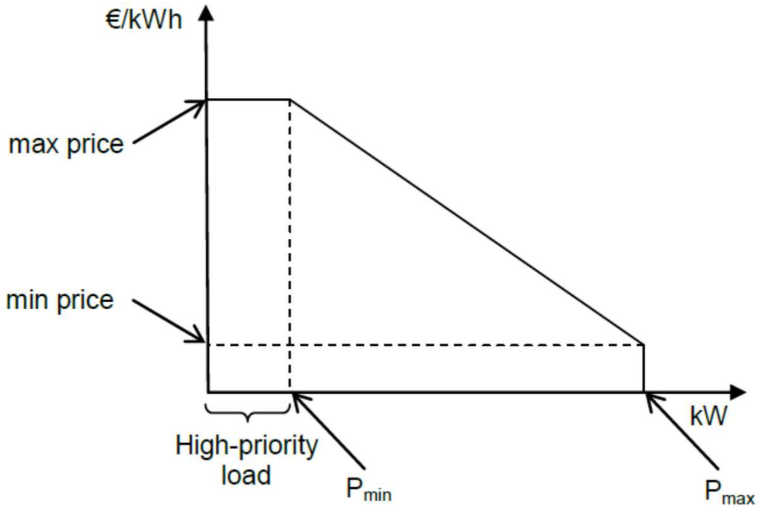

Figure 6: Simplified demand curve describing the consumer behavior

Table 13: Parameters of the inverse demand curve of the household consumers

ε_m	p_m (€/kWh)[1]	P_m (kW)[1]	a	b
-1.2	0.1676	0.428	0.307	-0.326

Parameters P_{min} and P_{max} vary throughout the day: P_{min} is equal to the sum of the refrigeration and lighting load (the last one is considered to be a high priority load only after the sunset and before the sunrise), while P_{max} is the maximum load to be served at each hour of the day, as shown in Figure 7. This figure shows accumulated load curves for a typical European household for a typical week day of the year (in Watts), which were put to use in order to derive P_{min} and P_{max} as described previously [3].

Parameters (p_m, P_m) derive as follows: according to the load curve of Figure 7 it is concluded that the annual consumption of the typical European household is approximately 2.700kWh. Therefore, the specific household belongs to Band DC (which includes consumers with annual consumption between 2.500kWh and 5.000kWh), according to the categorization established by Eurostat [4]. For this consumption Band the European average for the half-yearly prices during the 1st semester of 2010 is 0.1676 €/kWh, while the whole Band is considered to be represented by the mean value (3.750kWh per annum, which is translated to 0.428kW average load per hour).

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[1] Source of data: Eurostat

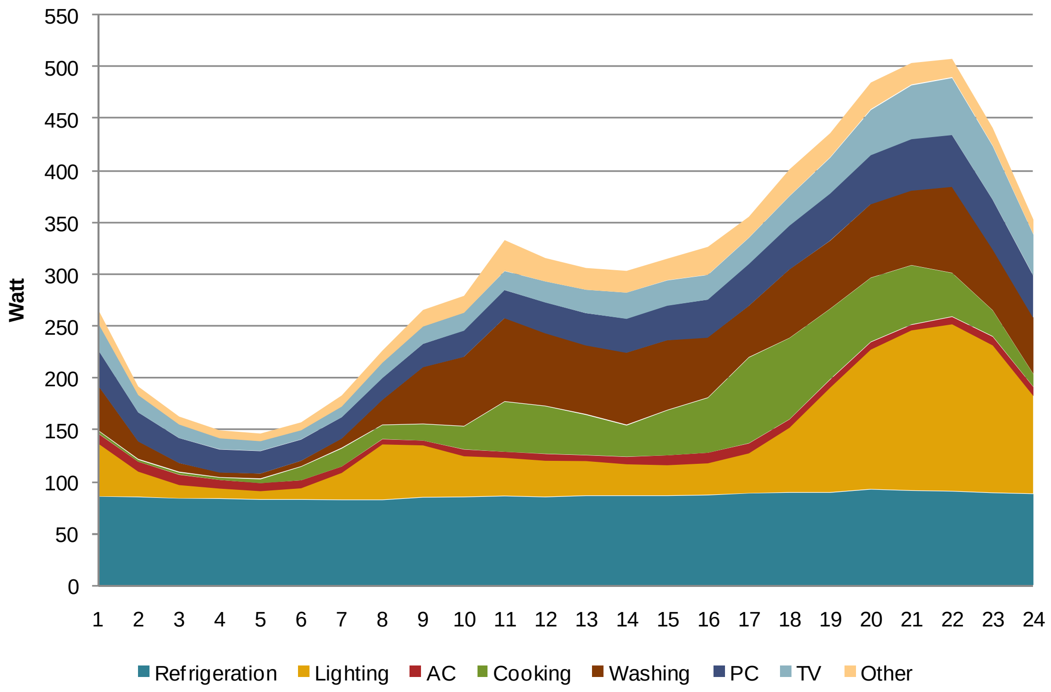

Figure 7: Accumulated load curves for a typical European household for a typical week day of the year

For a given price (p_1) announced by the aggregator the optimal response of the consumer (P_{con}) derives directly from the inverse demand curve (see Figure 8). In that case, the payoff for the consumer (more precisely, the utility the consumer acquires from using the specific amount of energy purchased at price p_1, the consumer surplus) is the area marked with blue in Figure 8.

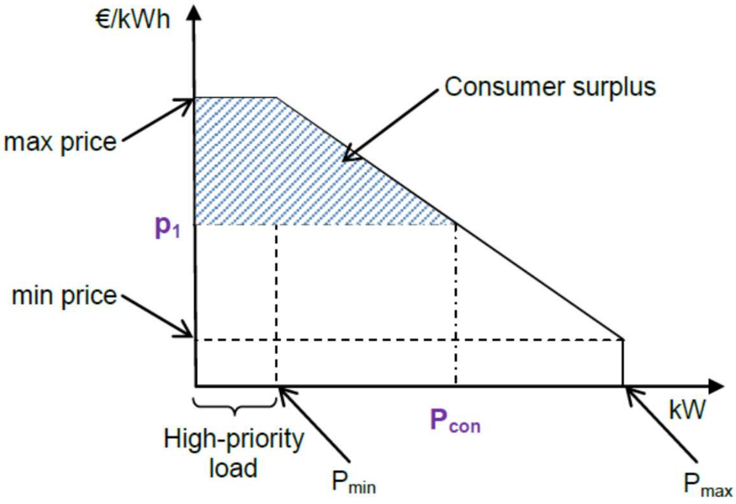

Figure 8: Inverse demand curve and payoff of the consumer

8.3.2 Distributed generation units (DG)

Microturbines select their production level (strategy space) according to the price announced by the aggregator. For our modelling, microturbines that use natural gas as fuel have been considered as distributed generation units. For the optimization of the production of the microturbine, only the variable costs have been taken into account.

