Coordinated Trading of Energy Resources and Pumped Storage Systems in Electricity Markets

BY

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DEDICATION

بسم الله الرحمن الرحيم

قُلْ إِنَّ صَلَاتِي وَنُسُكِي وَمَحْيَايَ وَمَمَاتِي لِلَّهِ رَبِّ الْعَالَمِينَ

To my dear father

To my lovely mother, brothers and sisters

To my sincere wife

My Dear Uncle (Sulyman)

My Dear Mother in Law

My Cousin (Hussam)

My Aunt (Siham)

To all friends and colleagues

To every one works in this field

To all of them,

I dedicate this work

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TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

LIST OF ABBREVIATIONS

The notations that used through the paper are stated bellow:

Indices:

t	Bidding period.
s	Scenario.
g	Thermal unit.
n	PSS unit.
d	Wind plant.
e	SegmentB.

Decision variables:

Pp	Optimal bid of thermal unit.
PH	Optimal bid of PSS unit.
PW	Optimal bid of wind plant.
P^{ac}	Actual power output from thermal.
Pg^{reg}, Pp^{reg}, Pt^{reg}	Regulation capacity from PSS in pumping mood, generation mood, and regulation capacity from thermal unit respectively.
P^{acm}	Actual power output from thermal corresponds to the market.
P^{acp}	Actual power output from thermal corresponds to PSS.
W^{acm}	Actual power output from wind plant corresponds to the market.
W^{acp}	Actual power output from wind plant corresponds to PSS.
H^{ac}	Actual power output from PSS unit.
U	Thermal unit state; 1 means ON; 0 means OFF.

P	PSS unit state; 1 means the unit in pumping mood; 0 means Not.
G	PSS unit state; 1 means the unit in generation mood; 0 means Not.
δ	Thermal power output corresponding to a segment of piecewise linear thermal heat rate curve.
ζ *and* η	Auxiliary variables for computing CVaR
MarkPump	Optimal offer from PSS to purchase energy from them market.
Pump	Total pumped energy through PSS.
V	Energy level in the upper reservoir
ρ	Spot market energy price.

Stochastic variables:

W^{ac}	Actual wind power output.
ρ, ρ^R	Spot market energy price and Regulation prices.
ρ^u, ρ^o	Under- and over-generation imbalance penalties as multipliers of the energy price.
ProbRu, ProbRd	Probability to do regulation up and down respectively.

Other variables:

PROFETS	Total expected profits.
$CVaR_\alpha$	Conditional value at risk at the α confidence interval.
α	Confidence level.
β	Risk-aversion parameter.
PFT	Thermal profits associated with a scenario.
PFW	Wind profits associated with a scenario.
PFPSS	PSS profits associated with a scenario.

PFIMB	Imbalances profits associated with a scenario.
ImbUp	Imbalance-up, or total over-generated energy in excess of combined schedule.
ImbDn	Imbalance-down, or total under-generated energy in deficit of combined schedule.
PSS	Pumped storage system
GENCO	Generation company
MCP	Market clearing price
DAM	Day-ahead marker
PSU	Pumped storage unit

Parameters and constraints:

StUpCost	Start-up cost of a thermal unit.
MinUp	Minimum up-time of a thermal unit.
MinDn	Minimum down-time of a thermal unit.
InitUp	Initial minimum up-time of a thermal unit.
InitDn	Initial minimum down-time of a thermal unit.
RU	Thermal ramp-up rate [megawatt per hour (MW/h)].
RD	Thermal ramp-down rate (MW/h).
FC	Thermal fuel cost.
a,b,c,d	Thermal heat rate curve parameters.
AA	Offset of a piecewise linear thermal heat rate curve.
Slope	Slope of a segment of the piecewise linear thermal heat rate curve.
BrkPt	Break point of a segment of the piecewise linear thermal heat rate curve.
Uic	Initial state of a thermal units.

$\overline{P}, \underline{P}$	Maximum and minimum thermal power output.
$\overline{W}$	Rated wind power output.
CHO	Operation cost for PSS unit.
$V^{initial}$	Initial energy level in the upper reservoir.
V^{final}	final energy level in the upper reservoir.
μp	Pumping efficiency.
μg	Pumping efficiency.
$\underline{V}, \bar{V}$	Minimum and maximum energy level in the upper reservoir.
$\overline{PSSU}$	Rated PSS unit power output.
NT	Number of periods.
Ns	Number of scenarios.
Ng	Number of thermal units.
Nd	Number of wind plants.
Nu	Number of PSS unit.
NE	Number of segments.
$\prod$	Probability of a scenario.

ABSTRACT

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Thesis Title : [Coordinated Trading of Energy Resources and Pumped-Storage Systems in Electricity Markets]

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This thesis deals with the coordinated energy and regulation trading in day-ahead markets, modeled as a mixed integer stochastic program. The idea is to analyze the trading through integration between pumped storage system (PSS) and coordinated wind-thermal generation. These generation units are usually owned by a generation company (GENCO) which is a price taker that performs an optimal self-scheduling for all generation units in order to determine optimal bidding strategy. The mathematical formulation takes into account several uncertain parameters, such as wind power outputs, prices for energy balancing and regulation, and regulation deployment signals. In addition, trading risks are accounted for using the metric of conditional value at risk (CVaR). The optimization problem is modeled using CPLEX software and the coordination between wind and thermal generation is assumed to be existing. Simulation results show that coordinated energy and regulation trading improved CVaR and total expected profit, in comparison to the uncoordinated trading.

ملخص الرسالة

الاسم الكامل: مصطفى سلامة مصطفى السويطي

عنوان الرسالة: الإتجار المنسق لمصادر الطاقة و محطات الضخ والتخزين في أسواق الكهرباء

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هذه الرسالة تتعامل مع مصادر الطاقة المنسقة لتجارة الكهرباء في سوق تنظيم الكهرباء وسوق الطاقة الكهربائية لليوم القادم, تم تمثيل المشكلة عن طريق استخدام البرمجة العشوائية المختلطة بأعداد صحيحة. الهدف من الدراسة هو تحليل التجارة من خلال الدمج بين محطات الضخ والتخزين (PSS) مع طاقة الرياح المتناسقة مع أنظمة التوليد الحرارية. مصادر الطاقة هذه عادة تكون مملوكة لشركة توليد (GENCO) المصنفة مستقبلة للمال المفذة لأفضل جدولة لكل وحدات التوليد الكهربائي من أجل الحصول على أفضل طريقة للمضاربة في أسواق الكهرباء. التمثيل الرياضي أخذ بعين الاعتبار عدة عوامل غير موثوق بها, مثل كمية الطاقة الممكن الحصول عليها من طاقة الرياح, و سعر الكهرباء لكل ساعة في اليوم المقبل, وأيضا قيمة الغرامات المتوقعة على الخلل في كمية الطاقة المزودة, و سعر تزويد خدمة تنظيم الكهرباء, وأخيرا الإشارات المرسلة لتحديد كمية الطاقة التي ستستخدم لتنظيم الكهرباء. في هذه الدراسة تم قياس معدل المخاطرة للمضاربة في أسواق الكهرباء عن طريق استخدام قيمة الخطر المشروط (CVaR). تم تمثيل المشكلة المستخدمة للحصول على الحل الأمثل عن طريق استخدام برنامج (CPLEX), والتنسيق بين التوليد من طاقة الرياح والوحدات الحرارية دائما موجود. نتائج المحاكاة التي تم الحصول عليها أظهرت أن التنسيق في العمل بين كل مصادر الطاقة المستخدمة للمضاربة في سوق الطاقة وسوق تنظيم الكهرباء أظهرت تحسين على CVaR وأيضا على مجموع الربح المتوقع بالمقارنة مع مصادر الطاقة غير المتناسقة في العمل.

CHAPTER 1

INTRODUCTION

1.1 Renewable Energy Values

Rapid demand in electricity is being observed globally in recent times. Furthermore, several forecasting studies expect a decrease in fossil fuel resources in the coming years. Depletion of conventional energy sources has necessitated the research for alternative form of energy. Environmental and economic benefits are also the motivating factors behind using renewable resources. Therefore, interest has increased drastically in renewable energy resources as a means to meet energy challenges in a sustainable ways [1, 2].

Figure 1.1 shows the global renewable power capacities. It is being observed that wind and solar energy are some of the main resources of renewable energy. A major challenge for integrating the renewable energy resources are their variability and limited controllability [3-5]. This can affect negatively the reliability, security, economic efficiency and stability of a power system [6, 7].

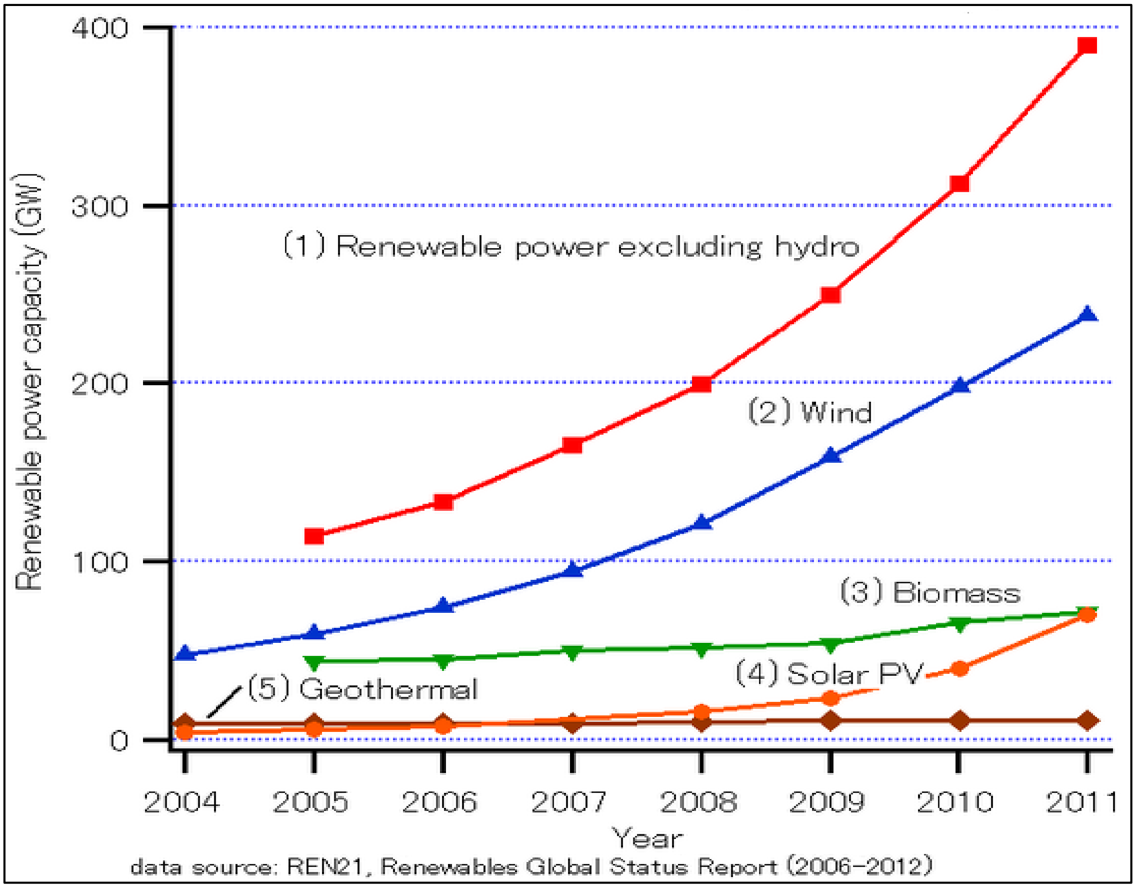

Figure 1-1 Global renewable power capacities (excluding hydro)[8]

Storage systems are proposed to mitigate these negative impacts and reduce the operational cost of power generation [6, 7, 9]. For larger systems having higher penetration of uncertain renewable energy, the use of bulk energy storage like pumped storage system is highly recommended [9, 10].

Sometimes the investment in large storage systems is economically better than the expansion in generation units, because these storage systems along with their storage ability also increase the generation capacity of the system [11, 12], and would allow more penetration of intermittent renewable energy [9, 12, 13].

1.2 Pumped Storage System

Pumped Storage System (PSS) is a hydro facility used to store energy in high scale power system. PSS consist of lower and upper reservoirs and pumped storage units (PSUs); which are hydro units can operate either in pumping or generation modes. The idea behind the use of PSS is that during off-peak generating hours when the generation cost is low, water is pumped to the upper reservoir. This is re-utilized via hydro-turbines during peak load hours, when generation cost is high [4, 5, 7, 10, 11, 14-20]. PSS usually has a larger upper reservoir giving it an ability to store larger amounts of energy. Integrating PSS with an existing system consisting of high uncertain renewable energy such as wind will increase the system security, reliability, and allow larger penetration of renewable energy resources [6, 9, 10].

1.3 PSS in Energy and Regulation Markets

1.3.1 Energy Market

In pool-based energy markets, the market price in each hour is determined based on bids/offers provided by supply and demand rule [5, 10, 21]. This feature has been employed in the Iberian market since 1st January 1998 in Spain, where as in Portugal the same has been employed since 1st July 2007[22]. Contrast to this, IRCOT market adopts bilateral contracts in energy trading [23-25].

In IBERIAN market the day-ahead market closes at 10.00 am just one day prior to the supply and the market clearing prices are published at 11.00 am. Once the day-ahead prices are cleared in an hour; all of the participants should commit to their schedule. To add more flexibility the market will be opened another time for negotiation between 11.00 am to 2.00 pm enabling the bilateral contracts. Then the system operator takes care of the technical constraints resulting from clearing the day-ahead market and the changes that happened when the bilateral contracts took place. Finally, before 4.00 pm the sustainable daily schedules including the secondary regulation market results will be published [5, 22].

The winning participants receive/pay the market clearing price, which is determined by the intersection between the demand and the supply curves in each hours. However, actual real time generation may deviate from the scheduled quantity. This is especially true when the generation company has uncertain generation like wind turbines. In addition, there are always changes from the demand side. These changes should be demolished to maintain the system security. Because of that, real time or spot prices are cleared in the real time hour by hour, as a generation company will pay/receive the spot price for its under-generated quantities [5, 10, 26]. In some markets such as the Iberian market, the penalties for over generation are different from under generation. For over generation, the generation company gets at most the market clearing price at that hour. For under-generation it pays at least the market clearing price [21, 27]. The presences of PSS can reduce the uncertainty level by decreasing or increasing the pumped or generated power during the pumping and generation modes. Figure 1.2 illustrates clearly the operation of PSS [5, 10, 19, 28].

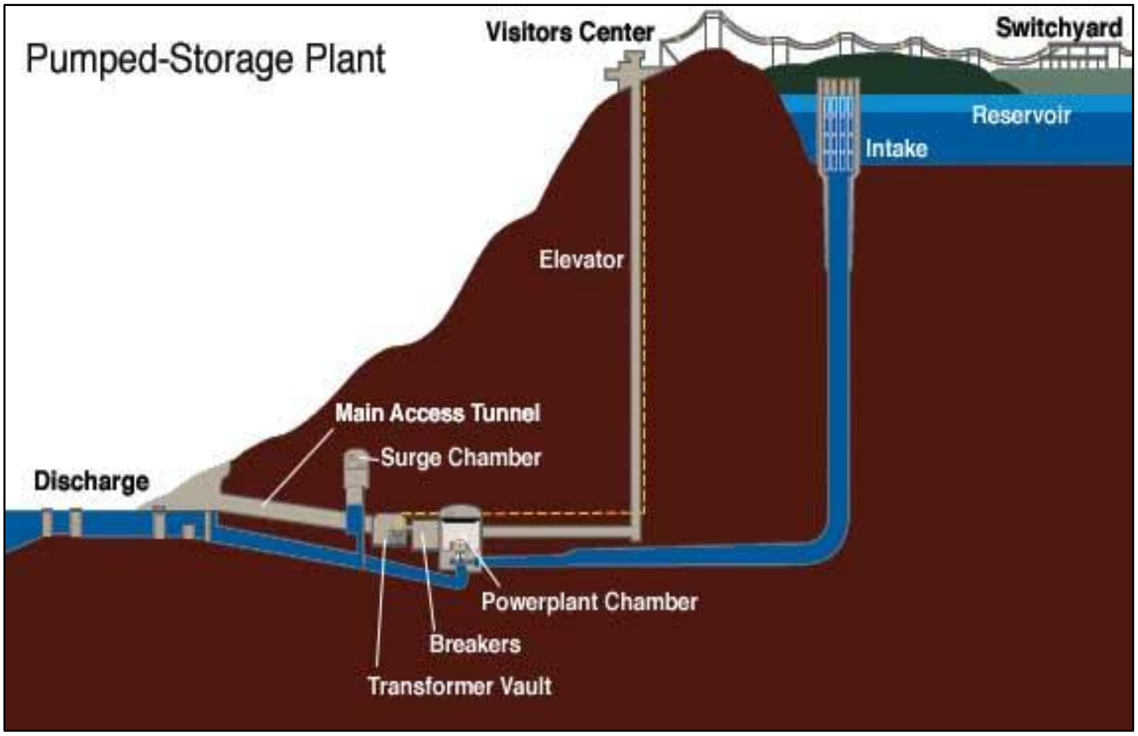

Figure 1-2 Pumped Storage Plant Configuration[28].

1.3.2 Secondary Reserve Market (Regulation Market)

High level of renewable energy penetration could cause power balancing and regulation or load following problems [29-31]. The fluctuations in the generation side poses extra cost to the GENCO as it needs to purchase either balancing services from the market or generators with fast response and high ramping rate [32]. Usually these generators have limited output power with very expensive operational cost [21]. These generators are needed not only for regulation purposes but at the same time they operate to minimize the deviation of the GENCO from its scheduled generation, otherwise paying penalty is a must and vice versa for the case of over generation [21]. However if the generation company owns a storage system, it can be a good solution to deal with surplus power generation. It is worth mentioning that to compensate the under generation mismatch, the storage system needs to be highly flexible to change its output in order to follow the regulation signals [29]. In Iberian market there are three types of regulation reserves; primary, secondary and tertiary. The primary reserve is considered as mandatory service. In Spain, the reaction of speed regulation should happen at least when the frequency deviation is more than 0.01 Hz. In Portugal, the primary reserve must be activated when frequency deviation is larger than 0.2 Hz. The primary reserve activation should remain at most for 15 seconds for disturbances that produce deviation less than 0.1 Hz and changes linearly from 15 to 30 seconds for deviation between 0.1 - 0.2Hz [22]. The secondary reserve is considered as remunerated ancillary service, each participant will get equivalent to the highest marginal price out of the accepted bids for engaging secondary reserve capacity, and the payment of the generated energy will be according to the energy prices. The secondary reserve should be activated in no more than 30 second and should stay not more than 15 min to bring the frequency back to nominal i.e. 50 Hz. The tertiary reserve should be activated in no more than 15 min, if the secondary reserve is not enough to bring the frequency back to nominal value and then each participant should be able to provide power for at least two consecutive hours [22]. For GENCOs it is beneficial to participate in more than one market such as energy and secondary reserve market, this could be more profitable for them especially if they own highly reliable and flexible resources.[10, 18, 29, 33-36].

1.4 Thesis Objectives

This thesis aims to develop and solve a mathematical formulation describing the profit function in order to bid in the energy and regulation markets. The uncertainties which are used in the system have been represented stochastically to build a scenario based optimization problem. The objectives of this thesis are:

1. To develop a profit-maximizing mathematical formulation for a generation company that owns thermal generation units, wind power plant and PSS, to obtain an optimal bidding strategy in the energy and regulation markets.
2. Determine the optimal self-schedules generation in different risk-aversion optimization.
3. Study the effect on the total profit and risk level by integrating PSS with wind-thermal generation in a coordinated and uncoordinated optimization in different risk-aversion optimization.

CHAPTER 2

LITERATURE REVIEW

2.1 Benefits of Using PSS

Several works have been reported in literature regarding the application of PSS in power system operation. In references [7, 16, 37] different techniques have been presented to determine the optimal installed capacity of the upper reservoir and the optimal capacity of the hydro units for PSS. In [37] the uncertainties in load and renewable generation forecasts have been taken into account by developing scenarios. Integration of wind power with the conventional generation system poses few technical constraints which might result wind curtailment [7, 38]. To increase the power sharing from a wind farm already existing and also to allow more penetration of wind power, hybrid systems consisting of wind and hydro power stations (HPSs) have been proposed. Introducing HPS will also increase the generation system capacity, thus the use of expensive units in peak generation periods can be avoided [38]. In reference [19], a robust unit commitment schedule has been done for thermal units under the worst case scenario of the wind generation. The main objective is to insure more reliability to the system by minimizing the total generation costs under this condition and study the effect of including PSUs on the total cost. The fluctuation behavior of wind generation is considered by developing scenarios depending on the historical wind date. The unit commitment schedule depends on these scenarios; so the quality of the unit commitment schedule will increase as much as the number of scenarios increased. The worst case scenario had been forecasted in each time horizon in the day and the unit commitment schedule had been obtained based on it. The formulation has been built to ensure high utilization of wind power and to minimize the total cost under the worst case scenario. The determination of the quality of a selected solution can be obtained by employing an integer variable which represents the uncertainty level in the wind generation. The adjustment of this variable controls the system robustness and the percentage sharing of the wind power. Next, minimizing the cost of the maximum utilized wind power can be obtained at any selection of this integer variable. The same methodology has been used to obtain the solution of the unit commitment with including the PSS. The result showed that PSS stores and generates more power when the uncertainty level increased in order to maintain the system robustness.

In this work, the wind output power is represented stochastically, but the prices of imbalances are not included. The main objective here is to ensure the system robustness not to maximize the owner profit by considering a pool based electricity market. In [5], PSS is proposed to manage the energy imbalances for a generation company that owns wind generation. The goal is to optimize day-ahead energy market bidding. Here the optimization problem is formulated as two-stage stochastic programming problem with two random parameters, wind generation and energy prices. The optimal bid for a day-ahead in the electricity spot market should be determined on spot, however; the optimal output from the generation facilities will be determined by the resources variables. In order to reduce the penalties that could be caused by energy deviations an isolated pumped-storage plant is used, where the objective is to maximize the generation company’s profit. To avoid paying penalties when the system has a large scale of wind penetration using fast thermal units could be a good solution. However, these units have a limited generation capacities and usually have high operation costs. For long term operation having PSS will be more efficient over these small thermal units as PSS operate at low operation cost with very high ramp response [14, 18, 20, 39]. PSS has an advantage of having very high ramp rate [10, 14, 29]. And it is recommended to be installed when the system contains high level of uncertain renewable penetration such as wind to reduce bidding risks for the company and consequently increase its profits [13, 19, 40]. This fast and large storage system can guarantee more profits by participating in both regulation and energy markets[10, 33].

In reference [37], a linear programming problem has been developed to optimize the capacity of the upper reservoir in the PSS in MWh and the installed hydro unit capacity in MW, taking into account the fluctuating behavior of the renewable generation and the load. Scenarios developed through fuzzy logic clustering determine the operating strategies. In this study the operation cost of the renewable generation is not included to avoid forcing the system to give the first priority to the renewable generation. The economic feasibility has been taken into account in order to determine the need of installing PSS, also to determine how much capacity of storage if it is required. The presence of the PSS can increase the sharing of renewable energy in the system by allowing the redundant generation. Enhancement in the economic issues is obtained by carrying out an economic dispatch and unit commitment in order to decrease the cost of generation energy by pumping energy during off-peak hours to the upper reservoir and reutilize this energy during the peak hours. Other benefit of PSS reported includes the decrease in the starting up and shutting down processes for thermal units eliminating a portion of startup cost. The total system load scenarios have been taken in an hourly basis whereas the sharing of the renewable energy generation (wind and hydro), the scenarios haven't been taken for a long time series like week or month.

In order to increase the system flexibility with large amount of wind penetration a storage system is needed. With large scale power system underground compressed air energy, pumped storage systems and installing heat boilers at selected combined heat and power locations could be used to increase the system flexibility from the operational point. The obtained results showed the benefit of installing storage systems will increase the system flexibility and an increased saving in the operational cost. Also the system can allow more wind power penetration as the size of the storage system is increased.

Reference [41] presents a smart grid as a solution to the generation fluctuation arising from renewable energy resources and fluctuations of the load. A methodology for smart grid optimal operation to minimize the interconnection point power flow fluctuation is presented. To satisfy the optimal operation controllable distributed loads have been employed such as heat pump and batteries. Reduction in the electricity cost and consumption could be achieved by minimizing the interconnection point power flows fluctuating.

In reference [42], a mathematical formulation to model a double fed adjustable speed pumped-storage units is developed. The machines in the system are modeled using the representation of the ac field excitation on the wire-wound rotor by representing the voltage in the d-q frame to control of the active and reactive power flow. Utilizing the equations for rotating mass motion and the swing of the rotating machines a dynamic model for the adjustable speed double fed PSUs is derived. There is a high similarity between the experiment real results of the dynamic analysis compared with the simulated results for the modeled system.

Proposing and playing an application approach to simulate the future of an electrical system of three islands in Greek containing wind power generation integrated with pumped-storage system has been performed in [43]. Contribution power from each unit in the system with minimum operation costs have been studied in employing a non-dynamic simulation analysis. The results have demonstrated that introducing pumped-storage system with two penstocks increases the system reliability. With high penetration of uncertain wind generation the system can pump the excess generation from the uncertain wind energy at any time even in peak-hours because the pumping decision is separate from the generation decision. Also the system will allow more wind penetration. Using pumped-storage system specially with high wind penetration is highly recommended owing to its financial, operational and environmental benefits[43].

The authors in [11]showed that PSS can add a good value to the ancillary market services by increasing the system security. The results proved that the existence of PSS achieves fast response emergency reserve by working in the pumping mode and it is the most efficient way for frequency regulation working in the generation mode.

The work in [20] studied the advantage of fast response of coordinated thermal and PSUs as a good resource for the spinning reserve and more efficient than using small thermal units only. The storage of energy during off-peak hours is used for peak shaving and improves system reliability and safety by adjusting frequency, load tracking and supplying reserve [14, 18, 39]. In [20], the unit commitment for the thermal-pumped storage units have been modeled and solved by using Adaptive Cooperative Co-evolutionary Algorithm. The objective function of the modeled system is to minimize emissions and the operational cost of the thermal-pumped storage units. The results showed that inclusion of pumped-storage units in the system improved the operating efficiency of the thermal units, and reduced the overall emission besides supporting the energy saving.

In reference [44], a pumping decision is taken depending on the wind forecasted and the existing price. A collocation method is developed to make an economic dispatch of wind and pump storage units taking into account the decision of pumping power (a discrete variable), while the dispatching generation has to be continuous. It also compared the profit between wind only and wind with a pump storage unit and proved that the wind with pump storage unit is more profitable.

Reference [15] works about the hybrid power system consisting of pumped-storage facilities and wind-solar. With the use of PSS an increase in the reliability of the system and the reduction in the power generation cost are achieved. This hybrid system reflects using new renewable energy system with good performances in the electricity market.

Reference [45] shows that in order to create more renewable energy-efficient and renewable-energy-friendly time of use (TOU) pricing is utilized. Intelligent dispatching system and energy storage devices are proposed to maximize the renewable energy sharing and the profit for renewable energy producers. Dispatching algorithm with several study cases demonstrate the effectiveness from both technical and economic viewpoints.

The authors in [46] used the hourly-discretized algorithm to optimize the daily operation for PSS linked with an uncertain wind farm for three different operation conditions. The optimal operation scheduling for PSS is considered to be depending on the available wind power forecasted with some uncertainty. Optimum operation of PSS showed improvement in the daily economic profit from the wind farm and made the output power from wind generation smoother. The integration of PSS with wind generation allowed the wind power producers to store the energy from their wind farms during off-peak hours instead of selling it on the spot and then regenerate during higher energy price. The wind speed stochastic characteristics have been presented using time series in 48 hours. The wind forecasting represented by the average value of the standard deviation determines the wind power scenarios using Monte Carlo simulation. A linear optimization problem for each scenario is solved employing an awarded factor in the objective function and constraints used are the pumping and generation efficiency for PSUs. The result proved that including a PSS with an uncertain wind generation can make a significant difference in the profit of the wind farm also allowing the system to commit their market bid.

In [47] a fuzzy logic generation scheduling model has been developed for an electric system having an uncertain wind generation and PSS. The fuzzy problem is formulated considering the constraints such as the requirement reserve, balance in load-generation and the wind generation. The results obtained using a fuzzy membership function is compared with a crisp non-linear mixed integer formulation using GAMS software. The comparison showed that the results obtained using the fuzzy generation made a significant difference in the profit over using the crisp formula. Also a reduction in the wind uncertainty is observed with fuzzy generation.

2.2 Ancillary Services Bidding Strategy

In reference [48], a PSS is used to allow the system to limit the intermittence impact of the wind power and to reduce the wind uncertainty level. Increased power sharing by wind energy demonstrated more power fluctuations in the network. Wind energy is considered to be highly constrained as an independent power producer. A mathematical formulation has been developed based on the wind generation forecasting and the forecasted demand. The formulation (deterministic) deals with one wind scenario. The market price, the power demand and the penalty cost are considered in the objective function being formulated as the generation deviation in the active power. There is no bidding strategy reported in the electricity market.

In reference [34], the authors propose a computational model via linear programming mathematical formulation to follow up the scheduled energy in the energy and reserve markets taking into account the security-constrained economic dispatch. This work is aimed to minimize the total costs in real time while operating the scheduled energy and operating reserve including spinning reserve and non-spinning reserve under technical and operational constraints. Deterministic approach for the uncertain variables is followed while dealing with the regulation market from the market side.

Participation in more than one market proves beneficial for generation companies looking to maximize profits. This is governed by the generators technical constraints such as the size of the generation units, type of fuel and other characteristic constraints. Revenues earned through selling of ancillary services provide more profit or cost reduction for generation companies in ancillary services markets. Participation in both energy and ancillary services markets proves more profitable for generation companies having large hydro generation units. Such participation will be more complicated and require a stochastic co-optimization approach. Solution could be obtained creating scenarios for each uncertain value to determine the optimal generation schedule and bidding strategy in the day-ahead markets. Reference [49] does not take into account the up/down imbalances and no risk analysis is carried out. The model formulation is limited to only hydrogenation although it could be easily extended to deal with more than one type of generation at the same time such as thermal, wind, storage system etc.

In the paper [33], the generation company owns a pumped-storage power plant. The problem formulation has been built based on deterministic day-ahead market prices. A mixed integer linear programming scheduling one week for the operation of the power storage power plant provides the expected profit. The authors demonstrated purchase of energy from the market during off-peak hours and resell the same in the energy and regulation market during on-peak hours. This work would be more realistic if the forecasted values (energy price, spot market price, on/off-peak hours, regulation price, and the probability of regulation up/down) had been forecasted stochastically.

A work in reference [26] proposed optimal day-ahead bidding strategy for a generation company in multimarket that included intraday markets and reserve market without considering the penalties for energy deviation between energy bids and actual real-time generation**.**

Another work in [35] proposed energy market model to encourage wind power producers to participate not only in energy market but also in regulation reserve market to provide fast response regulation services. This participation may protect the wind producers from paying penalties for their intra-hour mismatch generation i.e. part of the generation mismatch will be provided as regulation reserve services instead of appearing in energy balance side.

Some storage systems are proposed in [29] such as PSS, conventional hydro power plant, super capacitors, battery banks and other storage facilities, and an economic analysis had been done for each type of them, the comparisons among them depends on many factors such as ramp rate, response speed, life time, costs, environmental impact, efficiency, and other criteria.

In [17] a profit maximization mathematical formula had been developed to result an optimal bidding strategy for a company owned PSS unit with a limited capacity, the owner is assumed to participate in energy and spinning reserve market.

In [50] a scenario based model had been built for an independent power producer to participate in pool based market considering risk analysis.

The work in [11] showed that PSS can add a good value to the ancillary market services by increasing the system security. PSS have fast response ability which makes them favorable to be bid as the system reserve. The results in [11] showed that the presence of PSS helped to achieve fast response emergency reserve by working in the pumping mode and it is quite efficient for frequency regulation by working in the generation mode.

In [10] the bidding strategy for company owns multi stage hydro generation with PSS had been determined. The developed mathematical formulation enabled the company to participate in energy, regulation and spinning reserve markets without taking into account the penalties for the mismatch between the scheduled and actual real time generation. In addition, the participation from PSS in the regulation market is considered to be just in the generation mode but not considered the pumping mode. And the self-scheduling unit commitment has been obtained by maximizing the company profit. This scheduling depends on the forecasted market clearing price to participate in the energy market. In regulation market, one of three cases the company should be requested in real time; regulation up or regulation down or no regulation. The generation company will collect the ancillary service price for the engaged regulation capacity and it will be paid according to the spot price for the regulated energy in real time [10, 33, 49].

CHAPTER 3

SYSTEM DESCRIPTION

3.1 Background

The objective of this work is to maximize profits for a GENCO which owns five thermal units, one wind plant and a PSS. The benefits of coordinating wind-thermal trading over the uncoordinated wind and thermal units in DAM are presented in [21] which was further explored in terms of emissions reduction in [21, 51, 52]. These works utilized small thermal units to compensate the imbalances caused by intermittent wind generation or sometimes GENCO preferred to pay penalty for imbalances whichever proved to have reduced monetary loss.

In this work a PSS is proposed to be integrated with a generation system that has an uncertain renewable resource of wind. PSS is utilized to decrease the uncertainty level for the overall system and to decrease the bidding risk level by reducing the fluctuations caused by wind generation. It generates or absorbs the deviations between scheduled and the actual power generation in real time. PSS have high flexibility in both the pumping or generation modes along with large storage capacity.

Thus, in this work PSS is not only used to compensate for the uncertainty and improving the risk level, it is also proposed to enable the system to participate in the secondary regulation market along with its participation in energy market.

The total energy bidding volume can be calculated by adding the total bidding from all resources which are colored in blue in the schematic diagram for energy market in figure 3-1. Here the actual real time power generation from each unit in the system is colored in red. It is clearly shown that PSS can bid offers to purchase energy from the energy market when it works in the pumping mode and can bid for selling energy when it works in the generation mode. Figure 3-2 illustrates bidding from PSS and thermal units in the regulation market. Committed thermal units can bid in the regulation market where as the PSS can bid in regulation market when it works both pumping and generation modes.

