Kristin Dietrich[1], Jesus M. Latorre[1], Luis Olmos[2], Andres Ramos[1]

ADEQUATE REGULATION RESERVE LEVELS IN SYSTEMS WITH LARGE WIND INTEGRATION USING DEMAND RESPONSE

[1] Comillas Pontifical University, Spain, +3491542-2800, kristin.dietrich@iit.upcomillas.es
[2] European University Institute, Italy

-Preliminary Work -

Abstract
Installed wind capacity and contributions of wind to demand supply have grown in Spain in the last decade significantly. Wind is supplying a growing rate of demand. In specific situations it has supplied over 50% of Spanish demand. This has implications on the operation of the energy system. Systems facing large wind integration have to cope with production variability and uncertain predictability of wind resources. Thus, it is necessary to adapt reserve requirements to changing system conditions. Today thermal and hydro plants provide the regulation reserves. In the future, alternative reserve sources may gain more importance. The response of demand may be a possible way to provide these reserves. In this article, reserve requirements in a system facing high wind integration will be assessed. Demand response is considered as further reserve source in the system of Gran Canaria, an island belonging to Spain.

Introduction

Reserves are necessary to keep the balance between generation and demand in the electric system all the time. They are needed for both directions to increase generation and to lower it. Principally up-and down-reserves are focussed on compensating differences between real and forecasted demand and possible line or generator outages for the case of up-reserve. Reserve capacity is provided historically by thermal and hydro generators. Especially for small imbalances automatic response is necessary and thus generators have to react immediately. In the case of thermal generators this means that generators have to be online already and must preserve a part of their capacity for reserve needs. Hydro plants offer the convenience of immediate reaction and practically no ramping constraints as thermal generators do. In very wet or very dry times hydro plants may have restrictions to be used for reserve.

In Spain, different types of regulation reserves are distinguished depending on the response time and the time to be available after the activation. Primary, secondary and tertiary reserves are activated sequentially from the moment of reserve need until the programmable divergence management comes into action.

As installed capacity of wind has more than doubled in the last six years in Spain, reserves are used increasingly to cope also with wind production uncertainty. More capacity is planned for this intermittent energy source. Wind forecasting methods are improving but can´t give certainty for wind production outcome. Thus, the reserve level will be affected as well in the future by wind. As the capacity of the conventional generation park will stagnate or even decrease given the high share of wind energy in the future energy mix, reserve potential from thermal generators will decrease as well. So, other ways to provide reserves have to be found.

One possible way is to mobilize the other side of the generation-demand balance. Demand has been quite inelastic so far. In Spain the system operator offers an interruptible load program with payments proportional to the demand reduction in the case of emergency of industrial consumers. At the moment, over 200 customers participate in this program. These loads can give reserve in the case of a contingency but not for small variations between forecasted and real demand and wind production.

The focus of this paper will be in the provision of spinning reserve by demands. This type of reserve is needed often but only for a limited time span. Therefore the impact of demands offering reserve on operation and cost is analyzed.

Literature Review

Demand offering reserve

The authors of [1] distinguish six forms of ancillary services: continuous regulation and energy imbalance management under normal conditions, instantaneous contingency reserve and replacement reserves during system contingencies, voltage support and black start capability. Continuous regulation is used for minute to minute fluctuations. Energy imbalance management is somewhat slower and used as a bridge between regulation services and bids in reserve markets. During system contingencies instantaneous contingency reserve provides a rapid response to major disturbances and replacement reserves restore system stability with units with slower response time. Voltage support injecting or absorbing reactive power and black start capability after complete blackouts will not be discussed here. Depending on the country the denomination of specific reserve types may vary. Demand is already offering ancillary services in various countries, see [1] for experiences in five markets (Australia, UK, Nordic, ERCOT and PJM). They find that demands can offer ancillary reserves without problems under normal as well as contingency situations.

