Real-time Market Concept Architecture for EcoGrid EU – A Prototype for European Smart Grids

Yi Ding, Salvador Pineda, Preben Nyeng, Jacob Østergaard, Emil Larsen and Qiuwei Wu

***Abstract*-- Industrialized countries are increasingly committed to move towards a low carbon generating mix by increasing the penetration of renewable generation. Additionally, the development in communication technologies will allow small end-consumers and small-scale distributed energy resources to participate in electricity markets. It is out of question that current electricity markets need to be tailored to incorporate these changes regarding how electricity will be generated and consumed in the future. The EcoGrid EU is a large-scale EU-funded project, which establishes the first prototype of the future European intelligent grids. In this project, small-scale distributed energy resources and small end-consumers can actively participate in a new real-time electricity market by responding for 5-min real time electricity prices, which can provide balancing service for a power system with high penetration of renewable electricity generation. The real-time market concept architecture for EcoGrid EU is introduced in this paper, which provides a market-based platform and information and communication technology (ICT) infrastructure that extends the current electricity market to a shorter time horizon and to smaller assets.**

***Index Terms*— EcoGrid EU, real time market, smart grid**

NOMENCLATURE

Indexes and sets

g	Index of generating units
l	Index of loads
d	Index of distributed energy resources
t_i	Index of time steps
w	Index of wind farms
s	Index of scenarios
N_G	Number of generating units
N_L	Number of loads
N_{DER}	Number of distributed energy resources
N_i	Number of time steps
N_W	Number of wind farms
N_S	Number of scenarios

Constants

$P_g^{G,D}$	Scheduled generated power of unit g in the day-ahead market (MW)
$\overline{P_g^{G,UR}}$	Up- regulating power offered by unit g (MW)
$\overline{P_g^{G,DR}}$	Down- regulating power offered by unit g (MW)
$\lambda_g^{G,UR}$	Bidding cost of electricity for up-regulation of unit g (€/MWh)
$\lambda_g^{G,DR}$	Bidding cost of electricity for down-regulation of unit g (€/MWh)
V_l^{LOL}	Value of load shed corresponding to load l (€/MWh)
V_w^{Spill}	Value of wind spillage of wind farm w (€/MWh)
UR_g	Up-ramp of generating unit g (MW/h)
DR_g	Down-ramp of generating unit g (MW/h)
$P_{(l,t_i)}^{L,T}$	Reference power demand of load l at time t_i (MW)
$P_{(d,t_i)}^{DER}$	Reference power generated by DER d at time t_i (MW)
$P_{(w,t_i,s)}^{W,T}$	Wind power production of wind farm w at time t_i and scenario s (MW)
λ^D	Day-ahead price (€/MWh)
$\alpha_{(l,t_i,s)}$	Demand response parameter to real-time price signals of load l at time t_i and scenario s (€/MW^{2}h)
$\alpha_{(d,t_i,s)}$	DER response parameter to real-time price signals of DER d at time t_i and scenario s (€/MW^{2}h)
$P_{(l,t_i)}^{L,max}$	Maximum demand of load l at time t_i (MW)
$P_{(l,t_i)}^{L,min}$	Minimum demand of load l at time t_i (MW)
$P_{(d,t_i)}^{DER,max}$	Maximum production of DER d at time t_i (MW)
$P_{(d,t_i)}^{DER,min}$	Minimum production of DER d at time t_i (MW)
π_S	Probability of occurrence of scenario s

Variables

$P_{(g,t_i,s)}^{G,T}$	Total power generated by unit g at time t_i and scenario s (MW)
$P_{(g,t_i,s)}^{G,UR}$	Up-regulating power of unit g deployed at time t_i and scenario s (MW)
$P_{(g,t_i,s)}^{G,DR}$	Down-regulating power of unit g deployed at time t_i and scenario s (MW)
$L_{(l,t_i,s)}^{Shed}$	Load shedding imposed to consumer l at time t_i and scenario s (MW)
$W_{(w,t_i,s)}^{Spill}$	Wind spillage of wind farm w at time t_i and scenario s (MW)
$\lambda_{(t_i,s)}^{RT}$	Real-time price signal at time t_i and scenario s (€/MWh)
$\Delta P_{(d,t_i,s)}^{DER}$	Response of DER d at time t_i and scenario s (MW)

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The members of the EcoGrid EU Consortium are the TSO/DSO from Denmark (Energinet.dk and Østkraft), Belgium (Elia and Eandis), Portugal (EDPD Distribuição), and 7 universities/consultancy companies (DTU CET, TUT, SINTEF, TECNALIA, ECN, EnCT and AIT). The key industrial partners are Siemens AG and IBM Research. DTU CET is the task leader of real-time market concept architecture design. The total budget of EcoGrid EU is 25 million €.

$\Delta P^{L}_{(l,t_i,s)}$ Demand response of load l at time t_i and scenario s (MW)

I. INTRODUCTION

The future economic growth and jobs of European Union (EU) are heavily relying on the efficient and sustainable use of natural resources [1]. In the future energy framework of EU, the substantial contribution from renewable energy (e.g. wind & PV) and more efficient energy sources (e.g. CHP) to the generation mix plays an important role tackling the challenge of the climate change as well as improving the security of energy supply. In a medium term perspective the EU has agreed on a goal of 20 % renewable energy in final energy consumption in 2020 [2] and in a long run perspective (2050) this goal might be increased significantly.

The high penetration of renewable energy resources will also challenge the power grid of EU for two reasons. Firstly the high share of fluctuating and less predictable power production will increase the request of balancing services between generation and demand. The high penetration of renewable energy resources (RES) will also increase competition and costs for balancing power because the conventional energy resources are reduced and the need for balancing resource will increase. Secondly, the electrification of transport and heat will put a pressure on the distribution grids in the power system. However the current design of electricity markets is not sufficient to manage the future challenges the power system faces: Firstly hourly time resolution for markets may be too rough an approximation of the dynamics in the power system with high penetration of RES, which cannot precisely reflect actual status of power system operation. Secondly most of the end-consumers and small-scale distributed energy resources (DER) are difficult to provide balancing services in the current regulating power market structure e.g. requirements on bidding size, complex bidding strategies in the markets, complying with schedules and etc. Lastly current gate closure of the electricity markets many hours ahead may be too rigid as the accurate practicability of RES as the ability to supply is not known until maybe minutes or half hour ahead.