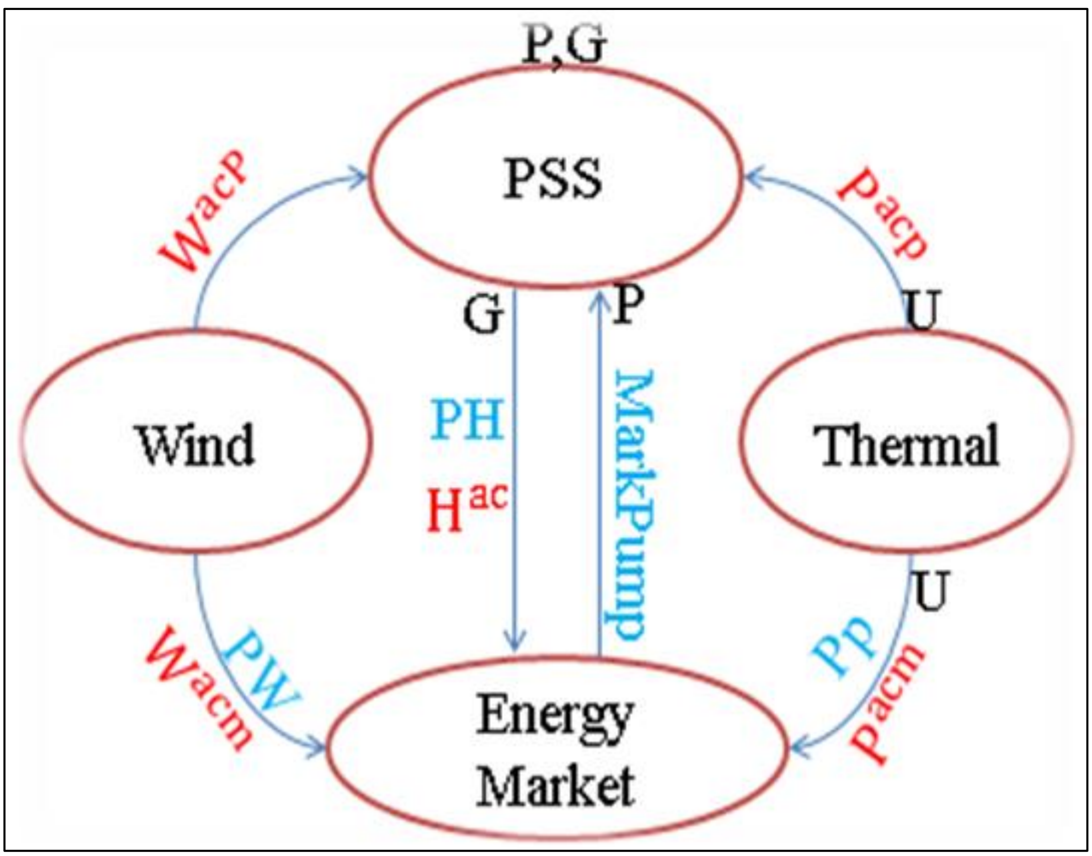

Figure 3-1 Energy market schematic diagram

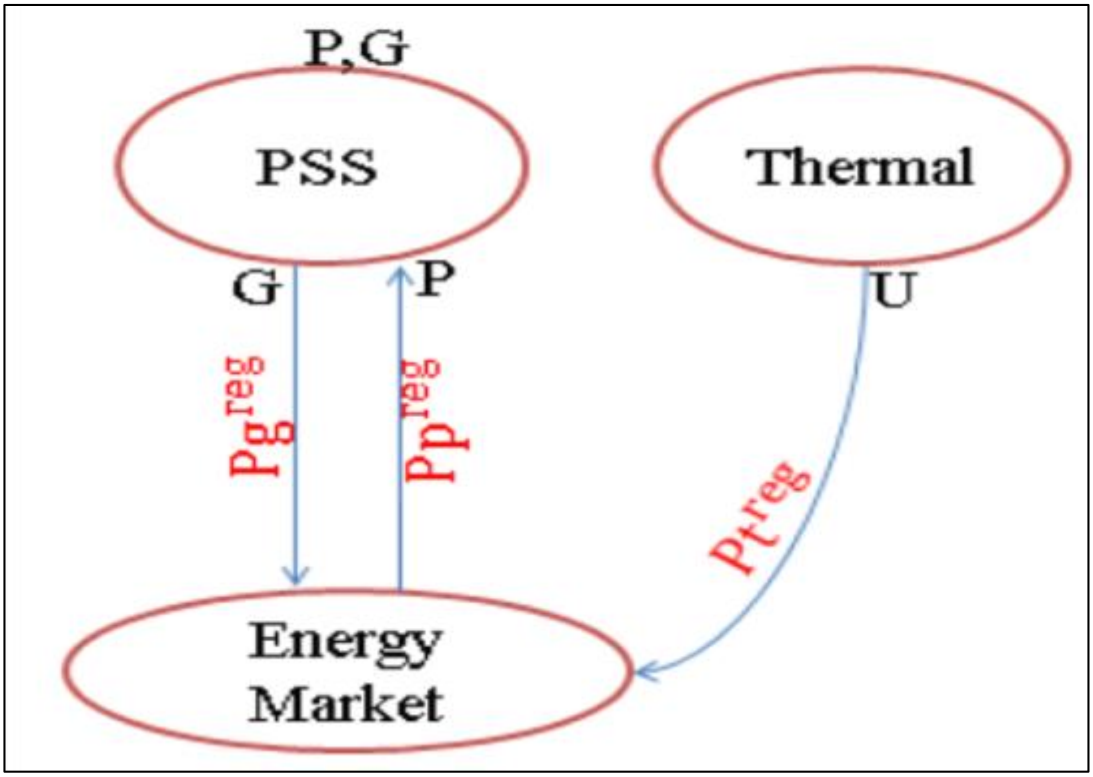

Figure 3-2 Regulation market schematic diagram

The values for uncertain variables will be explained in the next section and it have been forecasted as in [21] to build the scenario tree which consist of wind power output, energy price, imbalance up/down price, secondary regulation prices and the deployment signal for up/down regulation. Three values have been forecasted for each uncertain variable in each hour to create a scenario tree which contains 3x3x3x3x3 = 243 scenarios.

In this study, the coordination between wind and thermal units has always been assumed to exist. This work investigates the effect of coordinating PSS with wind-thermal units on the overall system profit and the bidding risk level. The CVaR which reflects the profit for the least profitable scenarios.

3.2 Stochastic Programming

The optimization problem is modeled as a stochastic program (SP). The stochastic parameters considered are wind power output, energy price, unbalance up/down price, secondary regulation prices and the deployment signal for up/down regulation. The results show that the coordinated PSS has advantages over the uncoordinated one by decreasing the risk and increasing the total profits. Also the results show the additional benefits of having PSS in both cases.

3.2.1 Scenario Generation

The scenarios for day-ahead hourly wind power outputs are generated using wind forecast and statistical properties for wind ramping rate. Using expected value and standard deviation for any given hour, N_s scenarios are generated. These wind power output generated in that manner might violates the ramping rate constraints, as these constrains are disregarded. Therefore, the values of wind power output must be modified to comply with ramping rate constrains, in order to correctly couple each two consecutive hours. To accomplish this task, a number of random values for wind power output in each value for every scenario are produced by adding a random ramping rate considering the mean value and the standard deviation to preceding value. The criteria for choosing one value from the set of random values are the minimum distance between the new value and the originally generated values. The procedure for scenario generation is detailed in the following steps:

Step1: Use the expected value and standard deviation for each given hour to generate Ns scenarios for each hour in the day-ahead separately $W_{t,Ns}^{ac}$.

Step2: Generate random ramping rate using standard deviation and mean for each hour.

Step3: Add the generated value in (2) to $W_{t,s}^{ac}$,this is the first value in the first hour in first scenario which is generated in (1), the obtained value here is $W_{t+1,s'}^{ac}$ .Repeat this for all scenarios.

Step4: Compare the obtained value in $W_{t+1,s'}^{ac}$ with all values in all scenarios $W_{t+1,s}^{ac}$ and select the closest one.

Step5: Swap the selected value in (4) to be associated with$W_{t,s}^{ac}$.

Step6: In the same way do the previous steps for all scenarios in hour 1.

Step7: Do the steps from (1) to (6) for all hours.

To generate scenarios for day-ahead energy market prices, imbalances prices, regulation market price, and regulation up/down deployment signals ARIMA models [21, 53] are commonly used. The participants receive market clearing price for their winning bids. Nevertheless real-time actual generation may deviate from the scheduled quantity.

3.2.2 Scenario Reduction Algorithm

In previously mentioned scenario generation process, a huge number of scenarios are obtained for each uncertain parameter. This makes the optimization problem overloaded with data and scenario tree intractable. Therefore, the number of scenarios is required to be reduced to have a reasonable number of scenarios. The algorithm used for reducing the number of scenarios is the forward selection algorithm [21, 54], the algorithm is executed in the following steps:

Step1: Start with empty subset ω whose first member has minimum sum of distances from members of original set Ω

Step2: The second member in ω is chosen such that the sum of distances of members of ω from members of Ω – ω is minimized

Step3: The procedures are continued until the desired number of scenarios is obtained.

3.3 The Tested System

The test system consists of one wind farm, five thermal units and one pumped storage power plant. The total maximum generation capacity in the tested system is 660MW; where 340MW is the maximum thermal installed capacity, the maximum generation capacity for the wind farm is 200MW, and the maximum upper reservoir capacity for PSS is 600MWh, mainly PSS consists of four units' 30MW each, these units can operate either as a hydro generator or as a pump.

3.3.1 Trading In Energy Market

First part of optimization is considering the optimal trading in energy market to come out with optimal bidding strategy for the coordinated PSS and uncoordinated one.

The technical characteristics for the thermal units and PSUs are presented in appendix. Note that the PSUs are assumed to have high flexibility; each unit can ramp from 0 MW to its full capacity in one hour.

In this part of work there are three uncertain parameters; day ahead wind outputs, day-ahead energy market prices and up/down imbalance prices. Five scenarios are used for each one of these parameters. That is, the scenario tree contains 5x5x5=125 Scenarios. For risk, a commonly used value of the confidence level of α=0.95 is used to calculate CVaR [21, 53].

3.3.2 Trading in Energy and Regulation Markets

In this part of work the test system consists of the same generation facilities which are used in the first part. In this part there are five uncertain values; day ahead forecasted wind output, day-ahead energy market price, up/down imbalances prices, day-ahead regulation price, and the regulation up/down deployment signals. Each one of these uncertain forecasted values has five scenarios, so the scenario tree contains 3^5=243 scenarios. In this part of work, a profits and bids risk levels have been compared in risk-neutral optimization with different cases of risk-aversion optimization of the coordinated PSS and the uncoordinated one. Another comparison has been done between the coordinated PSS and uncoordinated case for the total energy and regulation bids in different risk-aversion optimization.

CHAPTER 4

PROBLEM FORMULATION

4.1 Objective Function

The main objective of this study is to maximize the generation company profit which is considered as an independent power producer by introducing an optimal bidding strategy in both energy and secondary reserve markets. The $CVaR_{\alpha}$ is used as a risk metric to measure the bidding risk level at a confidant level α=0.95 for different values of risk-aversion parameter β. Here β is a weighting value needs to be set before starting the optimization algorithm. In a case when β=0 represents the risk-neutral operation. Where a risk-aversion attitude can be set by choosing β>0. All of technical and operational constraints for wind power plant, thermal units and PSS have been considered. Also energy and regulation markets constraints have been taken into account. The following equations represent objective function formula taking into account several scenarios of the uncertain variables.

$$\text{Maximize} \quad [\text{PROFITS} + \beta * \text{CVaR}_{\alpha}] \tag{4-1}$$

$$\text{Where } [\text{PROFITS}] = \sum_{s=1}^{Ns} \prod\nolimits_{s} * [\text{PFT}_s + \text{PFW}_s + \text{PFPSS}_s + \text{PFIMB}_s + \text{PFREG}_s] \tag{4-2}$$

The first term in (4-1) represents the expected profits of the generating company. As shown in (4-2), the profits term consists of five components. Equations (3)-(7) shows each of these components. Where $\mathrm{PFT_s}, \mathrm{PFW_s}, \mathrm{PFPSS_s}, \mathrm{PFIMB_s},$ and $\mathrm{PFREG_s}$ are scenario profits from thermal, wind, PSS, imbalances, and from regulation market respectively.

$$\mathrm{PFT_s} = \sum_{t=1}^{N_T} \sum_{g=1}^{N_G} \left(\rho_{ts} * \mathrm{Pp_{tsg}} - \mathrm{C_g}\left(\mathrm{P_{tsg}^{ac}}\right) - \max(0, \mathrm{StUp_{tg}} * (\mathrm{U_{tg}} - \mathrm{U_{t-1,g}})) \right) \qquad 4\text{-}3$$

$$\mathrm{PFW_s} = \sum_{t=1}^{N_T} \sum_{d=1}^{N_D} (\rho_{ts} * \mathrm{PW_{tsd}}) \qquad 4\text{-}4$$

$$\mathrm{PFPSS_s} = \sum_{t=1}^{N_T} \sum_{n=1}^{N_U} \rho_{ts} * \mathrm{PH_{tsn}} - \rho_{ts} * \mathrm{MarkPump_{ts}} - \mathrm{CHO} * (\sum_{n}^{N_U} \mathrm{H^{ac}} +$$

$$\mathrm{MarkPump_{ts}} + \mathrm{W_{ts}^{acp}} + \sum_{g=1}^{N_G} \mathrm{P_{tsg}^{acp}}) \qquad 4\text{-}5$$

$$\mathrm{PFIMB_s} = \sum_{t=1}^{N_T} (\rho_{ts}^{o} \rho_{ts} * \mathrm{ImbUp_{ts}} - \rho_{ts}^{u} \rho_{ts} * \mathrm{ImbDn_{ts}}) \qquad 4\text{-}6$$

$$\mathrm{PFREG_s} = \sum_{t=1}^{N_T} \rho_{ts}^{R} * \left(\sum_{n=1}^{N_U} \left(\mathrm{Pg_{tsn}^{reg}} + \mathrm{Pp_{tsn}^{reg}} \right) + \sum_{g=1}^{N_G} \mathrm{Pt_{tsg}^{reg}} \right) + \rho_{ts} * (\mathrm{ProbRu_{ts}} -$$

$$\mathrm{ProbRd_{ts}}) * \left(\sum_{n=1}^{N_U} \left(\mathrm{Pg_{tsn}^{reg}} + \mathrm{Pp_{tsn}^{reg}} \right) + \sum_{g=1}^{N_G} \mathrm{Pt_{tsg}^{reg}} \right) \qquad 4\text{-}7$$

Equation (4-3) contains the scenario profits from thermal units; taking into account the thermal operation cost per unit and the start-up costs per generation units per period. Equation (4-4) express the wind profits per scenario, this profit is a function of the energy prices $\boldsymbol{\rho_{ts}}$ and the bidding energy corresponds with wind $\mathrm{PW_{tsd}}$, in this term the operation and maintenance costs are assumed to be neglected. Equation (4-5) describes PSS scenario profits, it contains the revenue from PSS bidding energy where $\mathrm{PH_{tsn}}$ and $\mathrm{MarkPump_{ts}}$ represent the bid quantity from PSS unit to be sold to energy market and the offered energy quantity to be purchased from energy market respectively; the unit operation cost (CHO) of the PSS has been considered while unit is operate in the pumping mode or in the generation mode. Equation (4-6) presents the imbalance up profits and the imbalance down penalty per scenario; the imbalance up or down caused by the mismatch between the actual and scheduled generation. Only one of these two terms can have a non-zero value because the up and down generation can't occur at the same hour. ρ_{ts}^{o} and ρ_{ts}^{u} are used to represent over and under generation penalty factor. The mathematical explanations for up/down imbalances are expressed intensively in [22]. The regulation part is described in (4-7); the first part of the equation represents the expected revenue from regulation market for engaging regulation capacity. Where ρ_{ts}^{R} is day-ahead regulation market clearing price, $Pg_{tsn}^{reg}, Pp_{tsn}^{reg}$ are the bidding volumes from each PSS unit in each hour in each scenario when the unit operates in generation mode or pumping mode respectively, Pt_{tsg}^{reg} represents the bidding volume from each thermal unit in regulation market in each hour in each scenario. The second part represents the expected revenue from the regulated energy in each time segment in each scenario. Where $ProbRu_{ts}$ and $ProbRd_{ts}$ represent regulation up and down deployment signals respectively. Note that, PSS can perform regulation in generation mode and pumping mode. This is contrast to most works reported in literature include regulation only in generation mode [10, 33]. The second term in (4-1) represent a risk metric at a confidant level α. β is a weighting factor that represents the risk-aversion attitude.

4.2 The Constraints

4.2.1 Risk Analysis Constraints

For risk analysis constraints (4-8) – (4-10) are needed. As in the relation (4-9) the scenario profits should be more or equal the difference between the auxiliary variables ζ , η_s. As in equation 1 the least profitable scenarios started to be maximized in the CVaR when β is more than zero; that means the profits from these scenarios will be executed from the total profits. More scenarios could be added to the least profitable scenarios which are represented in CVaR when the value β increased [1, 21, 52, 55].

$$\zeta - \eta_s \leq [\mathrm{PROFETS}]_s \qquad 4\text{-}8$$

$$\eta_s \geq 0 \qquad 4\text{-}9$$

$$\mathrm{CVaRa} = \zeta - \frac{1}{1-\alpha} \sum_s^{N_s} \prod_s * \eta_s \qquad 4\text{-}10$$

4.2.2 Imbalances Modeling Constraints

Constraints (4-11) – (4-13) are employed to model the imbalances. Note that imbalances refer to the difference between the total bidding and actual power generation from wind, thermal and PSS. It is called imbalance down if this difference is positive, and vice versa. Constraint (4-12) sets the maximum value of the imbalance up. This case is reached when the total bids equal to zero but in real time there is a generation output. Constraint (4-13) sets the limits of imbalance down. The maximum limit can be reached if the total bids equal the maximum capacity of the generator resources but the actual generation in real time equal to zero.

$$\mathrm{ImbDn}_{\mathrm{ts}} - \mathrm{ImbUp}_{\mathrm{ts}} = \sum_{\mathrm{n}=1}^{\mathrm{N_U}} \mathrm{PH}_{\mathrm{tsn}} + \sum_{\mathrm{d}=1}^{\mathrm{N_D}} \mathrm{PW}_{\mathrm{tsd}} + \sum_{\mathrm{g}=1}^{\mathrm{N_G}} \mathrm{Pp}_{\mathrm{tsg}} - \sum_{\mathrm{d}=1}^{\mathrm{N_D}} \mathrm{W}_{\mathrm{tsd}}^{\mathrm{acm}} - \sum_{\mathrm{g}=1}^{\mathrm{N_G}} \mathrm{P}_{\mathrm{tsg}}^{\mathrm{acm}} - \sum_{\mathrm{n}=1}^{\mathrm{N_U}} \mathrm{H}_{\mathrm{tsn}}^{\mathrm{ac}} \qquad 4\text{-}11$$

$$0 \le \mathrm{ImbUp}_{\mathrm{ts}} \le \sum_{\mathrm{d}=1}^{\mathrm{N_D}} \mathrm{W}_{\mathrm{tsd}}^{\mathrm{ac}} + \sum_{\mathrm{g}=1}^{\mathrm{N_G}} \mathrm{P}_{\mathrm{tsg}}^{\mathrm{ac}} + \mathrm{H}_{\mathrm{ts}}^{\mathrm{ac}} \qquad 4\text{-}12$$

$$0 \le \mathrm{ImbDn}_{\mathrm{ts}} \le \sum_{\mathrm{d}=1}^{\mathrm{N_D}} \overline{\mathrm{W_d}} + \sum_{\mathrm{g}=1}^{\mathrm{N_G}} \mathrm{U}_{\mathrm{tg}} * \overline{\mathrm{P}}_{\mathrm{g}} + \sum_{\mathrm{n}=1}^{\mathrm{N_U}} \mathrm{G}_{\mathrm{tn}} * \overline{\mathrm{PSSU}} \qquad 4\text{-}13$$

4.2.3 Wind Operation Constraints

The actual wind generation is forecasted in each scenario in each hour of the day. Some of this power can be stored via PSS facilities and the rest can be delivered to the market. Equation (4-14) is installed to address this fact. Constraint (4-15) is employed to insure that the bidding energy from wind is within the wind plant capacity.

$$\mathrm{W}_{\mathrm{tsd}}^{\mathrm{ac}} = \mathrm{W}_{\mathrm{tsd}}^{\mathrm{acp}} + \mathrm{W}_{\mathrm{tsd}}^{\mathrm{acm}} \qquad 4\text{-}14$$

$$0 \le \mathrm{PW}_{\mathrm{tsd}} \le \overline{\mathrm{W_d}} \qquad 4\text{-}15$$

Where $\mathrm{W}_{\mathrm{tsd}}^{\mathrm{acp}}$ and $\mathrm{W}_{\mathrm{tsd}}^{\mathrm{acm}}$ are the actual wind power output with respect to energy market and PSS respectively.

4.2.4 Thermal Operation Constraints

4.2.4.1 Actual Thermal Output

Relation (16) demonstrates the fact that the total actual thermal generation can be either delivered to the market or stored in the PSS reservoir. Ramping rate constraints are given in (17). Relations (18) and (19) are employed to insure the bidding and actual power variables from the committed thermal units are within the unit's thermal constraints.

$$\mathrm{P}_{\mathrm{tsg}}^{\mathrm{ac}} = \mathrm{P}_{\mathrm{tsg}}^{\mathrm{acp}} + \mathrm{P}_{\mathrm{tsg}}^{\mathrm{acm}} \qquad 4\text{-}16$$

$$-\mathrm{RD}_{\mathrm{g}} \leq \mathrm{P}_{\mathrm{tsg}}^{\mathrm{ac}} - \mathrm{P}_{\mathrm{t-1,s,g}}^{\mathrm{ac}} \leq \mathrm{RU}_{\mathrm{g}} \qquad 4\text{-}17$$

$$\mathrm{U}_{\mathrm{tg}} * \underline{\mathrm{P}_{\mathrm{g}}} \leq \mathrm{Pp}_{\mathrm{tsg}} \leq \mathrm{U}_{\mathrm{tg}} * \overline{\mathrm{P}_{\mathrm{g}}} \qquad 4\text{-}18$$

$$\mathrm{U}_{\mathrm{tg}} * \underline{\mathrm{P}_{\mathrm{g}}} \leq \mathrm{P}_{\mathrm{tsg}}^{\mathrm{ac}} \leq \mathrm{U}_{\mathrm{tg}} * \overline{\mathrm{P}_{\mathrm{g}}} \qquad 4\text{-}19$$

Where $\mathrm{RU}_{\mathrm{g}}, \mathrm{RD}_{\mathrm{g}}$ represent thermal unit ramp up and down, $\mathrm{P}_{\mathrm{tsg}}^{\mathrm{ac}}$ is the total actual thermal generation from each unit in each hour in each scenario and $\mathrm{P}_{\mathrm{tsg}}^{\mathrm{acp}}, \mathrm{P}_{\mathrm{tsg}}^{\mathrm{acm}}$ represent the actual thermal output with respect to PSS and energy market respectively.

Constraints (4-20) to (4-22) have been employed to model the minimum up time constraints in each scenario. The first relation stats that the thermal unit is not allowed to be shut down unless it has been running for sufficient period of time, represented by $InitUp_g$. The second constraint guarantees that the thermal unit has been running for minimum up time from t=$InitUp_g + 1$ to $(NT - InitUp_g + 1)$ for the rest of planning horizon. The last constraint apply the minimum-up time constraint to insure that any thermal unit started at any of these periods remains on until the end of the planning horizon.

$$\sum_{t=1}^{\mathrm{InitUp_g}} \left(1 - \mathrm{U_{tg}}\right) = 0 \qquad 4\text{-}20$$

$$\sum_{n=t}^{t+\mathrm{InitUp_g}-1} \mathrm{U_{ng}} \geq \mathrm{MinUp_g}.\,(\,\mathrm{U_{tg}} - \mathrm{U_{t-1,g}}\,) \qquad 4\text{-}21$$
$$\forall \mathrm{t} = \mathrm{InitUp_g} + 1 \ldots.\,\mathrm{NT} - \mathrm{MinUp_g} + 1$$

$$\sum_{n=t}^{\mathrm{NT}} \mathrm{U_{ng}} - \left(\mathrm{U_{tg}} - \mathrm{U_{t-1,g}}\right) \geq 0 \qquad 4\text{-}22$$
$$\forall \mathrm{g}, \forall \mathrm{t} = \mathrm{NT} - \mathrm{MinUp_g} + 2 \ldots.\,\mathrm{NT}.$$

Similarly the formulation (4-23), (4-24) and (4-25) have been employed to enforce the minimum down time constraint.

$$\sum_{t=1}^{\mathrm{InitDn_g}} \left(\mathrm{u_{tg}}\right) = 0 \qquad 4\text{-}23$$

$$\sum_{n=t}^{t+\mathrm{MinDn_g}-1} (1 - \mathrm{u_{tg}}) \geq \mathrm{MinDn_g}.\,(\,\mathrm{u_{t-1,g}} - \mathrm{u_{t,g}}\,) \qquad 4\text{-}24$$
$$\forall \mathrm{g}, \forall \mathrm{t} = \mathrm{InitDn_g} + 1 \ldots.\,\mathrm{NT} - \mathrm{MinDn_g} + 1$$

$$\sum_{n=t}^{\mathrm{N_T}} (1 - \mathrm{u_{ng}}) - (\mathrm{u_{t,g}} - \mathrm{u_{t-1,g}}\ ) \geq 0 \qquad 4\text{-}25$$
$$\forall \mathrm{g}, \forall \mathrm{t} = \mathrm{N_T} - \mathrm{MinDn_g} + 2 \ldots.\,\mathrm{N_T}$$

4.2.4.2 Piecewise Linearization of Thermal Cost Curve

As shown in (4-26), a quadratic function is used to express the thermal units generation cost ($C_g(P_{tsg}^{ac})$) [21], [56]. This nonlinear function is piece-wise linearized, in order to make the optimization problem as a linear program. This is done using (4-26) - (4-30). In (4-27) the thermal generation is divided to intervals the total generation costs for the committed units is equal the cost of producing the minimum power (AA_g) added to cost of producing each interval (δ_{etsg}) involved in the generation curve. In order to calculate the total generation cost for the committed thermal unit equation (4-28) is employed and it represents the total actual generation from the committed thermal units including the power generation for regulation purposes. Equation (4-29) is used to determine the utilized energy from each segment of the linearized cost curve. The equation (4-30) is used to determine the cost of producing the minimum band from the committed thermal units.

$$C_g\left(P_{tsg}^{ac}\right) = FC_g * (a + bP_{tsg}^{ac} + c(P_{tsg}^{ac})^2) \qquad 4\text{-}26$$

$$C_g\left(P_{tsg}^{ac}\right) = FC_g * \left\{U_{t,g} * AA_g + \sum_{e=1}^{N_E} Slope_{etsg} * \delta_{etsg}\right\} \qquad 4\text{-}27$$

$$P_{tsg}^{ac} + (ProbRu_{ts} - ProbRd_{ts}) * \sum_{g=1}^{N_G} Pt_{tsg}^{reg} = \underline{P_g} * U_{tg} + \sum_{e=1}^{N_E} \delta_{etsg} \qquad 4\text{-}28$$

$$0 \leq \delta_{etsg} \leq BrkPt_{eg} - BrkPt_{e-1,g} \qquad 4\text{-}29$$

$$AA_g = a + b\underline{P_g^{ac}} + c\left(\underline{P_g^{ac}}\right)^2 \qquad 4\text{-}30$$

4.2.5 Non-decreasing Bidding Curves

Constraints (4-31)-(4-36) are employed to ensure non-decreasing bidding energy curves with respect to energy prices. Constraints (4-31) and (4-32) are linked with wind bidding curves. Constraints (4-33) and (4-34) are related to the thermal bidding curves. Lastly constraints (4-35) and (4-36) correspond to the PSS bidding curves. . In order to enforce non-decreasing bidding curves for all the generation units a sub scenario matrix s' is considered. Here ensures that the bidding in each period for all generation units is at least equal to or less than the bidding for s matrix, if the price in s' is higher compared to the price in s.

$$(\rho_{ts} - \rho_{t\grave{s}})(PW_{tsd} - PW_{t\grave{s}d}) \geq 0 \qquad 4\text{-}31$$

$$\text{if } (\rho_{ts} - \rho_{t\grave{s}}) = 0, (PW_{tsd} - PW_{t\grave{s}d}) = 0 \qquad 4\text{-}32$$

$$(\rho_{ts} - \rho_{t\grave{s}})\left(Pp_{tsg} - Pp_{t\grave{s}g}\right) \geq 0 \qquad 4\text{-}33$$

$$\text{if } (\rho_{ts} - \rho_{t\grave{s}}) = 0, \left(Pp_{tsg} - Pp_{t\grave{s}g}\right) = 0 \qquad 4\text{-}34$$

$$(\rho_{ts} - \rho_{t\grave{s}})(PH_{tsn} - PH_{ts\grave{n}}) \geq 0 \qquad 4\text{-}35$$

$$\text{if } (\rho_{ts} - \rho_{t\grave{s}}) = 0, (PH_{tsn} - PH_{ts\grave{n}}) = 0 \qquad 4\text{-}36$$

Another six constraints are utilized to ensure a non-decreasing bidding for the bidding regulation capacity from thermal units (4-37,4-38) and PSU, in generation (4-39,4-40) and pumping (4-41,4-42) modes.