In electric systems reserve must be available at very short notice and availability must be given during a certain time span. In fact, full-automated response may be necessary. The most direct way for loads to fulfil these requirements is via direct load control. An adequate metering infrastructure is as well necessary to monitor the response and check the adherence to demanded requirements. Authors in [2], who analyze the process of demand giving reserve in the New England market, confirm that demand is able to provide reserves within 30 minutes, some within 10 minutes. Thus, some demands overfulfill the requirements set for thermal generators. Other works confirm the ability of demands to react faster than many quick start units do. The work of [3] analyzes the reactions of air conditioning in a hotel complex. Many of the analyzed demands were capable of numerous shorts and as well to less frequent prolonged curtailments. This could be confirmed by [2] and [4]. Indeed, neither were demands subject to ramping or minimum on or off constraints such as some generators. Nor was the efficiency influenced by the curtailments [3]. Authors in [3] state that technically it may be more attractive for some loads to provide contingency reserve rather than peak reduction as this may be needed for various hours per day and various days in a row. In contrast, during a contingency, reserves may be needed only during a short time span until other reserves become operative.

A series of studies is focusing on these contingency situations and bring up the topic of reliability of the electric system. In the work of [5] demand offers reserve and load curtailments for contingency states. The load curtailments and generation redispatch are determined minimizing the market interruption cost. Reserve is paid a different price when it is necessary due to a contingency. Also authors in [6] and [7] analyze how direct load control can be used to give spinning reserve during a contingency. They perform a contingency analysis, select the most severe cases, calculate with an economic model the amount of demand participation in direct load control and confirm via simulation the economic and reliability benefits of demand giving reserve. The authors of [8] are a curtailment service provider describing its experience in offering demand side bids in reserve markets. This curtailment service provider manages reserve offers via remote monitoring, remote dispatch, data collection and reporting. Finally, the author of [9] shows that many aggregated small responsive loads with may provide greater reliability than fewer numbers of larger generators. For the main barrier to using demand to offer spinning reserve under normal system conditions of availability for a short time span, [10] proposes a solution. The total available reserve (thirty minutes) is split up into blocks and used sequentially.

If markets for reserve exist and demands can offer bids into these markets, price-quantity preferences can be expressed with demand functions. The authors of [11] use a market model where demand and reserve is jointly dispatched. Offers are submitted by consumers and generators for energy, upspinning reserve, downspinning reserve, and two kinds of standby reserve. Preferences are expressed with a piecewise linear load benefit function. This function is crossed with the generation cost function to clear the market. They find gains in social welfare which are due to the flexibility introduced by demand-side bids. Consumer increase their profits and market power decreases. In [12] an elastic demand curve is used for offering secondary reserve. The authors identify costs associated to the secondary reserve: frequency deviations, automatic load shedding as a last resource and deviations over the scheduled power exchanges. The authors of [13] argue that when formulating demand reserve functions as step-down functions, these don´t represent appropriately the reserve value. The value of spinning contingency reserve is impacted by the reliability and dynamic characteristics of system components, the system operation policies, and the economic aspects such as the risk preferences of the demand.

Effects of high wind share on reserve

In the former works mentioned in subsection 2.1 reserves where provided by demands without making special emphasis on system with high integration of intermittent energy sources. The presented studies on continuation do take into account how reserves are affected by high wind integration. The authors of [14, 15, 16] analyze especially the impact wind production has on the regulation reserves. In [14] the authors analyse local data from wind farms and show that wind power fluctuations due to wind speed variations are neither completely random considering magnitudes and ramping rates nor extreme. Considering the already existing regulation needs for load, wind power variations may be of less importance if they are to be smaller than existing load variations. They find that regulation reserves are highest if wind is intermediate as both very low and very high wind situations don´t show many fluctuations due to minimum and maximum capacity of wind generators. Nonetheless the author of [15] estimates higher reserve requirements due to higher proportion of installed wind capacity and calculates the cost coming along with wind output variations.

Probabilistic criteria are applied in various works ([17, 18, 19]) to determine reserve requirements. The authors of [17] take load shedding incidents as reliability criterion (related to LOLE Loss of load expectations). Partial and full generator outages are considered. To represent the wind power forecasting errors they use a Gaussian stochastic variable. The reserve level is then related to the reliability over the year. The authors in [18] argue that spinning reserve requirements are set with deterministic requirements. They show three approaches to provide spinning reserve. First, the traditional approach to setting spinning reserve requirements which includes a cost minimizing objective function and ramp constrained reserve restrictions. The second approach determines the maximum allowable probability of risk constraints. Here, the objective function is as well cost minimizing but a reserve restriction is omitted. Instead a restriction limiting the probability of curtailing load (e.g. LOLP) is introduced. A third approach to providing spinning reserve is penalizing the expected cost of interruptions within the objective function. The expected energy non served is weighted with the value of lost load. Then they optimize the spinning reserve requirements using a cost-benefit analysis. They apply stochastic demand and use a cost-benefit analysis to find the optimal spinning reserve amount. Reliability assessment based on a probabilistic method is used in the work of [19] to evaluate the impacts of wind integration from different aspects of planning and operation of a power system. Different reliability models of wind generation are presented in this work.