Thus, the cost function describing the microturbine is:

$$p = A \cdot P_{DG}^2 + B \cdot P_{DG} + C$$

For a given price (p_2) announced by the aggregator, DG units solve the following problem, in order to determine the optimal production level:

$$\max\left\{p_2 \cdot P_{DG} - \left(A \cdot P_{DG}^2 + B \cdot P_{DG} + C\right)\right\} \Rightarrow P_{DG} = \frac{p_2 - B}{2 \cdot A}$$

Naturally the optimal power production of the DG unit is not independent from the production during the previous hour. The ramp rate as well as the technical minimum of the unit poses two restrictions, which are by no means negligible and are properly taken into account.

8.3.3 EVs

EVs can act either as a load or as production. They are, therefore modelled in a different way depending on the operation mode. In any case, a set of parameters needs to be defined:

1) The capacity of the batteries (in kWh)
2) The average charging time (in h)
3) The efficiency (in kWh/km)
4) The range (in km)
5) The charge rate (in kWh/h)
6) The charge and discharge efficiency (in %)
7) The availability of the vehicle (1 when the vehicle is connected to the grid, 0 otherwise).

Parameters 1-6 depend on the vehicle, while parameter 7 depends solely on the behaviour of the driver. Figure 9 presents the kilometers driven (per hour of the day) as a percentage of the total kilometers on a weekly basis [5]. Such a diagram allows us to define the hours of the day when the vehicle will be in movement (mainly 8:00-9:00 in the morning and 17:00-18:00 in the afternoon).

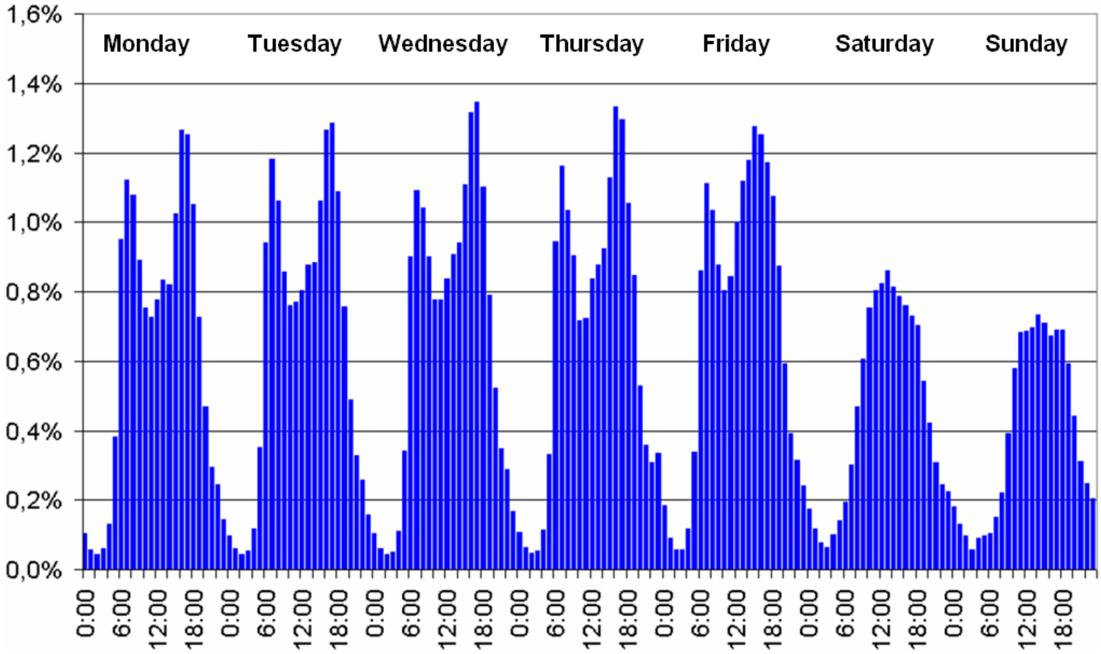

Figure 9: Kilometers driven (per hour of the day) as a percentage of the total kilometers on a weekly basis

Taking into account the fact that the owner of an EV aims at maximizing his personal comfort level, it is only logical to assume that while the vehicle can inject energy to the grid, the state-of-charge (SOC) of the batteries should be such that at any time the owner can perform his tasks without having to relinquish any of the activities that depend on his vehicle. This minimum SOC can be named mobility comfort level and is calculated by considering an average range of the journeys performed in a day. According to [6] for an EV with 160km range, 68.4% of all weekday journeys are 60km (return) or less. Thus, the minimum SOC will be 60km/160km = 37.5%.

For simulating the behaviour of the EVs, maximum and minimum values for the SOC per hour are defined. While the EV is available, the SOC lies between 100% and the mobility comfort level as defined earlier. While the EV is on the move, discharging of the batteries takes place and the SOC lies between 100%-km/range and (mobility comfort level)-km/range. In the worst case scenario, in which after the completion of the journey the SOC is lower than the minimum allowed, the EV will not be considered available directly after the journey, since the batteries will need to be recharged until the minimum allowed SOC is reached (mobility comfort level). The distance travelled affects the SOC of the batteries. As a result the EV might not be available for discharging, even though it is grid-connected. Thus, the availability of the vehicle for the hours directly after the journey is modified in a proper manner, to take into account the charging of the vehicle. Figure 10 depicts the results of previously described procedure applied for an EV with the following characteristics: range = 160km, efficiency = 0.15kWh/km, charge rate = 3.43 kWh/h, charge efficiency = discharge efficiency = 89.44%, battery capacity = 24 kWh, which performs two journeys of 30km each during one day.