Non-decreasing bidding constraints for the regulation capacity from each thermal unit:

$$\left(\rho_{ts}^{R} - \rho_{t\grave{s}}^{R}\right)\left(Pt_{tsg}^{reg} - Pt_{t\grave{s}g}^{reg} \right) \geq 0 \qquad 4\text{-}37$$

$$\text{if}\left(\rho_{ts}^{R} - \rho_{t\grave{s}}^{R}\right) = 0, \left(Pt_{tsg}^{reg} - Pt_{t\grave{s}g}^{reg}\right) = 0 \qquad 4\text{-}38$$

Non-decreasing bidding constraints for regulation capacity from each PSU which is operate in generation mood:

$$\left(\rho_{ts}^{R} - \rho_{t\grave{s}}^{R}\right)\left(Pg_{tsg}^{reg} - Pg_{t\grave{s}g}^{reg}\right) \geq 0 \qquad 4\text{-}39$$

$$\text{if}\left(\rho_{ts}^{R} - \rho_{t\grave{s}}^{R}\right) = 0, \left(Pg_{tsg}^{reg} - Pg_{t\grave{s}g}^{reg}\right) = 0 \qquad 4\text{-}40$$

Non-decreasing bidding constraints for regulation capacity from each PSU which is operate in pumping mood:

$$\left(\rho_{ts}^{R} - \rho_{t\grave{s}}^{R}\right)\left(Pp_{tsg}^{reg} - Pp_{t\grave{s}g}^{reg}\right) \geq 0 \qquad 4\text{-}41$$

$$\text{if}\left(\rho_{ts}^{R} - \rho_{t\grave{s}}^{R}\right) = 0, \left(Pp_{tsg}^{reg} - Pp_{t\grave{s}g}^{reg}\right) = 0 \qquad 4\text{-}42$$

4.2.6 Non-Increasing Offers Curves

The stored energy through PSS in the upper reservoir should be delivered from energy market in the uncoordinated case while it is a combination between the purchased energy, actual wind generation and actual thermal generation in the coordinated case. To ensure that the energy price is inversely proportion to the offered energy quantity constraints (4-43) and (4-44) are used.

$$(\rho_{ts} - \rho_{t\grave{s}})(\mathrm{MarkPump}_{tsn} - \mathrm{MarkPump}_{t\grave{s}}) \leq 0 \qquad 4\text{-}43$$

$$\text{if } (\rho_{ts} - \rho_{t\grave{s}}) = 0, (\mathrm{MarkPump}_{tsn} - \mathrm{MarkPump}_{t\grave{s}}) = 0 \qquad 4\text{-}44$$

4.2.7 Pumped Storage System Constraints

The actual power generation and the bidding from each PSU operate in the generation mode in each hour and each scenario should be within its upper and lower capacity limits, as given by (4-45) and (4-46).

$$0 \leq \mathrm{PH}_{tsn} \leq \mathrm{G}_{tn} * \overline{\mathrm{PSSU}} \qquad 4\text{-}45$$

$$0 \leq \mathrm{H}^{ac}_{tsn} \leq \mathrm{G}_{tn} * \overline{\mathrm{PSSU}} \qquad 4\text{-}46$$

Equation (4-47) express the total pumped energy through each PSU operates in the pumping mode in each hour in each scenario should be within its lower and upper limits. The energy level in the upper reservoir in each scenario in each hour of the day is described in equation (4-48); it is clearly shown the energy level in each time each hour (V_{ts}) depends on the previous energy level interval ($\mathrm{V}_{t-1,s}$) and the total pumped (Pump_{tsn}) or generated energy via PSS facilities in the current interval taken into account the generation and pumping efficiencies. Note that the energy level in all hours in each scenario should be within the minimum and maximum limits of the upper reservoir as in (4-49). But the initial energy and final energy levels in all scenarios are given by (4-50) and (4-51), respectively.

$$0 \leq \sum_{n=1}^{N_U} \mathrm{Pump}_{tsn} \leq \sum_{n=1}^{N} \mathrm{P}_{tsn} * \overline{\mathrm{PSSU}} \qquad \text{4-47}$$

$$V_{ts} = V_{t-1,s} + \left\{\mu_P * \left(\sum_{n=1}^{N_U} \mathrm{Pump}_{tsn}\right) - \frac{1}{\mu_G} \left(\sum_{N=1}^{N_U} H_{tsn}^{ac} + (\mathrm{ProbRu}_{ts} - \mathrm{ProbRd}_{ts}) * \sum_{n=1}^{N_U} \mathrm{Pg}_{tsg}^{reg}\right)\right\} \qquad \text{4-48}$$

$$\underline{V} \leq V_{ts} \leq \overline{V} \qquad \text{4-49}$$

$$V_{ts} = V^{\mathrm{Initial}}, \; t = 0 \qquad \text{4-50}$$

$$V_{ts} = V^{\mathrm{Final}}, \; t = 24 \qquad \text{4-51}$$

Equation (4-52) shows the total pumped energy to the upper reservoir; it is a combination from the actual thermal and wind generation in addition to the purchased energy from the market in each hour in each scenario.

$$\sum_{n=1}^{N_U} \mathrm{Pump}_{tsn} = \mathrm{MarkPump}_{ts} + W_{ts}^{acp} + \sum_{g=1}^{N_G} P_{tsg}^{acp} + (\mathrm{ProbRd}_{ts} - \mathrm{ProbRu}_{ts}) * \sum_{n=1}^{N_U} \mathrm{Pp}_{tsg}^{reg} \qquad \text{4-52}$$

Each PSU can operate in one of three modes; pumping mode, generation mode, or offline mode. Offline means the PSU is not operated in either the first two modes. To achieve this purpose constraint (4-53) is employed. G and P are integer decision variables which represent the PSU operating mode, i.e. generation or pumping modes. Constraints in (4-54) and (4-55) are employed to ensure each PSU should stay in the offline mode at least for one hour when it is needed to change the mode from the generation mode to the pumping mode or the opposite [10, 33]. All of the PSUs in all scenarios in PSS are assumed to be initially in the offline mode which is clearly shown in (4-56) and (4-67).

$$\mathrm{P}_{\mathrm{tsn}} + \mathrm{G}_{\mathrm{tsn}} \leq 1 \tag{4-53}$$

$$\mathrm{P}_{\mathrm{t-1sn}} + \mathrm{G}_{\mathrm{tsn}} \leq 1 \tag{4-54}$$

$$\mathrm{P}_{\mathrm{tsn}} + \mathrm{G}_{\mathrm{t-1sn}} \leq 1 \tag{4-55}$$

$$\mathrm{G}_{\mathrm{0sn}} = 0 \tag{4-56}$$

$$\mathrm{P}_{\mathrm{0sn}} = 0 \tag{4-57}$$

4.2.8 Regulation Market Constraints

4.2.8.1. PSS Generation Mode Constraints

Constraints (4-58) to (4-61) are employed for bidding engaged capacity of PSS in secondary regulation reserve market. These constraints will be activated when PSU works in generation mode. Equation (4-58) ensures that the maximum engaged capacity from each PSU, when it works in generation mode could be a half of its' capacity while constraint (4-59) enforce that when PSU operates in pumping mode. Constraint (4-60) is used to ensure that the maximum regulation down capacity is at most equals the PSS unit's actual generation. Constraint (4-61) is used to guarantee that the actual energy generated from the PSU and the power generation that could be asked for regulation up must not exceed the unit capacity.

$$\mathrm{Pg}_{\mathrm{tsn}}^{\mathrm{reg}} \leq \overline{\mathrm{PSSU}}/2 \qquad 4\text{-}58$$

$$\mathrm{Pp}_{\mathrm{tsn}}^{\mathrm{reg}} \leq \overline{\mathrm{PSSU}}/2 \qquad 4\text{-}59$$

$$\mathrm{Pg}_{\mathrm{tsn}}^{\mathrm{reg}} \leq \mathrm{H}_{\mathrm{tsn}}^{\mathrm{ac}} \qquad 4\text{-}60$$

$$\mathrm{Pg}_{\mathrm{tsn}}^{\mathrm{reg}} + \mathrm{H}_{\mathrm{tsn}}^{\mathrm{ac}} \leq \overline{\mathrm{PSSU}} * \mathrm{G}_{\mathrm{tsn}} \qquad 4\text{-}61$$

4.2.8.2 PSS Pumping Mode Constraints

PSS can participate in regulation market when it is being in a pumping mode. It can provide this service by decreasing or increasing its' pumped power. Constraint (4-49) ensure that the amount of bidding capacity from each unit in regulation market should not exceed its pumped energy in each scenario for each hour; because of that the unit can reduce its' pumping to zero when it's asked to do regulation up on its' maximum accepted regulation capacity. Constraint (4-50) is employed to guarantee that the total pumped power from each unit and the bidding capacity in the regulation market should not be more than the unit's rated power. This means the unit can increase the pumped energy to reach its' maximum limit if it's asked to do regulation down.

$$\sum_{n=1}^{\mathrm{N_U}} \mathrm{Pp}_{\mathrm{tsn}}^{\mathrm{reg}} \leq \mathrm{MarkPump}_{\mathrm{ts}} \qquad 4\text{-}62$$

$$\mathrm{Pp}_{\mathrm{tsn}}^{\mathrm{reg}} + \mathrm{Pump}_{\mathrm{tsn}} \leq \overline{\mathrm{PSSU}} * \mathrm{P}_{\mathrm{tsn}} \qquad 4\text{-}63$$

4.2.8.3 Thermal Regulation Market Constraints

The aim of regulation service is to follow the small changes in the load to maintain the system frequency. The frequency deviation needs to be maintained by secondary regulation service. The amount of frequency deviation that requires secondary reserve is quite small compared with the tertiary reserve (may be a difference of 1 Hz). The committed thermal units also can be involved to participate in secondary regulation reserve market constrained with its' ramping up and down rates as in (4-64) and (4-65). Constraint (4-66) ensures that the regulation power can go up till it reaches the upper limit. Equation (4-67) has been employed to guarantee that the regulation power can't go down exceeding the lower thermal unit when it's asked to reduce its' output power with the total accepted regulation capacity to do regulation down services.

$$Pt_{tsg}^{reg} \leq RU_g * U_{tg} \tag{4-64}$$

$$Pt_{tsg}^{reg} \leq RD_g * U_{tg} \tag{4-65}$$

$$Pt_{tsg}^{reg} + P_{tsg}^{ac} \leq \overline{P_g} * U_{tg} \tag{4-66}$$

$$Pt_{tsg}^{reg} + P_{tsg}^{ac} > \underline{P_g} * U_{tg} \tag{4-67}$$

CHAPTER 5

RESULTS AND DISCUSSION

5.1 Solution Methodology

In this work, the optimal bidding strategies are developed for a GENCO having a wind power plant, five thermal units, and PSS. Few papers reported in the literature carried out an investigation by considering coordination between wind and thermal power plants. In this thesis, the coordination between wind power plant and thermal units is assumed to always exist. In the first part of the work, three uncertain parameters (wind power output, energy market prices, and imbalances prices) have been considered. Five scenarios are developed for each uncertain parameter to obtain the scenario tree containing 125 scenarios. The uncoordinated and uncoordinated operation of PSS and generation units for different risk-aversion parameter β is simulated. The case with β=0 is called risk-neutral optimization, while the case when β>0 represents the risk-aversion attitude optimization. The CVaR at confidant level α and total profit for both coordinated and the uncoordinated operations are obtained.

In the next part of the work, the investigation has been carried out for the coordinated and uncoordinated operation among the generation units in order to obtain the optimal bidding strategy in energy and regulation markets. The scenario tree is built by considering five uncertain parameters (wind power output, energy market prices, up/down imbalances prices, regulation prices, and up/down regulation deployment signals). The total number of scenarios in this case is equal to 243. A simulation study is carried out to determine the CVaR at confident level α and total profit for both the coordinated and the uncoordinated operation of the PSS for different risk-aversion parameter β. It is worth to mention that PSS provides energy and regulation services while working in the pumping and generation modes.

5.2 Wind-Thermal-PSS in Energy Market

In this part of work several tests have been done on the proposed system algorithm to come out with comparable results from the coordinated Wind-Thermal-PSS generation, and a coordinated Wind-Thermal generation uncoordinated with PSS. The results mainly are the bidding and offering strategies with several risk-aversion levels. The obtained results are also involving the next 24 hours self-schedule unit commitment for the thermal units and pumped storage power plant. The additional profits and CVaR resulted by installing PSS are also discussed.

5.2.1 Profits Comparisons and PSS Values

Table 1-5 contains the profits comparison between coordinated PSS with the uncoordinated one for different values of risk-aversion parameter. It also presents the additional value in the profit by providing PSS with the coordinated Wind-Thermal. In risk-neutral case (β=0), the additional profit made by coordinating PSS to the coordinated Wind-Thermal units is equal to 2530€. The coordinated PSS profit is increased by 675€ over the uncoordinated one with percentage gain equal to 0.418 %. It is clearly shown the profit is slightly decreased when risk-aversion levels increased to improve CVaR by including more scenarios to the least important risky scenarios.

Table 5-1 **EXPECTED PROFITS AND (PROFITS AND CVaR) GAINS WITH DIFFERENT β**

Coordinated (W+T+PSS)				Coordinated (W+T)		Uncoordinated (PSS)		Coordinated (W+T) +Uncoordinated(PSS)				
β	Profit (€)	CVaR	PSS Value (€)	Profit(€)	CVaR	Profit (€)	CVaR	Profit	CVaR	Profit gain (€)	Profit gain (%)	CVaR gain (%)
0	164460	112410	2530	161930	110530	1855	-105	163785	110425	675	0.412	1.798
0.1	164400	116640	2500	161900	114700	1843	421	163743	115121	657	0.401	1.319
0.2	164230	117600	2480	161750	115710	1838	462	163588	116172	642	0.392	1.229
0.3	164170	117820	2610	161560	116380	1830	488	163390	116868	780	0.477	0.815
0.4	163850	118750	2500	161350	116990	1830	488	163180	117478	670	0.411	1.083
0.5	163840	118760	2570	161270	117180	1820	510	163090	117690	750	0.460	0.909
0.6	163660	119110	2400	161260	117210	1821	510	163081	117720	579	0.355	1.181
0.7	163050	120040	2600	160450	118420	1821	510	162271	118930	779	0.480	0.933
0.8	162820	120320	2630	160190	118750	1821	510	162011	119260	809	0.499	0.889
0.9	162820	120330	2630	160190	118760	1821	510	162011	119270	809	0.499	0.889

The first column in Table 5-1 represents the risk attitude. Risk neutral operation can be done by choosing β equal to zero. In this case the total profit and CVaR for the coordinated operation are 164460€ and 112410€ respectively. It can be noticed that the profit from PSS only in the coordinated case is 2530€. The total wind thermal profit in the uncoordinated optimization is equal to 161930 €, where CVaR is 110530. In this case the profit from PSS is 1588€ and CVaR is -105€. It can be observed that the total profit and CVaR for the uncoordinated operation are 163785€ and 110425€. Where the additional profit and CVaR of the coordinated operation over the uncoordinated case are

675€ and 110425€ respectively. In this case the profit gain which is achieved from the coordination is 0.412%, and CVaR gain is 1.798% which is considered to be a significant enhancement in CVaR. The system has been tested for several risk-aversion attitudes. The complete results are shown in Table 5-1.

5.2.2 Thermal Unit Commitment Schedules

Table 5-2 provides PSU commitment state schedule for the PSS units. Each PSU can be in one of three states pumping, generation, or off-line; P and G represent either the unit in the pumping mode or in the generation mode, respectively in the coordinated PSS. P_{un} and G_{un} represent the PSU state in the uncoordinated PSS. PSS is utilized more often in the coordinated case over the uncoordinated one by 1.5 times. This is because it is not only the purchased energy from the market is used to be stored in the upper reservoir, but also a portion of the actual wind and thermal generation could be stored in the scenarios that have slightly low energy price take into account the lowest imbalance up prices scenarios. Moreover, this allow the PSS to operate more often in the generation mode that's mean PSS can supply the mismatch between the actual and the bidding in wind and thermal energy in the scenarios that have slightly high imbalance down and energy prices.

Table 5-2 **PSUs STATE SCHEDULE FOR COORDINATED AND UNCOORDINATED PSS, β=0**

Hour Number	**h1**	**h2**	**h3**	**h4**	**h5**	**h6**	**h7**	**h8**	**h9**	**h10**	**h11**	**h12**
Unit Number	**1234**	**1234**	**1234**	**1234**	**1234**	**1234**	**1234**	**1234**	**1234**	**1234**	**1234**	**1234**
P	0000	1000	1111	1111	1111	1111	1011	0000	0000	0000	0000	0000
G	0111	0000	0000	0000	0000	0000	0000	0100	1111	1111	1111	1111
P un	0000	0000	1111	1111	1111	1111	0000	0000	0000	0000	0000	0000
G un	1111	0000	0000	0000	0000	0000	0000	0000	0000	1111	1111	1111
Hour Number	**h13**	**h14**	**h15**	**h16**	**h17**	**h18**	**h19**	**h20**	**h21**	**h22**	**h23**	**h24**
Unit Number	**1234**	**1234**	**1234**	**1234**	**1234**	**1234**	**1234**	**1234**	**1234**	**1234**	**1234**	**1234**
P	0000	0000	0000	1000	1100	0000	0000	0000	0000	0000	0000	0111
G	1111	1111	0111	0011	0011	0011	0011	1111	1111	1111	0000	1000
P un	0000	0000	0000	0000	0000	0000	0000	0000	0000	0000	0000	1000
G un	1111	1111	0000	0000	0000	0000	0000	1111	1111	1111	0000	0000

Tables 5-3 shows the thermal unit commitment schedule for coordinated and uncoordinated PSS at risk-neutral case. In this case, the coordination did not change the commitment schedule of any of thermal units.

Table 5-3 **THERMAL UNIT COMMITMENT SCHEDULE FOR COORDINATED AND UNCOORDINATED PSS, β=0**

Beta=0	Hours(1-24)																							
Unit 1	1	0	0	0	0	0	0	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
Unit 2	0	0	0	0	0	0	0	0	**1**	**1**	**1**	**1**	**1**	**1**	0	0	0	0	0	**1**	**1**	**1**	0	0
Unit 3	0	0	0	0	0	0	0	**1**	1	1	1	1	1	1	**1**	**1**	**1**	**1**	**1**	1	1	1	**1**	0
Unit 4	1	1	0	0	0	0	0	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	0
Unit 5	1	1	0	0	0	0	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1

Tables 5-4 is showing the thermal unit commitment schedule for β=0.5 in both coordinated and uncoordinated PSS, where the bolded digits in Tables 5-3 and 5-4 are showing the difference in the thermal unit commitment schedule from risk-neutral case and the risk-aversion at level β=0.5. To avoid the risky scenarios at risk-neutral case as in Table 5-3 the thermal units needs to be committed more often than the case of β=0.5. Where the imbalances are compensated by PSS in risk-aversion case to avoid operating the costly units as much as possible.

Table 5-4 THERMAL UNIT COMMITMENT SCHEDULE FOR COORDINATED PSS, β=0.5

Beta=0.5	Hours(1-24)																						
Unit 1	1	0	0	0	0	0	0	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
Unit 2	0	0	0	0	0	0	0	0	**0**	**0**	**0**	**0**	**0**	**0**	0	0	0	0	0	**0**	**0**	**0**	0	0
Unit 3	0	0	0	0	0	0	0	**0**	1	1	1	1	1	1	**0**	**0**	**0**	**0**	**0**	1	1	1	**0**	0
Unit 4	1	1	0	0	0	0	0	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	0
Unit 5	1	1	0	0	0	0	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1

5.2.3 Energy Bids and Offers

Figures 5-1, 5-2, and 5-3 shows the offered energy to be purchased from energy market to energize PSUs in hours 3, 5, and 6, respectively. Most of the time, the offered energy in the uncoordinated PSS is much higher than it in the coordinated one; because the system use a portion of the wind and thermal power output to decrease the purchased energy.

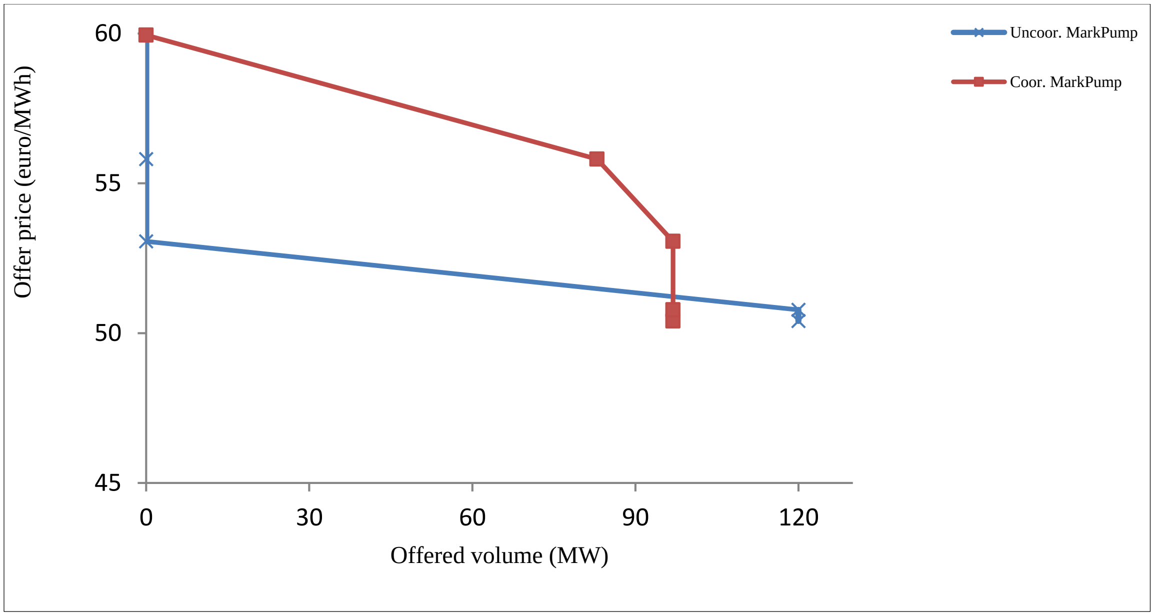

Figure 5-1 **Offered energy curve for hour 3, β=0.**

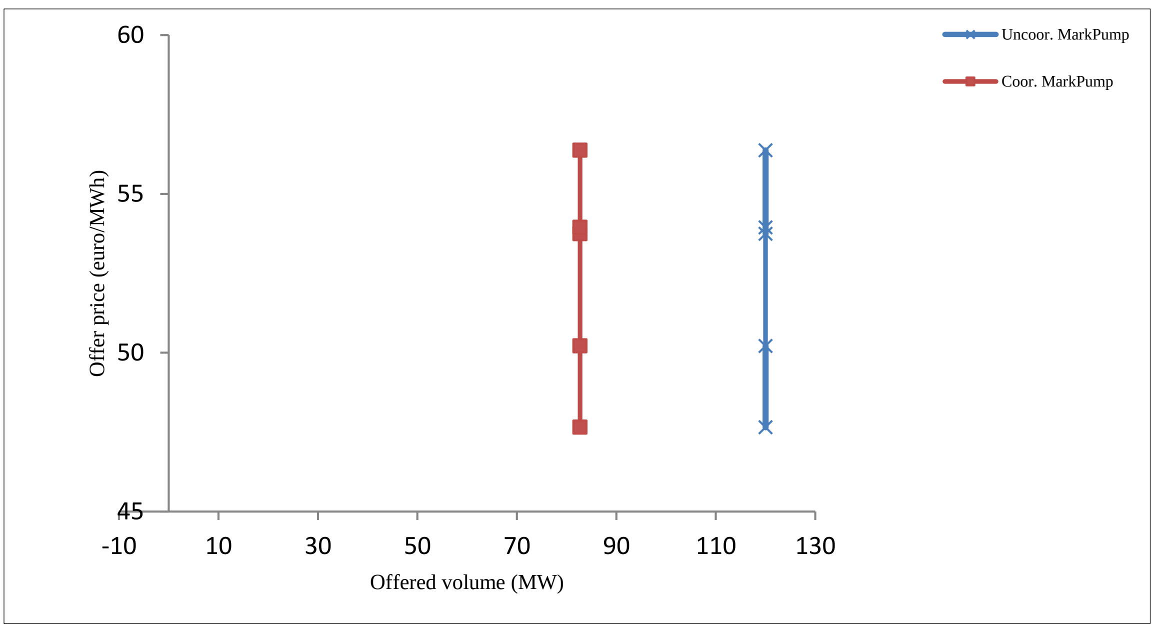

Figure 5-2 **Offered energy curve for hour 5, β=0.**

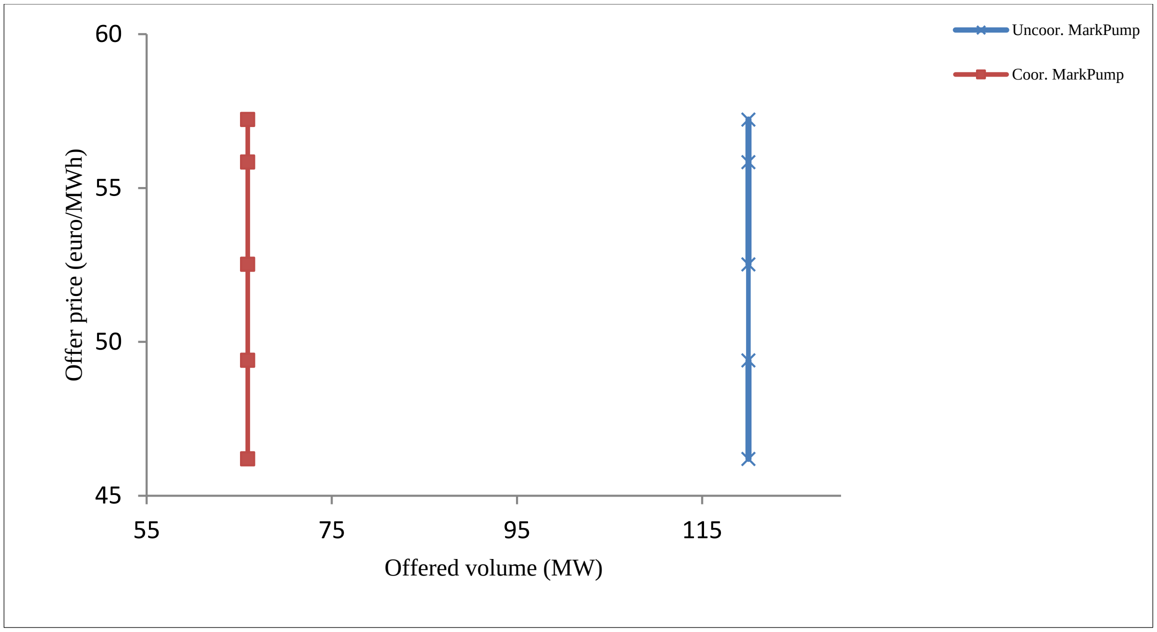

Figure 5-3 Offered energy curve for hour 6, β=0.

Figure 5-4 depicts the expected value of the pumped energy in the coordinated PSS at Risk-neutral level. Clearly in the low energy price periods (from hour 3 to hour6), the expected value of the pumped energy from the market is much higher than others. However the other pumping mode periods (hour 2, 7, and 24) the expected value of the pumped energy from the market goes to zero, where the expected values of the pumped energy from the actual wind and thermal generation remain above zero, therewith the expectation value of the pumped energy from the actual wind power always much higher than the expected value of the pumped energy from thermal generation.

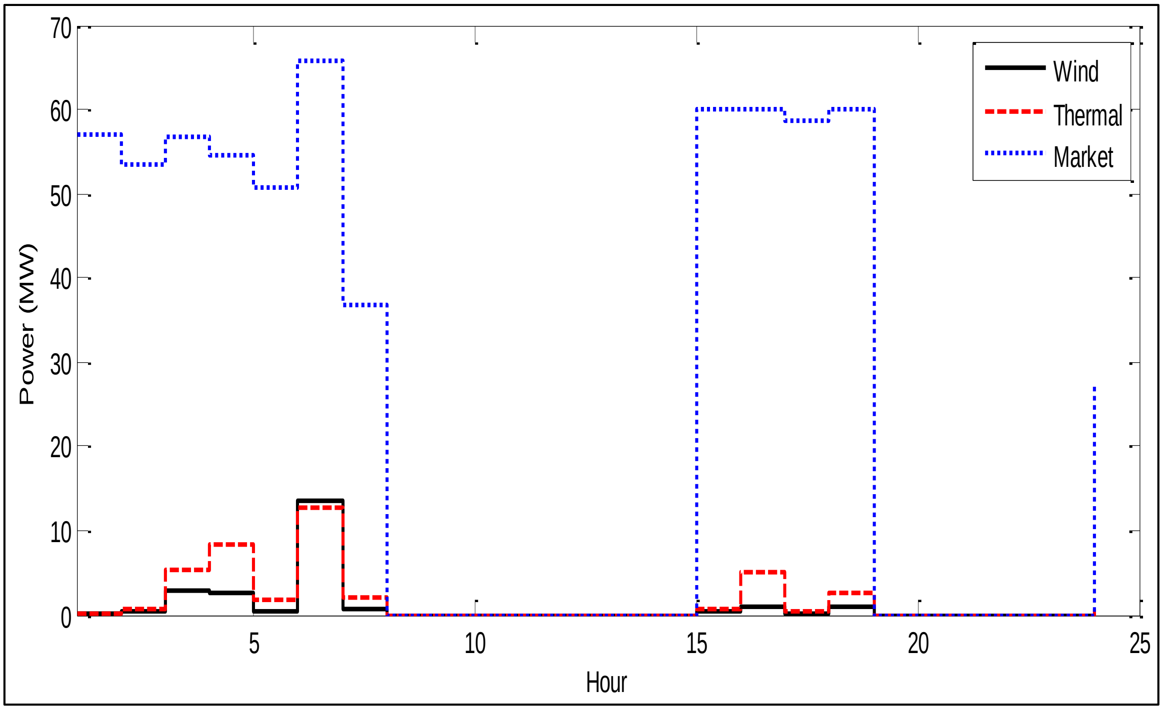

Figure 5-4 **Expectation Values of the Pumped Energy, β=0.**

Figures 5-5 to 5-7 show the bidding curves for hours 1,9,11 and 20 respectively at Risk neutral case for coordinated and uncoordinated PSS. In all hour's coordinated and uncoordinated thermal biddings are different with same unit commitment schedule, also in hours 11 and 21 the coordination PSS make a big difference in PSS bidding curves. It can be noticed also the bidding volumes in the coordinated operation from wind plant most of the time are less than the bidding volumes in the uncoordinated case; that is because some of wind energy is used to be stored in PSS reservoir.

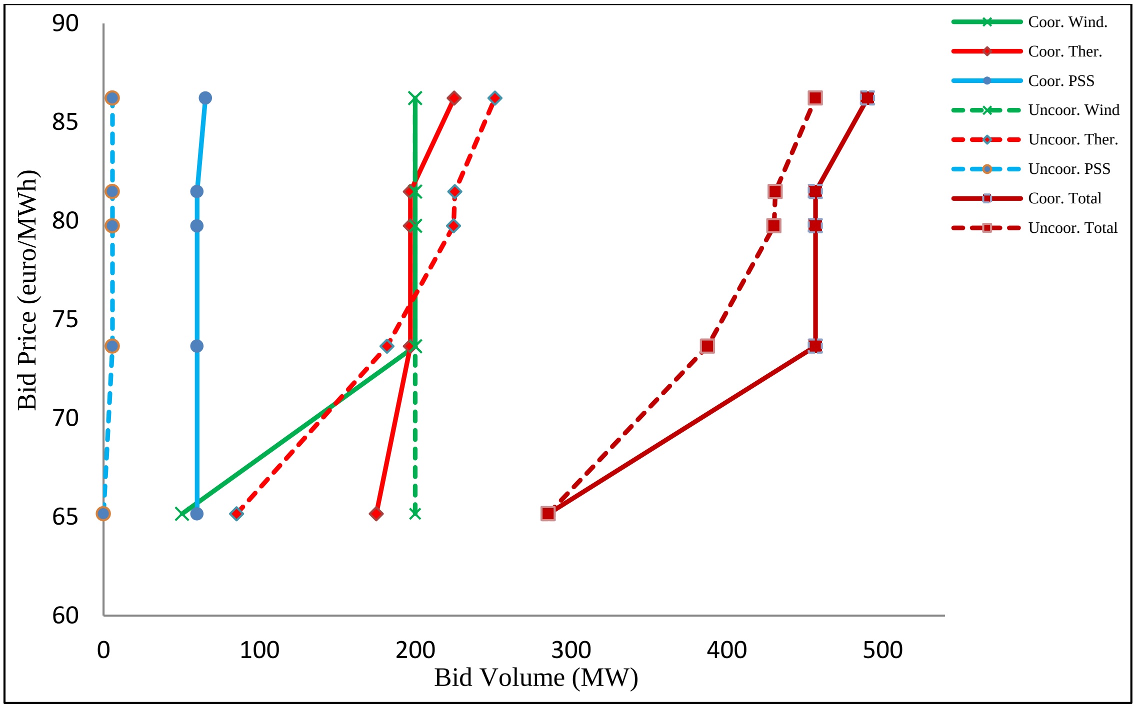

Figure 5-5 **Bidding curves for hour11, β=0.**

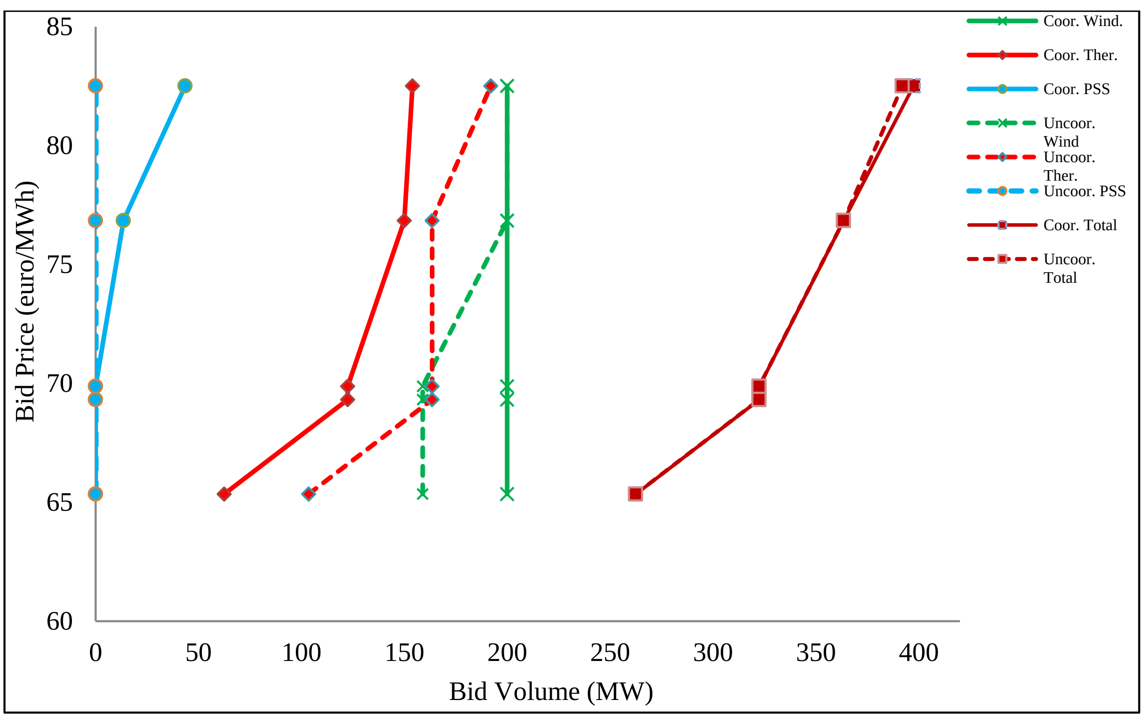

Figure 5-6 **Bidding curves for hour19, β=0.**

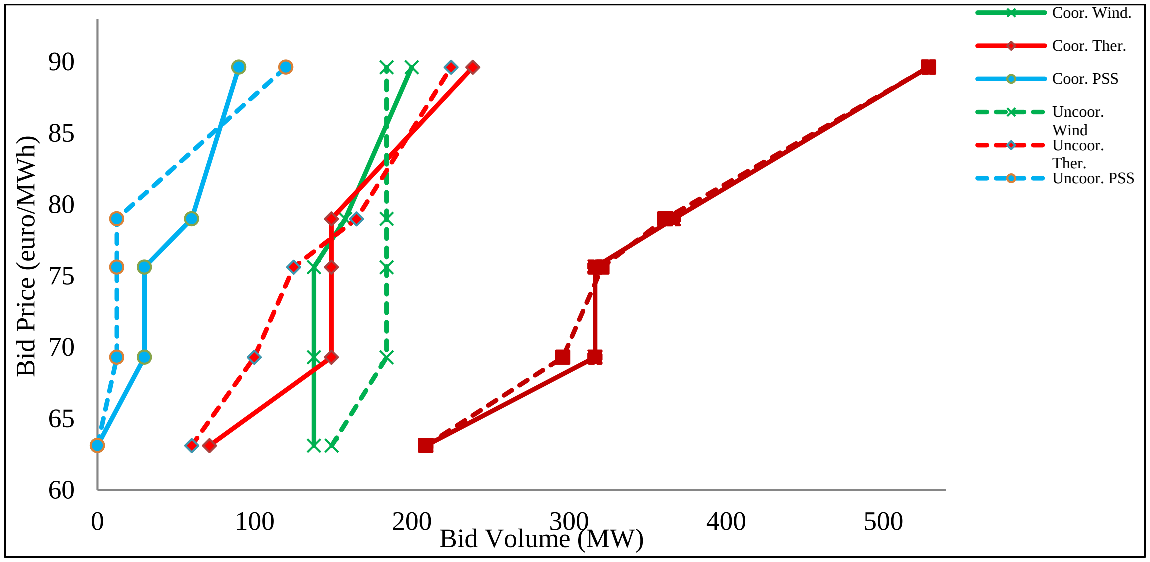

Figure 5-7 **Bidding curves for hour20, β=0.**

Figures 5-8 to 5-10 provide the bidding curves at risk-averse for coordinated and uncoordinated PSS in hours 11, 19, and 20 respectively when PSS work in generation mode. It's worthy to mention that the coordination change the bidding curves for thermal and PSS.