In contrast to the former works, which determine higher reserve requirements due to wind energy the authors of [16] allocate a part of the operating reserves to wind plants. They use a probabilistic method based on the expected energy not served. Reserve needs are distributed to plants depending on their capacity. Using a pessimistic case they allocate reserves to 20% of rated wind capacity for a limited number of hours and 3% on average.

This paper will analyze how active demand is able to provide reserve. Two cases will be analyzed. One where Demand Side Management in the form of demand shifting is introduced at the same time as demand is capable of providing reserve. In the other one demand will only be able to offer reserve but not to shift load. The modeling will be applied to the island of Gran Canaria. It is neither interconnected with other systems nor does it have at its disposal a hydro plant. So, in contrast to other works, variable intermittent energy production cannot be smoothed with flexible hydro power or energy importation or exportation. Furthermore interactions of demand shifting and reserves have not been studied yet in detail.

The Modeling Approach

Unit Commitment

Unit Commitment problems determine the minimum cost schedule for power plants in order to meet the system demand in the short term and satisfy further restrictions in the power system. Results are startup and shutdown decisions for each generation plant in each hour. Unit commitment problems have been subject to much research, since poor management of power resources can turn out very costly.

In the proposed optimization problem, operational costs are to be minimized over the whole day. We take into account the demand balance constraint, up-and down reserve, minimum and maximum generation capacities, ramping constraints and the logic sequence for the startup and shutdown decisions. The unit commitment problem is solved for each day of the study horizon of a year. Decision variables include startup and shutdown decisions, $on_{p,t}$ and $off_{p,t}$, and unit commitment decisions $uc_{p,t}$. Set p refers to time periods and t to thermal generators. The generation output is split up into two parts. The parameter minimum generation output, $PTMin_t$, and the decision variable $pt_{p,t}$ representing the generation over minimum output for each generation plant. Non-served energy nse_p is another decision variable of this problem. As explained, in the objective function (equation 1), the operation cost of the whole power system, COp_{ante}, is minimized.

$$COp_{ante} = \sum_{p,t}[CVar_t \cdot PTMin_t \cdot uc_{p,t} + CFix_t \cdot uc_{p,t} + CVar_t \cdot pt_{p,t} + COn_t \cdot on_{p,t} + CNse \cdot nse_p] \quad (1)$$

In the former equation (1) decision variables unit commitment $uc_{p,t}$ and startup decisions $on_{p,t}$ for the 24 hours are multiplied by the corresponding costs, namely the fixed cost $CFix_t$ and the startup costs COn_t. The cost term including the minimum generation output for each generation unit is included when the generation unit is committed in this period. Then, minimum generation $PTMin_t$ and generation output over minimum $pt_{t,p}$ are multiplied with the variable cost $CVar_t$ for all hours. Each unit of non-served energy nse_p will cost $CNse$ in each hour.

Constraints are shown in equations (2) to (10). Parameter names begin with capital letters whereas variable names start with lower case letters.

$$DRef_p - PI_p - nse_p = \sum_t PTMin_t \cdot uc_{p,t} + pt_{p,t} \quad (2)$$

$$\sum_t (PTMax_t - PTMin_t) \cdot uc_{p,t} - pt_{p,t} \geq RsUp_p \quad (3)$$

$$\sum_t pt_{p,t} \geq RsDo_p \quad (4)$$

$$pt_{p,t} \leq (PTMax_t - PTMin_t) \cdot uc_{p,t} \quad (5)$$

$$pt_{p,t} - pt_{p-1,t} \leq PTUp_t \quad (6)$$

$$pt_{p-1,t} - pt_{p,t} \leq PTDo_t \quad (7)$$

$$\sum_p on_{p,t} \leq uc_{p,t}, if\ p \geq p' - MOn_t + 1\ and\ p \geq p' \quad (8)$$