Smart grids will be the backbone of the future electricity network of EU for integrating the high penetration of RES and flexible participation of customers [3]. The development and expansion of communication systems and intelligent metering capabilities will enable the end-consumers and small-scale DER to respond to market price signal [4] and participate in the system balancing. For addressing the future needs and challenges of the upcoming power systems, an efficient, market-based tool is necessary for handling the future challenges of power systems. The EcoGrid EU is a large-scale EU-funded project, which establishes the first prototype of the future European intelligent grids. It will demonstrate a market concept that is designed to incorporate small-scale DERs as well as flexible demand into the existing electricity markets, balancing tools, and operation procedures. The basic architecture of the Ecogrid EU is based on a new real-time electricity market, which allows small-scale DERs and flexible demand receive and react on variable 5-min electricity prices. The existing market framework will be expanded for integrating the EcoGrid EU real-time market as shown in Fig.1 [9].

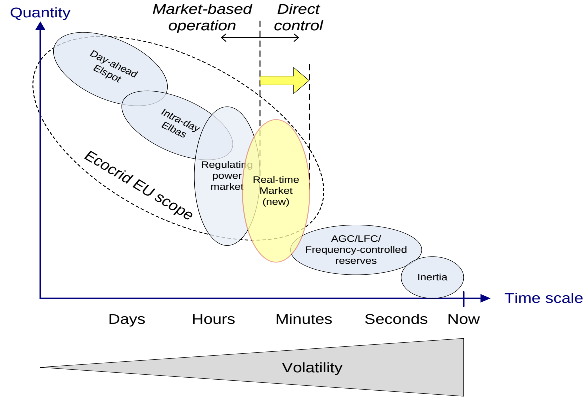

Fig. 1 The integration of real-time market into existing markets

The new real-time market extends the current electricity market to a shorter time horizon and to smaller assets, which can be utilised for short-term, intra-hour balancing. An overview of the Ecogrid EU project is briefly presented in the ISGT conference [9].

This paper is focused on the architecture design of Ecogrid EU real-time market. The conjunction of the EcoGrid EU system with present market operations and procedures are described. Timeline and price signal designs are also discussed. Optimization models for real-time price settlement and forecast are presented in the paper.

II. REAL-TIME MARKET CONCEPT ARCHITECTURE

Fig.2 presents an overview of the real-time market architecture. The real-time price is set on the basis of the system operation status, which reflects the needs of balancing power and/or congestions in the transmission/distribution system. If no imbalance or congestion exists, the real-time price will be the same as the day-ahead spot price of the operational hour.

The participating prosumers (both consumers and producers) will respond to the price signal for adjusting the real time consumption or production comparing with the day-ahead scheduling and providing balancing power. The time resolution of the real-time market is 5-min, which indicates the price will be updated frequently, every 5 minutes. In principle, the prosumers can take actions, such as turning off or on selected appliances, charging electric vehicles, etc., at any time according to the real-time electricity price. Since the electricity price can potentially change every 5 minutes, it is expected to let automatic smart controllers make the optimal decision based on the price signals and end-user's more static preferences, and subsequently control the DER units and/or smart appliances to change their electricity consumption or generation. A smart meter with 5 minutes metering interval will record the total consumption and/or generation of the prosumer. Through a metering system meter value data will be transferred to a retailer which handles contractual and settlement issues.

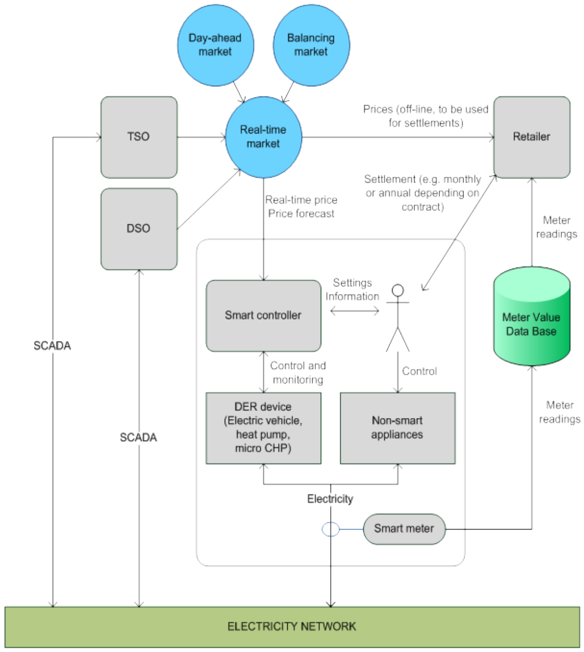

Fig. 2 EcoGrid EU concept architecture

The Ecogrid EU real-time market is a bidless electricity market: the submissions of plans and bid as known from existing electricity markets will not be part of the EcoGrid EU market [9]. It is in that sense a true real-time market, according to the definition in [5], which can greatly minimize the transactions costs of prosumers participating in the market because they simply respond to the current market price set by the market operator. This market concept differs from other smart grid solutions, e.g. the Olympic Peninsula market [6] and the PowerMatcher energy management system [7, 8], where agents submit bids to an auction for establishing an equilibrium price.