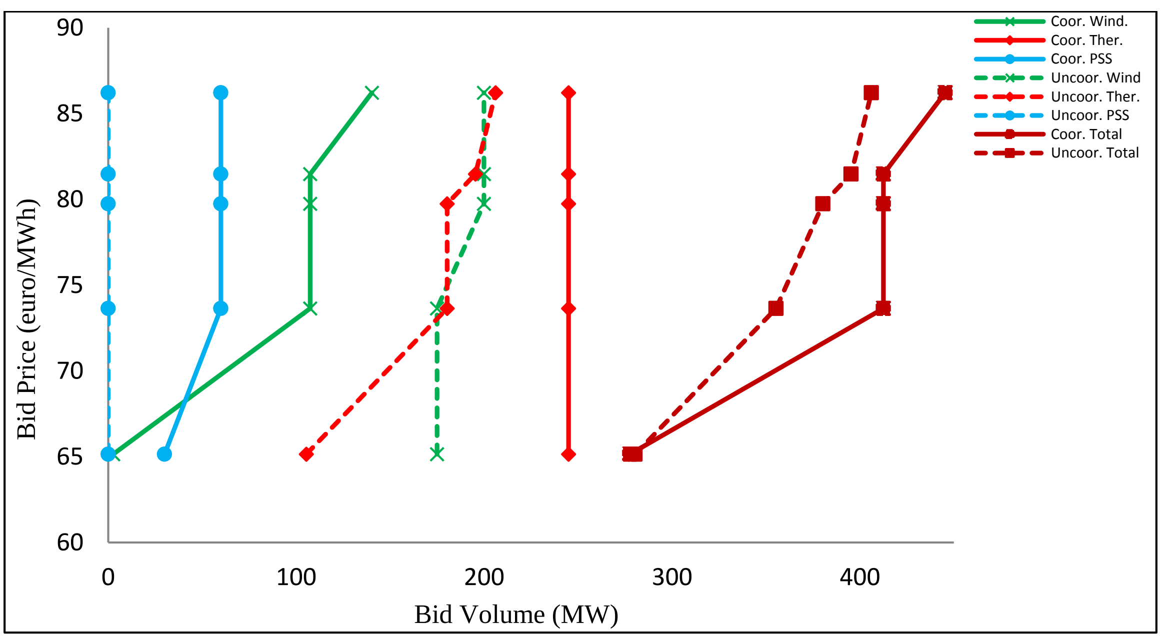

Figure 5-8 **Bidding curves for hour11, β=0.5.**

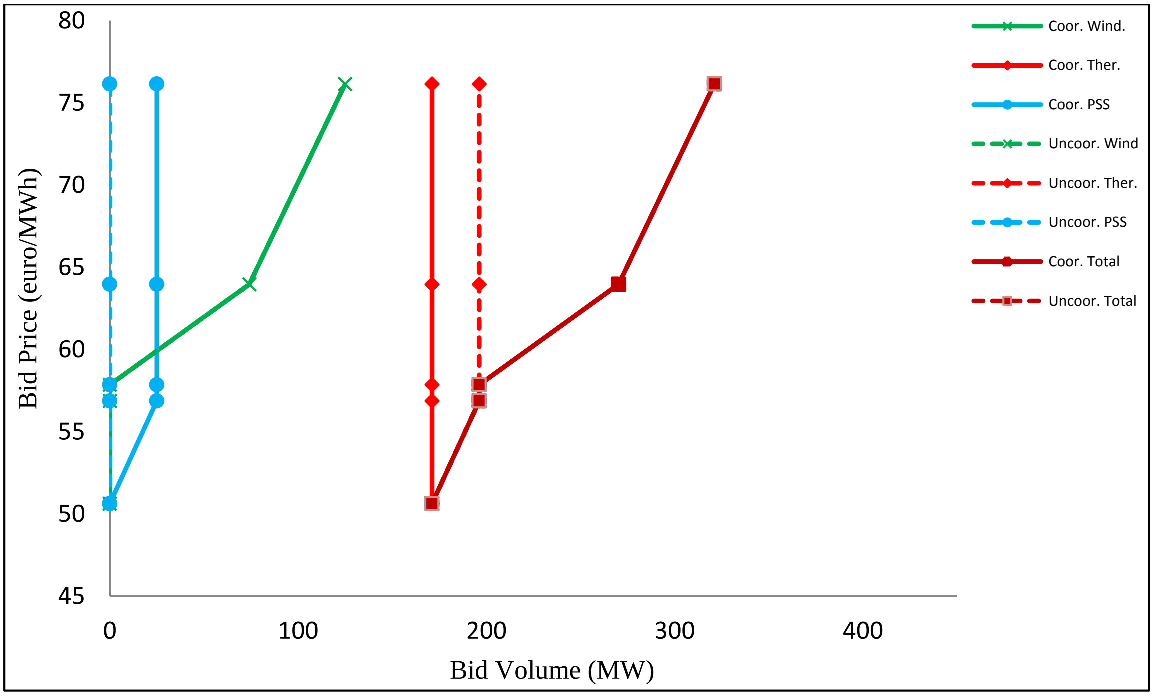

Figure 5-9 **Bidding curves for hour19, β=0.5**

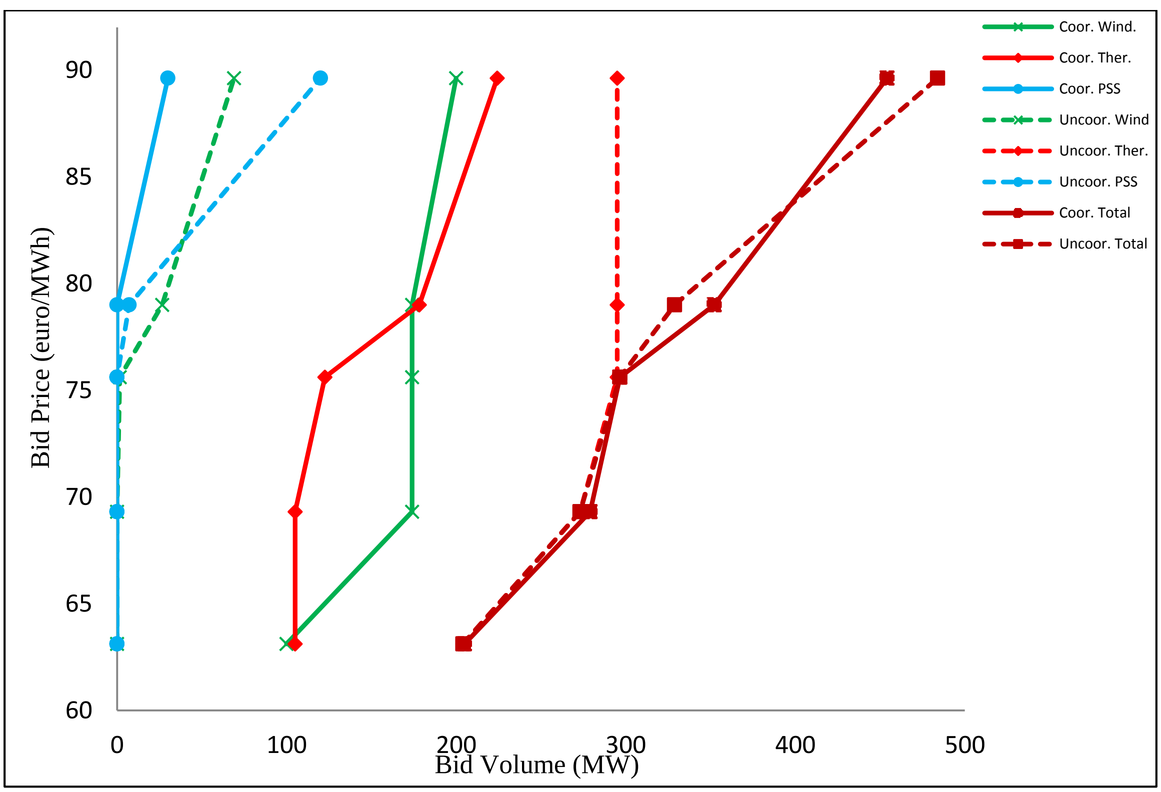

Figure 5-10 **Bidding curves for hour20, β=0.5.**

Figure 5-11 shows the difference total bidding curves at risk-neutral and risk-averse (β=0.5), the result shows the total bidding in risk neutral curves are more or equal the total bids in risk-averse curves. PSS and thermal units tend to be committed more often at risk neutral case.

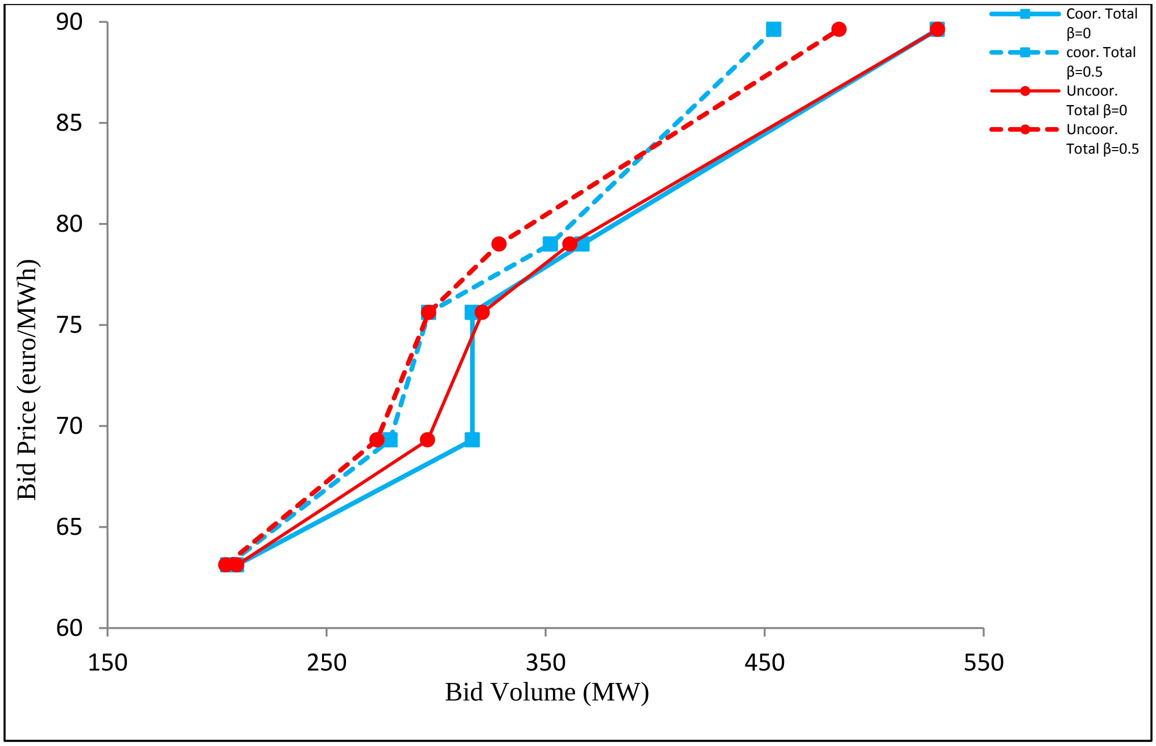

Figure 5-11 **Total bidding curves for coordinated and uncoordinated PSS for hour20, β=0& β=0.5.**

Figures 5-12 and 5-13 show the bidding curves for hours 5 and 6 respectively at risk-neutral optimization. Where figures 5-14 and 5-15 show the bidding curves for the same hours at risk-aversion optimization β=0.5. Obviously, the coordination reduces PSS and total bidding volumes to purchase energy from the market in both risk-neutral and risk-aversion optimization.

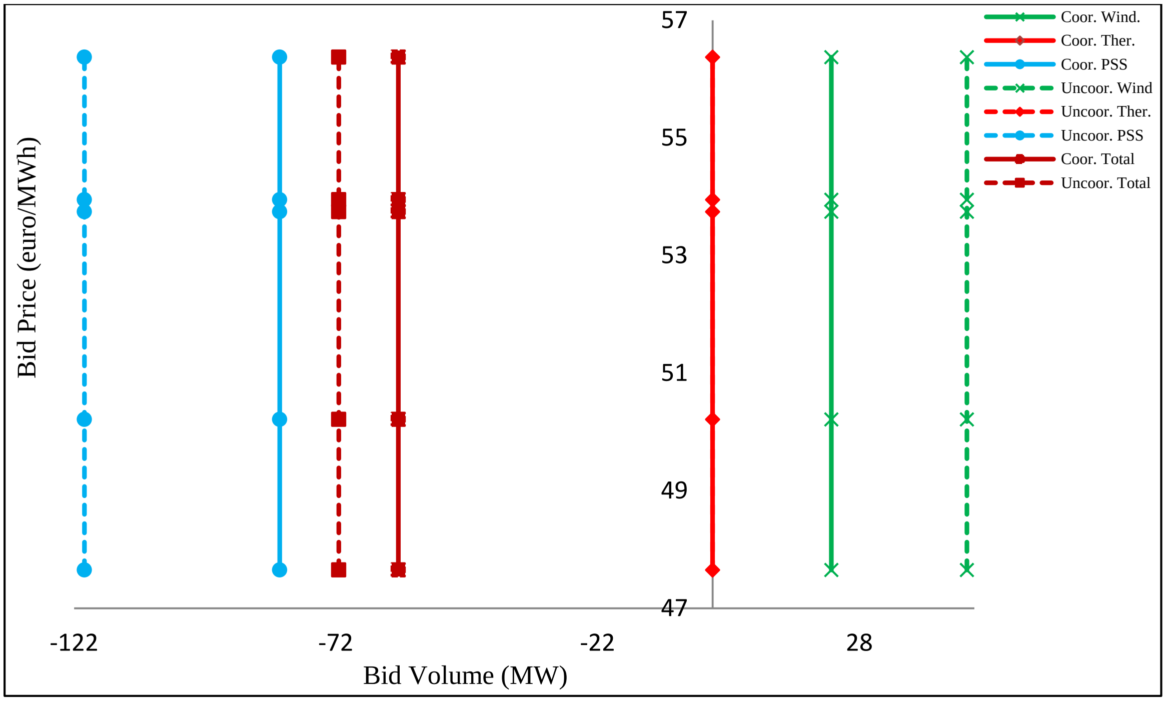

Figure 5-12 **Total bidding curves for coordinated and uncoordinated PSS for hour 5, β=0.**

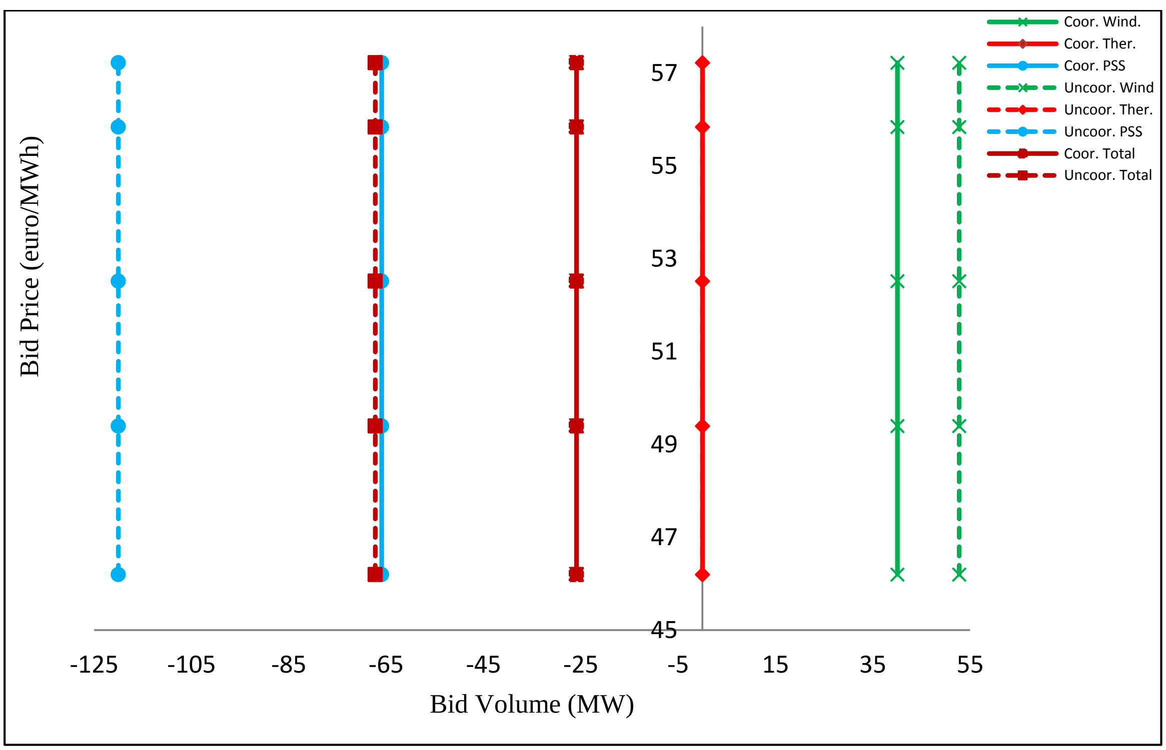

Figure 5-13 **Total bidding curves for coordinated and uncoordinated PSS for hour 6, β=0.**

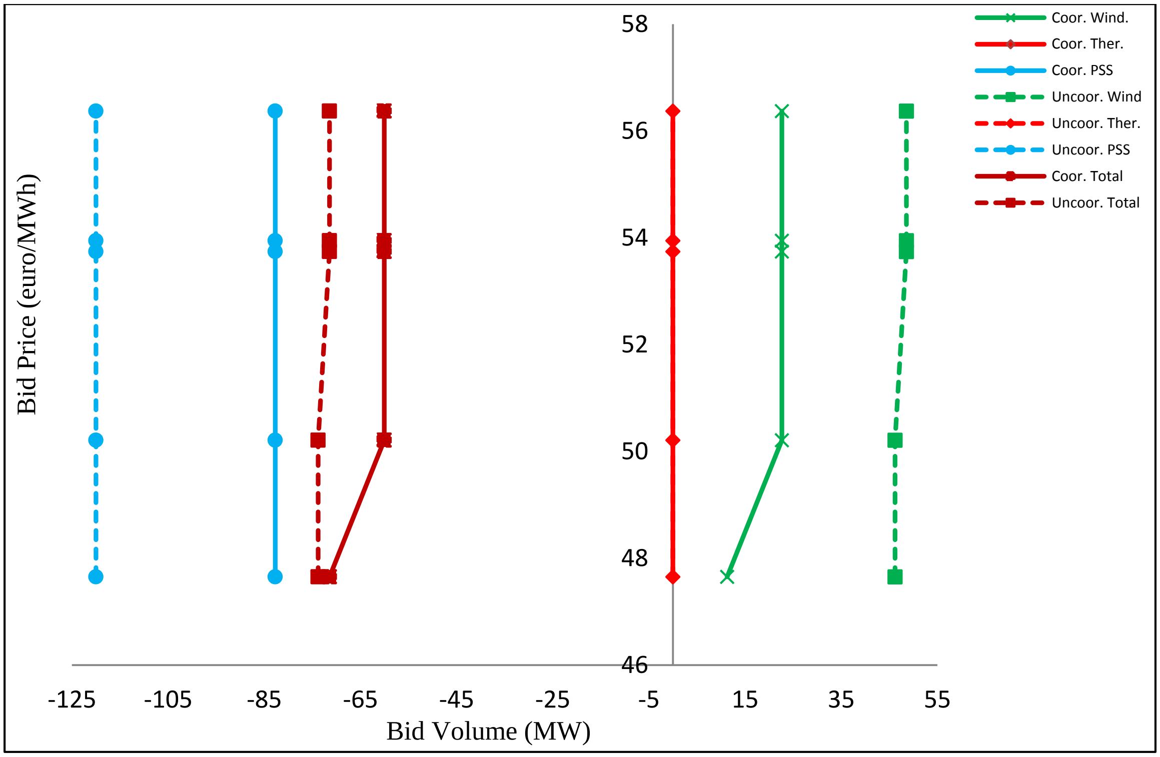

Figure 5-14 **Total bidding curves for coordinated and uncoordinated PSS for hour 5, β=0.5.**

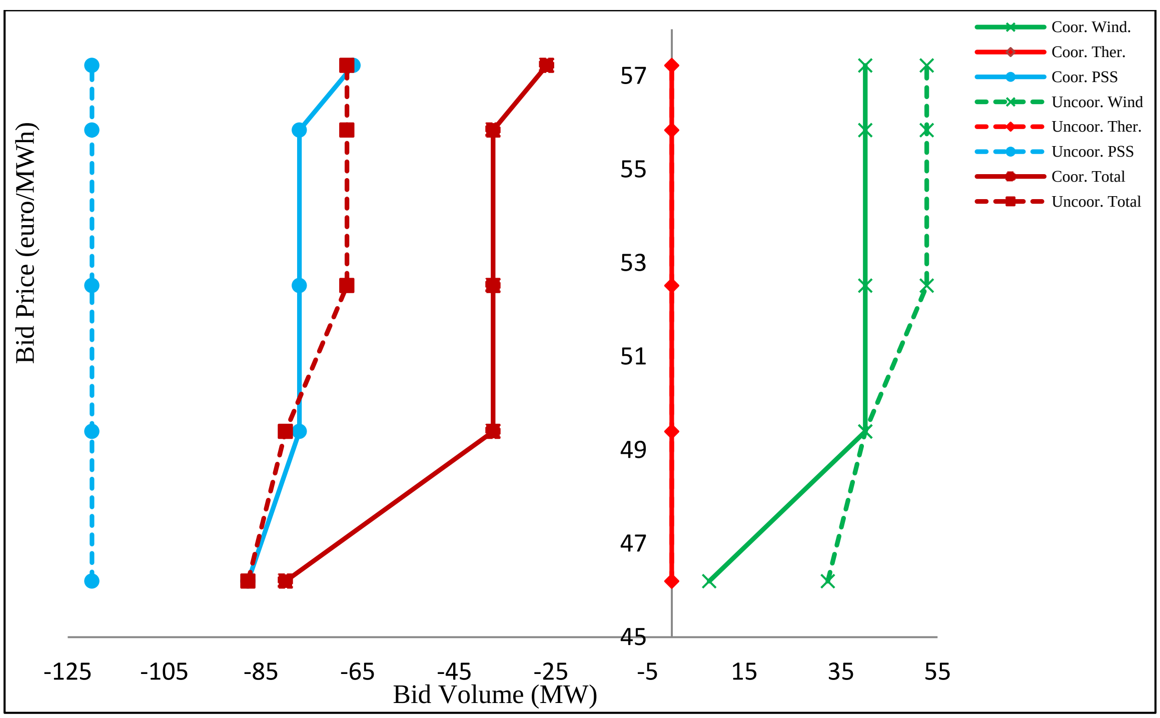

Figure 5-15 **Total bidding curves for coordinated and uncoordinated PSS for hour 6, β=0.5.**

5.2.4 Risk Analysis and Profits Gains

Figures 5-16 and 5-17 shows the relationship between the expected profit and CVaR in different risk-aversion for the coordinated and uncoordinated PSS respectively, as expected results CVaR increases and the profit decreases with the increasing of β.

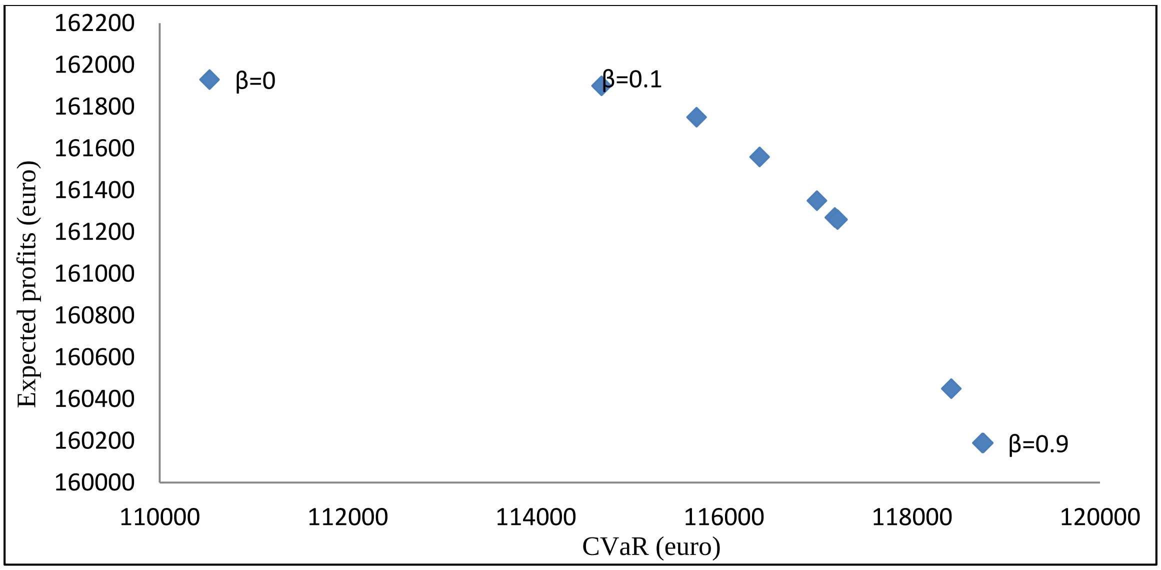

Figure 5-16 **Expected profits and CVaR for uncoordinated wind-thermal bidding**

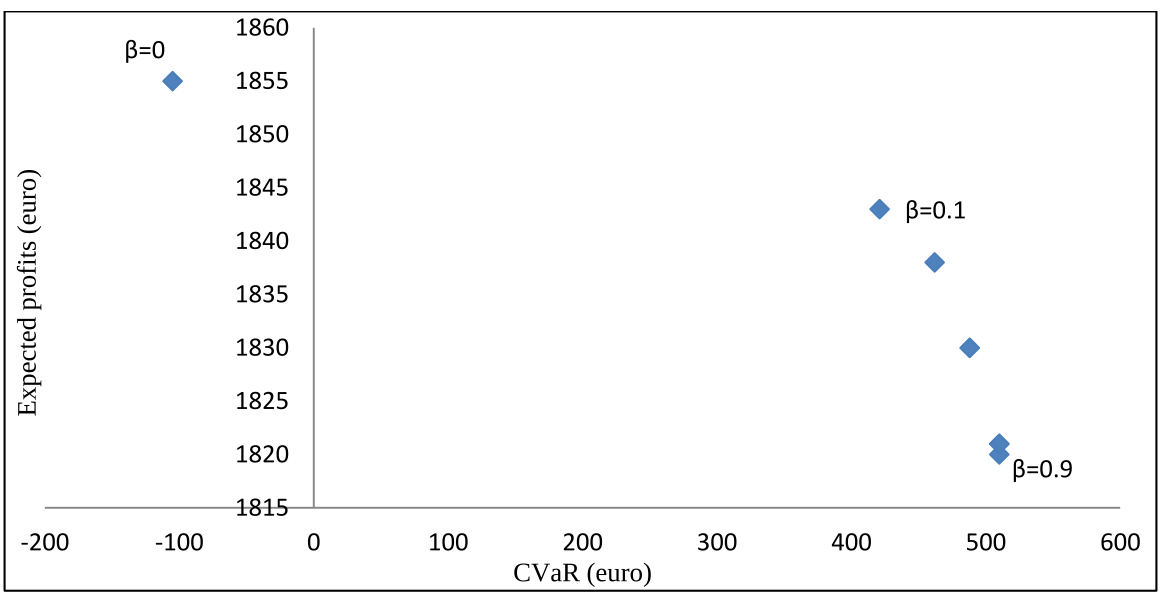

Figure 5-17 **Expected profits and CVaR for uncoordinated PSS bidding**

It’s worthy to mention that when β increased from 0 to 0.1 the expected profit decreased by 0.0356% and CVaR increased by 4.2527% in the uncoordinated bidding; however the same change in β in the coordinated case cause increase in CVaR by 3.763 and decreasing in the profits by 0.0356%, where the expected profits and CVaR are still much higher in the coordinated PSS over than the uncoordinated one and it’s clearly shown in figure 5-18.

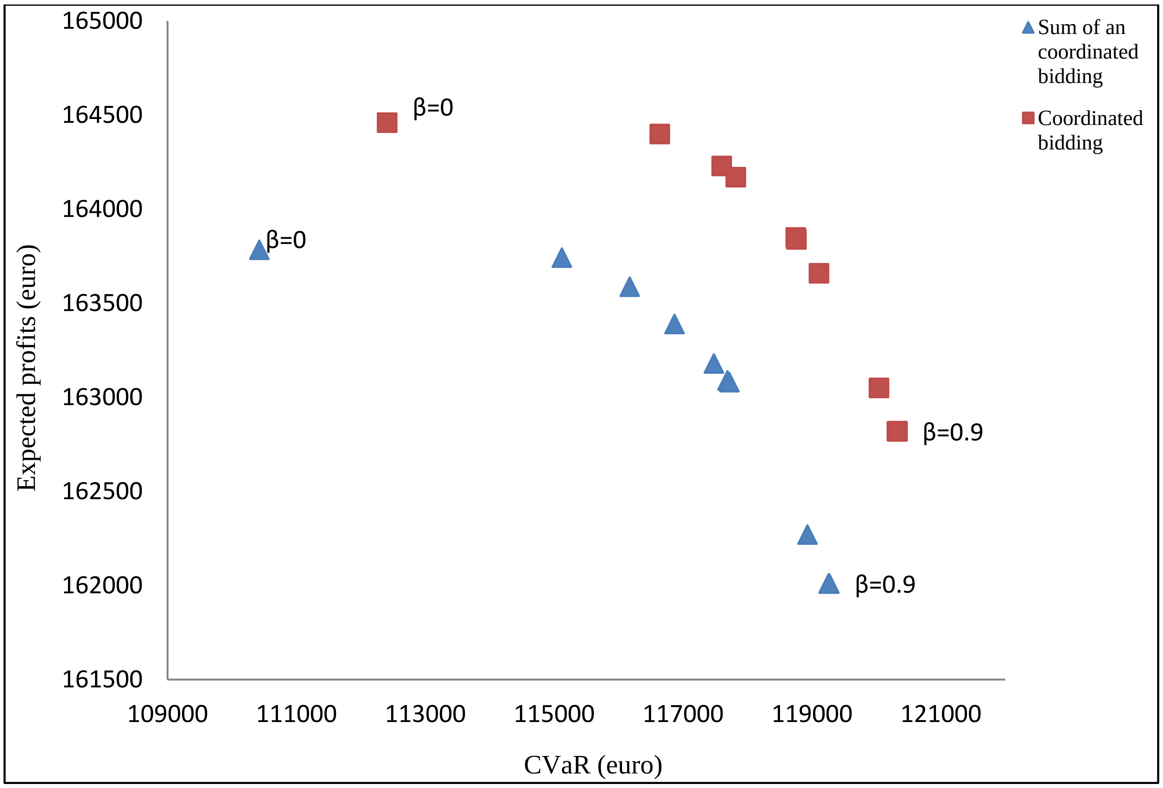

Figure 5-18 **Expected profits and CVaR for coordinated uncoordinated bidding**

At risk-neutral case percentage profit gain from the coordination of PSS over the uncoordinated one is 0.412% and the CVaR gain is 1.798%, it’s clearly observed from figure 6.18 and Table 5-1 these gains remain positives and around these values as β increased.

In this part of work the mixed integer stochastic programming have been solved to obtain the optimal bidding strategy for a GENCO owns wind-thermal generation integrated with PSS, the additional values by coordinate PSS with the existent wind-thermal units have been obtained. PSS can be considered as a good solution to demolish the uncertainty in the system which caused by owning uncertain generation resources such wind turbine. PSS make a significant difference in risk level as well as in the total profits. The mathematical formulation that used in this work is valid and suitable to be used by generation companies to participate in a pool based day-ahead energy market.

5.3 Wind-Thermal-PSS in Energy and Regulation Markets

In this part of work PSS is proposed to be integrated with wind-thermal generation system. The aim is to maximize the GENCOs' profit which is can be obtained through mixed integer stochastic optimization problem. The optimal self-scheduling for all generation units will be obtained to achieve the best bidding strategy in both day-ahead energy and regulation markets. In this part of work there are five uncertain parameters; day ahead forecasted wind output, day-ahead energy market price, up/down imbalances prices, day-ahead regulation price, and the regulation up/down deployment signals. Each one of these uncertain forecasted values has three scenarios, so the scenario tree contains 3^5=243 Scenarios. In this work the simulation for the tested system has been run several times with different values risk aversion parameter β for the coordinated and uncoordinated cases to compare risk neutral bidding with risk-averse optimization. The results show that all thermal units need to be always committed which is expected because it’s worthy for thermal units to bid in regulation market besides generating to compensate for power balances caused by wind plants. In the coordinated case, PSS is used to compensate these mismatches where thermal units assist PSS when its’ generated energy is not enough to cover the imbalances. This coordination increases the system robustness; in other words the total expected profit will increase along with significant enhancement in the bidding risk level.

5.3.1 Risk-Neutral Operation

In this case the optimization objective function is solved with β=0 for coordinated and uncoordinated PSS. The percentage change in profit from coordinated and uncoordinated operation for PSS and wind-thermal generation is considered as profit gain. The CVaR gain is assumed to be the percentage change in CVaR from total uncoordinated to the coordinated operation. The profit and CVaR gains in this case are 8.9% and 625.975% respectively; CVaR gains in all cases are considered to be high, in fact this caused by a significant drop in CVaR in the uncoordinated operation when the bidding in regulation market is added. It can be noticed that the CVaR for wind-thermal in the uncoordinated operation from Table 5-1 is equal to 110530 € this value is achieved by participating in energy market only where CVaR drop significantly to 12474 € when the participation in regulation market is also considered. This doesn’t happen with the coordinated operation neither with the uncoordinated PSS. Table 5-5 shows the profits and CVaR for different risk-aversion levels which are achieved by changing the risk-aversion parameter (β) in both optimization cases. Table 5-6 shows the decision variables for each PSU. These show the status of each unit in both generation and pumping modes for coordinated as well as uncoordinated PSS case. Where, letters P and Pun are the pumping decision variables while G and Gun are generating decision variables, in coordinated and uncoordinated PSS respectively.