$$\sum_p off_{p,t} \leq 1 - uc_{p,t}, if\ p \geq p' - MOff_t + 1\ and\ p \geq p' \quad (9)$$

$$uc_{p,t} - uc_{p-1,t} = on_{p,t} - off_{p,t} \quad (10)$$

Equation (2) assures that demand is balanced all the time. Demand $DRef_p$ and intermittent wind production PI_p are given parameters. Up and down-reserve ($RsUp_p$ and $RsDo_p$) constraints (equations (3) and (4)) make sure that a reliability margin exists in case that one of the generation plants fails or errors in wind or demand predictions must be counteracted. In equation (5), the maximum generation output of a generation plant $PTMax_t$ limits generation output $pt_{p,t}$ over the generation minimum $PTMin_t$. Equations (6) and (7) limit the maximum variation of production output in two consecutive hours. Maximum ramps for each generation unit are expressed with $PTUp_t$ and $PTDo_t$. Equations 8 and 9 refer to the minimum on and off times, MOn_t and $MOff_t$ for each generator after a start-up or shut-down, respectively. The unit commitment restriction (eq. (10)) relates the state of each generator in each hour and the preceding one. While unit commitment variables are binary, startup and shutdown decisions can be continuous, since equation (10) forces them to take binary values.

Demand Side Management

Demand shifting aims to move demand from peak hours to offpeak hours to flatten the demand profile and therefore to lower system costs. As DSM schemes can have manifold forms, two ways to model demand shifting measures will be presented here. In the first one, the decision to shift demand is taken using a pure cost criterion. In the second one, elasticities and demand functions are introduced to model demand reactions.

The first approach models the behavior of consumers as a centralized decision making process. This is similar to the way the system operator acts. He knows the system situation and decides on a cost basis. This could be the case if enough electric devices with an activated delay option were available. So, demand could be delayed automatically to other hours. The demand d_p is then considered as a variable instead of a parameter. Thus, the demand coverage equation (2) in the problem without considering DSM above is changed slightly. The variable d_p is computed from the original demand $DRef_p$ given for one hour subtracting from it the downward demand variation $dVar_{p,do}$ and adding to it the upward demand variation $dVar_{p,up}$ (see equation 11). The sets *up* and *do* refer to the direction of demand changes: rises of consumption in demand valleys and reductions in peak hours. The new demand balance is expressed in equation 12.

$$d_p = DRef_p + dVar_{p,up} - dVar_{p,do} \tag{11}$$

$$d_p - PI_p - nse_p = \sum_t PTMin_t \cdot uc_{p,t} + pt_{p,t} \tag{12}$$

Authors in [20] show that under conditions of perfect competition, maximizing consumer and producer surplus corresponds to minimizing the area below the supply curve (supply cost). This approach has been chosen here. Instead of maximizing the social benefit, a cost-minimizing approach is applied.

The operation cost to be minimized when applying demand shifting is CO_p. This is the sum of the formerly described variable operation cost without demand management COp_{ante} in equation (1). The inconvenience of shifting the demand is expressed with a transaction cost CTr_p for demand rises $dVar_{p,up}$. Demand in high price times is lowered to achieve cost savings but must be consumed during other hours. . Thus, charging the transaction cost on demand increases represents the nuisance of organizing the shift of load to those hours where these increases occur. Demand variations must be balanced during one day (equation (14)). Furthermore, the maximum demand to be shifted from one hour to another is limited using equations

(15) and (16). Here B_{do} and B_{up} quantifies the maximum amount of shiftable demand for each hour and demand direction. This means that demand variations $dVar_{p,do}$ and $dVar_{p,up}$ are limited in both directions in rising power consumption (*up*) and in reducing it (*do*).

$$COp = COp_{ante} + \sum_p [CTr_p \cdot dVar_{p,up}] \tag{13}$$

$$\sum_p dVar_{p,up} = \sum_p dVar_{p,do} \tag{14}$$

$$B_{do} \cdot DRef_p \geq dVar_{p,do} \geq 0 \tag{15}$$

$$B_{up} \cdot DRef_p \geq dVar_{p,up} \geq 0 \tag{16}$$

When introducing the ability of demand to offer reserve various equations are affected. The variable for balance reserve provided by demands is a positive variable which is introduced in the reserve calculation shown in equations 17 and 18.