In the Nordic power system, the existing regulating power (RP) market is the market place for providing balancing power, which is mainly addressing larger generating units and large consumers (several MW). The RP market provides up and down regulation necessary for the four national TSOs in the Nordic countries for maintaining system balance. The large power producers, large consumers and aggregated smaller loads will submit bids (minimal 10 MW) to the RP market and the TSOs accept bids based on a common merit order bid list before or during each hour of operation to keep the system balanced. The Ecogrid EU real-time market is not used to replace the RP market, which works well for providing accurate quantity of up or down regulation required by the TSO. The Ecogrid EU real-time market overlaps/complements the RP market, which will become an additional source of balancing power via an aggregated response from the numerous DERs and flexible electricity demand on a volunteer basis. Consequently, the settlement of real-time prices is close coordinated with the development of the marginal cost of the activated bids in the RP market. Fig. 3 illustrates the correlation between price and quantity in these markets [9]: In the left part of the illustration representing the RP market, the TSO will activate the bids for obtaining the required quantity of balancing power, and the marginal cost of the RP market is the most/least expensive activated bids. In the right part of the illustration representing the real-time market, the TSO will set the real-time price, and the certain quantity of balancing power can be induced by prosumers responding to the price. Suppose the required total balancing power is $P_2^{real} + P_1^{reg}$, where P_1^{reg} is activated from the RP market and P_2^{real} is produced from the real time market. The marginal cost of the RP market is strongly correlated with the real-time price. The optimization models for real-time price settlement and forecast will be discussed in section IV.

Fig. 1 Conceptual illustration of the relation between the Nordic regulating power market (left) and the Ecogrid EU real-time market (right).

III. TIMELINE DESIGN AND PRICE SIGNAL DESIGN

This section is aimed at presenting the main design and implementation features regarding the detailed timeline of the real-time price signal. One of the main design requirements is that the real-time price signal is sent directly from the real-time market place managed by the TSO to the market participants.

A. Overall Timeline Design

An overall timeline of price signals sent to the prosumers is shown in Fig.4.

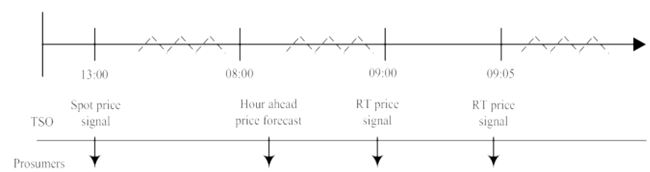

Fig. 4 Timeline of price signals

As shown in Fig. 4, when the day-ahead spot market (NordPool) settled at around 13:00, hourly spot price signals for the whole next day are published at the real-time market place. The day-ahead spot price represents a good prediction of the real-time price. The spot price signals will not be used for response of prosumers, but are only provided to the prosumers to enable them to plan their production or consumption of the next day. Further price forecasts can be delivered closer to the actual operating time. For example, between 08:00 and 09:00 of the next day, an hour ahead price forecast signal would be published by TSO. This is used to estimate the 5-minute real-time prices between 09:00 and 10:00. It is based on the predicted requirements of balancing by the TSO during the operational hour. During operation, the real-time signal for a 5-minute interval will be published ahead of the starting time of the interval. For example, the real-time price signal for time interval between 09:00 and 09:05 will be published before 09:00 (e.g. 08:59:00). Setting and publishing the price ahead of the starting time of the interval avoids problems regarding communication delays. How much ahead the real-time price signal should be published is a trade-off between on the one hand allowing as short delay as possible from identification of a balancing need to a response by the prosumers, and on the other hand getting a better response from the prosumers (some DER devices may have a start-up time). It is expected that publishing 1 minute before operation would provide sufficient time for most DER devices.

Fig. 4 illustrates the timeline of events inducing a response in the real-time market as well as in the regulating power market. At time 09:00 there is no requirements of balancing actions, and the real-time price signal sent to prosumers will simply correspond to the spot price of that hour. At time 09:02, the TSO needs total $P_2^{real} + P_1^{reg}$ MW additional power because a major generating unit is out of service. The TSO activates bids from the regulating power market immediately, which can obtain P_1^{reg} regulating power in 15 minutes. The TSO also prefers a response from prosumers, and therefore, a real-time price signal will be published to prosumers in the following 5-minute interval (09:05 to 09:10) to obtain P_2^{real} additional power.

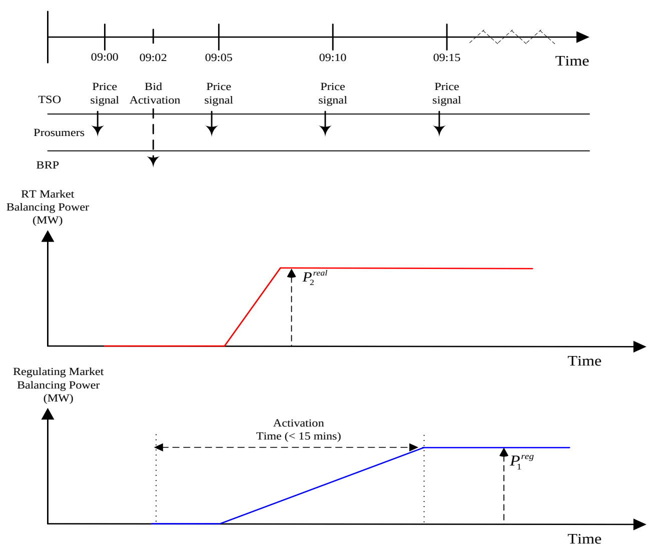

Fig. 4 Timeline of events inducing additional power in the real-time market as well as in the regulating power market

B. Price Signal Design

Another important topic is the format of the price signal. The basic data structure of the price signal format includes the following information:

- Starting time (date + time in UTC-time)
- Duration (in seconds)
- Price (in €/MWh (usually with two digits))
- Signal type (RT = real-time price, FP = forecast price)
- Event trigger (No, start, stop and other commands)
- Checksum

The starting time in the EcoGrid EU implementation will normally be a whole number of 5 min. for the real-time price, e.g. 9:00, 9:05, 9:10 or 9:01, 9:06, 9:11 etc. In future implementations using the EcoGrid EU concept the 5 minute intervals may be changed. The resolution of the starting time is seconds. The signal type indicates whether the price will be used for settlement (real-time price) or whether it is a forecasted price. Event trigger can be included to enable future direct control schemes e.g. demand response program of contingency events for load shedding. Event trigger signal set as "Start" indicates that the prosumer should respond to a contingency event. In this case, the customers can be compensated based on the emergency contract. The checksum is also added to the price signal, which is used to check for errors in the price signal.