Table 5-5 PROFITS AND CVaR COMPARISONS IN DEFFEREN RISK-AVERSION LEVELS

Coordinated (W+T+PSS)				Coordinated (W+T)		Uncoordinated (PSS)		Coordinated (W+T)+Uncoordinated (PSS)		Profits and CVaR gaines		
β	Profit (€)	CVaR	PSS Value (€)	Profit (€)	CVaR	Profit (€)	CVaR	Profit	CVaR	Profit gaine (€)	Profit gaine (%)	CVaR gaine (%)
0	236721	112860	27416	209305	12474	8093	3072	217398	15546	19323	8.888	625.975
0.1	236670	137160	27820	208850	33192	8080	3587	216930	36778.6	19740.1	9.100	272.934
0.2	236290	139820	27960	208330	36780	8008	4037	216338	40816.7	19952.5	9.223	242.556
0.3	236020	140870	29130	206890	42519	8008	4037	214898	46555.7	21122.5	9.829	202.584
0.4	235830	141420	30310	205520	46700	8008	4037	213528	50736.7	22302.5	10.445	178.733
0.5	235620	141870	31750	203870	50306	7739	4670	211609	54976.4	24011.2	11.347	158.056
0.6	235370	142330	33520	201850	54011	7653	4837	209503	58848.3	25867.5	12.347	141.859
0.7	235280	142470	34810	200470	56151	7653	4837	208123	60988.3	27157.5	13.049	133.602
0.8	235230	142540	36520	198710	58515	7500	5029	206210	63543.8	29019.8	14.073	124.318
0.9	235160	142630	37990	197170	60353	7500	5029	204670	65381.8	30489.8	14.897	118.149

Table 5-6 PSUs STATE SCHEDULE FOR COORDINATED AND UNCOORDINATED PSS, β=0

Hour	**h1**	**h2**	**h3**	**h4**	**h5**	**h6**	**h7**	**h8**	**h9**	**h10**	**h11**	**h12**
Unit Number	1234	1234	1234	1234	1234	1234	1234	1234	1234	1234	1234	1234
P	1111	1111	1111	1111	1111	1111	11**0**1	0000	0000	0000	0000	0000
G	0000	0000	0000	0000	0000	0000	0000	00**1**0	1111	1111	1111	1111
P un	0000	1111	1111	1111	1111	1111	11**1**1	0000	0000	0000	0000	0000
G un	0000	0000	0000	0000	0000	0000	0000	00**0**0	1111	1111	1111	1111
Hour	**h13**	**h14**	**h15**	**h16**	**h17**	**h18**	**h19**	**h20**	**h21**	**h22**	**h23**	**h24**
Unit Number	1234	1234	1234	1234	1234	1234	1234	1234	1234	1234	1234	1234
P	0000	0000	**1111**	**1111**	**1111**	**1111**	0000	0000	0000	0000	0000	0110
G	1111	**0000**	0000	0000	0000	0000	**00**1**0**	1111	1111	1111	**1**00**1**	**1**00**1**
P un	0000	0000	**0000**	**0000**	**0000**	**0000**	0000	0000	0000	0000	0000	1111
G un	1111	**1111**	0000	0000	0000	0000	**11**11	1111	1111	1111	**0**00**0**	**0**00**0**

The change in the status of PSUs for coordinated vs. un-coordinated case is clearly obvious in Table 5-6. The change of the unit's status is represented by bolded digits, most obvious for hours 15-18. Figures 5-19, 5-20, 5-20, and 5-22 show wind, thermal and PSS bidding curves in energy market for coordinated and uncoordinated PSS in hours6, 11, 18, 20, and 21. In hour 18 there is no bidding in energy market from PSS in both coordinated and uncoordinated case as shown in figure 5-21. However; PSS still offer bidding in regulation market, this increase the offered capacity as well as the total expected profits.

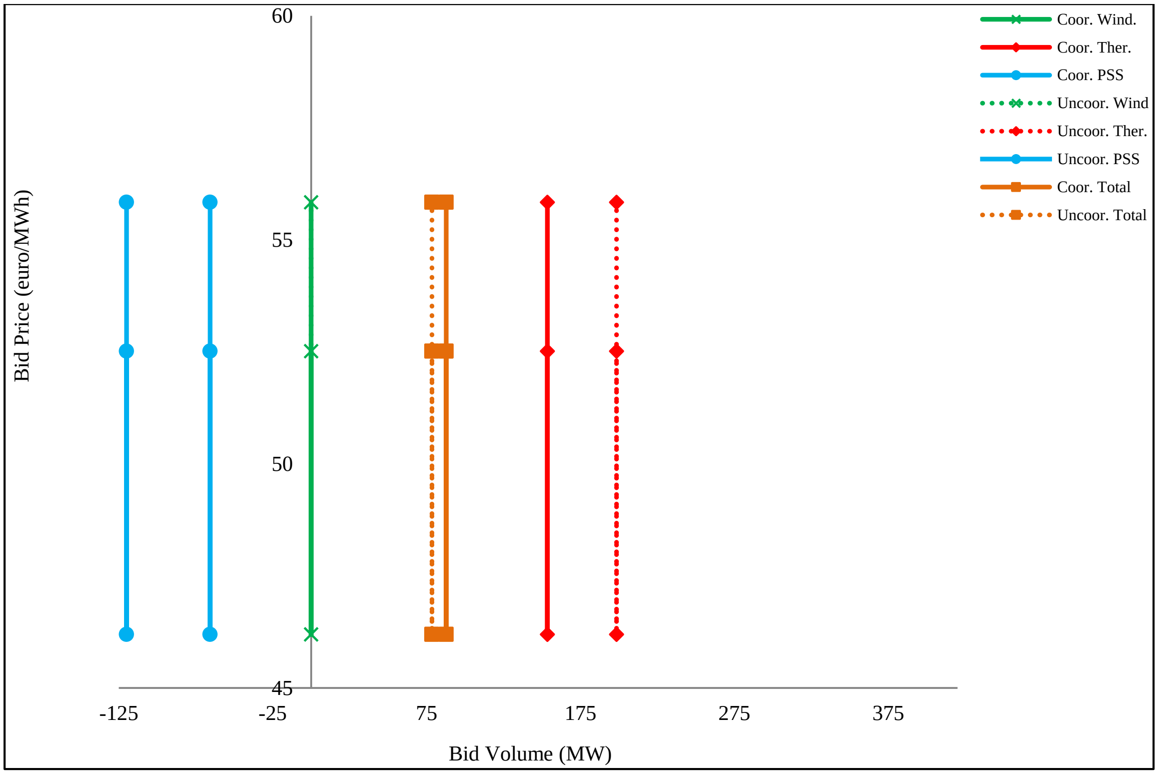

Figure 5-19 **Bidding curves in energy market for hour 6, β=0.**

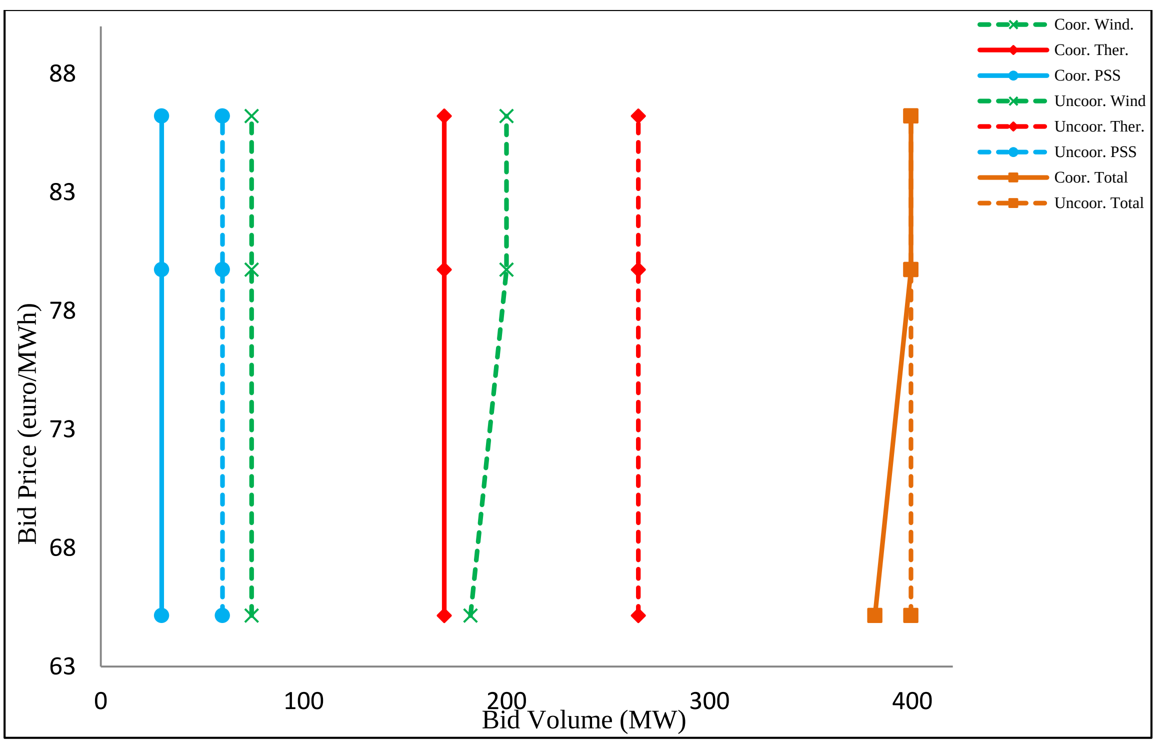

Figure 5-20 **Bidding curves in energy market for hour 11, β=0.**

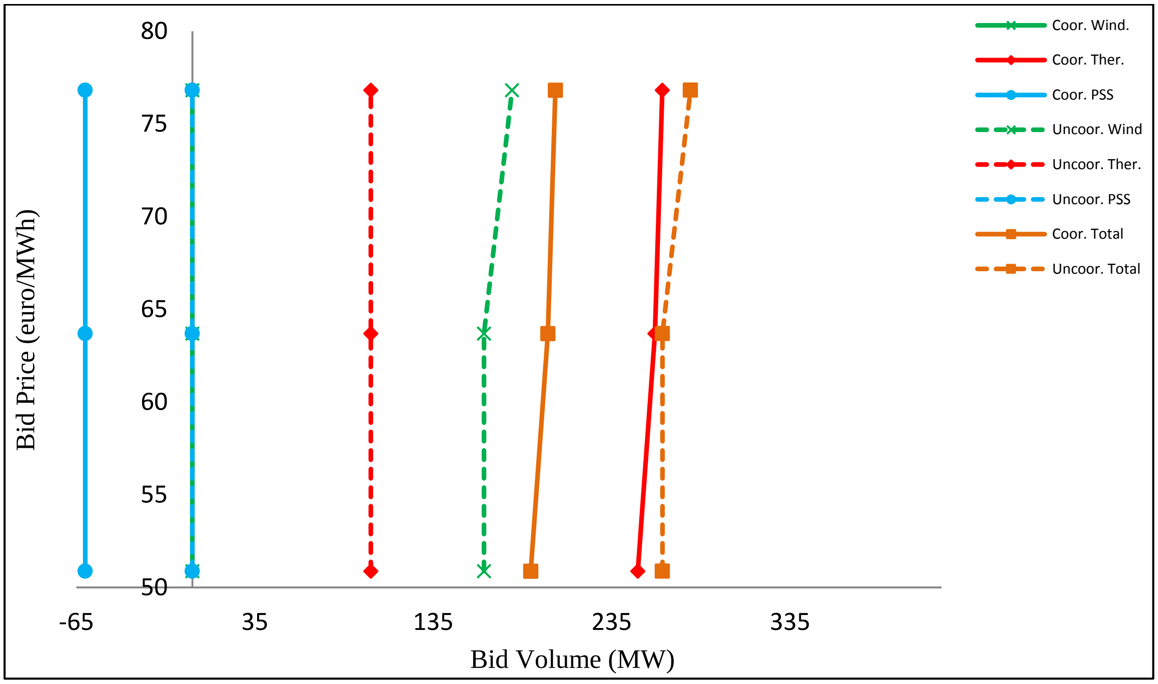

Figure 5-21 **Bidding curves in energy market for hour 18, β=0.**

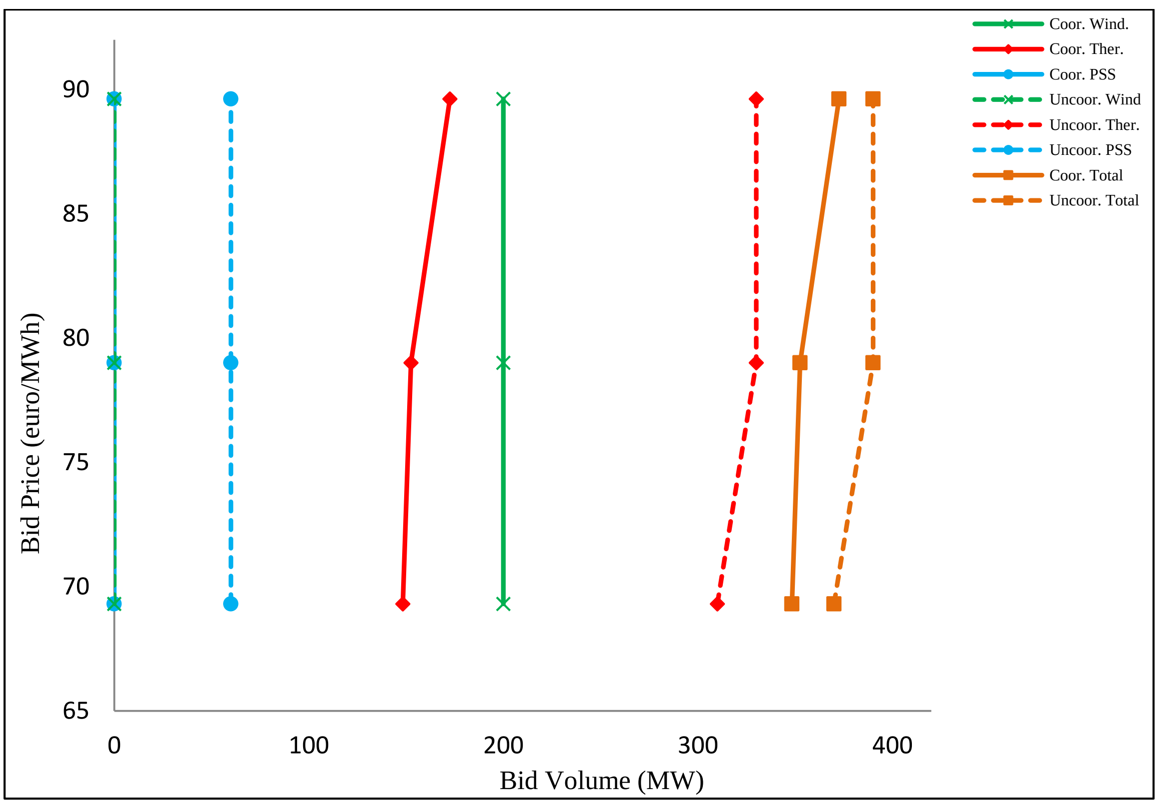

Figure 5-22 **Bidding curves in energy market for hour 20, β=0.**

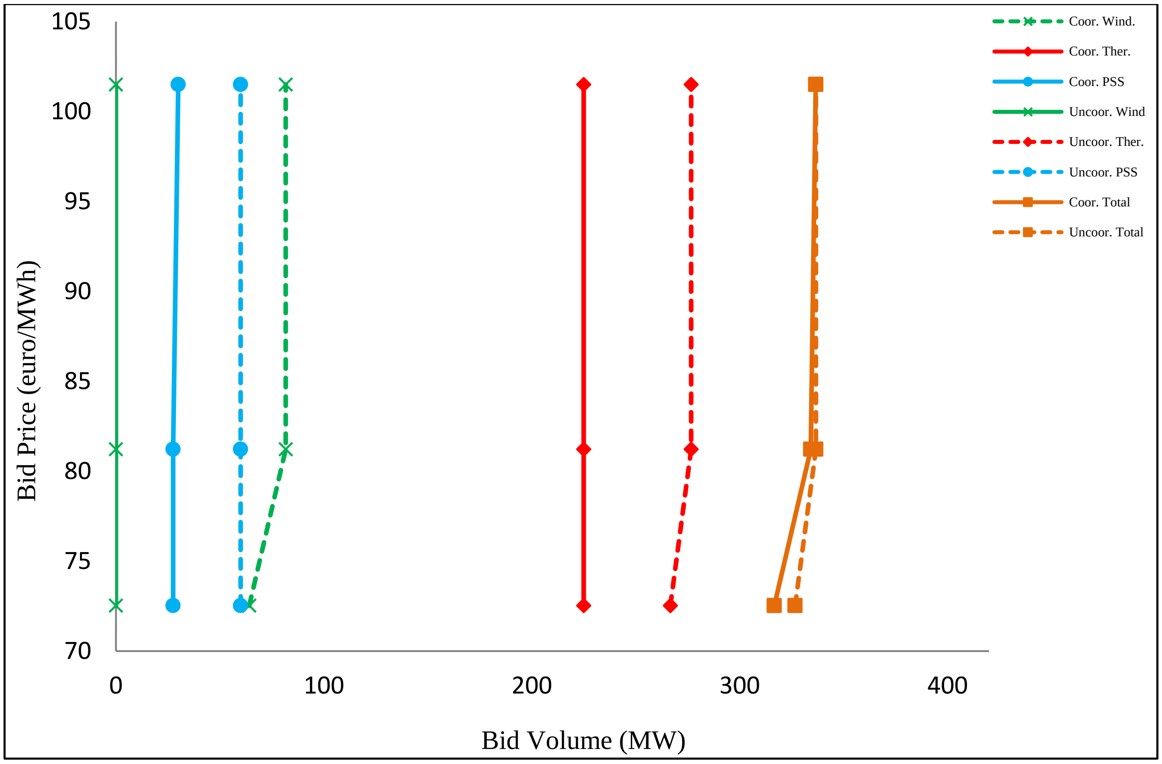

Figure 5-23 Bidding curves in energy market for hour 21, β=0.

5.3.1.1 Regulation Market Bidding

The regulation bidding curves for hours 6, 11, 18, 20, and 21 are shown in figures 5-24, 5-25, 5-26, 5-27, and 5-28 respectively for coordinated and uncoordinated PSS. It is obvious that the offered regulation capacity is a function of regulation price, most of the time the lowest forecasted prices are worthy enough to offer the maximum thermal and PSS units' capacity to be engaged for regulation purposes. Referring to figures 5-24 and 5-26 a conclusion can be made that regulation bidding is possible even in the pumping mode is contrast to the work reported in literature [9, 17] were regulation was done only in the generation mode.

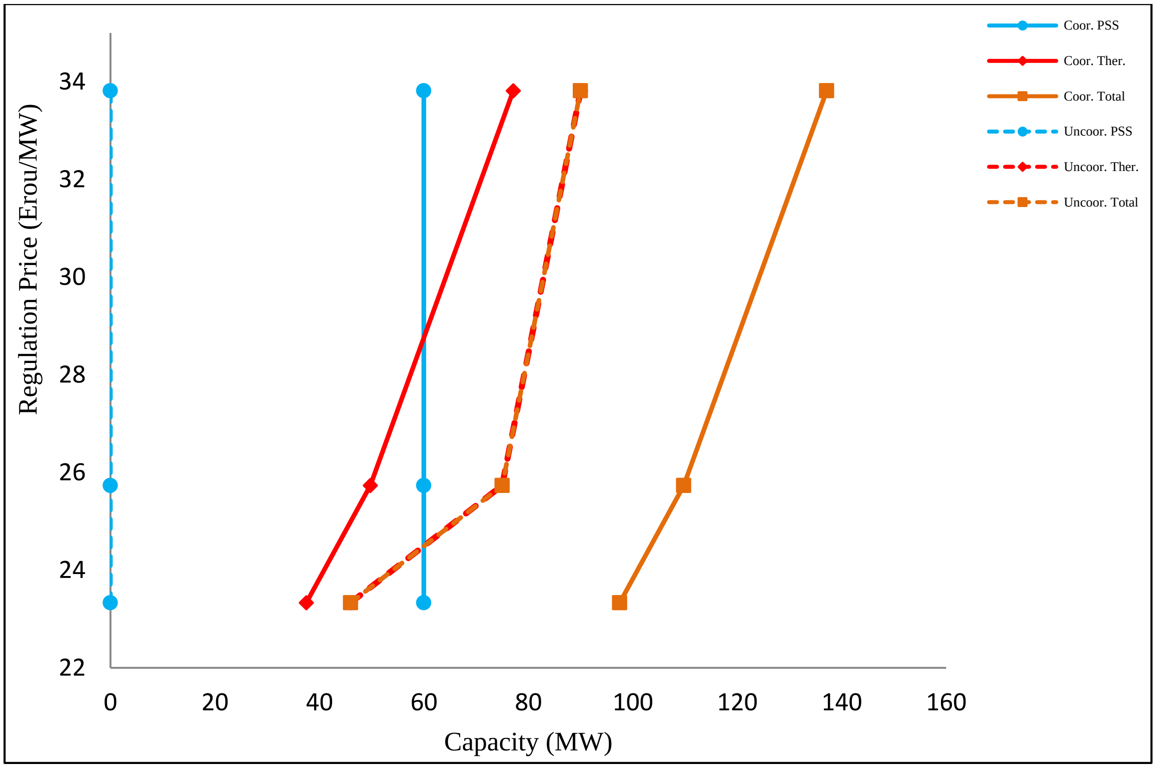

Figure 5-24 **Bidding curves in regulation market for hour 6, β=0.**

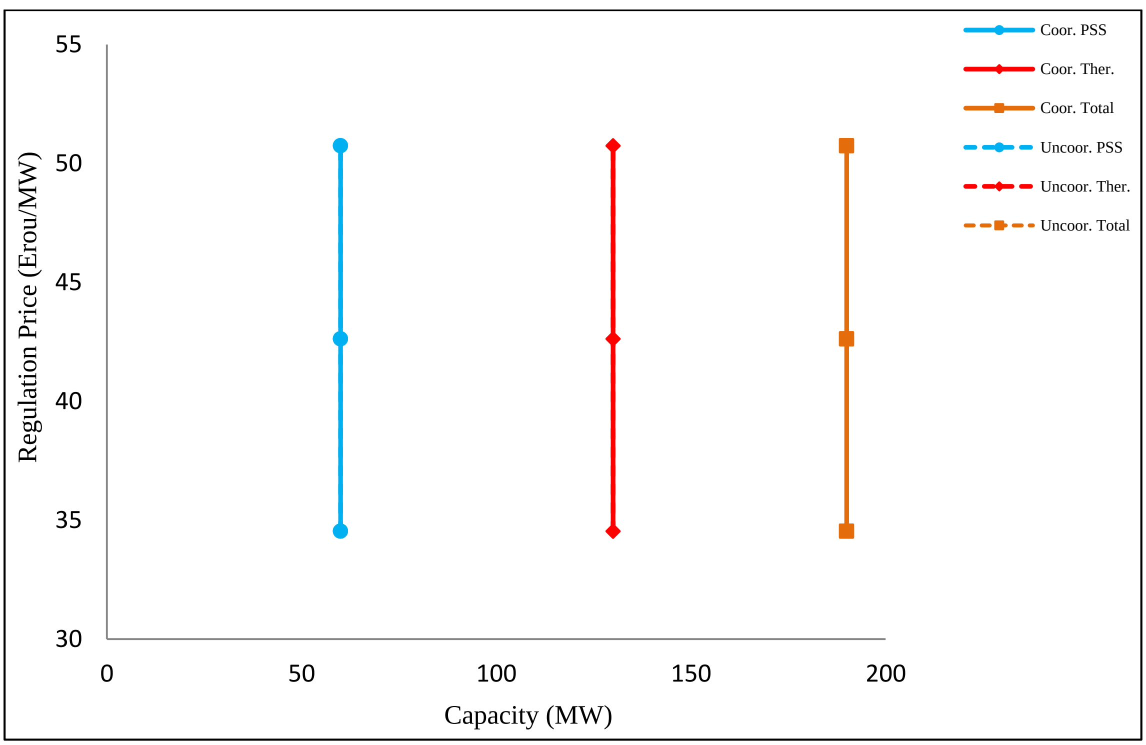

Figure 5-25 **Bidding curves in regulation market for hour 11, β=0.**

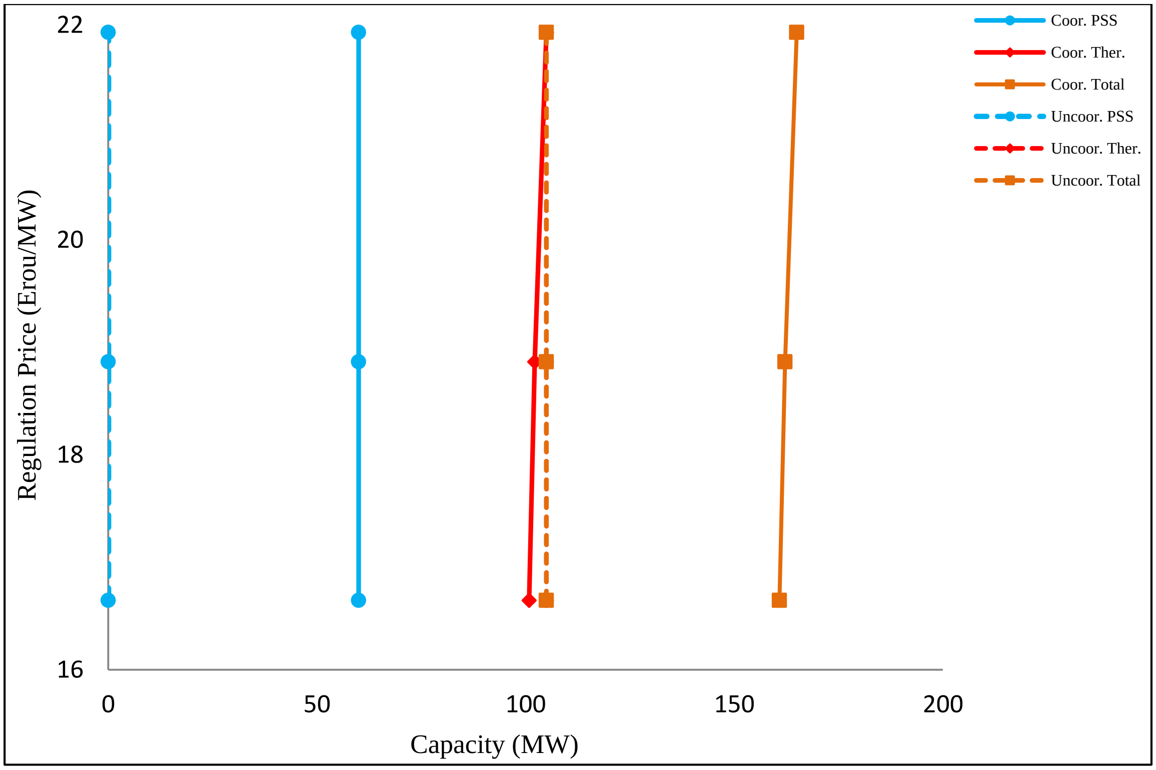

Figure 5-26 **Bidding curves in regulation market for hour 18, β=0.**

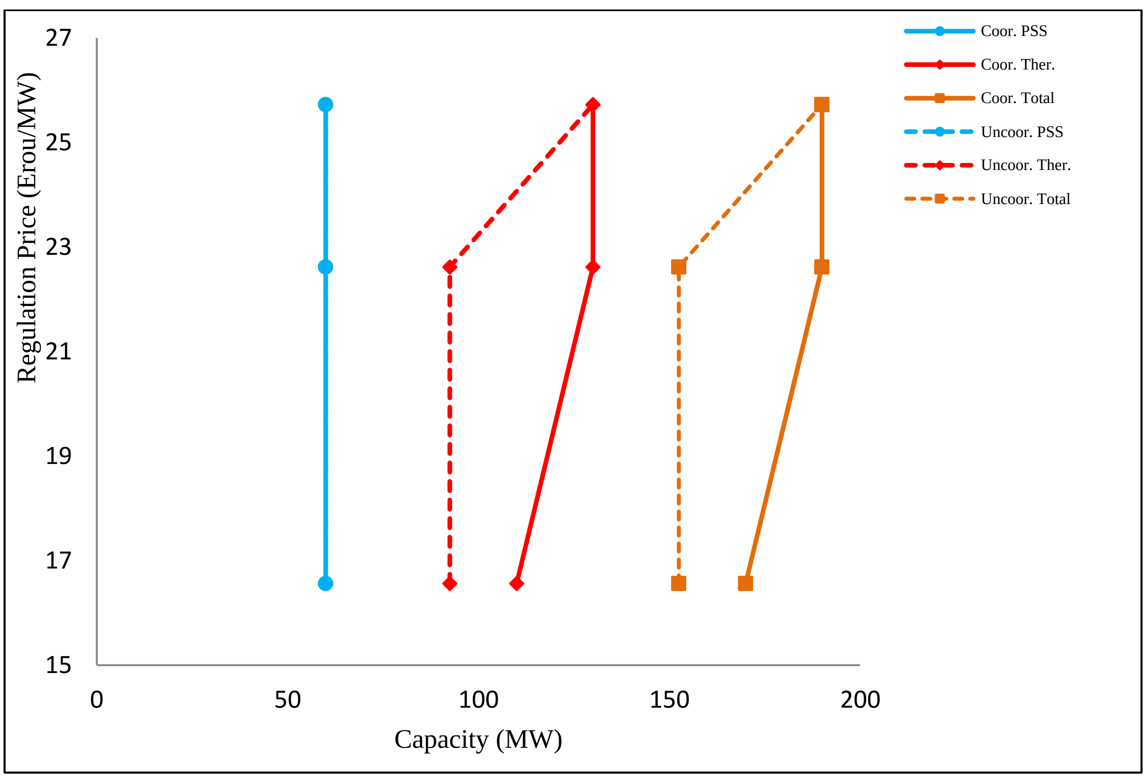

Figure 5-27 **Bidding curves in regulation market for hour 20, β=0.**

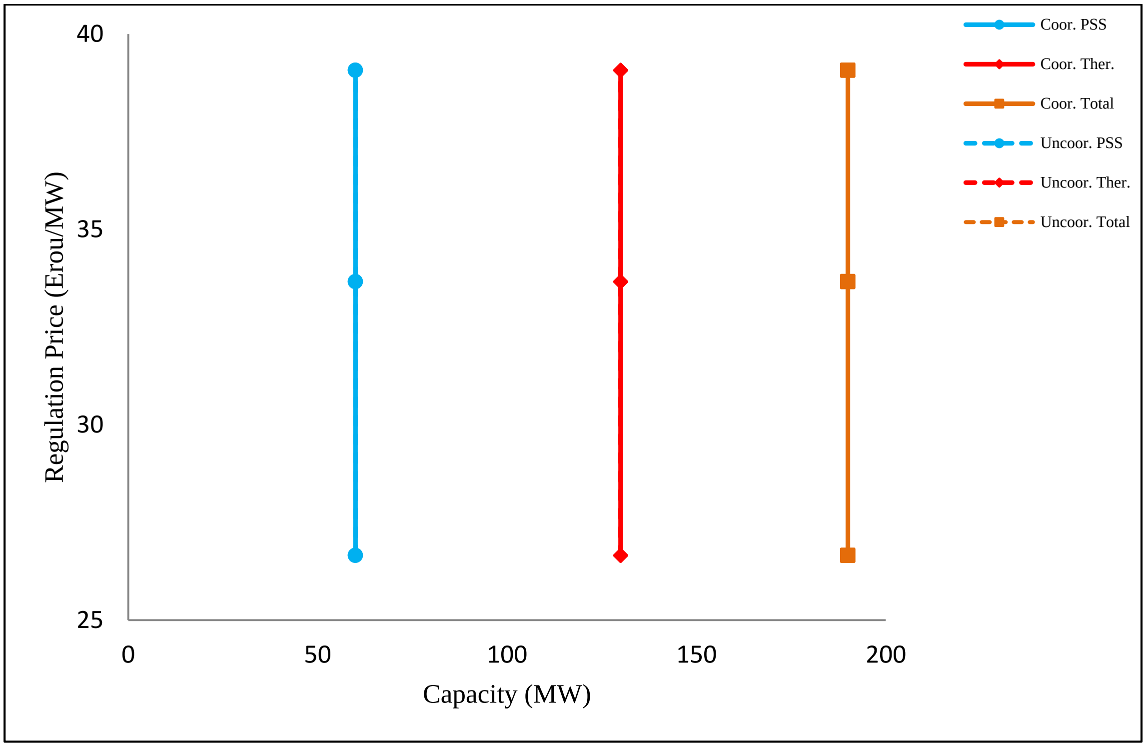

Figure 5-28 **Bidding curves in regulation market for hour 21, β=0**

5.3.1.2 Energy Market Purchasing Offers

Figure 5-29, 5-30 and 5-31 shows the energy offer bids for hours 3, 5, and 24, respectively, to purchase energy from energy market for storage purposes. It is clearly illustrated that PSS is not being utilized on its' rated capacity in energy market because it's worthy to keep free capacity for regulation bidding unless the energy price bidding is low enough like in hour 3 as shown in figure 5-25.