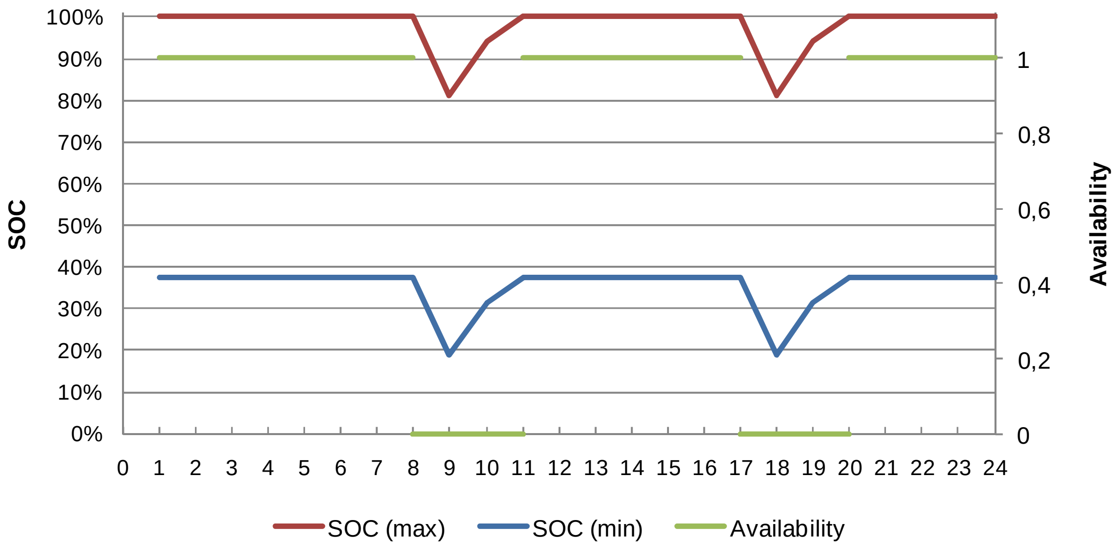

Figure 10: Minimum and maximum allowable SOC and availability of the EV

Having already defined the values that envelope the SOC of the batteries, during the hours of availability, EVs choose the action that maximizes their payoff among the following:

1) Discharging: the payoff for the EVs is merely the product of the energy supplied times the price offered by the aggregator for buying that amount of energy.
2) Charging: the payoff for the EVs is calculated in a similar manner as for the consumers.

Every hour that the EV is available, the choice whether to charge or to discharge depends on a simple comparison between the two payoffs achieved by the two different states.

8.3.4 Aggregator

As already mentioned, the aggregator chooses the prices at which he sells (p_1) and buys (p_2) electricity (strategy space). These prices are directly affected by the price at which the aggregator purchases the electricity from the wholesale market. However, he can follow two strategies: either low prices, or high prices. Depending on his forecast regarding the loads he has to serve, he chooses a different strategy: for the hours when the load is very high (low), p_1 as well as p_2 are high (low) in order to achieve lower (higher) demand levels and higher (lower) production levels (Figure 11).

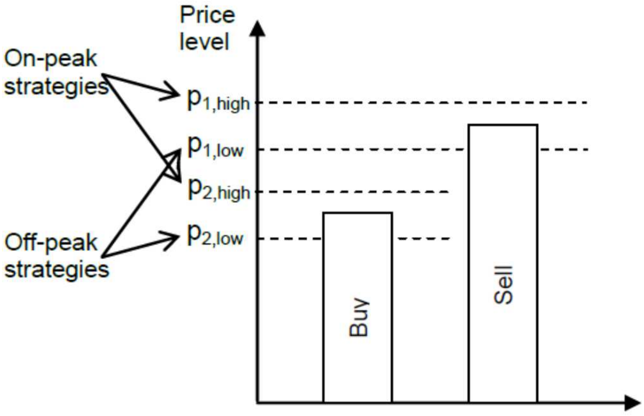

Figure 11: Off-peak and on-peak strategies followed by the aggregator

In order for the simulation to be as close to reality as possible, for $p_{2,low}$ real wholesale market data have been used (see paragraph 10.1.4, Figure 12) made available by the Hellenic TSO [7]. The other three price levels are derived as follows:

$p_{1,low} = 1.2 \cdot p_{2,low}$

$p_{2,high} = f(p_{2,low})$[2]

$p_{1,high} = 1.2 \cdot p_{2,high}$

The payoff function of the aggregator depends on whether the EVs charge, discharge or do nothing:

- EVs charge

$u_{agg} = p_1 \cdot (P_{con} + P_{EV}) - p_2 \cdot P_{DG} - p_{wholesale} \cdot (P_{con} + P_{EV} - P_{DG}) - p_{fine} \cdot (P_{con,total} - P_{con})$

If $P_{con} + P_{EV} - P_{DG} > 0$, $p_{wholesale}$ is the price at which the aggregator buys electricity from the wholesale market.

If $P_{con} + P_{EV} - P_{DG} < 0$, $p_{wholesale}$ is the price at which the aggregator sells electricity to the wholesale market.

- EVs discharge

$u_{agg} = p_1 \cdot P_{con} - p_2 \cdot (P_{DG} + P_{EV}) - p_{wholesale} \cdot (P_{con} + P_{EV} - P_{DG}) - p_{fine} \cdot (P_{con,total} - P_{con})$

- EVs do nothing

$u_{agg} = p_1 \cdot P_{con} - p_2 \cdot P_{DG} - p_{wholesale} \cdot (P_{con} - P_{DG}) - p_{fine} \cdot (P_{con,total} - P_{con})$

where

p_1: selling price to the consumers

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[2] In order to perform the simulation, values for $p_{2,high}$ were artificially generated by using a random term so that they vary between 110% and 130% of $p_{2,low}$.

P_{con}: consumers' optimal consumption levels

p_2: buying price from production units

P_{DG}: production units' optimal production levels

P_{EV}: EVs optimal response (either charging or discharging)

$p_{wholesale}$: wholesale prices for selling/buying the excess/deficit of energy

p_{fine}: fine imposed on the aggregator for the part of the load that is not served.