Fig. 5 illustrates a real-time price signal for settlement sent at 2011-05-28 09:13:20:

Starting time	Duration (s)	Electricity Price (€/MWh)	Signal type	Event trigger	Checksum
2011-05-28 09:15:00	300	35.40	RT	No	13983

Fig.5 A real-time price signal

The real-time price signal can be represented as XML response to a HTTP Post:


```
<priceSignal>
<id typeId="string">1013</id>
<entry>    // This is the price forecast
<startTime
typeId="DateTime">20110528T092000</startTime>
<duration typeId="short">300<duration>       // [s]
<price typeId="double">38.80</price>       // [€/MWh]
<realTimeType typeId="string">FP</realTimeType>
<eventTrigger typeId="string">No<eventTrigger>
…
</entry>
…
</priceSignal>
```


Fig. 6 illustrates a price forecast signal sent at 2011-05-28 09:13:20:

Starting time	Duration (s)	Electricity Price (€/MWh)	Signal type	Event trigger	Checksum
2011-05-28 09:20:00	300	38.80	FP	No	13983

Fig.6 A price forecast signal

IV. Optimization Models for Real-Time Price Settlement and Forecast

The TSO will operate the real-time market in parallel with the regulating power market for balancing the electricity network in the real-time. In order to do that the TSO has the following certain information:

- Cleared quantities to be generated and consumed as well as resulting prices from the day-ahead spot market.
- Up and down regulating bids (quantities and prices) submitted by generating units.

- Technical constraints of generating units such as maximum output and ramp limits.

Moreover, the TSO has to make its decisions taking into consideration some uncertain parameters, such as:

- Power production of RESs, mainly wind production.
- Aggregated response of prosumers to real-time electricity prices.

Taking into account both the known information and the uncertain parameters, the TSO has to determine:

- The deployment of up and down regulating power.
- The real-time electricity price and forecast to be sent to the market players.

Proposed optimization models for the TSO operating the real-time market in parallel with the regulating power market are developed in the following paragraphs, which are also used for real-time price settlement and forecast.

A. Real-time Price Settlement Model

At time t_0, suppose that there is an imbalance between demand and generation because of operational disturbance or major disturbance. Frequency controlled based reserve such as primary reserve will respond automatically to restore the balance between demand and generation. Equation (1) determines the frequency controlled based reserve deployed at time t_0 (LF_0) when disturbance happens:

$$LF_{t_0} = \sum_{l}^{N_L}\left(P^{L,T}_{(l,t_0)}+\Delta P^{L}_{(l,t_0)}-L^{Shed}_{(l,t_0)}\right)-\sum_{g}^{N_G}\left(P^{G,D}_{g}+P^{G,UR}_{(g,t_0)}-P^{G,DR}_{(g,t_0)}\right)$$
$$-\sum_{d}^{N_{DER}}\left(P^{DER,T}_{(d,t_0)}+\Delta P^{DER}_{(d,t_0)}\right)-\sum_{w}^{N_W}\left(P^{W,T}_{(w,t_0)}-W^{Spill}_{(w,t_0)}\right) \qquad (1)$$

At the mean time, the TSO will activate regulating power and send real-time price signal to prosumers for securing sufficient balance power at time t_1. There are two major functions of the activated balancing power from RP market and real-time market:

- Relieving the existing frequency controlled based reserve activated at time t_0 : LF_0 .
- Handling the expected system operational changes such as demand, wind power generation and DERs from time t_0 to t_1 : $\left\{\sum_{l}^{N_L}\left(P^{L,T}_{(l,t_1)}-P^{L,T}_{(l,t_0)}\right)-\sum_{d}^{N_{DER}}\left(P^{DER,T}_{(d,t_1)}-P^{DER,T}_{(d,t_0)}\right)-\sum_{w}^{N_W}\left(P^{W,T}_{(w,t_1)}-P^{W,T}_{(w,t_0)}\right)\right\}$, where $P^{W,T}_{(w,t_1)}$ represents the expected wind production in t_1.

Time t_1 is very close to the current time t_0, e.g., less than 5 minutes. The very short forecast of available wind power generation can be quite accurate and therefore it is assumed as a known value in the proposed model. Likewise, the TSO will also utilize the "most" expected prosumers' responses to real-time price signals to balance the system. Equation (2) illustrates the balance between demand and generation at time t_1:

$$\left\{\sum_{l}^{N_L}\left(\Delta P^{L}_{(l,t_0)}+L^{Shed}_{(l,t_1)}-\Delta P^{L}_{(l,t_1)}-L^{Shed}_{(l,t_0)}\right)\right\}+\sum_{d}^{N_{DER}}\left(\Delta P^{DER}_{(d,t_1)}-\Delta P^{DER}_{(d,t_0)}\right)$$
$$+\sum_{g}^{N_G}\left\{P^{G,UR}_{(g,t_1)}-P^{G,DR}_{(g,t_1)}-P^{G,UR}_{(g,t_0)}+P^{G,DR}_{(g,t_0)}\right\}-\sum_{w}^{N_W}\left(W^{Spill}_{(w,t_1)}-W^{Spill}_{(w,t_0)}\right)$$
$$=LF_{t_0}+\left\{\sum_{l}^{N_L}\left(P^{L,T}_{(l,t_1)}-P^{L,T}_{(l,t_0)}\right)-\sum_{d}^{N_{DER}}\left(P^{DER,T}_{(d,t_1)}-P^{DER,T}_{(d,t_0)}\right)-\sum_{w}^{N_W}\left(P^{W,T}_{(w,t_1)}-P^{W,T}_{(w,t_0)}\right)\right\} \qquad (2)$$

The TSO will use the following single-period optimization model for the deployment of up and down regulating power and determination of real-time price for maintaining the system balance at time t_1.