$$\sum_t (PTMax_t - PTMin_t) \cdot uc_{p,t} - pt_{p,t} + dRs_{p,up} \geq RsUp_p \tag{17}$$

$$\sum_t pt_{p,t} + dRs_{p,do} \geq RsDo_p \tag{18}$$

$$B_{do} \cdot DRef_p \geq dVar_{p,do} \cdot dRs_{p,do} \geq 0 \tag{19}$$

$$B_{up} \cdot DRef_p \geq dVar_{p,up} \cdot dRs_{p,up} \geq 0 \tag{20}$$

Furthermore total reactive demand (including both demand shifting and reserve offers) is limited to B_{do} and B_{up} shown in equations 19 and 20. These equations replace equations (3) and (4) as well as (15) and (16).
If demand can be shifted and furthermore provide reserve, the amount of shifted demand is reduced to offer reserve with free demand variation capacities.

Case Study of Gran Canaria

Gran Canaria is a small island in Spanish territory belonging to the Canary Islands. Being an island and thus in costal area, wind production is becoming an important part of the generation mix. Significant changes in wind output cannot be smoothed by importing or exporting electricity, but have to be compensated by local power generation and demand. Gran Canaria does not have hydro plants which could react to wind production variations. Wind energy as well as demand are expected to grow significantly in the upcoming years. Here, we analyze which effects DSM measures could have on the demand profile during a year and how these would reduce costs in the system.

Data and assumptions on consumer behavior

The generation system considered in the case example corresponds to the one possibly available in 2011. Forecast data are based on the Energy Plan of the Canary Islands [21]. Gran Canaria has two generation sites consisting of a total of 20 units. By 2011, an additional unit will be available. There are four different generation technologies: combined cycle, gas turbine, steam turbine and diesel motors. Electricity generation is mainly based on the heavy fuels gasoil and fueloil. Total installed capacity will amount to 1158 MW. Generation costs used for determining the dispatch are regulated in Canarias and were taken from [22].
Wind time series have been adapted to the case of Gran Canaria taking into account [23]. Annual demand and peak demand forecasts are taken from [21]. For 2011, they are assumed to be 4,183 TWh and 768.38 MW, respectively, which corresponds to an increase of 17.9% and 19.4% compared to 2007 values. Authors in [21] estimate the installed wind energy in 2007 to be 76 MW and objectivize it to more than triple to 272 MW in 2011. Regulation reserves are provided for each hour.
The load shifting potential is difficult to quantify, as few studies are available. The author in [24] analyses different household appliances and their potential to delay their load consumption. He concludes that 5 to 20% of these devices would use a delay option in the future. Other authors in [25] state that the percentage of consumers that could be adherent to load shifting could amount to 19%. Given that our model includes not only domestic but also commercial and industrial consumers, a conservative limit to shiftable demand of 8% of total demand has been applied (see equations (15) and (16)).
The model has been written using GAMS 23.3. Cplex 12.1 hs been used to solve the mixed integer problem on an Intel Core2 Duo with CPU E8500, 3.16GHz and 3.23GB RAM.

Results and discussion

First, the model has been calculated with demands able of both, shifting demand and offering reserve. Then, demand has been limited to offer reserve only. In figure 1 different settings of demand abilities are compared.

Up and *Down* denominate the direction of the offered reserve. *DS&RES* stands for the ability of demand to shift demand and offer reserve while *onlyRES* refers to the limitation of demand only to offer reserve. Figure 1 illustrates that demand in both settings is able to provide a significant share of total reserves. In the *DS&RES* case during night hours reserve offered by demands is relatively low, around 10% or less while it amounts on average to 19% during day hours. Demand that is reduced during peak hours of the day is shifted to offpeak hours during the night. Thus, it results more economic to increase the demand during night time than to offer reserve. Absolute values range from almost 0 (at 6 o´clock) to 25 MW (at 11 o´clock) for up reserve. Down reserves follow another profile. More reserves are offered by demand during offpeak hours in the night and between day peaks. Overall amount of downwards reserves is much lower as it does not take into account the generator outage. Absolute values are between almost 0 and 3.5 MW (22 and 15 o´clock). On average 6\% of the total down reserve is provided by demand.