$P_{con,total}$: total load level ideally served (Figure 7)

For $p_{wholesale}$ let it be noted that two price levels were considered (one for buying and one for selling electricity), which cannot be influenced by the aggregator.

The fine imposed on the aggregator for the part of the load that is not served (p_{fine}) is constant throughout the day and motivates the aggregator to offer lower p_1 in order for a greater part of the load to be served using the available energy stored in the batteries of the EVs (if any).

9 DETAILED ALGORITHM OF THE MODEL

The general procedure followed has already been described in Figure 4. In this paragraph we elaborate the procedures that each player follows in order to calculate his optimal response from an algorithmic point of view.

9.1 Consumer function

Input: p_1, $P_{con,max}$, $p(P_{con,max})$, $P_{con,min}$, $p(P_{con,min})$

Output: $P_{con}(t)$, $u_{con}(t)$

- If $p_1 > p(P_{con,min})$, then only the high-priority load is served ($P_{con} = P_{con,min}$) and the payoff for the consumer equals zero ($u_{con} = 0$).
- If $p_1 \leq p(P_{con,min})$, then the consumer selects his consumption level as depicted in Figure 8 (P_{con} such that $p(P_{con}) = p_1$) and his payoff equals the consumer surplus (u_{con} = area marked with blue in the same figure).

9.2 Distributed generation function

Input: p_2, $P_{DG}(t+1)$[3], A, B, C, ramp rate, $P_{DG,min}$, $P_{DG,nominal}$

Output: $P_{DG}(t)$, $u_{DG}(t)$

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[3] Since the problem is solved using the backwards-induction method, the previous state of the DG is $P_{DG}(t+1)$, and the current state is $P_{DG}(t)$. As a result, when the optimal is to have $P_{DG}(t) = 0$ while $P_{DG}(t+1) \neq 0$, it is only natural that the DG unit turns on, in which case the payoff function should include the start-up cost.

Given p_2, the optimal production level is calculated as: $P_{DG} = \frac{p_2 - B}{2 \cdot A}$ and the payoff received for the specific production level as: $\left(p_2 - \left(A \cdot P_{DG}^2 + B \cdot P_{DG} + C\right)\right) \cdot P_{DG}$

- If $P_{DG} > P_{DG,nominal}$ then the production is fixed on the maximum the unit allows ($P_{DG} = P_{DG,nominal}$) and the payoff is recalculated.
- If $P_{DG} < P_{DG,min}$ two possibilities are examined:
  - If it is allowed by the ramp rate, then $P_{DG} = 0$ and the payoff has to take into account the start-up cost of the unit[4].
  - If the ramp rate of the unit does not allow P_{DG} to be equal to 0, then $P_{DG} = P_{DG,min}$ and the payoff is recalculated.
- For all the other cases, the optimal production level should not be higher or lower than the ramp rate allows.

9.3 EVs function

Input: p_1, p_2, SOC(t+1), SOC_{max}, SOC_{min}, availability, $P_{DG,max}$, $p(P_{DG,max})$, $P_{DG,min}$, $p(P_{DG,min})$

Output: SOC(t), $u_{EV}(t)$, charge flag(t)[5]

- If the EV is not available for t-1 and if SOC(t) < SOC_{min}, it is in charging mode. Otherwise the EV chooses between charge and discharge mode by comparing the payoff offered by each one of them (see below).
- If the EV is not available for t, then by default it is in discharging mode due to travel (SOC(t) = SOC(t+1) - km·efficiency/capacity, charge flag = 0) and $u_{EV} = 0$.
- For all the other cases the EV chooses between charge and discharge mode by comparing the payoff offered by each one of them.
  - The discharge profit is equal to the product (discharge rate·a·p_2), where a is the discharge efficiency.
  - The charge profit is calculated using exactly the same method as the consumers, but with different values for $P_{con,max}$, $p(P_{con,max})$, $P_{con,min}$, $p(P_{con,min})$, which are now $P_{EV,max}$, $p(P_{EV,max})$, $P_{EV,min}$, $p(P_{EV,min})$. In Table 14 the parameters of the inverse demand curve used for the EVs charging mode are presented, where EVs are considered load best described by Band DD, according to the categorization established by Eurostat.

Table 14: Parameters of the inverse demand curve of the EVs for the charging mode

ε_m	p_m (€/kWh)[6]	P_m (kW)[5]	a	b
-1.2	0.1604	1.712	0.294	-0.078

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[4] The start-up cost of the unit is considered constant and equal to 0.8·C.

[5] The charge flag equals 1 when the EV is in charging mode, 0 when the EV batteries discharge due to travelling and -1 when the EV is in discharging mode.

[6] Source of data: Eurostat

9.4 Aggregator function

Input: p_1, p_2, $p_{wholesale}$, p_{fine}, $P_{con}(t)$, $P_{DG}(t)$, $P_{EV}(t)$, charge_flag(t)

Output: $u_{agg}(t)$

- If the EV is in charging mode (charge_flag(t)=1), then:
  $u_{agg}(t)=p_1 \cdot (P_{con}(t)+P_{EV}(t)-p_2 \cdot P_{DG}(t)-p_{wholesale} \cdot (P_{con}(t)+P_{EV}(t)-P_{DG}(t))-p_{fine} \cdot (P_{con,total}-P_{con}(t))$
- If the EV is in discharging mode (charge_flag(t)=-1), then:
  $u_{agg}(t)=p_1 \cdot P_{con}(t)-p_2 \cdot (P_{DG}(t)+P_{EV}(t))-p_{wholesale} \cdot (P_{con}(t)+P_{EV}(t)-P_{DG}(t))-p_{fine} \cdot (P_{con,total}-P_{con}(t))$.
- If the EV is unavailable due to travelling (charge_flag(t)=0), then:
  $u_{agg}(t)=p_1 \cdot P_{con}(t)-p_2 \cdot P_{DG}(t)-p_{fine} \cdot (P_{con,total}-P_{con}(t))$.