The objective function (3) is to minimize the regulating power cost taking into account the prosumer' response (demand and DERs) to real-time price signals. Note that the costs of load shedding and wind spillage are also considered. In the prosumer' response model, a linear correlation between the electricity consumption or generation of an aggregation of prosumers (consumers or DERs) and the real-time electricity price is considered, which have been used in most technical literature. The detailed description of prosumer' response model is discussed in Appendix.

$$\text{Minimize}_{P^{G,UR}_{(g,t_1)},P^{G,DR}_{(g,t_1)},\Delta P^{L}_{(l,t_1)},\Delta P^{DER}_{(d,t_1)},L^{Shed}_{(l,t_1)},W^{Spill}_{(w,t_1)},\lambda^{RT}_{t_1}}$$
$$\left\{\begin{array}{l}\sum_{g}^{N_G}\left(P^{G,UR}_{(g,t_1)}\cdot\lambda^{G,UR}_{g}-P^{G,DR}_{(g,t_1)}\cdot\lambda^{G,DR}_{g}\right)\\ +\sum_{l}^{N_L}\left(-\lambda^{D}\cdot\Delta P^{L}_{(l,t_1)}+\frac{1}{2}\alpha_{(l,t_1)}\cdot\Delta P^{L}_{(l,t_1)}\cdot\Delta P^{L}_{(l,t_1)}+V^{LOL}_{l}\cdot L^{Shed}_{(l,t_1)}\right)\\ +\sum_{d}^{N_{DER}}\left(\lambda^{D}\cdot\Delta P^{DER}_{(d,t_1)}+\frac{1}{2}\alpha_{(d,t_1)}\cdot\Delta P^{DER}_{(d,t_1)}\cdot\Delta P^{DER}_{(d,t_1)}\right)+\sum_{w}^{N_W}V^{Spill}_{w}\cdot W^{Spill}_{(w,t_1)}\end{array}\right\} \qquad (3)$$

The objective function is subject to equation (2) and following constraints:

$$P^{G,T}_{(g,t_1)}=P^{G,D}_{g}+P^{G,UR}_{(g,t_1)}-P^{G,DR}_{(g,t_1)},\ \forall g \qquad (4)$$

$$0\le P^{G,UR}_{(g,t_1)}\le\overline{P^{G,UR}_{g}},\ \forall g \qquad (5)$$

$$0\le P^{G,DR}_{(g,t_1)}\le\overline{P^{G,DR}_{g}},\ \forall g \qquad (6)$$

$$P^{G,T}_{(g,t_0)}-DR_g\le P^{G,T}_{(g,t_1)}\le P^{G,T}_{(g,t_0)}+UR_g,\ \forall g \qquad (7)$$

$$-\alpha_{(l,t_1)}\cdot\Delta P^{L}_{(l,t_1)}=\lambda^{RT}_{t_1}-\lambda^{D},\ \forall l \qquad (8)$$

$$\alpha_{(d,t_1)}\cdot\Delta P^{DER}_{(d,t_1)}=\lambda^{RT}_{t_1}-\lambda^{D},\ \forall d \qquad (9)$$

$$P^{L,min}_{(l,t_1)}\le P^{L,T}_{(l,t_1)}+\Delta P^{L}_{(l,t_1)}\le P^{L,max}_{(l,t_1)},\ \forall l \qquad (10)$$

$$P^{DER,min}_{(d,t_1)}\le P^{DER,T}_{(d,t_1)}+\Delta P^{DER}_{(d,t_1)}\le P^{DER,max}_{(d,t_1)},\ \forall d \qquad (11)$$

$$L^{Shed}_{(l,t_1)}\ge 0,\ \forall l \qquad (12)$$

$$W^{Spill}_{(w,t_1)}\ge 0,\ \forall w \qquad (13)$$

Equation (4) determines the total power generated by each large unit at time t_1. Note that this power is equal to the scheduled generation in the day-ahead market plus the deployment of regulating power at time t_1.

Constraints (5) and (6) limit the deployment of up and down regulating power according to the submitted bids.

Ramp limits of large generating units are imposed through equation (7).

Equations (8) and (9) determine the response of the flexible demand and distributed energy resources, respectively, to a real-time price variation. Moreover, $\alpha_{(l,t_1)}$ and $\alpha_{(d,t_1)}$ correspond to the expected value of the response parameter to real-time electricity prices of the consumers and DERs, respectively.

The maximum and minimum changes in the power consumed and produced by these prosumers are bounded through constraints (10) and (11).

Finally, constraints (12)-(13) are positive variable declarations.

By solving the above optimization problem using commercial software like GAMS, we can obtain real time price at time t_1, the response of flexible response and DERs, the deployment of up and down regulating power, and marginal cost of activated up or down regulating power.

B. Real-time Price Settlement and Forecast Model

In real life, only a real-time price signal for the next five minute may not be sufficient for market players for scheduling their production or consumption in an optimal way. Short-term and accurate real-time price forecast (e.g. price forecast for the operational hour) based on the predicted requirements of balancing power can be delivered to market players for optimally adjusting their production or consumption planning. Inspired by that, a multi-period optimization model for determining real-time price and price forecast should also be developed. Uncertain parameters such as wind production and aggregated response of consumers and DERs to real-time electricity prices are approximated by discrete distributions with scenarios.

The TSO will use the following multi-period stochastic optimization model for determining real-time price at time t_1 and price forecasts at $t_i (\forall i = 2,...,N_i)$ for different possible scenarios. The TSO also determines the deployment of up and down regulating power at time t_1 and time $t_i (\forall i = 2,...,N_i)$ for possible scenarios, respectively. The objective function of the proposed model will then be the maximization of the expected social welfare throughout the study horizon, i.e., the minimization of the reserve deployment cost by the generators and DERs for providing balancing power plus wind spillage cost minus the utility losses of the consumers. As shown in (14), the objective function includes two items. The first item represents the corresponding cost at time t_1, which is the same as (4). The second item represents the expected cost incurred from time t_2 to t_{N_i}:

$$\begin{aligned}
&\underset{\substack{P^{G,UR}_{(g,t_1)},P^{G,DR}_{(g,t_1)},P^{G,UR}_{(g,t_i,s)},P^{G,DR}_{(g,t_i,s)},\Delta P^{L}_{(l,t_1)},\Delta P^{L}_{(l,t_i,s)},\Delta P^{DER}_{(d,t_1)},\Delta P^{DER}_{(d,t_i,s)},\\ L^{Shed}_{(l,t_1)},L^{Shed}_{(l,t_i,s)},W^{Spill}_{(w,t_1)},W^{Spill}_{(w,t_i,s)},\lambda^{RT}_{t_1},\lambda^{RT}_{(t_i,s)}}}{\text{Minimize}}
\left\{\begin{array}{l}
\sum\limits_{g}^{N_G}\left(P^{G,UR}_{(g,t_1)}\cdot\lambda^{G,UR}_g - P^{G,DR}_{(g,t_1)}\cdot\lambda^{G,DR}_g\right)\\
+\sum\limits_{l}^{N_L}\left(-\lambda^{D}\cdot\Delta P^{L}_{(l,t_1)}+\frac{1}{2}\alpha_{(l,t_1)}\cdot\Delta P^{L}_{(l,t_1)}\cdot\Delta P^{L}_{(l,t_1)}+V^{LOL}_l\cdot L^{Shed}_{(l,t_1)}\right)\\
+\sum\limits_{d}^{N_{DER}}\left(\lambda^{D}\cdot\Delta P^{DER}_{(d,t_1)}+\frac{1}{2}\alpha_{(d,t_1)}\cdot\Delta P^{DER}_{(d,t_1)}\cdot\Delta P^{DER}_{(d,t_1)}\right)+\sum\limits_{w}^{N_W}V^{Spill}_w\cdot W^{Spill}_{(w,t_1)}
\end{array}\right\}+ \\
&\sum_{s}^{N_S}\sum_{i=2}^{N_i}\pi_s\cdot\left\{\begin{array}{l}
\sum\limits_{g}^{N_G}\left(P^{G,UR}_{(g,t_i,s)}\cdot\lambda^{G,UR}_g - P^{G,DR}_{(g,t_i,s)}\cdot\lambda^{G,DR}_g\right)+\\
\sum\limits_{l}^{N_L}\left(-\lambda^{D}\cdot\Delta P^{L}_{(l,t_i,s)}+\frac{1}{2}\alpha_{(l,t_i,s)}\cdot\Delta P^{L}_{(l,t_i,s)}\cdot\Delta P^{L}_{(l,t_i,s)}+V^{LOL}_l\cdot L^{Shed}_{(l,t_i,s)}\right)+\\
\sum\limits_{d}^{N_{DER}}\left(\lambda^{D}\cdot\Delta P^{DER}_{(d,t_i,s)}+\frac{1}{2}\alpha_{(d,t_1)}\cdot\Delta P^{DER}_{(d,t_i,s)}\cdot\Delta P^{DER}_{(d,t_i,s)}\right)+\sum\limits_{w}^{N_W}V^{Spill}_w\cdot W^{Spill}_{(w,t_i,s)}
\end{array}\right\}
\end{aligned} \quad (14)$$

The objective function (14) is subject to constraints (2), (4)-(13) and following constraints:

$$P^{G,T}_{(g,t_i,s)} = P^{G,D}_g + P^{G,UR}_{(g,t_i,s)} - P^{G,DR}_{(g,t_i,s)}, \forall g, \forall i=2,...,N_i, \forall s \quad (15)$$

$$\begin{aligned}
&\sum_{l}^{N_L}\left(P^{L,T}_{(l,t_i,s)}+\Delta P^{L}_{(l,t_i,s)}-L^{Shed}_{(l,t_i,s)}\right)-\sum_{g}^{N_G}P^{G,T}_{(g,t_i,s)}\\
&-\sum_{d}^{N_{DER}}\left(P^{DER,T}_{(d,t_i,s)}+\Delta P^{DER}_{(d,t_i,s)}\right)-\sum_{w}^{N_W}\left(P^{W,T}_{(w,t_i,s)}-W^{Spill}_{(w,t_i,s)}\right)=0 \quad (16)\\
&, \forall i=2,...,N_i, \ \forall s
\end{aligned}$$

$$0 \le P^{G,UR}_{(g,t_i,s)} \le \overline{P^{G,UR}_g}, \forall g, \forall i=2,...,N_i, \forall s \quad (17)$$

$$0 \le P^{G,DR}_{(g,t_i,s)} \le \overline{P^{G,DR}_g}, \forall g, \forall i=2,...,N_i, \forall s \quad (18)$$

$$P^{G,T}_{(g,t_{i-1},s)} - DR_g \le P^{G,T}_{(g,t_i)} \le P^{G,T}_{(g,t_{i-1},s)} + UR_g, \forall g, \forall i=2,...,N_i, \forall s \quad (19)$$

$$-\alpha_{(l,t_i,s)} \cdot \Delta P^{L}_{(l,t_i,s)} = \lambda^{RT}_{(t_i,s)} - \lambda^{D}, \ \forall l, \ \forall i=2,...,N_i, \forall s \quad (20)$$

$$\alpha_{(d,t_i,s)} \cdot \Delta P^{DER}_{(d,t_i,s)} = \lambda^{RT}_{(t_i,s)} - \lambda^{D}, \ \forall d, \forall i=2,...,N_i, \forall s \quad (21)$$

$$P^{L,min}_{(l,t_i)} \le P^{L,T}_{(l,t_i)} + \Delta P^{L}_{(l,t_i,s)} \le P^{L,max}_{(l,t_i)}, \ \forall l, \ \forall i=2,...,N_i, \forall s \quad (22)$$

$$P^{DER,min}_{(d,t_i)} \le P^{DER,T}_{(d,t_i)} + \Delta P^{DER}_{(d,t_i,s)} \le P^{DER,max}_{(d,t_i)}, \ \forall d, \ \forall i=2,...,N_i, \forall s \quad (23)$$

$$L^{Shed}_{(l,t_i,s)} \ge 0, \ \forall l, \ \forall i=2,...,N_i, \forall s \quad (24)$$

$$W^{Spill}_{(w,t_i,s)} \ge 0, \forall w, \forall i=2,...,N_i, \forall s \quad (25)$$

Equation (15) determines the total power produced by each large generating unit, time period and scenario.