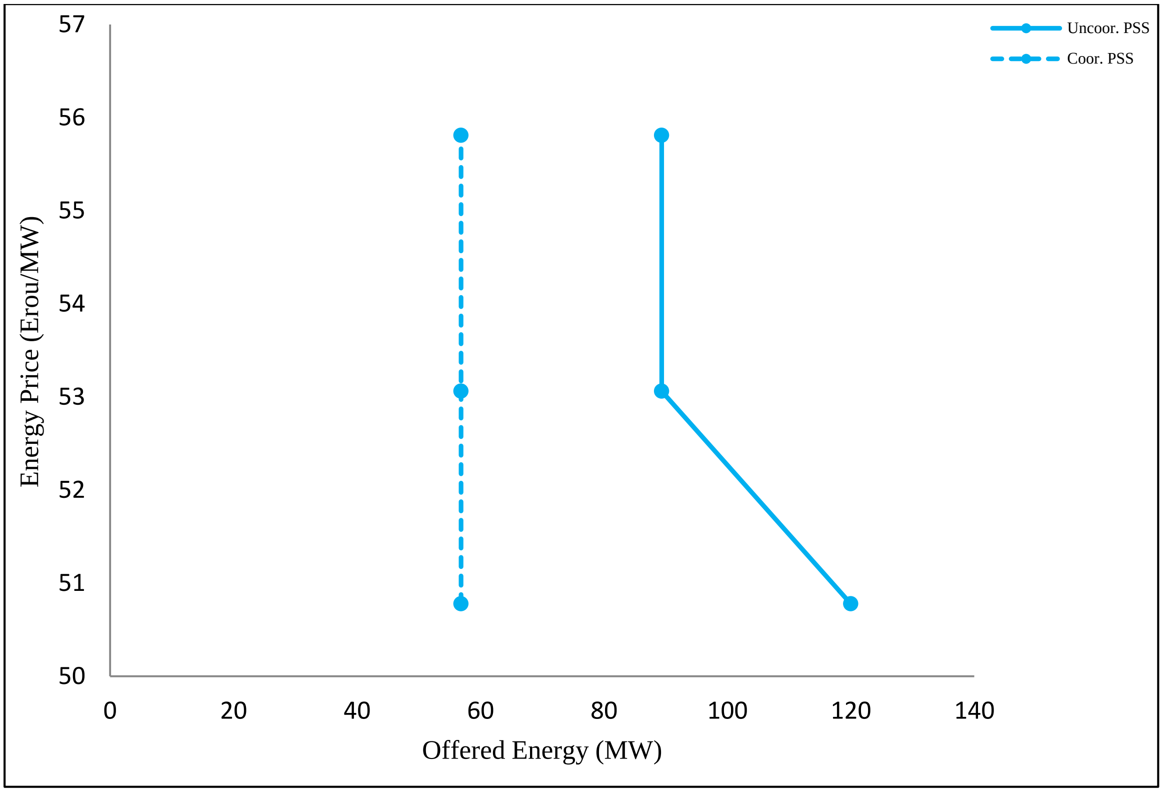

Figure 5-29 **Purchasing offers curve in energy market for hour 3, β=0.**

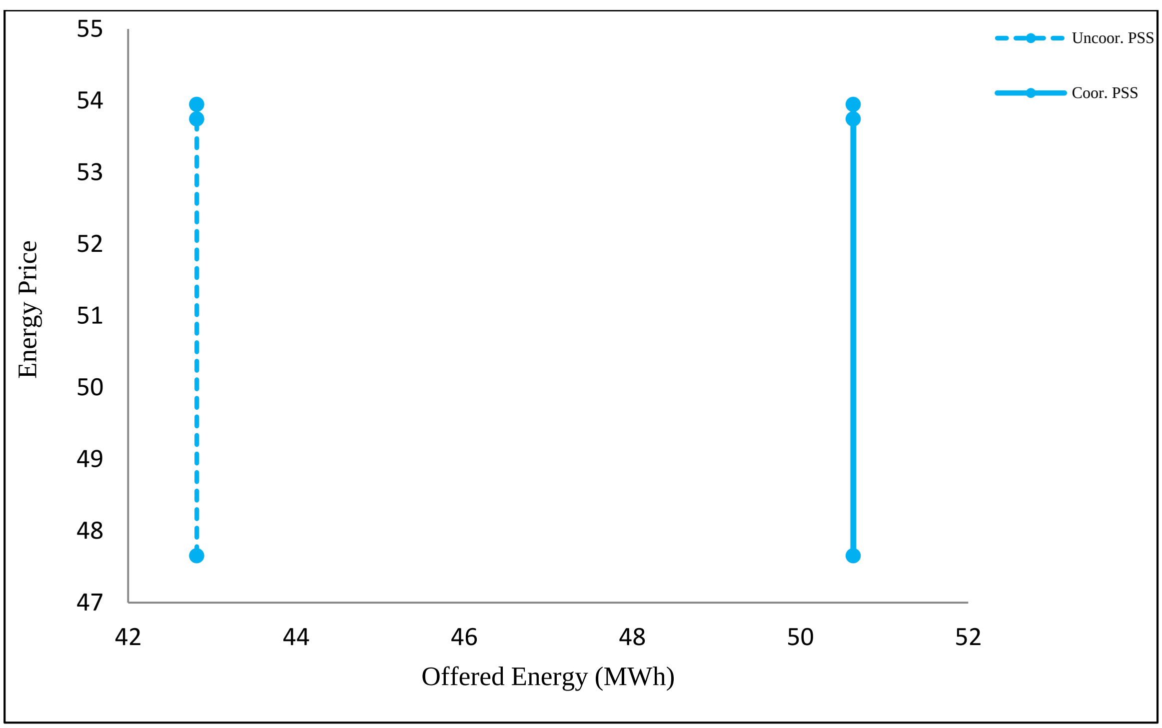

Figure 5-30 **Purchasing offers curve in energy market for hour 5, β=0.**

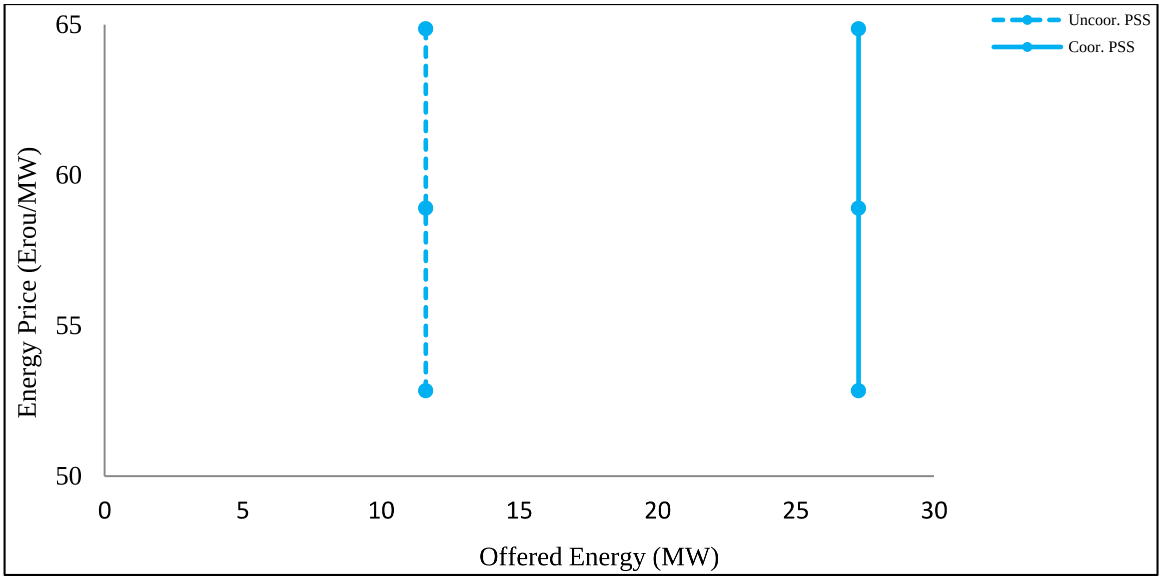

Figure 5-31 Purchasing offers curve in energy market for hour 24, β=0.

Figure 5-32 depicts the expected values of the pumped energy in the coordinated PSS in Risk-neutral level. Clearly, the pumping is expected to take place in low price periods, and the expected pumping energy imported from the market is much higher than the expected pumping energy from thermo and wind plant.

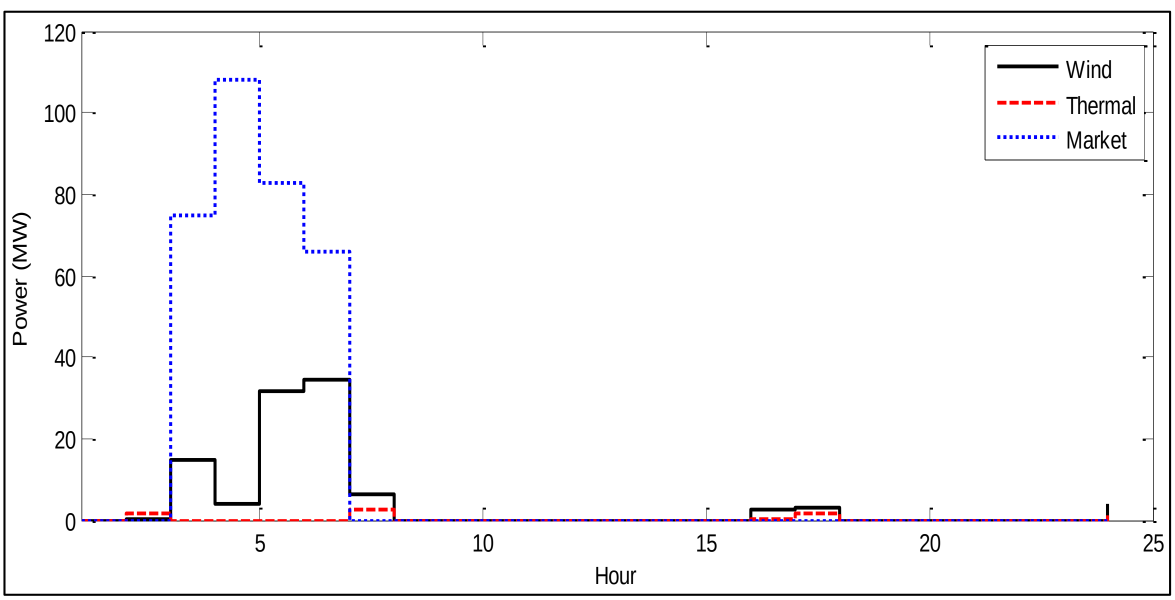

Figure 5-32 Expected Values of the Pumped Energy, β=0.

Figures 5-35 and 5-36 present the relationship between profits and CVaR in different risk-aversion for uncoordinated total bids and coordinated bids respectively. Obviously, CVaR in the coordinated case is significantly higher than CVaR for the uncoordinated bids which is clearly shown in figure 5-34. Also, it can be noticed from the figures that β=0.9 corresponds to the highest value of CVaR while β=0 corresponds to the lowest value of CVaR. It is clear that the lowest value of CVaR for the coordinated bids is higher than the highest value of CVaR in the uncoordinated bids. Also the lowest expected profit for the coordinated bids is much higher than the highest expected profit for the uncoordinated bids.

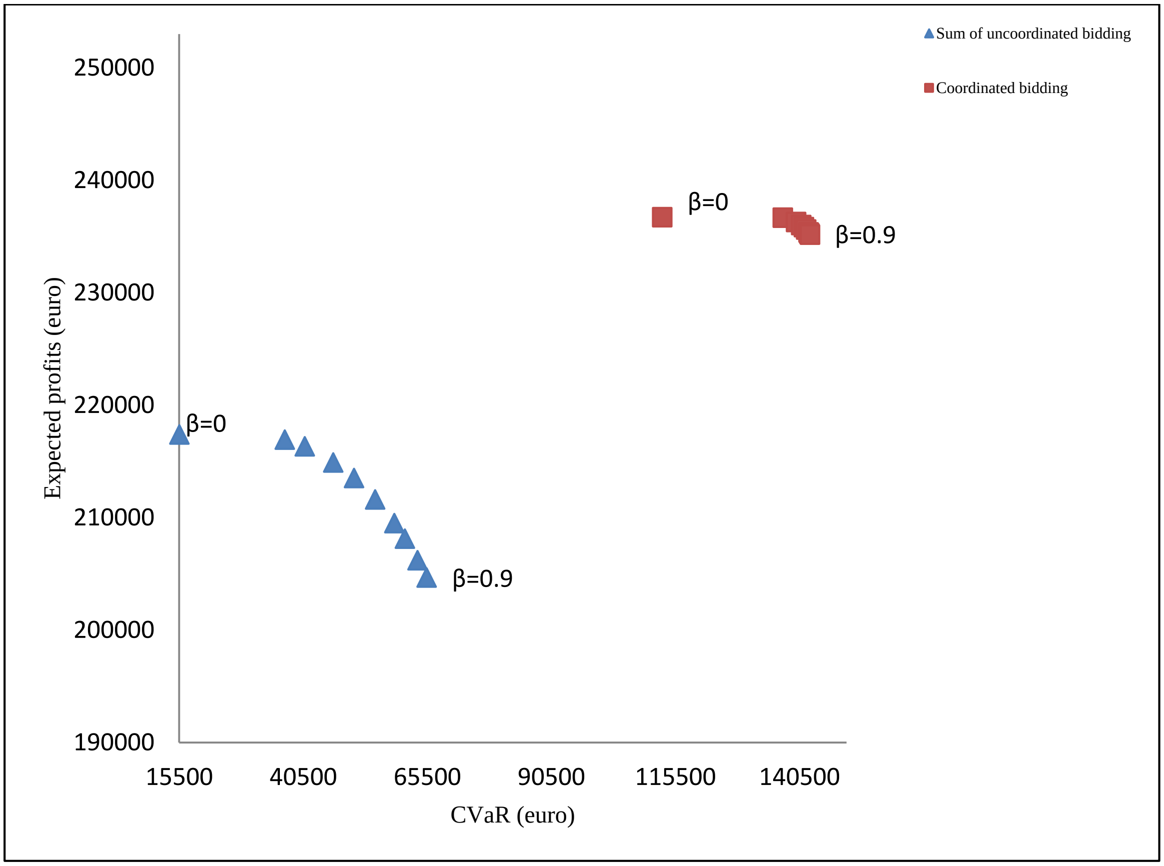

Figure 5-33 **Expected profits and CVaR for the total coordinated and uncoordinated bids.**

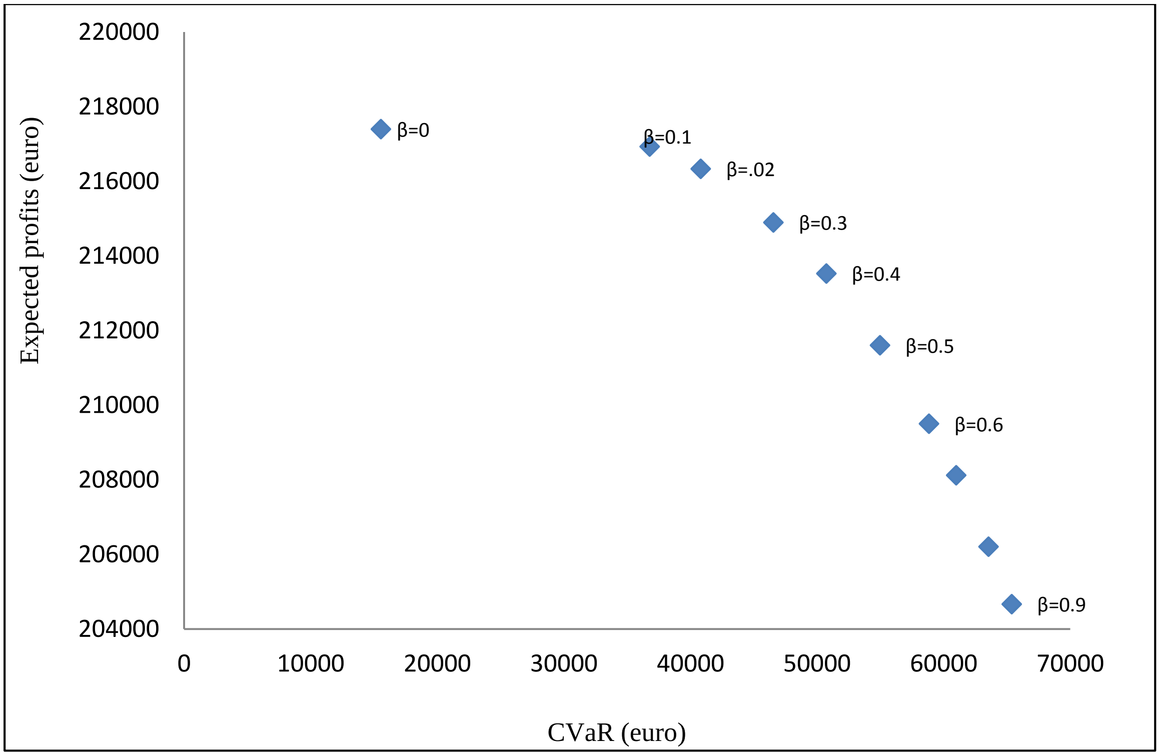

Figure 5-34 **Expected profits and CVaR for the uncoordinated bids.**

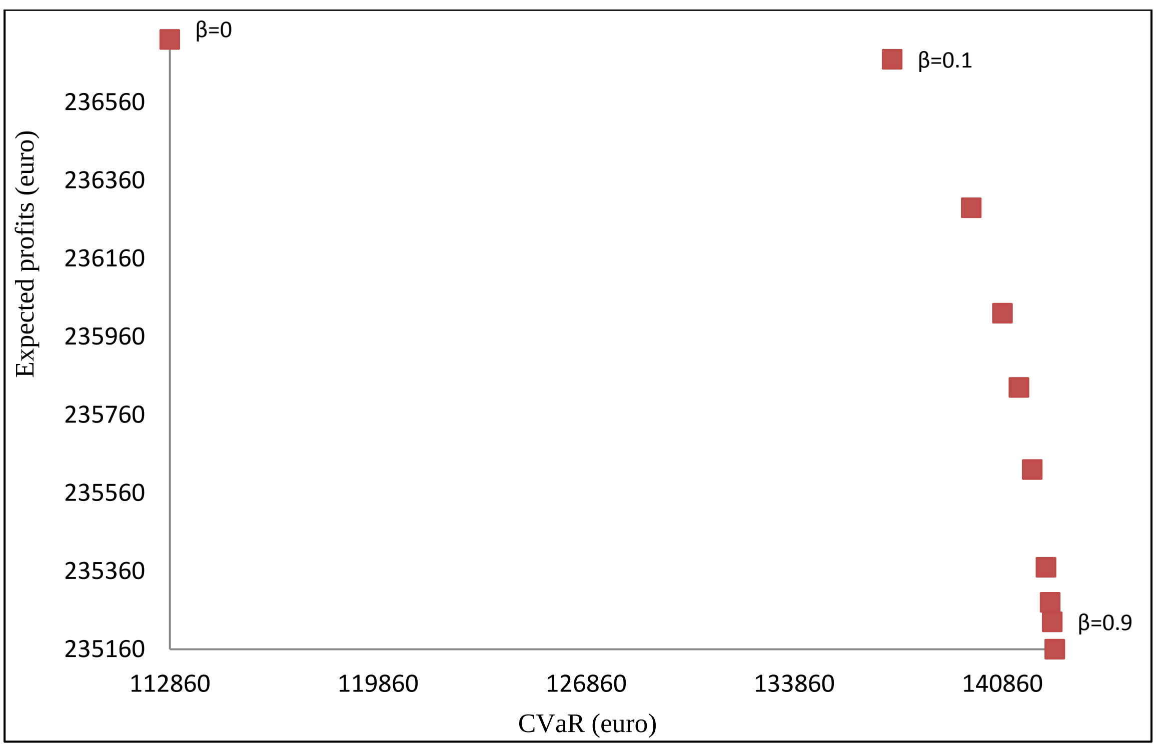

Figure 5-35 **Expected profits and CVaR for the coordinated bids.**

5.3.2 Risk-Aversion Optimization

In risk-aversion case, the optimization problems for the coordinated and uncoordinated PSS are solved with β=0.5. The results show that the total bids from all system resources are decreased to decrease the risk level, and in some periods a number of PSS units were shut down as shown in Table 5-7. All PSUs were shut down in hour 10 in uncoordinated case, where in the coordinated case the decision variable for PSUs have not been affected. The bolded digits show the difference in PSUs decision variables where the lined digits show the difference between risk-aversion operation and risk-neutral case which is exposed in Table 5-7.

Table 5-7 PSUs STATE SCHEDULE FOR COORDINATED AND UNCOORDINATED PSS, β=0.5

Hour Number	**h1**	**h2**	**h3**	**h4**	**h5**	**h6**	**h7**	**h8**	**h9**	**h10**	**h11**	**h12**
Unit Number	**1234**	**1234**	**1234**	**1234**	**1234**	**1234**	**1234**	**1234**	**1234**	**1234**	**1234**	**1234**
P	**1111**	1111	1111	1111	1111	1111	111**0**	0000	0000	0000	0000	0000
G	0000	0000	0000	0000	0000	0000	0000	000**1**	1111	**1111**	1111	1111
P un	**0000**	1111	1111	1111	1111	1111	111**1**	0000	0000	0000	0000	0000
G un	0000	0000	0000	0000	0000	0000	0000	000**0**	1111	**0000**	1111	1111
Hour Number	**h13**	**h14**	**h15**	**h16**	**h17**	**h18**	**h19**	**h20**	**h21**	**h22**	**h23**	**h24**
Unit Number	**1234**	**1234**	**1234**	**1234**	**1234**	**1234**	**1234**	**1234**	**1234**	**1234**	**1234**	**1234**
P	0000	0000	**1111**	**1111**	**1111**	**1111**	0000	0000	0000	0000	0000	**00**11
G	1111	**0000**	0000	0000	0000	0000	**0000**	1111	1111	1111	**11**00	**11**00
P un	0000	0000	**0000**	**0000**	**0000**	**0000**	0000	0000	0000	0000	0000	**11**11
G un	1111	**1111**	0000	0000	0000	0000	**1111**	1111	1111	1111	**00**00	**00**00

Figures 5-36 to 5-40 expose the energy bids for the coordinated and uncoordinated system for hours 6, 11, 18, 20, and 21 respectively in risk-aversion level where β=0.5. The total bids are expected to be less or equal the bids in risk-neutral case in the coordinated and uncoordinated optimization; because the least profitable scenario will be extended to include more scenarios to reduce the bidding risk level. This action usually leads to obtain lower profit since the weight of the least profitable scenarios is increased.

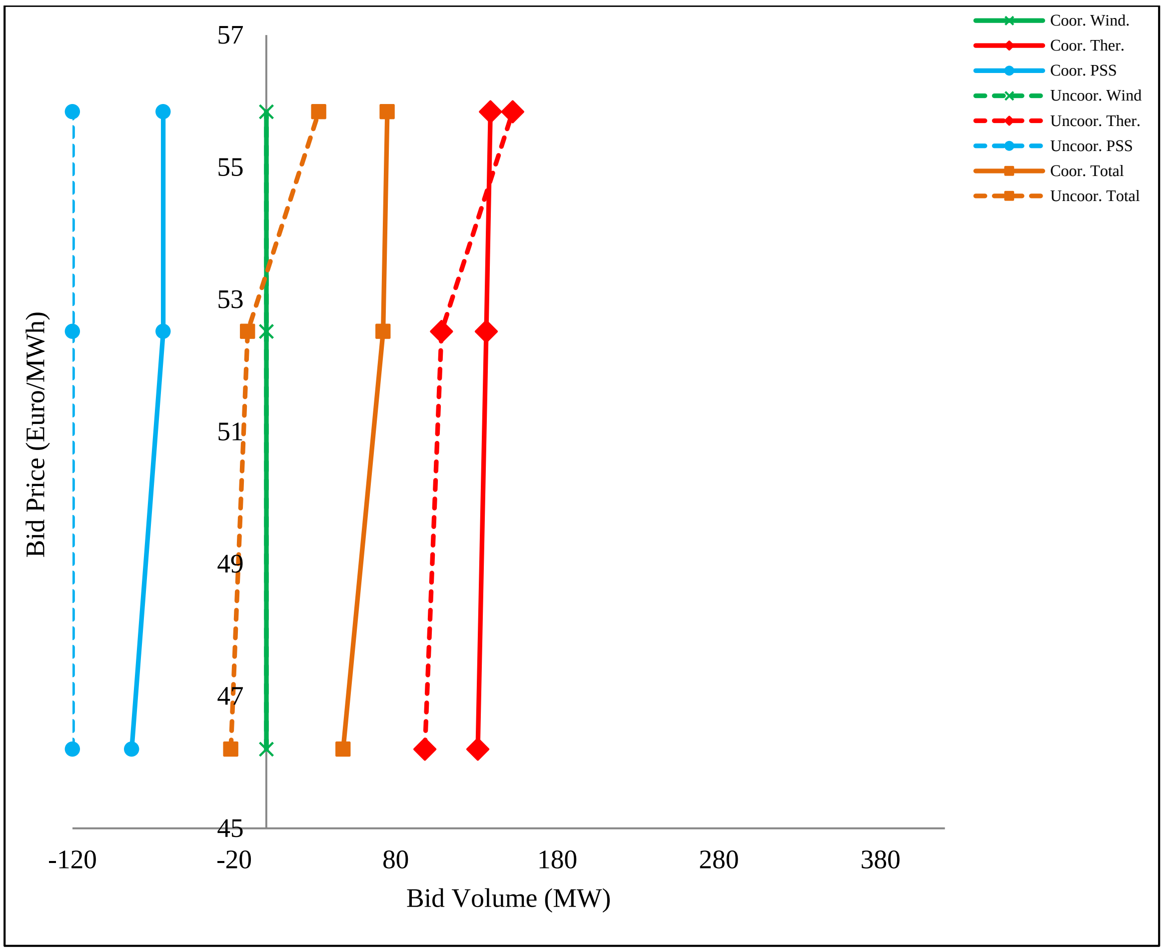

Figure 5-36 **Bidding curves in energy market for hour 6, β=0.5.**

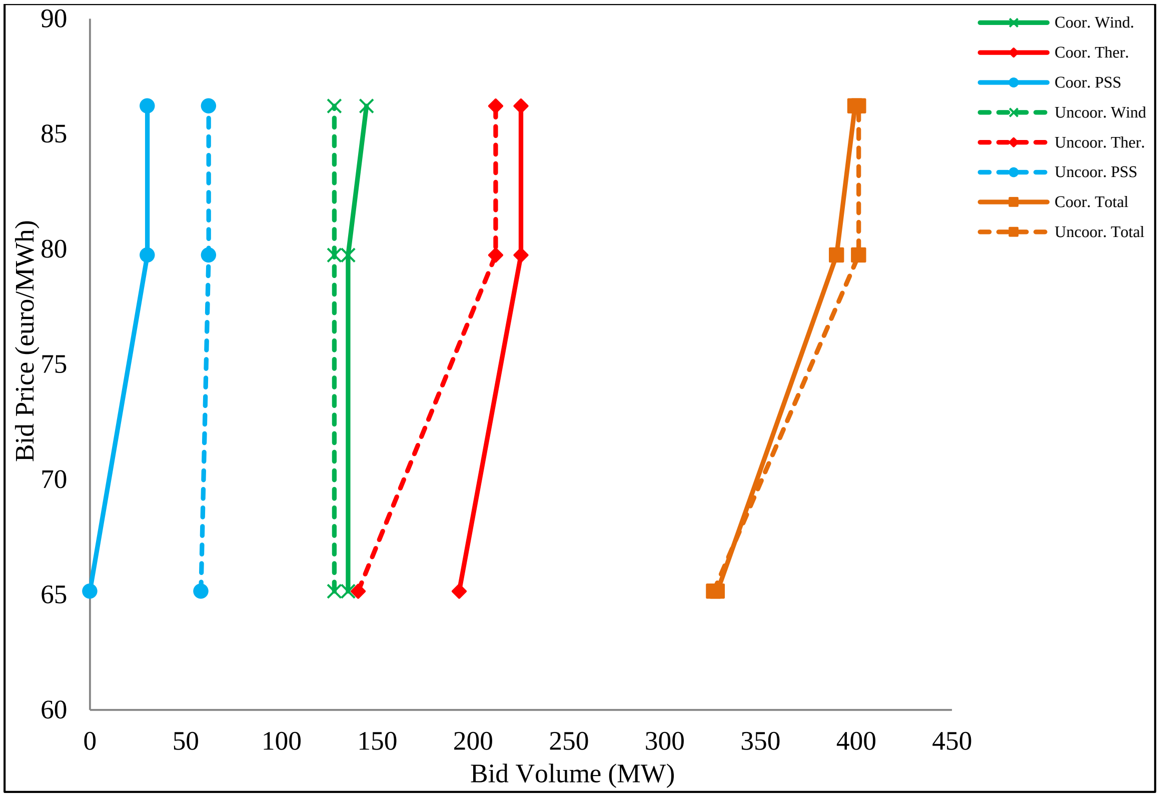

Figure 5-37 Bidding curves in energy market for hour 11, β=0.5.

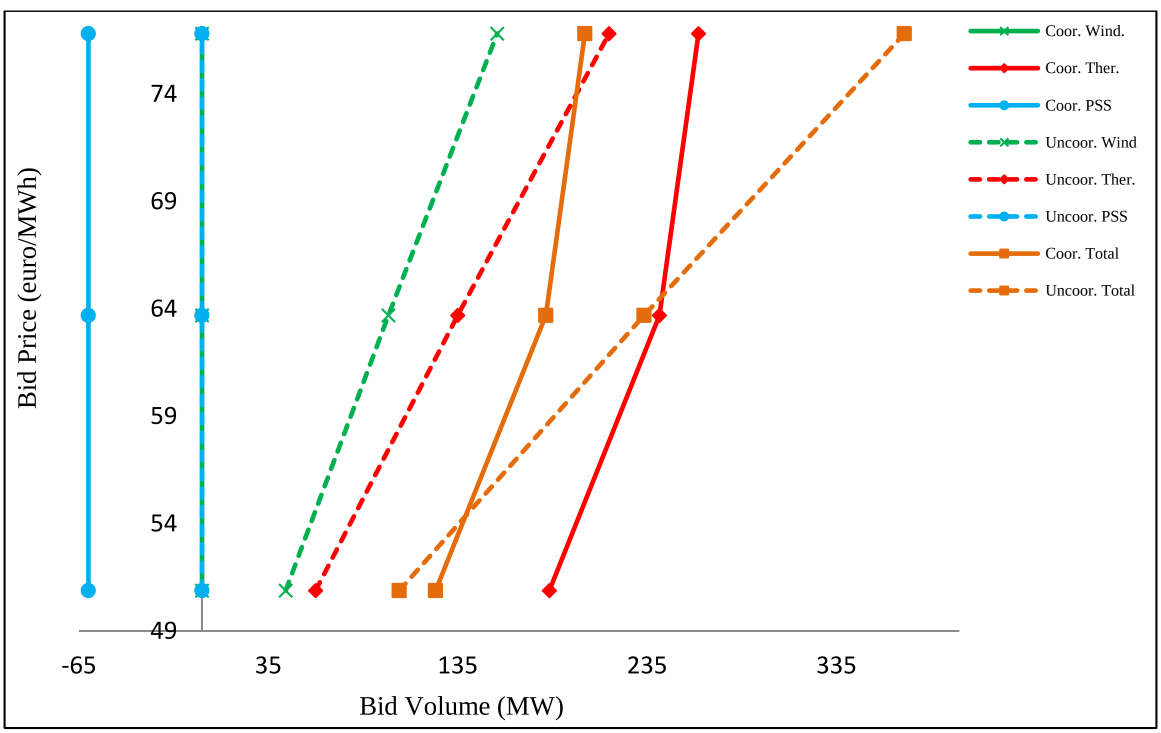

Figure 5-38 Bidding curves in energy market for hour 18, β=0.5.

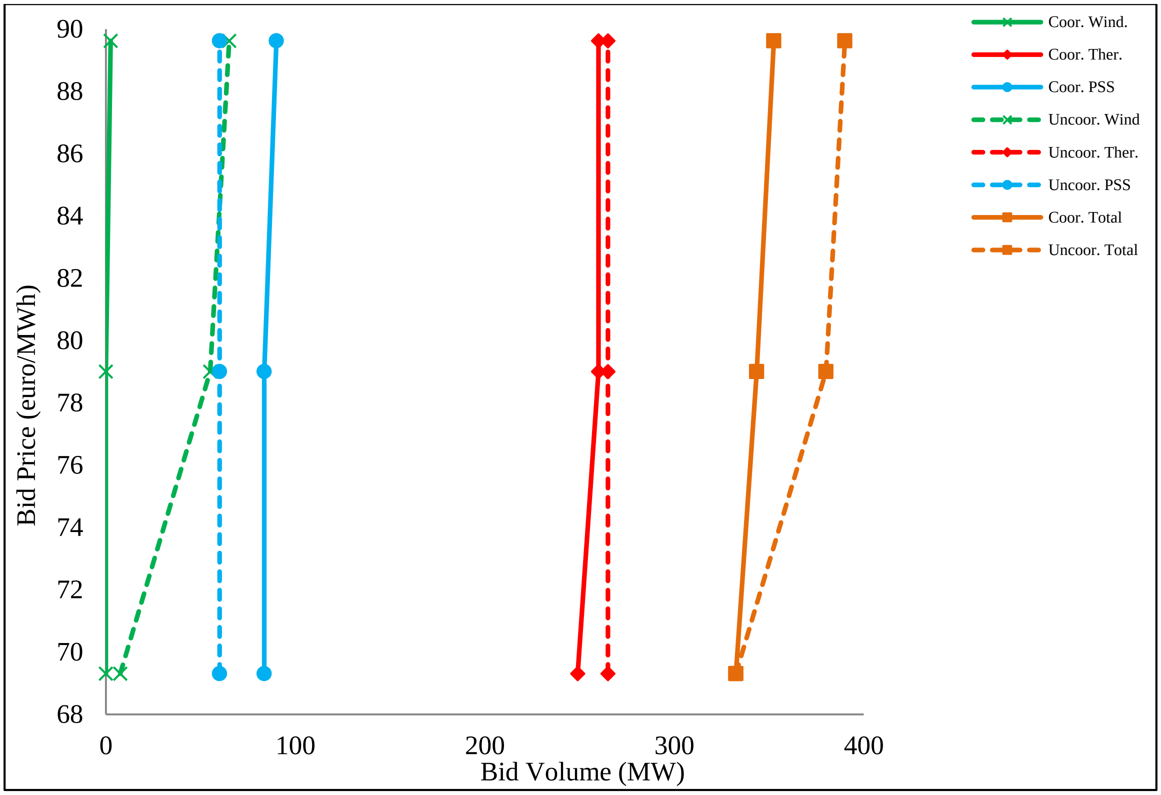

Figure 5-39 **Bidding curves in energy market for hour 20, β=0.5.**

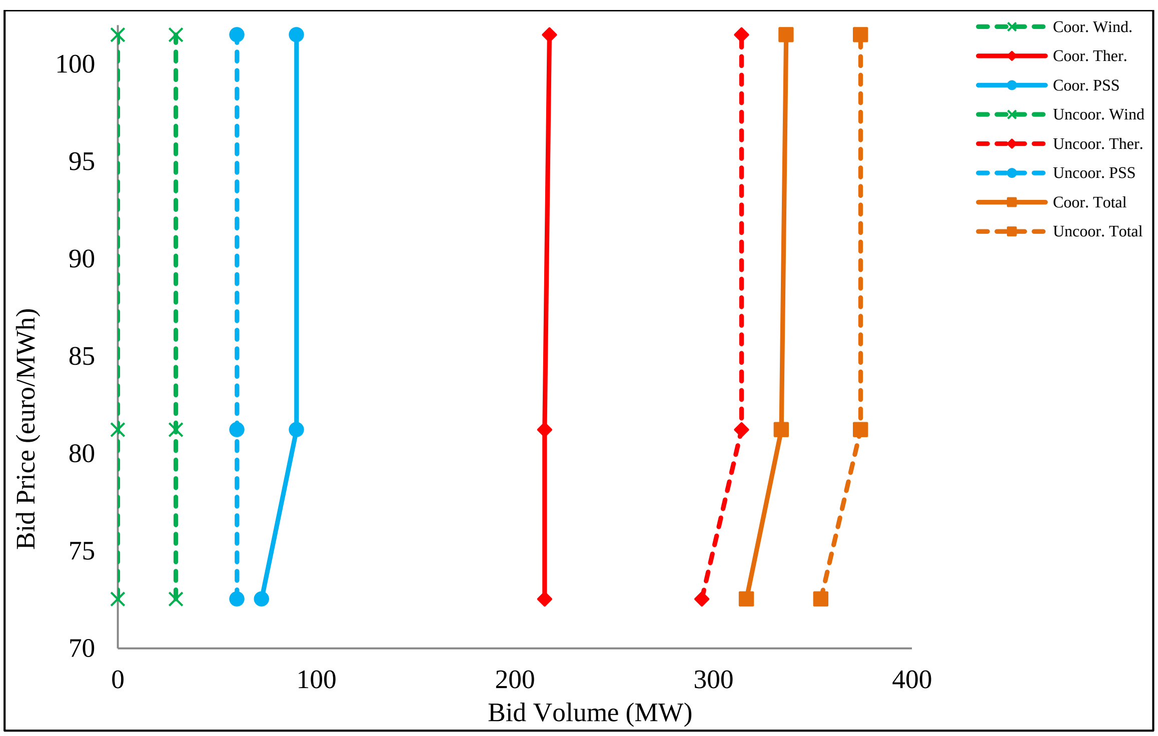

Figure 5-40 **Bidding curves in energy market for hour 21, β=0.5.**

The offers for purchasing energy from energy market for hours 3, 5 and 24 are shown in figures 5-41, 5-42 and 5-43 respectively. Most of the time, the coordinated energy offers are much higher than the energy offers in the uncoordinated case.