Note: $P_{EV}(t)$ = SOC(t+1)-SOC(t))·capacity

10 SIMULATION RESULTS

The above described procedure is applied in order to examine the impact of the EVs on the operation of the retail market. Two cases are examined: with and without the presence of EVs. Furthermore, in the first case, various penetration levels of EVs are examined.

10.1 Input data

10.1.1 Household consumers

As already mentioned in paragraph 8.3.1, household consumers are described by the demand curve given in Figure 6. The parameters of that curve vary from hour to hour (Table 13). By combining these parameters with the load curves describing the consumption of a typical European household (Figure 7) we obtain, for each hour of the day, a vector consisting of four values ($P_{con,max}$, $p(P_{con,max})$, $P_{con,min}$, $p(P_{con,min})$) that fully describes the specific demand curve.

10.1.2 Distributed generation

The values of the parameters A, B and C of the DG cost function are presented in Table 15 [8]. The remaining characteristics of the microturbine are given in Table 16.

Table 15: Constants A, B and C of the DG cost function

A (¢€/kWh)	B (¢€/kWh)	C (¢€/h)	Minimum capacity (kW)	Maximum capacity (kW)
0.01	4.37	0.01	6	30

Table 16: Technical and economical characteristics of the microturbine

Ramp-rate	10%/min
Start-up cost	80%·C

10.1.3 Electric vehicles

Table 17 presents the technical characteristics of the EV considered for the simulation, which is a Nissan Leaf, while Table 18 presents the mobility characteristics of the driver considered for the simulation.

Table 17: Technical characteristics of the EV

Capacity of the batteries	24 kWh
Average charging time	7-8 h
Efficiency	0.15 kWh/km
Range	160 km
Charge rate	3-3.43 kWh/h
Charge and discharge efficiency	89.44%

Table 18: Mobility characteristics of the driver

Availability hours	9:00-17:00, 18:00-8:00
Average daily distance travelled	60km

10.1.4 Aggregator

The results of the application of the procedure for obtaining the price levels that will comprise the strategies of the aggregator as described in paragraph 8.3.4, on real wholesale market data are given in Figure 12. For selling (p_1) and buying (p_2) electricity, the aggregator chooses between two strategies: either low prices ($p_{1,low}$, $p_{2,low}$), or high prices ($p_{1,high}$, $p_{2, high}$).

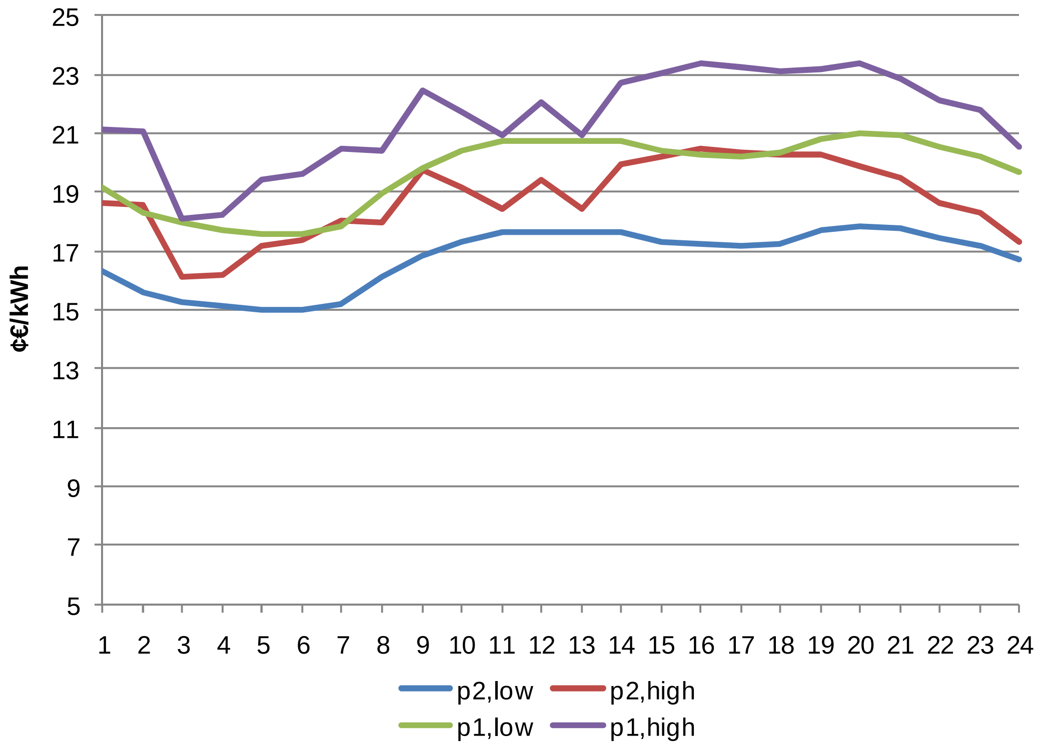

Figure 12: Strategies followed by the aggregator ($p_{1,low}$ – $p_{2,low}$, $p_{1,high}$ – $p_{2,high}$)

10.2 Results

In order to examine the influence of the existence of the EVs on the retail price levels, three scenarios were considered:

Scenario 1: the only players considered are the consumers, the DG units and the aggregator.

Scenario 2: EVs are added as a fourth player acting only as a load.

Scenario 3: as in Scenario 2, considering the extra capability of the EVs to offer energy to the grid.

For the cases where EVs are present, two penetration levels are considered:

- Low penetration: 10% of the total vehicle fleet are EVs,
- High penetration: 25% of the total vehicle fleet are EVs.

Figure 13 and Figure 14 present the optimal selection for the aggregator for buying and selling prices for the three scenarios considered for two penetration levels of EVs. The comparison of Scenarios yields some useful conclusions:

- During hours of high load (10:00-24:00) the aggregator selects the high priced strategies (Scenario 1, Figure 13), which leads to a substantial reduction in the actual load served (Scenario 1, Figure 15).
- The additional load due to the EVs (Scenario 2), leads – as previously – to higher prices (during hours 1:00, 8:00 and 9:00) (Scenario 2, Figure 13 and

Figure 14). High prices during 8:00pm lead to a further reduction in the load served (Scenario 2, Figure 15).