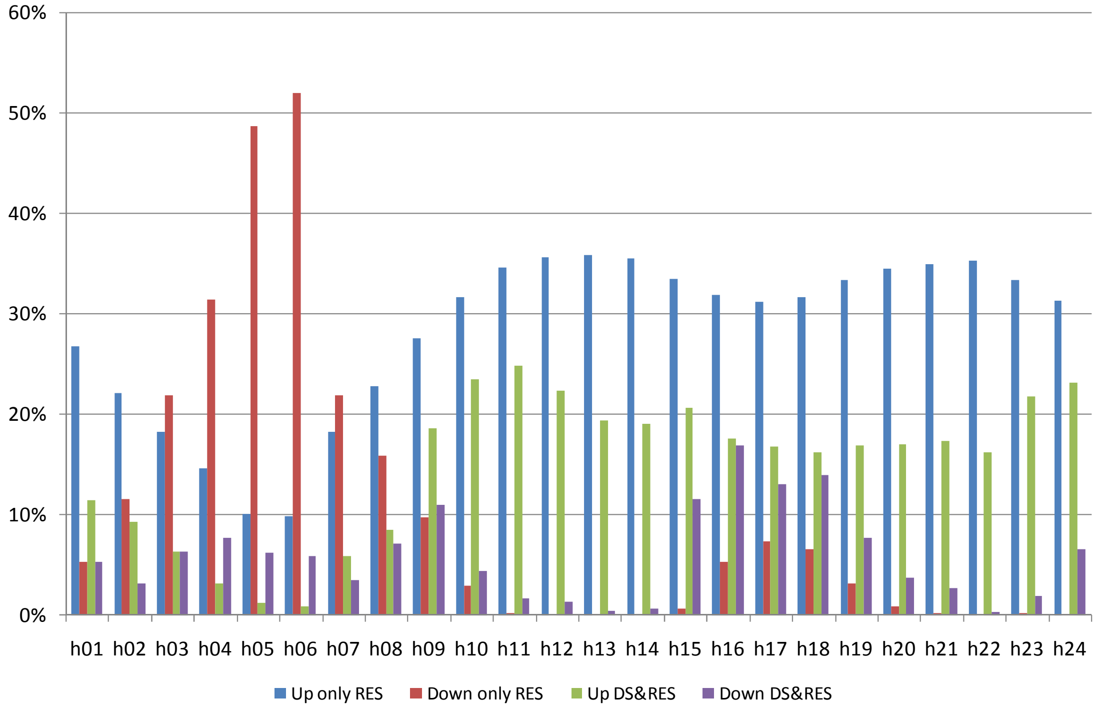

Figure 1: Share of total reserves provided by demands for different settings

When demand is not able to shift, but only to offer reserve, more demand capacity can be offered. So, a share of total reserves of up to 35% can be reached during peak hours. Downwards reserves follow the same pattern as during the mixed *DS&RES* case (see herefore as well figure 2). The share of down reserve for the *onlyRES* case in figure 1 is very high due to the small magnitude of reserve. Absolute magnitudes for up and down reserves range from 9.5 to 36 MW and from 0 to 7.5 MW, respectively.

In total, during the whole year almost 4 million $ are saved when demand can be shifted and provide reserves. This amount corresponds to a daily saving of 10,946$ which is equal to 0.93% of total cost. When demand offers only reserves savings are even greater 4.91 million $, 17,000$ per day or 1.13%.

Reserves offered by demand affect mainly CCGT and steam turbines as these technologies provided around 97% of total reserve needs before introducing responsive demand.