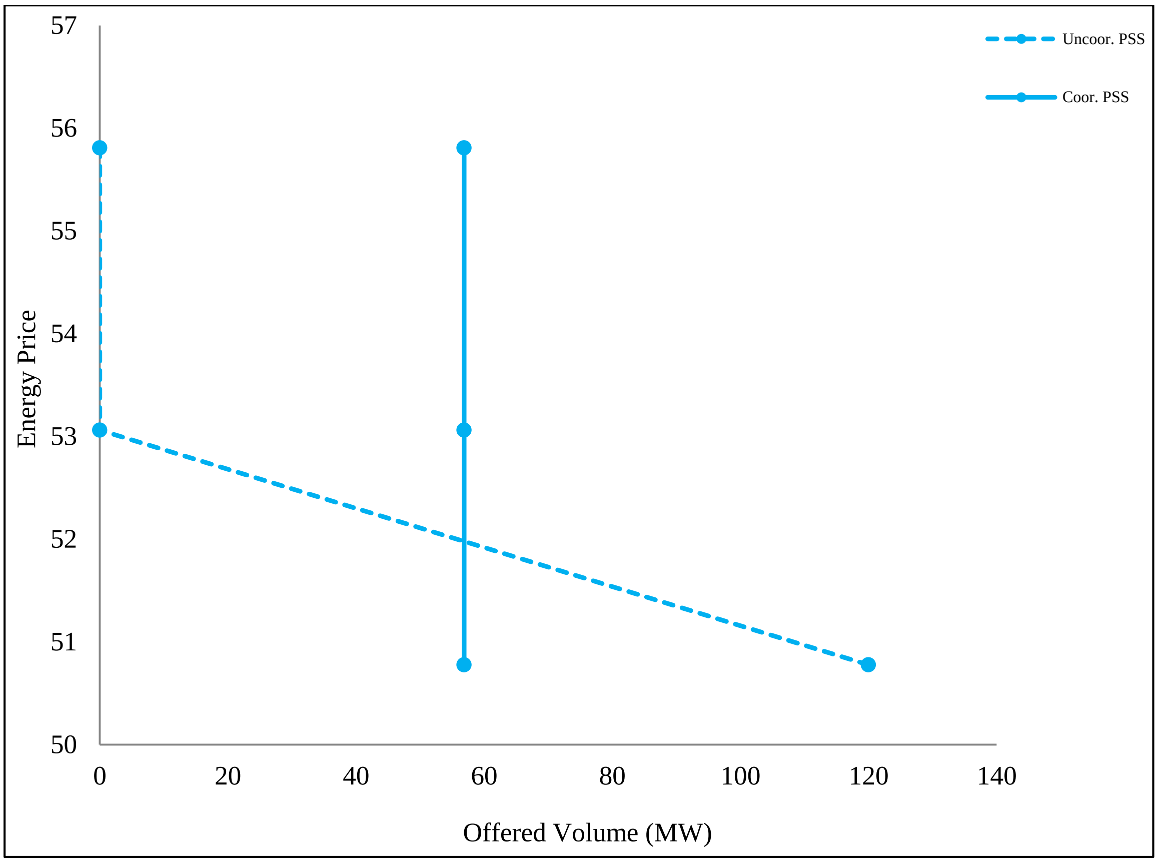

Figure 5-41 **Purchasing offers curve in energy market for hour 3, β=0.5.**

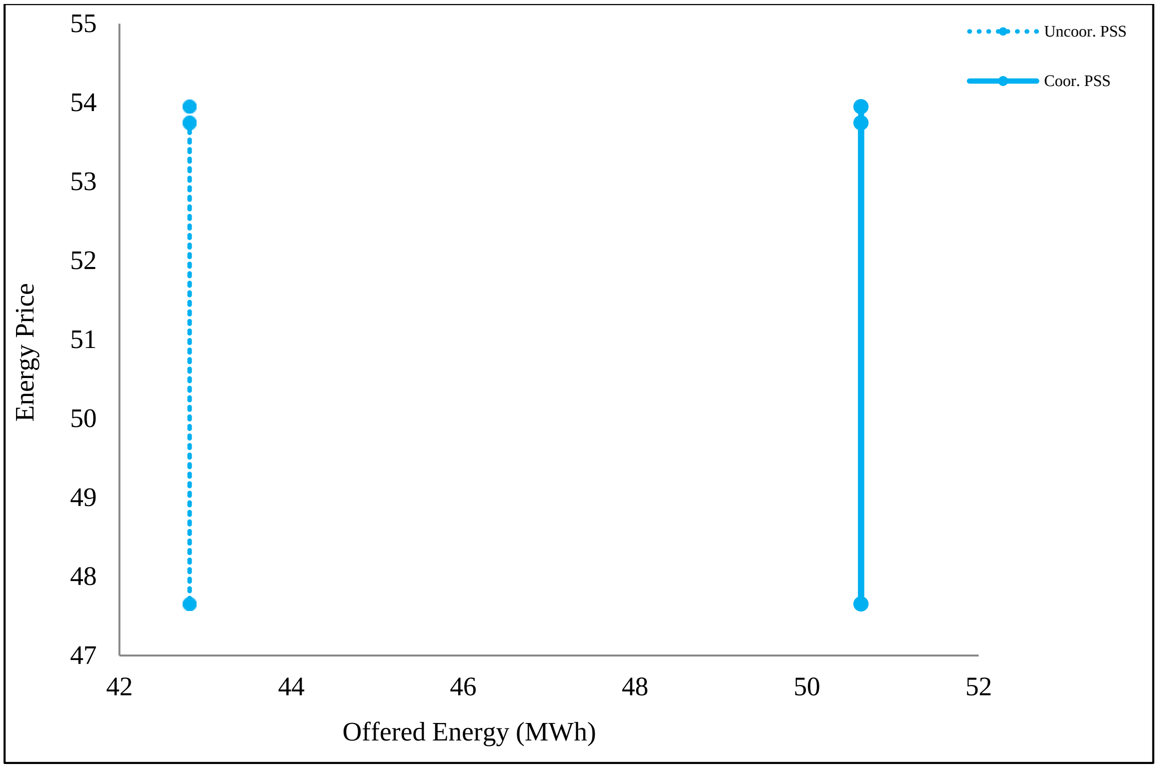

Figure 5-42 **Purchasing offers curve in energy market for hour 5, β=0.5.**

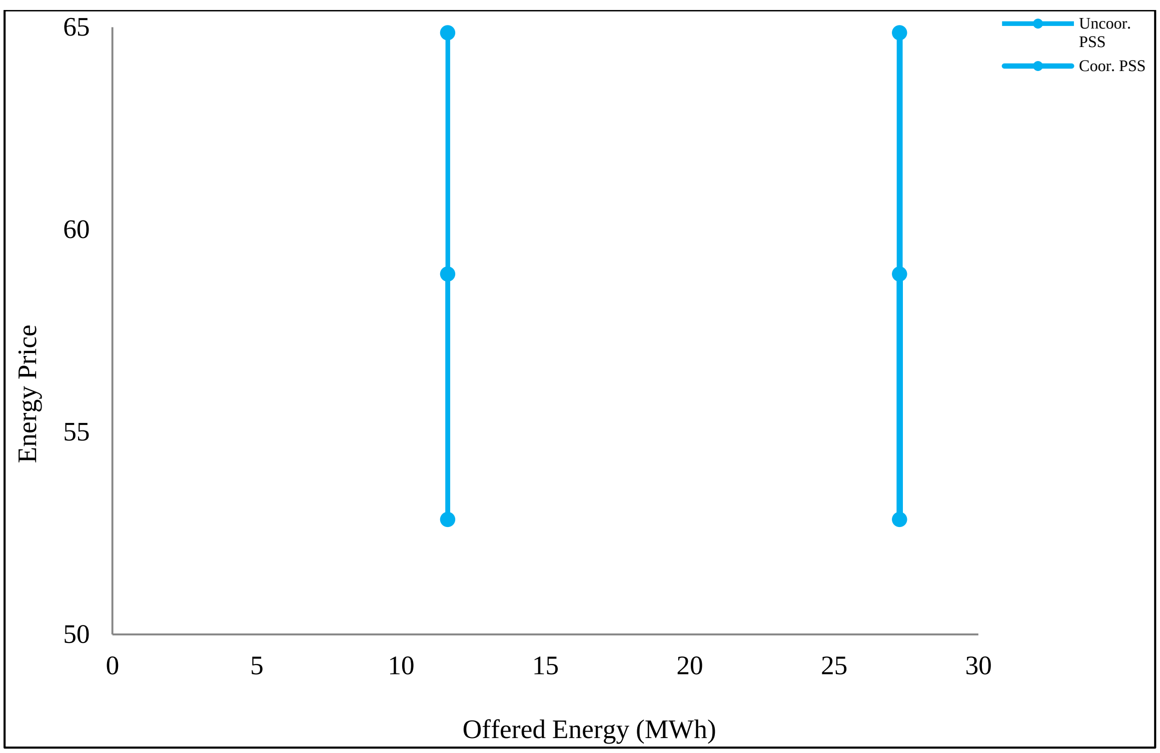

Figure 5-43 **Purchasing offers curve in energy market for hour 24, β=0.5.**

Figures 5-44 to 5-48 show the bidding capacities in regulation market for hours 6, 11, 18, 20 and 21 respectively in risk-aversion optimization for coordinated and uncoordinated resources. In figures 5-44 and 5-46 there are bidding in regulation market from PSS while it works in pumping mode.

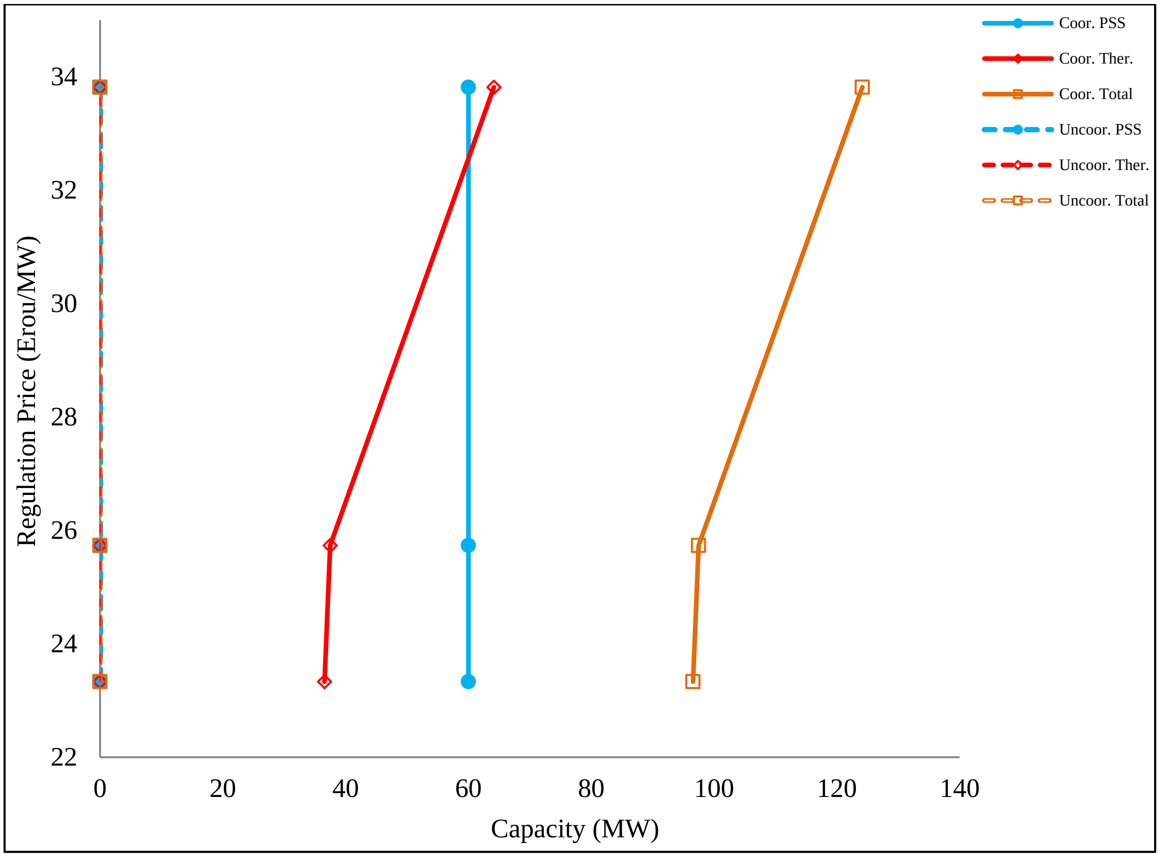

Figure 5-44 **Bidding curves in regulation market for hour 6, β=0.5.**

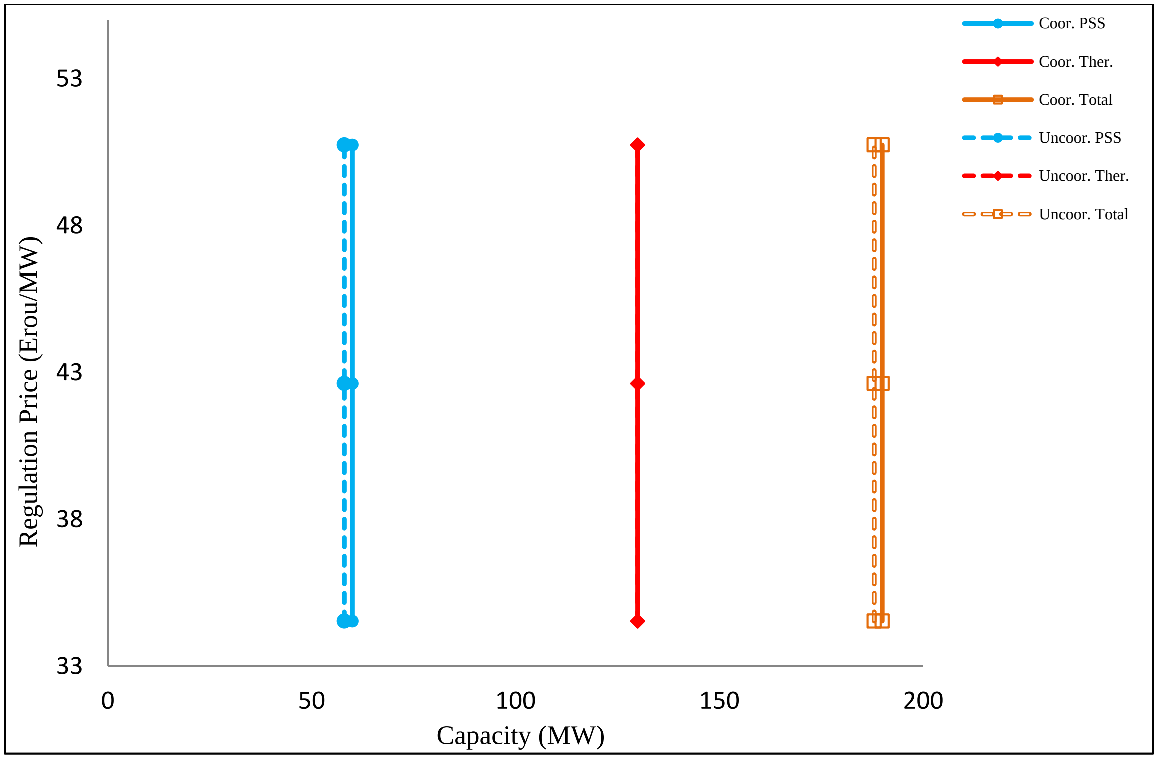

Figure 5-45 **Bidding curves in regulation market for hour 11, β=0.5.**

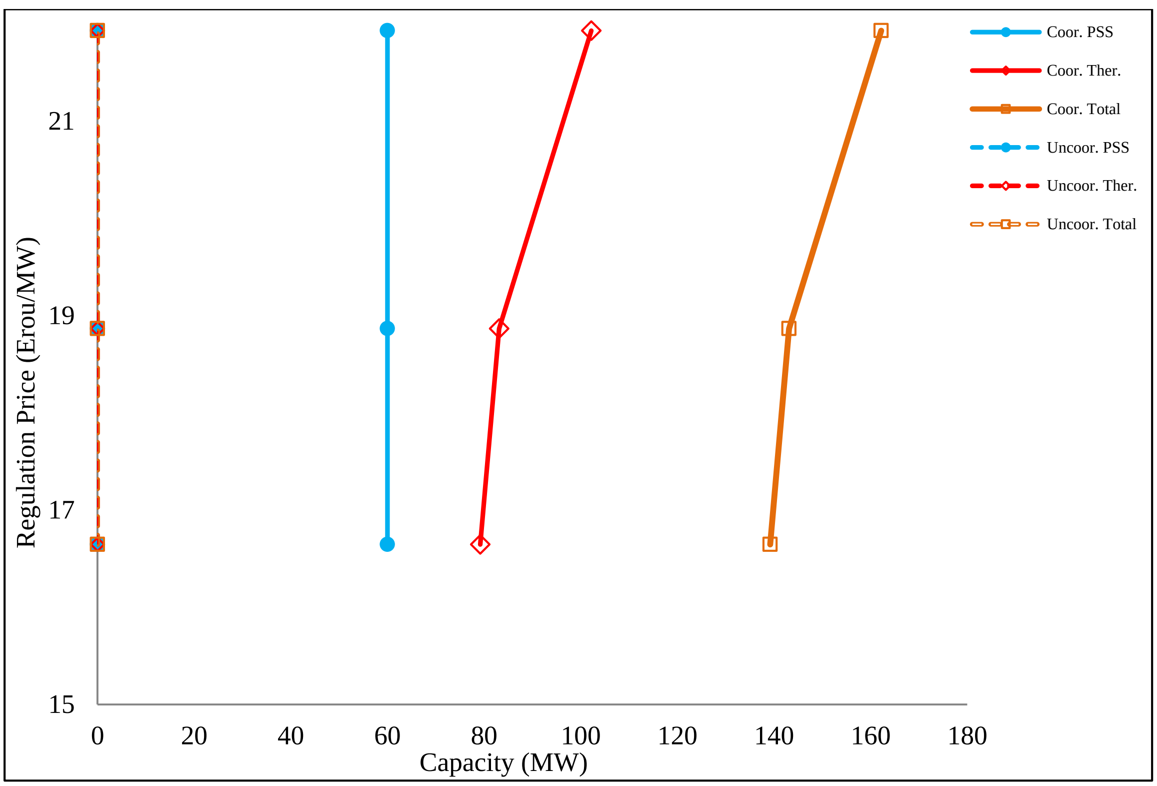

Figure 5-46 **Bidding curves in regulation market for hour 18, β=0.5.**

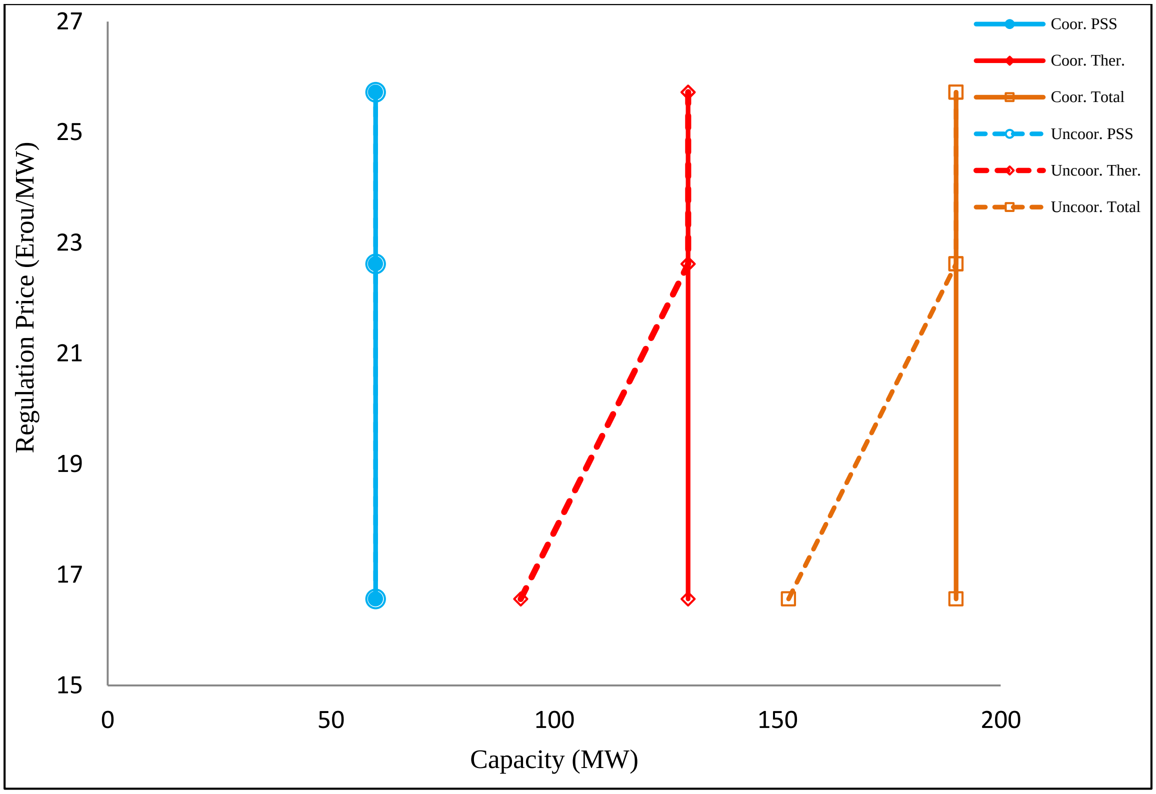

Figure 5-47 **Bidding curves in regulation market for hour 20, β=0.5.**

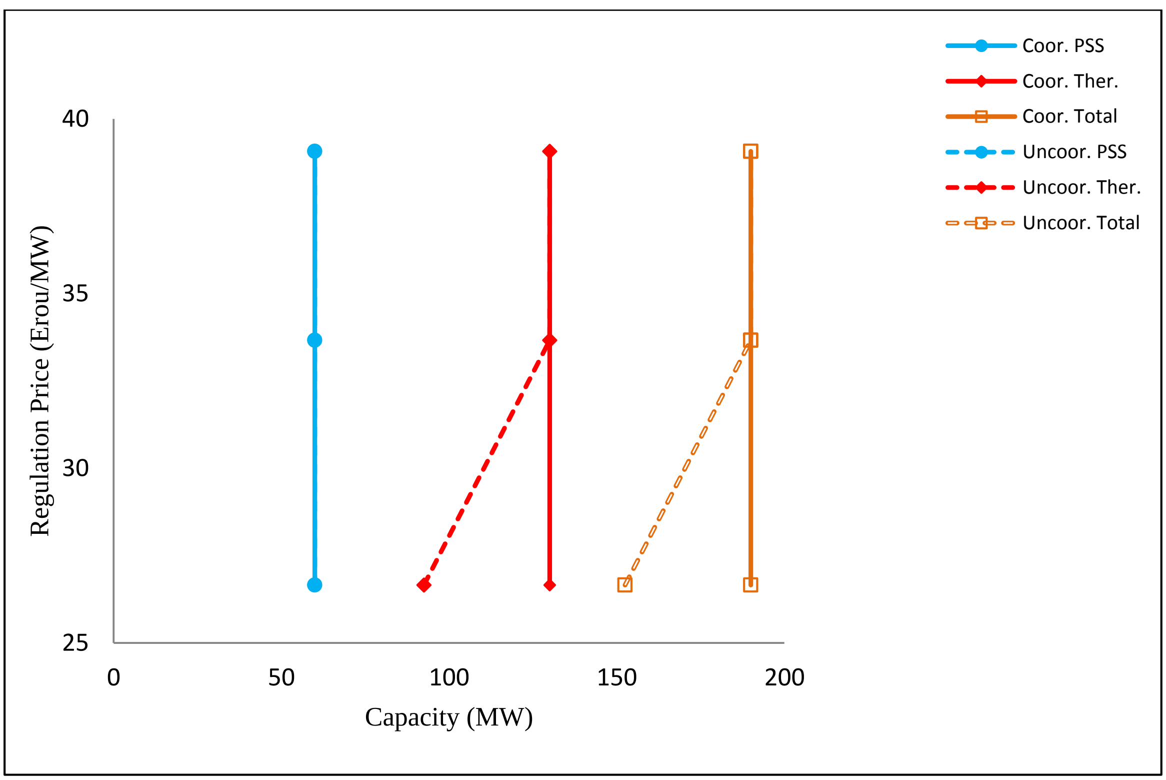

Figure 5-48 **Bidding curves in regulation market for hour 20, β=0.5.**

From the previous results, in both risk-neutral and risk-aversion cases, it can be noticed that the total bidding volumes in energy market for uncoordinated optimization are always more or equal to the total bids for the coordinated operation. This is mainly because in the coordination there is more possibility to enlarge bid volumes in regulation market. Therefore, the total bids in the regulation market for the coordinated optimization are always higher than the bids for the uncoordinated case.

5.3.3 Risk-Neutral and Risk-Aversion Comparisons

Figures 5-49 to 5-53 illustrate the difference between risk-neutral and risk-aversion optimization for total coordinated and uncoordinated bidding in energy market. It can be noticed that the total bids in risk-aversion case are always less or equal the total bids in risk-neutral optimization in the coordinated operation. Where this fact most of the time is true in the uncoordinated case. Figures 5-54 to 5-58 show the difference between risk-neutral and risk-aversion bidding in regulation market. The total bids in risk-aversion case most of the time are less or equal the total bids in risk-neutral optimization which is expected to avoid risky scenarios and improve CVaR.

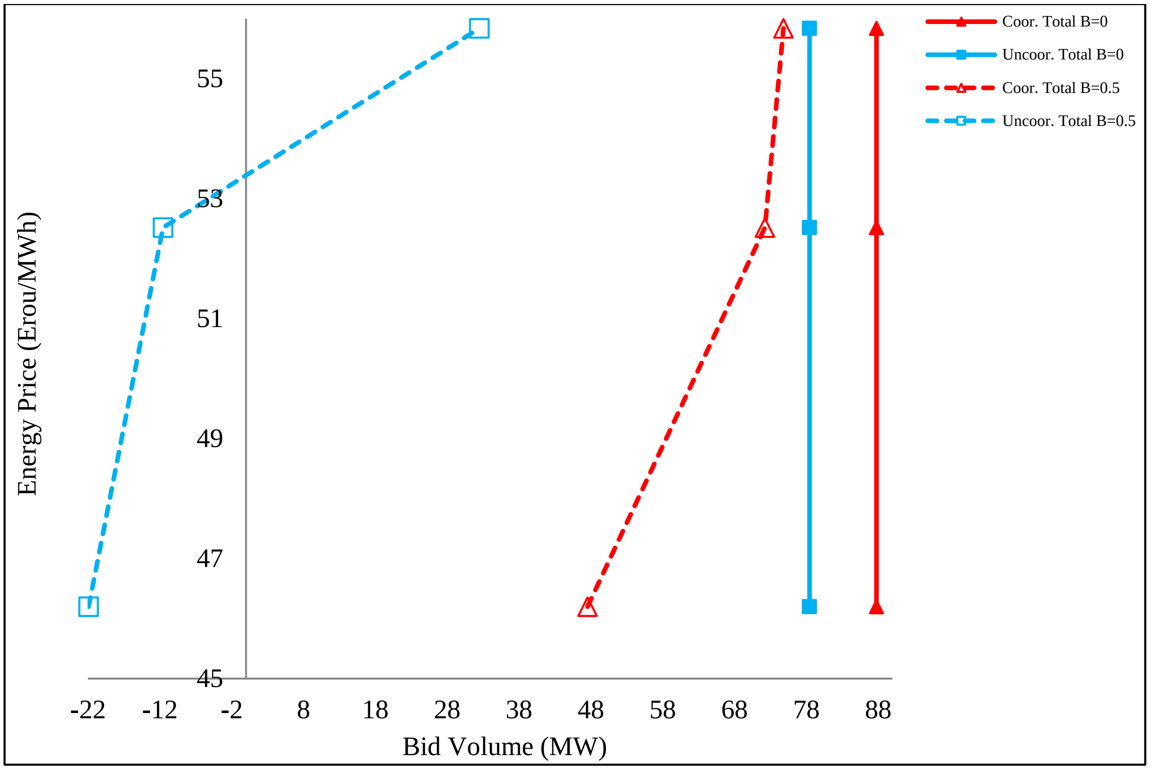

Figure 5-49 **Total energy bidding curves for coordinated and uncoordinated sources for hour 6, β=0& β=0.5.**

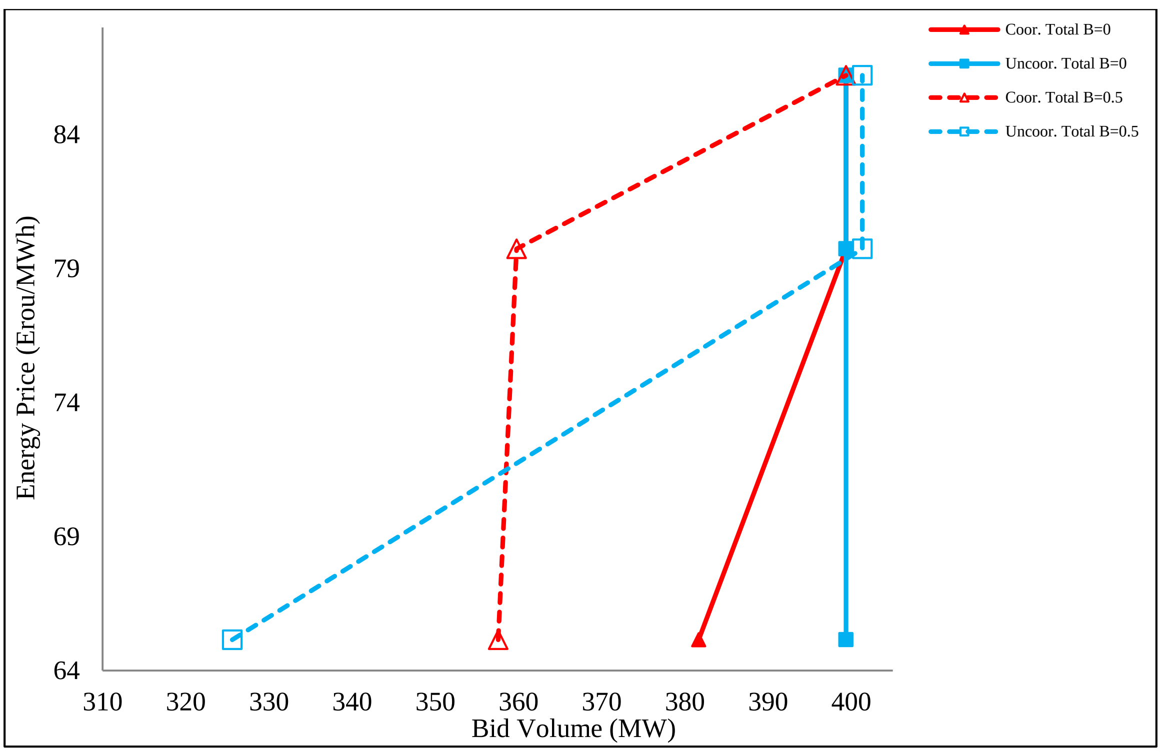

Figure 5-50 **Total energy bidding curves for coordinated and uncoordinated sources for hour 11, β=0& β=0.5.**