- Considering EVs not only as a load but as a potential source of energy (Scenario 3) leads to even greater variations in the price levels when compared to Scenarios 1 and 2. While for hours 10:00 and 23:00 high load levels would have been responsible for high prices (as in Scenario 1), this is not the case for Scenario 3 (Figure 13). At the specific hours, EVs inject energy to the grid (Figure 18), which allows for a greater part of the household load to be served (Figure 15, Scenario 3).
- Higher levels of EV penetration affect the prices even more. In addition to the aforementioned changes in the prices for hours 10:00 and 23:00, lower prices are now achieved for hour 22:00. However, during hours of low household load, EVs optimal response – which is to charge – (Figure 17 and Figure 18, hours 5:00, 6:00 and 7:00) leads to an increase in the total load to be served, thus, resulting in higher price levels (Figure 14, Scenario 3)

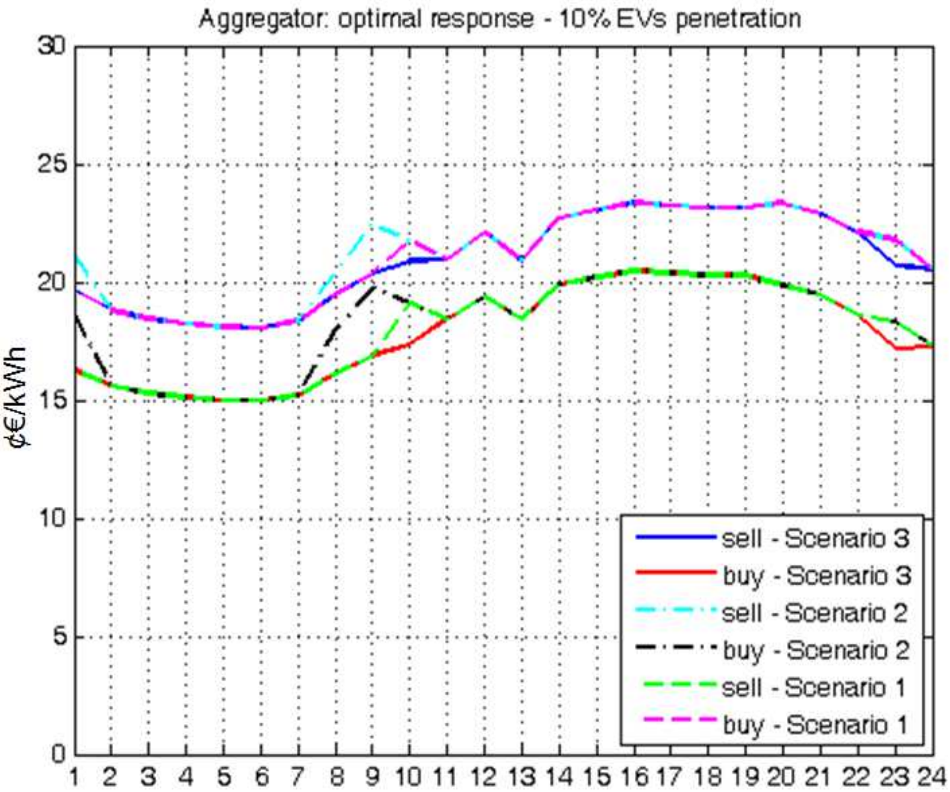

Figure 13: Aggregator optimal selection for buying and selling prices (in ¢€/kWh) for the three scenarios – EV penetration: 10%

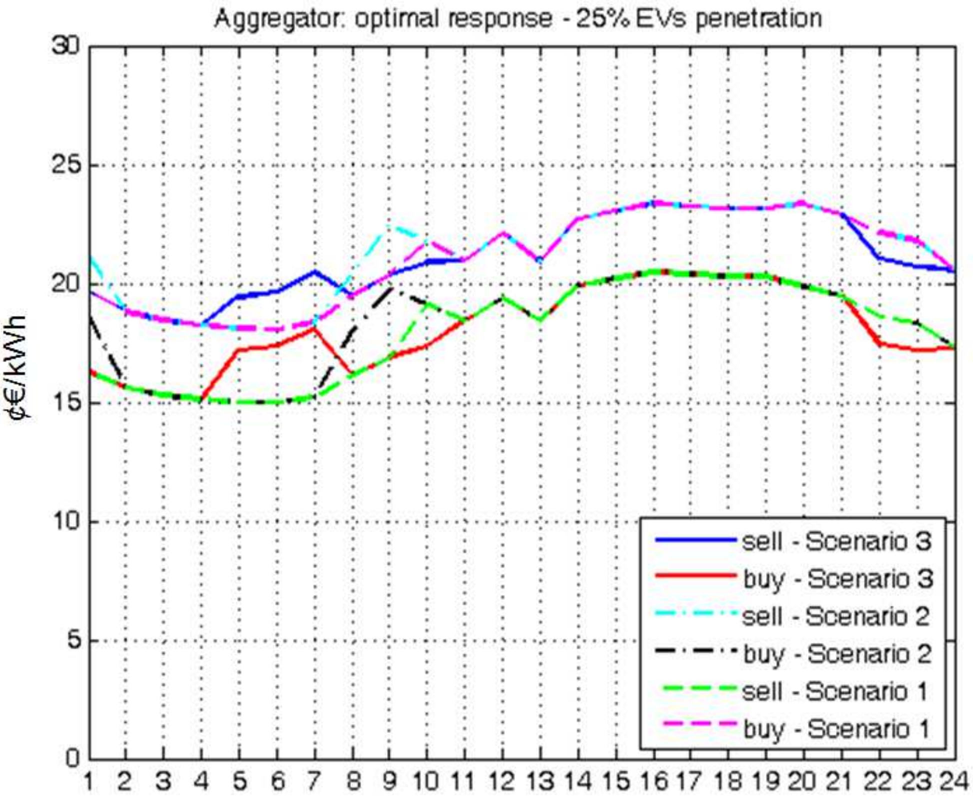

Figure 14: Aggregator optimal selection for buying and selling prices (in ¢€/kWh) for the three scenarios – EV penetration level: 25%