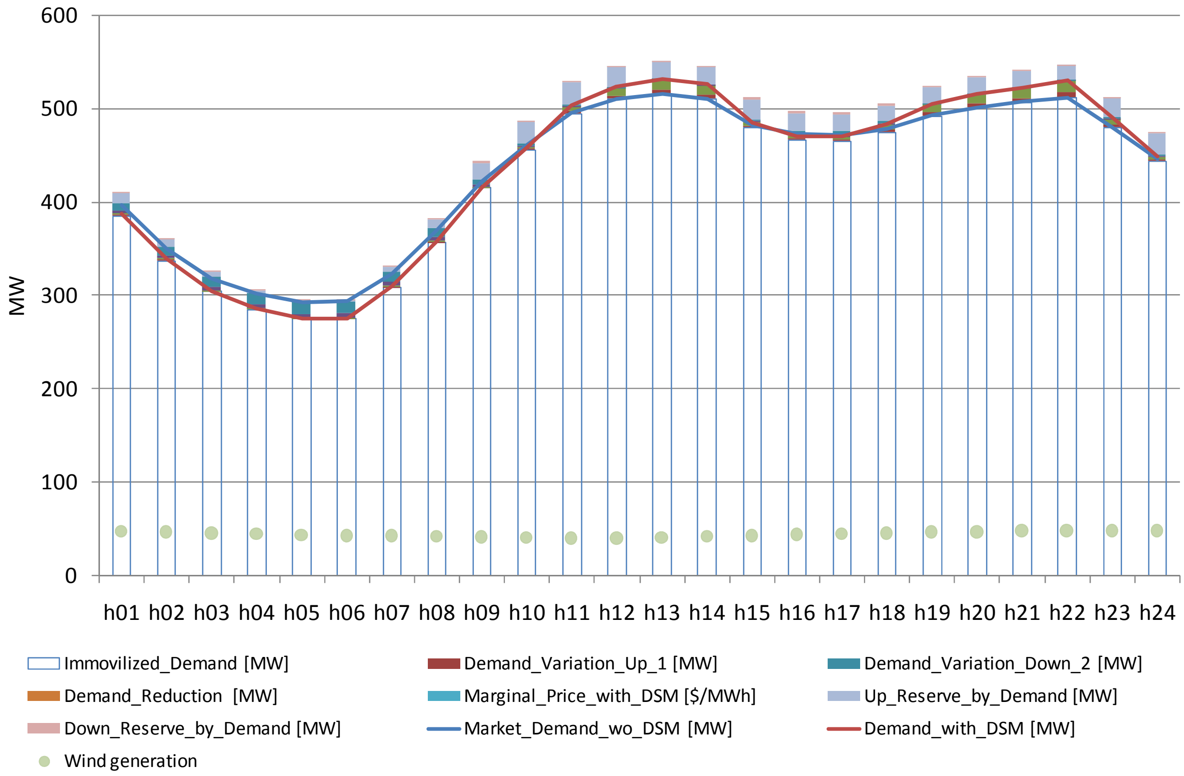

Figure 2: Demand shifting and reserve offered by demand on the average day

Up and down reserves include 10% of forecasted wind energy production. Furthermore reserve takes into account 3% of demand and for the case of up reserve as well the largest generation unit. Installed wind capacity for the chosen reference year 2011 amounts to 19% of total installed generation capacity. Wind energy accounts for around 10% of supplied demand during the whole year. Thus, the influence of wind in reserve needs is rather small. In the analyzed system which does not have neither hydro plants nor interconnections to other systems to balance wind variations, this is already an important amount to deal with. Another situation may be given when looking into the near future, for example to the year 2015 where 411 MW of installed wind capacity are planned. This would account for almost 18% of demand for the whole year and 26% of installed generation capacity.
In the future on the one hand more wind capacity will be installed and thus higher shares of wind forecasting error may be taken into account. On the other hand improvements in forecasting techniques may limit the forecasting error. At the moment it is open how wind energy will influence future reserve needs. It may be of advantage to consider reserves with a probabilistic criterion as decribed in the works of subsection 2.2.

Conclusions

Renewable intermittent energy sources are becoming an important part of the energy systems worldwide. High wind generation capacity normally leads to higher reserve requirements. Adaptations of the systems are necessary. Therefore, reserve requirements need to be linked to the amount of installed wind capacity and to wind production forecast. These requirements can be reduced through demand response. Besides this, demand may be able to offer cheaper and more flexible regulation reserves than thermal plants. This can be especially relevant in emergency or critical situations.

Future work may include studying in detail how increasing wind production should be taken into account when determining optimal reserve levels. Probabilistic modeling of the reserve and wind is another open task. Furthermore aggregation of many small loads into a virtual power plant may be interesting to analyze.

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