The power balance at each time period and scenario is enforced through equation (16).

Constraints (17) and (18) limit the maximum deployment of up and down regulating power at each time period and scenario.

The generating unit ramps bound the power generated at each time period and scenario through constraint (19).

The response of consumers and DER to real-time electricity price variations is described through equations (20) and (21), respectively. Likewise, the maximum and minimum changes of the consumers and DER's are imposed through constraints (22) and (23).

Constraints (24) and (25) are positive variable declarations. By solving the above optimization problem, we can obtain real time prices, the response of flexible response and DERs, the deployment of up and down regulating power, and marginal cost of activated up or down regulating power at each time period with different scenarios.

V. Quantitative Analyses

This section is aimed at presenting numerical examples about the settlement and forecasting of the real-time electricity price. Two examples are proposed to illustrate the optimization models according to the models described in section IV. The correlation between the real-time price and marginal cost in the RP market is quantitatively analyzed in this section. In the first one, the real-time price signal for the next time period is determined without considering inter-temporal constraints, or in other words, only the data corresponding to the next time period are accounted for. On the other hand, in the second example, both the real-time electricity price for the next time period and the real-time price forecast for the rest of the horizon are determined taking also into account the possible realization of the uncertain parameters (demand response and wind power production) during a longer time horizon (e.g., one hour).

A. Quantitative analyses for real-time price settlement model

The time horizon of this first example is just one time period. The generating unit characteristics are presented in Table 1. There is one wind farm with a scheduled production equal to 100 MW and two loads, one of them is totally inflexible to price changes (l_1) and another one (l_2) can change its consumption according to a elasticity parameter equal to $\alpha_{(l2,t_1)}$. The sum of the consumption scheduled for both loads during each time step of the analyzed hour is assumed to be known, constant and equal to 450 MW. However, in this analysis, the proportion between flexible and inflexible demand will be changed according to the following equations: $P^{L,T}_{(l_1,t)} = (1-\beta)\cdot 450$ and $P^{L,T}_{(l_2,t)} = \beta \cdot 450$, where β is a parameter between 0 and 1 indicating the penetration of flexible demand in the system.

As stated in section IV.A, the wind power production in the next time period is known because forecast error are negligible in a very short-term like, for example, 5 minutes ahead. However, it can be different from the wind production scheduled in the day-ahead market (which in this example is equal to 100 MW). To analyze the influence of the wind forecast error on the real-time price settlement, the real wind power production during the next time period is changed from 80 MW to 120 MW. In this example, the value of β and $\alpha_{(l2,t_1)}$ are set to 0.1 and 0.5, respectively. The real-time price signal for the next time step as well as the cost of the marginal unit in the regulating market are plotted in Fig. 7 as a function of the wind power production.

Note first that if the wind power is equal to the expected value (100 MW) the value of the real-time price is equal to the day-ahead price (22 €/MWh) and the marginal cost in the regulating power market is also equal to this value. From this point, if the wind production is lower than the expected one, the real-time price signal increases in order to encourage the flexible demand to decrease its consumption and balance the system. The real-time price signal keeps increasing until it reaches 23 €/MWh, which is the offer of generating unit g_1 to provide up-regulating power. At this point, a decrease of the wind power production will be completely balanced by an increase of the up-regulating power of unit g_1 up to a maximum of 3 MW (which is the maximum production of this unit according to its ramps constraint) without any need to increase the real-time price. Once the maximum production of unit g_1 is reached, a decrease of the wind power producer will involve again an increase of the real-time price. Note that a similar explanation is valid if the wind power production is higher than expected.

Table 1
Simulation date for generating unit characteristics

g	$P_g^{G,D}$	UR_g	DR_g	$\lambda_g^{G,UR}$	$\overline{P_g^{G,UR}}$	$\lambda_g^{G,DR}$	$\overline{P_g^{G,DR}}$
	MW	MW/12min	MW/12min	€/MWh	MW	€/MWh	MW
g_1	150	3	3	23	10	20	10
g_2	100	5	5	25	20	18	20
g_3	100	10	10	27	30	16	30

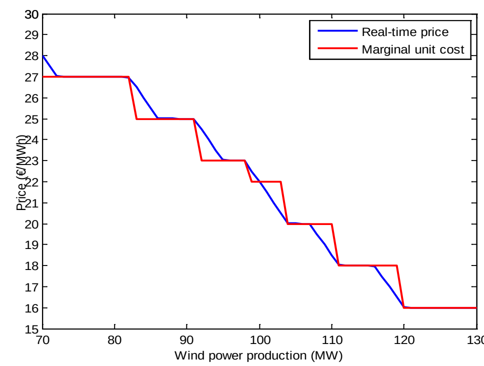

Fig. 7 The real-time price and marginal cost in the RP market (base case)

B. Quantitative analyses for real-time price settlement model

We present a multi-period optimization problem to determine the real-time price signal taking into account a longer decision horizon as well as inter-temporal technical constraints. The need of modeling the wind power uncertainty in a longer decision horizon is considered.

The time horizon of this example is equal to 1 h and, for the sake of simplicity, this time horizon has been divided into five time steps of 12 minutes each. There is only one wind producer in the system with a scheduled power production for the next hour equal to 100 MW. However, closer to the real-time operation, the production of this wind farm is characterized by two scenarios, one of high wind and another of low wind, presented in Table 2. Other conditions are set as the same as the first example.

The probability of each scenario is computed as $\pi_{s1} = 1-\chi$ and $\pi_{s2} = \chi$, where χ is a parameter between 0 and 1 determining the probability of having high wind production. We will analyze the value of the real-time price to be sent for the next 12 minutes ($\lambda^{RT}_{(t_1)}$) as a function of the probability distribution of the two wind power scenarios. The values of $\alpha_{(l2,t_i)}$ and β are equal to 0.5 and 0.1 respectively. The value of the parameter χ is changed from 0.1 to 0.9 with 0.01 steps. The resulting optimal real-time price signal is illustrated in Fig. 8.