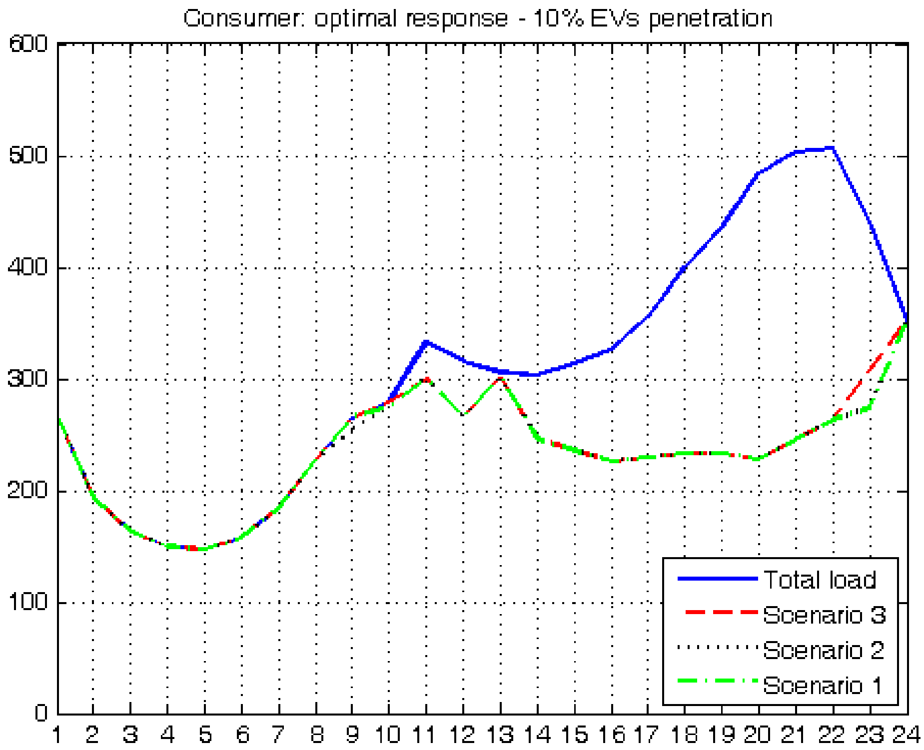

Figure 15: Consumer's optimal response for the three Scenarios- 10% penetration level

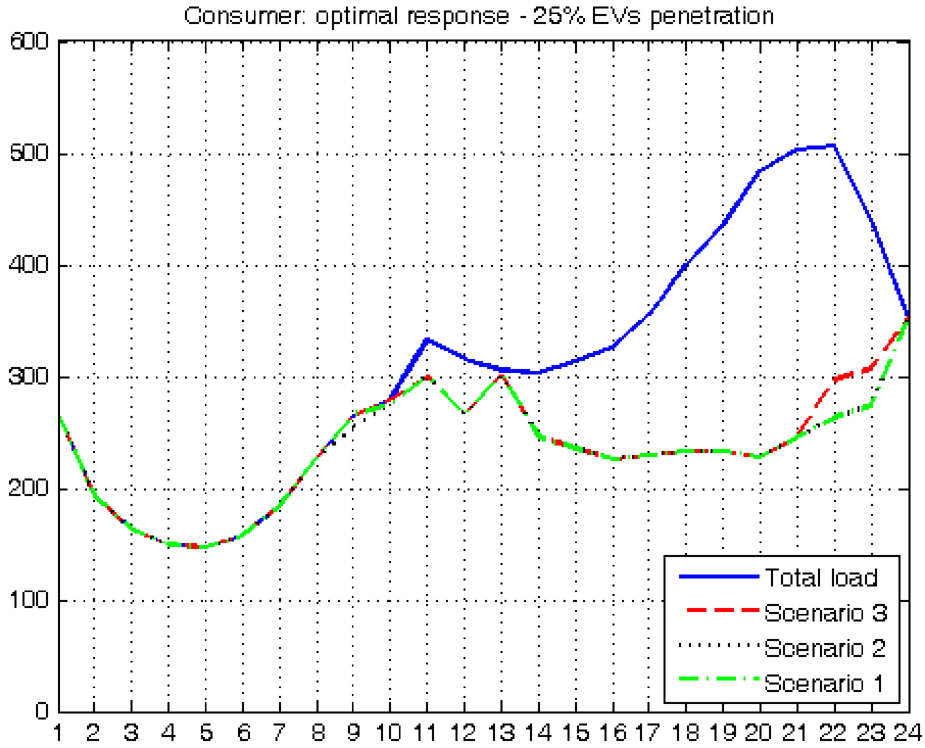

Figure 16

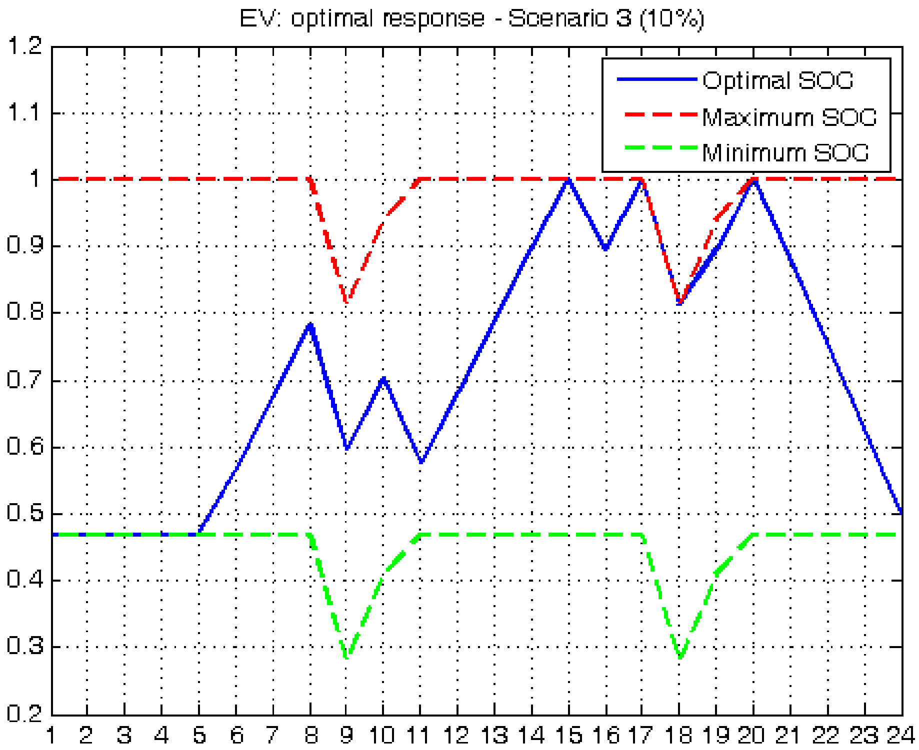

Figure 17: State of charge of the EV batteries for Scenario 3 – EV penetration level: 10%