Table 2
Two scenarios of wind farm production

$P^{W,T}_{(w,t_i,s)}$	t_1	t_2	t_3	t_4	t_5
s_1	100	80	90	60	70
s_2	100	120	110	140	130

If χ is equal to 0.5, which means that the probability of having high wind is the same that having low wind, the real-time price is equal to the day-ahead price to make the flexible consumers load equal to the expected one. On the other hand, if the probability of having high wind power production increases (which means that down regulation will be probably needed), the TSO decides to deploy some down-regulation reserves during time step t_1 to be “ready" for the most likely scenario. Therefore, since the wind production during t_1 is equal to the expected one, the real-time price signal is higher than the day-ahead price in order to make consumers to reduce their electricity consumption and then compensate the deployment of down-regulation reserves during t_1.

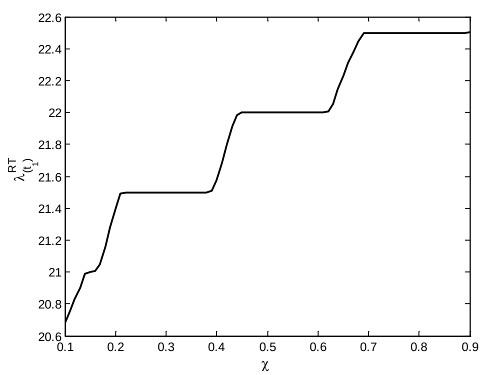

Fig. 8 Optimal real-time prices

VI. Conclusion

The quick increase of penetration of RES into the generation portfolio as well as the possible participation of small end-consumers and DERs in electricity markets due to the development of ICT will change the way of understanding and operating current power systems. A new bidless real-time electricity market that allows the participation of small DERs as well as small end-consumer is proposed in this paper. In the proposed market structure, a one-way real time price signal is sent to the prosumers in order to eliminate the imbalance between the electricity production and consumption.

VII. References

[1] Communication from the commission to the European Parliament, the Council, the European Economic and Social Committee and the Committee of the Regions, Smart Grids: from innovation to deployment, Brussels, 2011.

[2] Communication from the commission to the European Parliament and the Council, Renewable Energy: Progressing towards the 2020 target, Commission Staff Working Document, Brussels, 2011.

[3] SAP AG, Smart Grids for Europe – Benefits, Challenges and best Practices, the SAP Perspective, 2011.

[4] F. L. Alvarado, Controlling power systems with price signals, Decision Support Systems, Vol. 40, 2005, pp. 495-504.

[5] S.Stoft, Power System Economics: Designing Markets for Electricity, IEEE Press, 2002.

[6] D. Hammerstrom and et al., “Pacific Northwest GridWiseTM Testbed Demonstration Projects, Part I. Olympic Peninsula Project, National Technical Information Service”, U.S. Department of Commerce, October 2007.

[7] J. K. Kok, M. J. J. Scheepers, and I. G. Kamphuis, “Intelligence in electricity networks for embedding renewables and distributed generation,” in *Intelligent Infrastructures*, R. Negenborn, Z. Lukszo, and J. Hellendoorn, Eds. Springer, Intelligent Systems, Control and Automation: Science and Engineering Series, 2010.

[8] J.K. Kok, B. Roossien, P.A. MacDougall, O.P. Pruissen, G. Venekamp, I.G. Kamphuis, J.A.W Laarakkers, and C.J. Warmer, “Dynamic Pricing by Scalable Energy Management Systems - Field Experiences and Simulation Results using PowerMatcher”, *IEEE Power and Energy Society General Meeting 2012*, IEEE, 2012.

[9] Y. Ding, P. Nyeng, J. Østergaard, M. D. Trong, S. Pineda, K. Kok, G. B. Huitema and O. S. Grande, “Ecogrid EU – A Large Scale Smart Grids Demonstration of Real Time Market-based Integration of Numerous Small DER and DR”, *IEEE PES Innovative Smart Grid Technologies (ISGT) Europe Conference*, October 2012.

Appendix

The consumption changes of a flexible end-consumer as a function of the electricity price is represented in the Fig. 9.

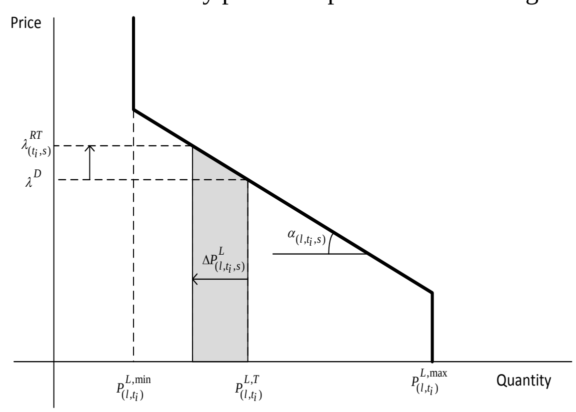

Fig. 9 The consumption change as a function of the electricity price

As it can be inferred from the Fig.9, an increase of the real-time electricity price with respect to the day-ahead price for that particular area causes a decrease of the consumption of the flexible end-consumer. Consequently, the utility of that consumer is reduced a quantity equal to the shaded area, i.e., $\Delta U_l = -\lambda^{D} \cdot \Delta P^{L}_{(l,t_i,s)} + \frac{1}{2}\alpha_{(l,t_i,s)} \cdot \Delta P^{L}_{(l,t_i,s)} \cdot \Delta P^{L}_{(l,t_i,s)}$,which is the term included in the objective function (3).

The similar model for the set of DERs responsive to real-time electricity prices can also be developed. The cost increase of DERs because of the increase of real time price with respect to the day-ahead price can be determined as:

$$\Delta C_d = \lambda^{D} \cdot \Delta P^{DER}_{(d,t_i,s)} + \frac{1}{2}\alpha_{(d,t_i,s)} \cdot \Delta P^{DER}_{(d,t_i,s)} \cdot \Delta P^{DER}_{(d,t_i,s)}$$