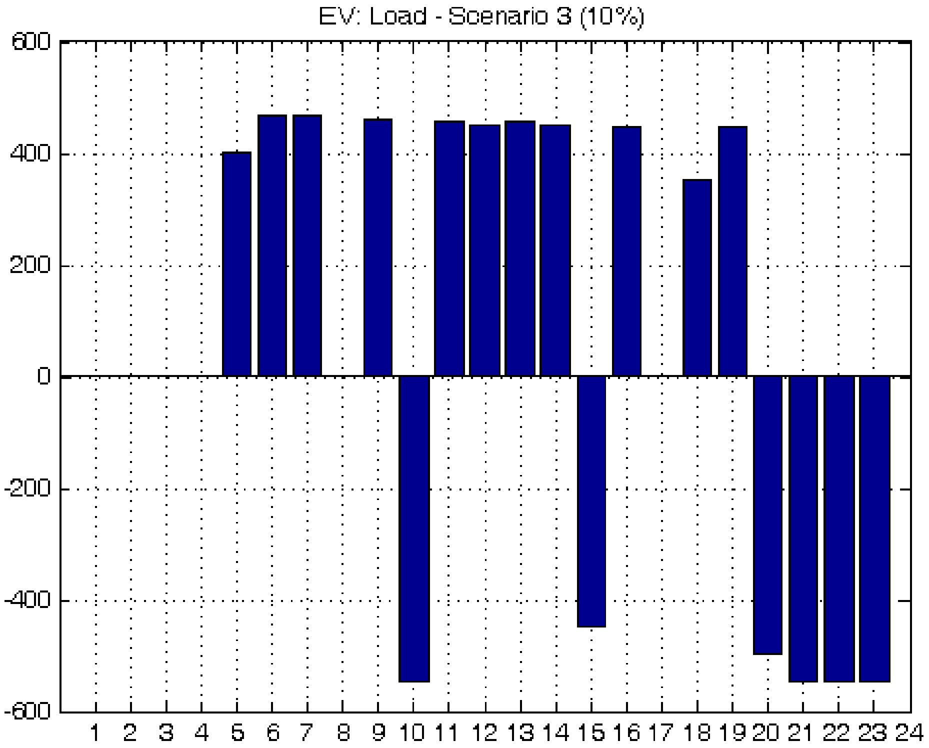

Figure 18: EVs' optimal response – Scenario 3, 10% penetration level

11 PRELIMINARY CONCLUSIONS

Simulation of the operation of the electricity market in the presence of various levels of EV penetration is performed by using two different approaches: optimization in conjunction with simulation and game theory with the results showed previously.

Using both optimization and simulation, the comparison of the results obtained in the study cases presented lead to the conclusion that when there is a high penetration of EVs with the ability to give power to the grid, the prices of the system decrease. When the EVs do not have the ability to give power to the grid, the price increases lightly (not so lightly in the valley hours).

Moreover, the use of smart EVs not only reduces the prices, it also improves the reliability of the system, reducing the NSE.

Using the game theory approach, the comparison of the results of these three scenarios with their variations (penetration level), leads to the following conclusions:

- During hours that the load is expected to be high the aggregator chooses high price levels in order to attenuate the increase in load.
- The addition of EVs that act only as load, results – as previously – to high prices.
- For the third scenario, the previous observations hold for the hours when EVs absorb energy from the grid. The opposite effect is observed during the hours that EVs inject energy to the grid: the prices are pushed downwards, and a greater part of the load is served. Furthermore, higher EVs' penetration level affects the prices in a similar way during a greater part of the day (see Table 19).

Table 19: Percent change of the price levels for selling and buying electricity per hour of the day - Scenarios 2 and 3 with respect to Scenario 1

Hour of day	Scenario 2		Scenario 3 – 10%		Scenario 3 – 25%	
Price / Hour of day	sell	buy	sell	buy	sell	buy
1	7.7	14.4	0.0	0.0	0.0	0.0
2	0.0	0.0	0.0	0.0	0.0	0.0
3	0.0	0.0	0.0	0.0	0.0	0.0
4	0.0	0.0	0.0	0.0	0.0	0.0
5	0.0	0.0	0.0	0.0	7.5	14.7
6	0.0	0.0	0.0	0.0	8.7	16.0
7	0.0	0.0	0.0	0.0	11.5	18.7
8	4.6	11.3	0.0	0.0	0.0	0.0
9	10.5	16.9	0.0	0.0	0.0	0.0
10	0.0	0.0	-4.0	-9.4	-4.0	-9.4
11	0.0	0.0	0.0	0.0	0.0	0.0

12	0.0	0.0	0.0	0.0	0.0	0.0
13	0.0	0.0	0.0	0.0	0.0	0.0
14	0.0	0.0	0.0	0.0	0.0	0.0
15	0.0	0.0	0.0	0.0	0.0	0.0
16	0.0	0.0	0.0	0.0	0.0	0.0
17	0.0	0.0	0.0	0.0	0.0	0.0
18	0.0	0.0	0.0	0.0	0.0	0.0
19	0.0	0.0	0.0	0.0	0.0	0.0
20	0.0	0.0	0.0	0.0	0.0	0.0
21	0.0	0.0	0.0	0.0	0.0	0.0
22	0.0	0.0	0.0	0.0	-4.8	-6.1
23	0.0	0.0	0.0	0.0	-5.0	-6.3
24	0.0	0.0	0.0	0.0	0.0	0.0
Average	0.9	1.8	-0.2	-0.4	0.6	1.2

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