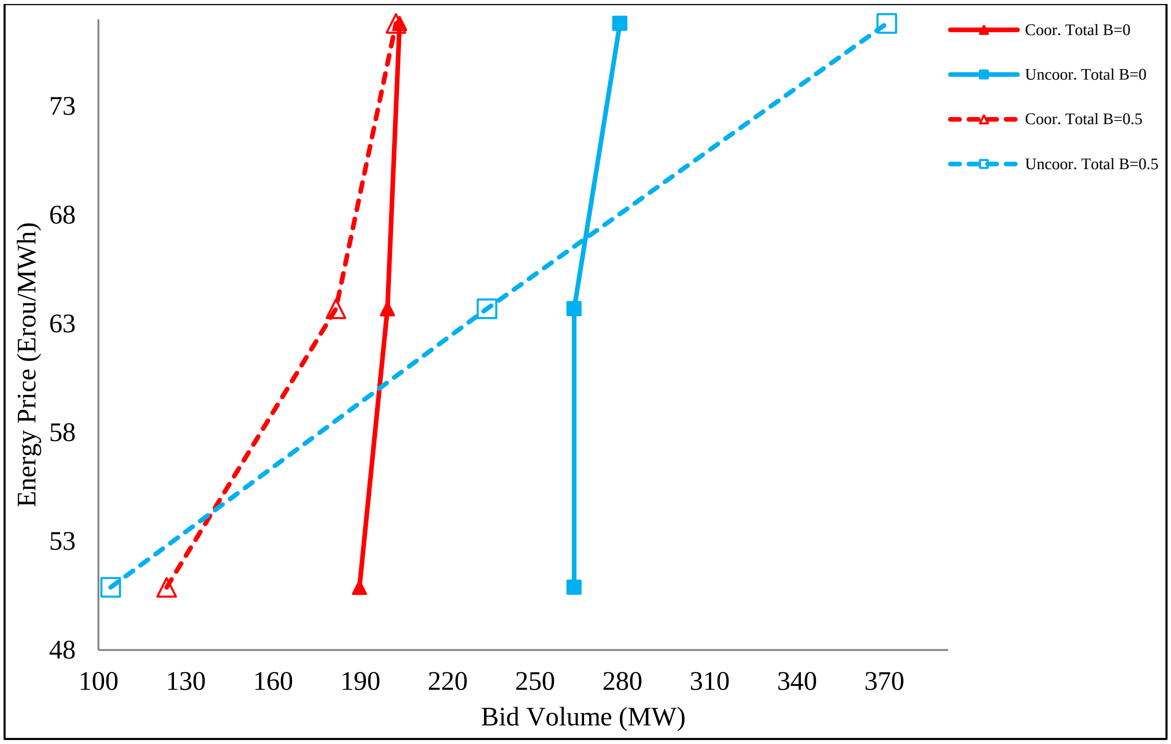

Figure 5-51 **Total energy bidding curves for coordinated and uncoordinated sources for hour 18, β=0& β=0.5.**

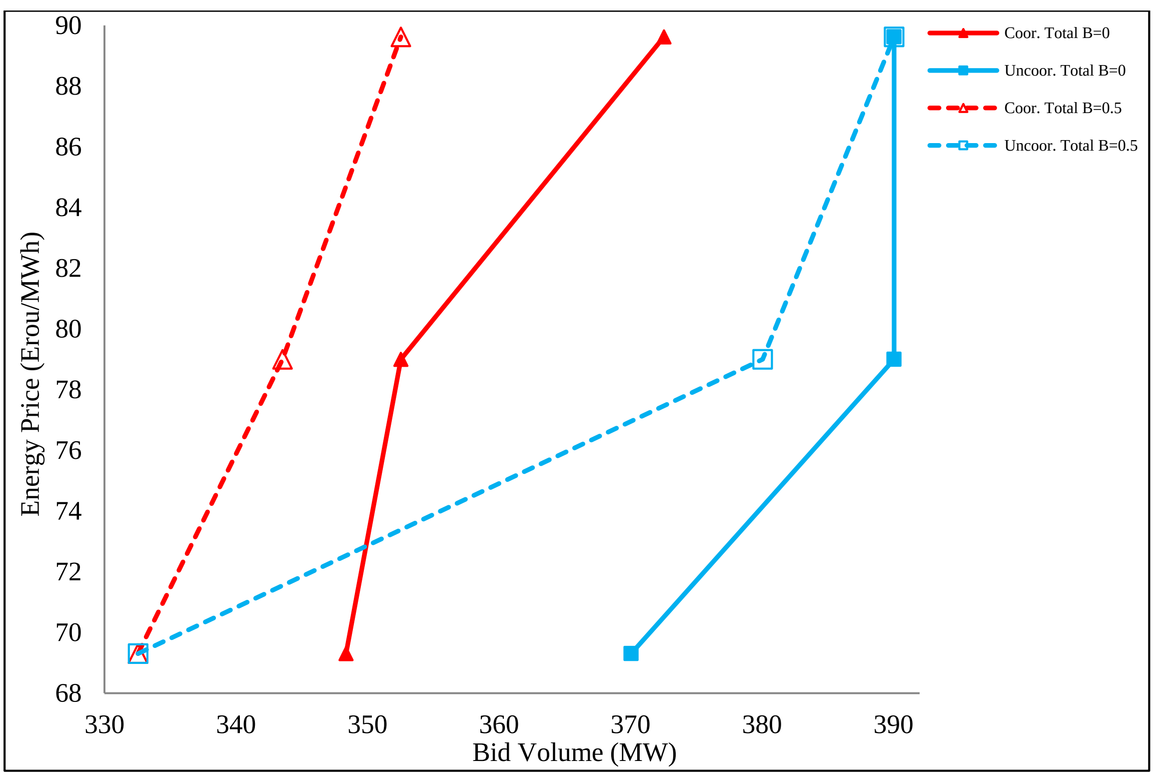

Figure 5-52 **Total energy bidding curves for coordinated and uncoordinated sources for hour 20, β=0& β=0.5.**

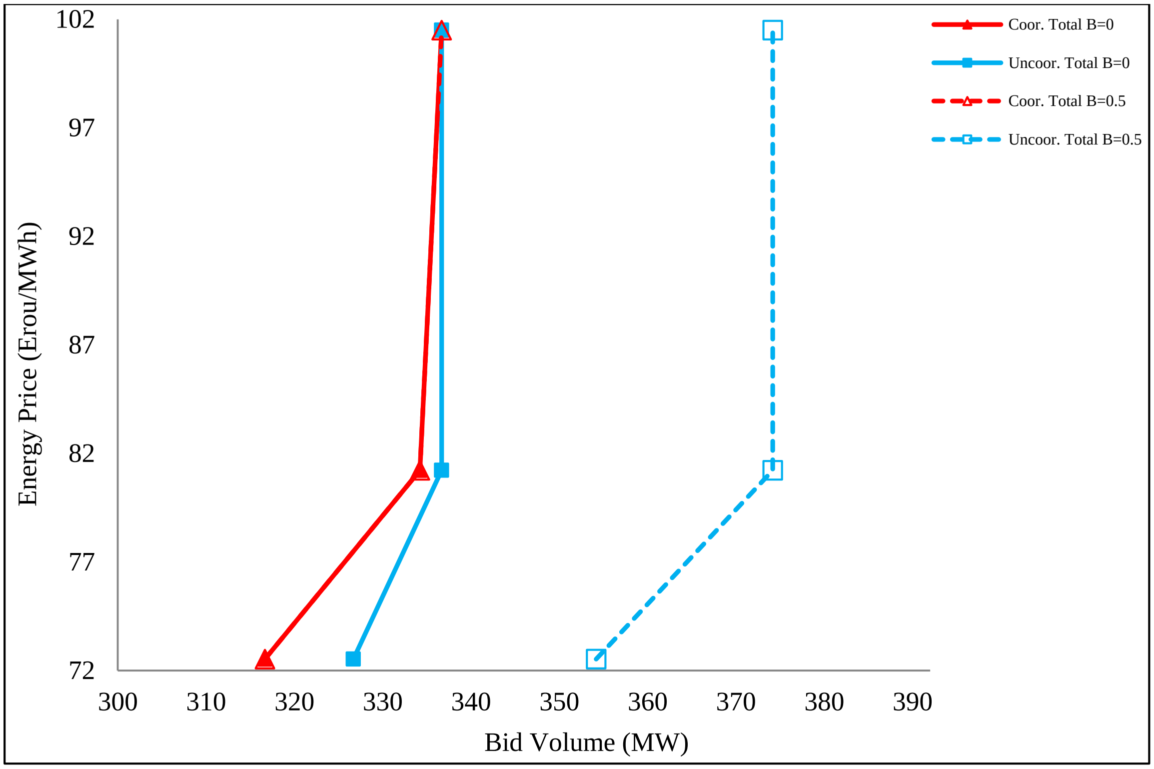

Figure 5-53 Total energy bidding curves for coordinated and uncoordinated sources for hour 21, β=0& β=0.5.

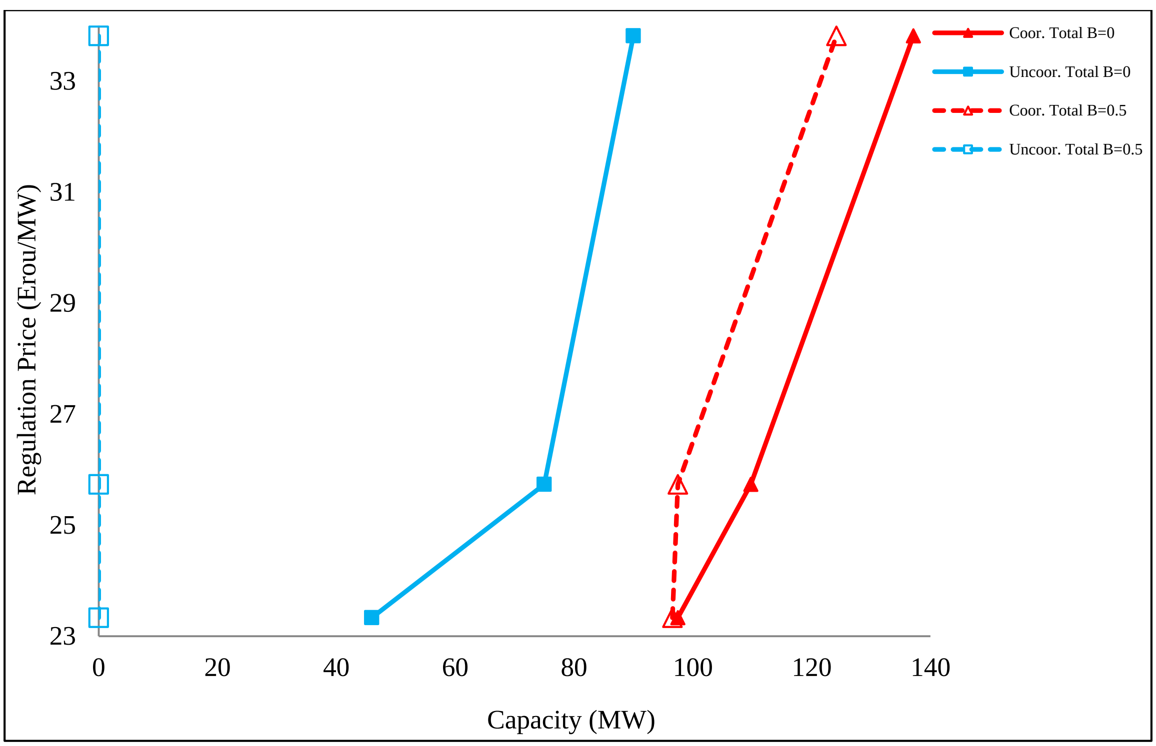

Figure 5-54 Regulation bidding capacity curves for coordinated and uncoordinated sources for hour 6, β=0& β=0.5.

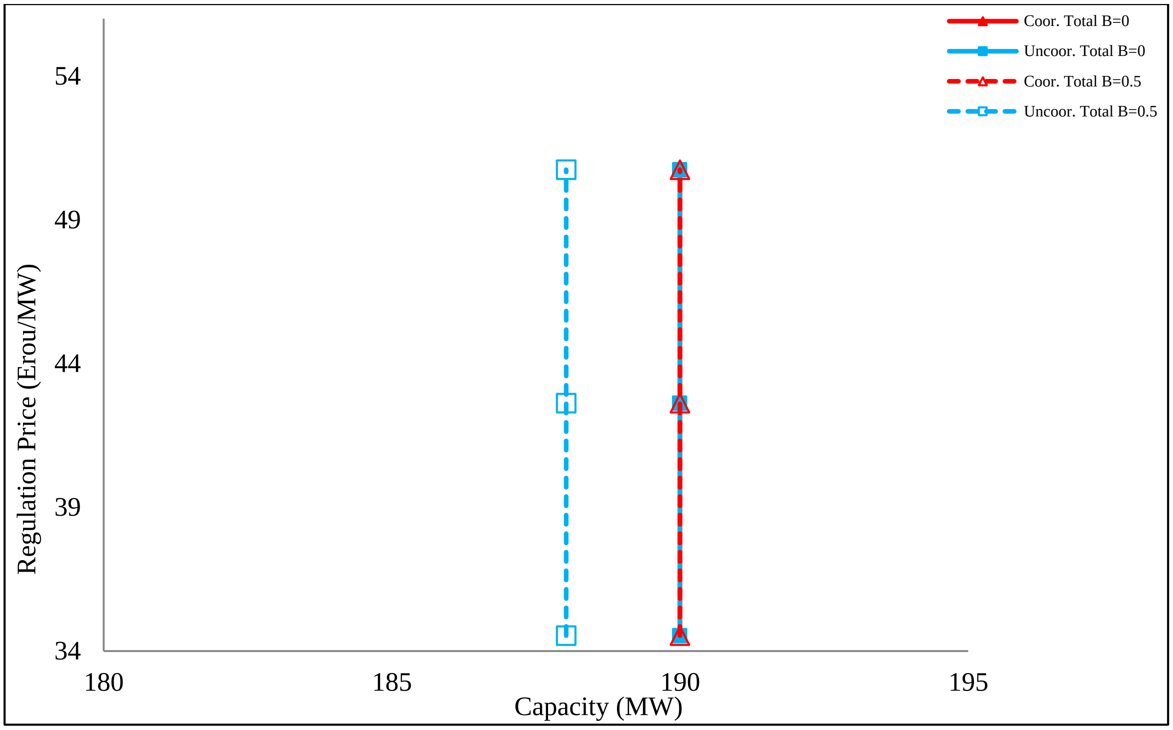

Figure 5-55 **Regulation bidding capacity curves for coordinated and uncoordinated sources for hour 11, β=0& β=0.5.**

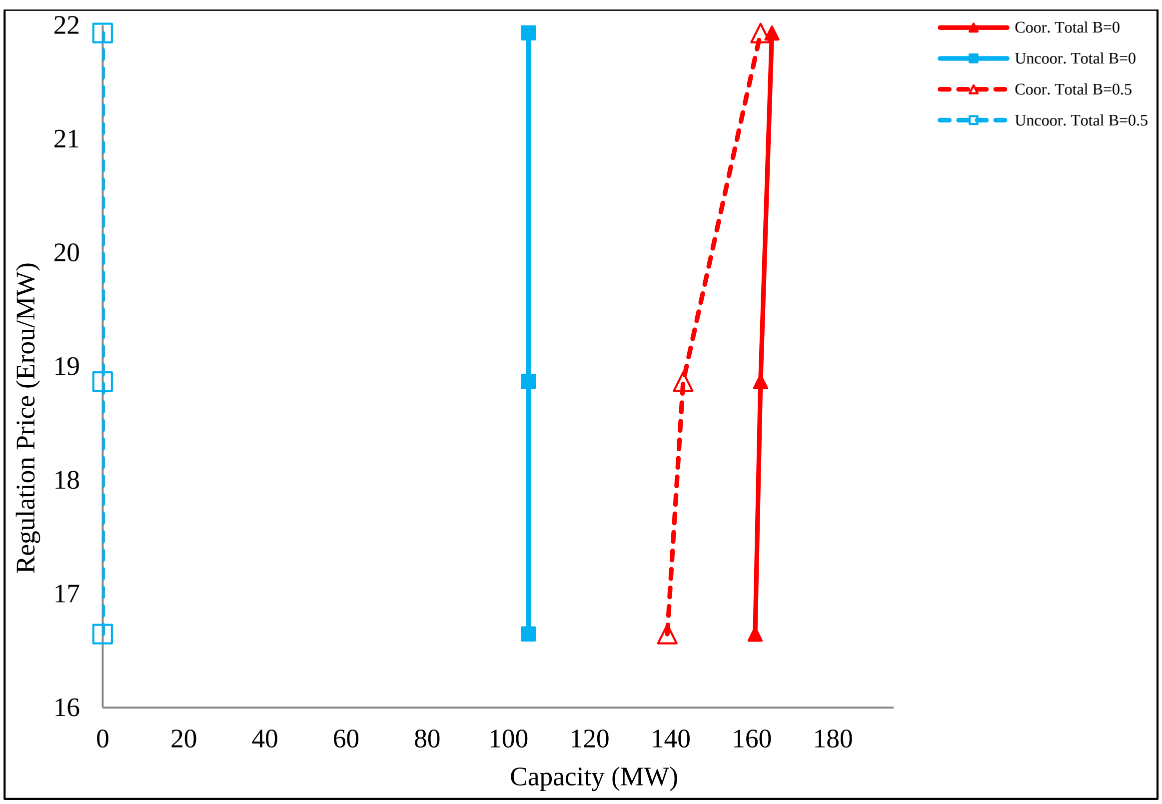

Figure 5-56 **Regulation bidding capacity curves for coordinated and uncoordinated sources for hour 18, β=0& β=0.5.**

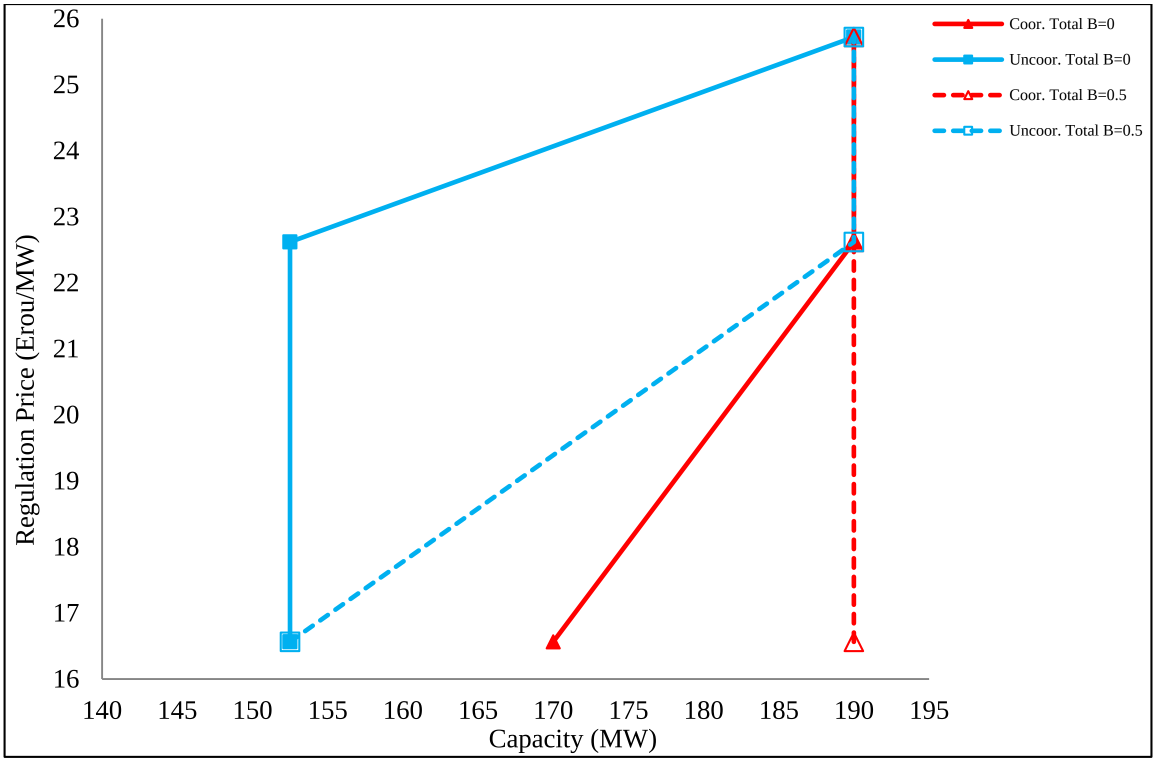

Figure 5-57 **Regulation bidding capacity curves for coordinated and uncoordinated sources for hour 20, β=0& β=0.5.**

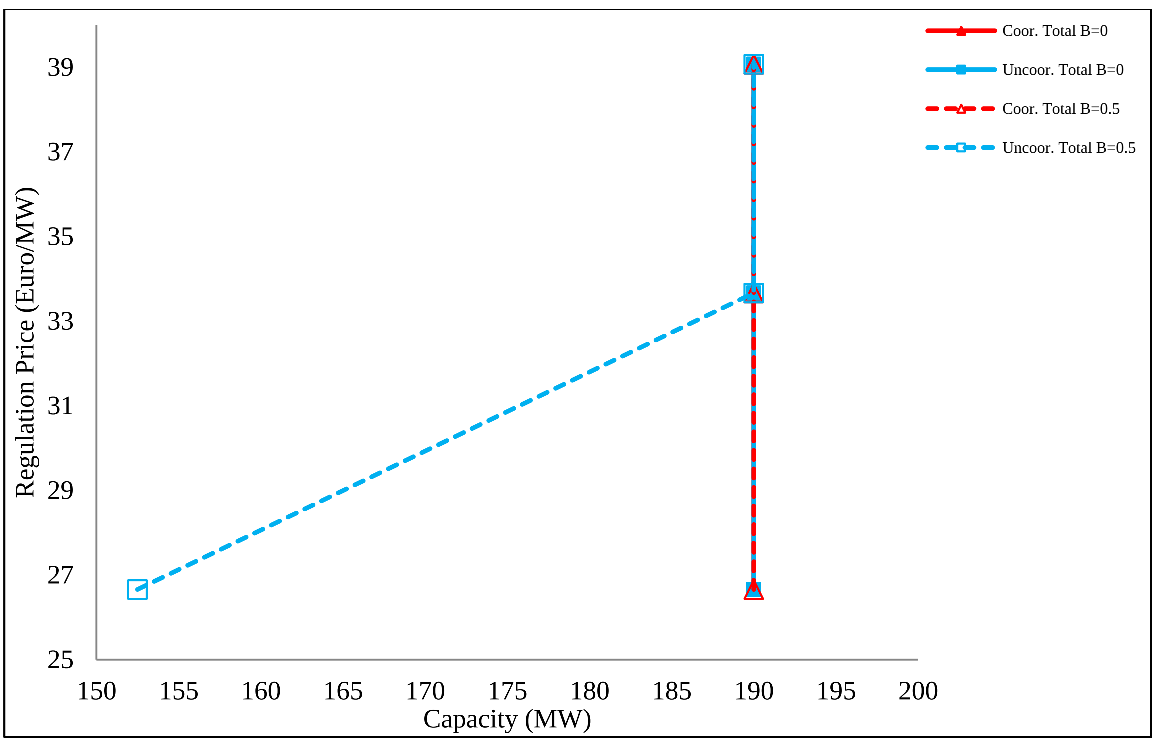

Figure 5-58 **Regulation bidding capacity curves for coordinated and uncoordinated sources for hour 21, β=0& β=0.5.**

5.4 Sensitivity Analysis

Table 5-8 shows the effect of choosing deterministic values for each uncertain parameter on the total profit and on CVaR. It is clearly shown the regulation signals hold the lowest impact on the bidding risk level and on the profits. Where the highest impact on the profit and CVaR have been noticed when wind output is selected deterministically, this is expected because the wind output power is highly uncertain parameter.

Table 5-8 SENSITIVITY ANALYSIS FOR THE COORDINATED OPERATION, β=0.

	%Change in Profit	**%Change in CVaR**
Regulation Prices	-1.01005	18.05777
Regulation Signals	0.348089	2.14425
Wind Output	4.476578	59.2504
Energy Prices	1.392779	32.69537
Imbalances Price	1.476844	14.75279

CHAPTER 6

CONCLUSIONS

In this work the optimal bidding strategies in energy and regulation markets have been obtained for energy generation system consists of five thermal units, wind plant, and a pumped storage system. Risk mechanism has been used to avoid the risk concomitant high wind imbalances scenarios. The presence of PSS assists in reducing the risk as well as increases the profit by pumping a portion of the energy generated from uncertain wind plant. The simulation studies are carried out in risk-neutral and risk-aversion optimization for both coordinated and uncoordinated PSS. CVaR is used as a risk metric to measure the risk associated with bids.

When the GENCO participates in energy market only, the enhancements in profit and CVaR for the coordinated operation over the uncoordinated operation are 0.412% and 1.798% respectively in risk-neutral optimization. While in the risk-aversion optimization, when $\beta = 0.5$, the profit is enhanced by 0.46% and the CVaR is enhanced by 0.909%.

When the system starts participating in energy and regulation markets, the CVaR declines by 88.7% for wind-thermal generation in the uncoordinated case. This declination appears as enhancement of 625.975% in CVaR for the coordinated operation over the uncoordinated operation when $\beta=0$ and 118.14% when $\beta=0.9$ both in the energy and regulation trading cases. Whereas the profits increased significantly by 8.888% when$\beta=0$ and by 14.897% when $\beta=0.9$.

In the coordinated PSS, the CVaR is enhanced by 0.4% for energy and regulation trading over the energy trading for the case of risk-neutral optimization. Finally, it is evident that the system robustness has increased significantly due to the presence of PSS when the GENCO trades in energy market. While, for trading in energy and regulation market the robustness of the coordinated PSS appears more prominent.

APPENDEX A

The thermal units and PSS characteristics data that used in this paper are given in Tables A-1 and A-2 respectively.

Table A-1: THERMAL UNITS' DATA

unit	Pmin (MW)	Pmax (MW)	MinUP (Hrs)	MinDn (Hrs)	RU (MW/Hr)	RD (MW/Hr)	Uic (Hrs)	StUpCost (€)	a (Mbtu/h)	b (Mbtu/h)	c (Mbtu/h)
1	0.01	50	1	1	50	50	0	0	0	80	0
2	5	45	1	1	15	15	0	88	85.51	70.86	0.188
3	5	45	1	1	15	15	0	88	82.34	68.23	0.181
4	25	100	5	5	50	50	0	110	32.99	64.42	0.042
5	25	100	5	5	50	50	0	110	32.99	57.92	0.042

Table A-2: PSS UNITS' DATA

unit	Pmin (MW)	Pmax (MW)	MinUP (Hrs)	MinDn (Hrs)	RU (MW/Hr)	RD (MW/Hr)	StUpCost (€)	CHO (€/MWh)	Pumping efficiency	Generation efficiency
All	0	30	0	0	30	30	0	3	0.85	0.9

References

[1] G. Akhtar and A. T. Al-Awami, "Emission-aware energy trading by coordinating thermal & wind power generation," in *Power Engineering, Energy and Electrical Drives (POWERENG), 2013 Fourth International Conference on*, 2013, pp. 1023-1027.

[2] C. Flavin and M. H. Aeck, "ENERGY FOR DEVELOPMENT."

[3] J. P. Barton and D. G. Infield, "Energy storage and its use with intermittent renewable energy," *Energy Conversion, IEEE Transactions on*, vol. 19, pp. 441-448, 2004.

[4] W. Leonhard and E. M. Grobe, "Sustainable electrical energy supply with wind and pumped storage-a realistic long-term strategy or utopia?," in *Power Engineering Society General Meeting, 2004. IEEE*, 2004, pp. 1221-1225.

[5] J. Garcia-Gonzalez, R. R. de la Muela, L. M. Santos, and A. M. González, "Stochastic joint optimization of wind generation and pumped-storage units in an electricity market," *Power Systems, IEEE Transactions on*, vol. 23, pp. 460-468, 2008.

[6] K. Rohrig and B. Lange, "Improving security of power system operation applying DG production forecasting tools," in *Power and Energy Society General Meeting-Conversion and Delivery of Electrical Energy in the 21st Century, 2008 IEEE*, 2008, pp. 1-6.

[7] M. Khatibi and M. Jazaeri, "An analysis for increasing the penetration of renewable energies by optimal sizing of pumped-storage power plants," in *Electric Power Conference, 2008. EPEC 2008. IEEE Canada*, 2008, pp. 1-5.

[8] S. A. Al Jaber, A. Z. Amin, C. Clini, R. Dixon, M. Eckhart, M. El-Ashry, S. G. B. Pradhan, A. Haddouche, D. Hales, and K. Hamilton, "Ren21."

[9] B. Ummels, E. Pelgrum, and W. Kling, "Integration of large-scale wind power and use of energy storage in the Netherlands' electricity supply," *Renewable Power Generation, IET*, vol. 2, pp. 34-46, 2008.

[10] S. J. Kazempour, M. Hosseinpour, and M. P. Moghaddam, "Self-scheduling of a joint hydro and pumped-storage plants in energy, spinning reserve and regulation markets," in *Power & Energy Society General Meeting, 2009. PES'09. IEEE*, 2009, pp. 1-8.

[11] C.-C. Wu, W.-J. Lee, C.-L. Cheng, and H.-W. Lan, "Role and Value of Pumped Storage Units in an Ancillary Services Market for Isolated Power Systems-Simulation in the Taiwan Power System," in *Industrial & Commercial Power Systems Technical Conference, 2007. ICPS 2007. IEEE/IAS*, 2007, pp. 1-6.

[12] A. Tuohy and M. O'Malley, "Impact of pumped storage on power systems with increasing wind penetration," in *Power & Energy Society General Meeting, 2009. PES'09. IEEE*, 2009, pp. 1-8.

[13] K. Qian, Y. Jiang, and Z. Li, "Improve wind energy penetration in an isolated power system by a stand-alone wind pumped storage hydropower plant," in *Remote Sensing, Environment and Transportation Engineering (RSETE), 2011 International Conference on*, 2011, pp. 406-411.

[14] C. Wang, X. Niu, F. Li, X. Li, M. Lei, L. Fu, and R. Ni, "Consideration of pumped storage as a black-start source in Shandong power grid of China," in *Innovative Smart Grid Technologies-Asia (ISGT Asia), 2012 IEEE*, 2012, pp. 1-5.

[15] R. Li, B. Wu, X. Li, F. Zhou, and Y. Li, "Design of wind-solar and pumped-storage hybrid power supply system," in *Computer Science and Information Technology (ICCSIT), 2010 3rd IEEE International Conference on*, 2010, pp. 402-405.

[16] G. Chen, D. Liu, F. Wang, and C. Ou, "Determination of installed capacity of pumped storage station in WSP hybrid power supply system," in *Sustainable Power Generation and Supply, 2009. SUPERGEN'09. International Conference on*, 2009, pp. 1-5.

[17] N. Lu, J. H. Chow, and A. A. Desrochers, "Pumped-storage hydro-turbine bidding strategies in a competitive electricity market," *Power Systems, IEEE Transactions on,* vol. 19, pp. 834-841, 2004.

[18] W. Li, J. Huang, G. Li, and Z. Wang, "Research on optimizing operation of the single reservoir of hybrid pumped storage power station," in *Electric Utility Deregulation and Restructuring and Power Technologies (DRPT), 2011 4th International Conference on*, 2011, pp. 1389-1394.

[19] R. Jiang, J. Wang, and Y. Guan, "Robust unit commitment with wind power and pumped storage hydro," *Power Systems, IEEE Transactions on,* vol. 27, pp. 800-810, 2012.

[20] C. Xingying, W. Hexian, and Z. Xiaohua, "Studies on the Unit Commitment of Thermal-Pumped Storage Plant Considering the Rapid Adjustment Characteristic of Pumped Storage Plant," in *Computer Distributed Control and Intelligent Environmental Monitoring (CDCIEM), 2011 International Conference on*, 2011, pp. 1314-1318.

[21] A. T. Al-Awami and M. A. El-Sharkawi, "Coordinated trading of wind and thermal energy," *Sustainable Energy, IEEE Transactions on,* vol. 2, pp. 277-287, 2011.

[22] M. R. Council, *DESCRIPTION OF THE OPERATION OF THE MIBEL*, 2009.

[23] J. Yu and S. X. Wang, "A study of ERCOT real-time energy market price," in *Power Engineering Society General Meeting, 2006. IEEE*, 2006, p. 6 pp.

[24] J. Yu, S. Teng, and J. Mickey, "Evolution of ERCOT Market," in *Transmission and Distribution Conference and Exhibition: Asia and Pacific, 2005 IEEE/PES*, 2005, pp. 1-6.

[25] Y. Li and J. N. Jiang, "Experience with operating the ancillary-service markets in ERCOT," in *Power Engineering Society General Meeting, 2007. IEEE*, 2007, pp. 1-6.

[26] C. Corchero and F. Heredia, "Optimal Day-Ahead bidding in the MIBEL's multimarket energy production system," in *Energy Market (EEM), 2010 7th International Conference on the European*, 2010, pp. 1-6.

[27] A. M. Greenhall, "House bat management," vol. Resource Publication 143, ed. Jamestown, ND: Northern Prairie Wildlife Research Center Online, 1982.

[28] C. Schoppe, "Wind and Pumped-Hydro Power Storage: Determining Optimal Commitment Policies with Knowledge Gradient Non-Parametric Estimation," Princeton University, 2010.

[29] B. Yang, Y. Makarov, J. Desteese, V. Viswanathan, P. Nyeng, B. McManus, and J. Pease, "On the use of energy storage technologies for regulation services in electric power systems with significant penetration of wind energy," in *Electricity Market, 2008. EEM 2008. 5th International Conference on European*, 2008, pp. 1-6.

[30] C. Loutan and D. Hawkins, *Integration of renewable resources: transmission and operating issues and recommendations for integrating renewable resources on the California ISO-controlled grid*: California ISO, 2007.

[31] Y. Makarov, S. Lu, B. McManus, and J. Pease, "The future impact of wind on BPA power system ancillary services," in *Transmission and Distribution Conference and Exposition, 2008. T&D. IEEE/PES*, 2008, pp. 1-5.

[32] J. T. Saraiva, H. Heitor, N. Correia, and R. Araujo, "Ancillary services—The current situation in the iberian electricity market and future possible developments," in *PowerTech, 2011 IEEE Trondheim*, 2011, pp. 1-8.

[33] S. Jalal Kazempour, A. Yousefi, K. Zare, M. P. Moghaddam, M. Haghifam, and G. Yousefi, "A MIP-based optimal operation scheduling of pumped-storage plant in the energy and regulation markets," in *Universities Power Engineering Conference, 2008. UPEC 2008. 43rd International*, 2008, pp. 1-5.

[34] V. Siriariyaporn and M. Robinson, "Co-optimization of energy and operating reserve in real-time electricity markets," in *Electric Utility Deregulation and Restructuring and Power Technologies, 2008. DRPT 2008. Third International Conference on*, 2008, pp. 577-582.

[35] J. Liang, S. Grijalva, and R. G. Harley, "Increased wind revenue and system security by trading wind power in energy and regulation reserve markets," *Sustainable Energy, IEEE Transactions on*, vol. 2, pp. 340-347, 2011.

[36] U. Kreutzer, *Untersuchungen über die Regulation der Bildung glykolytischer Endprodukte in marinen Invertebraten*, 1987.

[37] P. D. Brown, J. Peas Lopes, and M. A. Matos, "Optimization of pumped storage capacity in an isolated power system with large renewable penetration," *Power Systems, IEEE Transactions on*, vol. 23, pp. 523-531, 2008.

[38] S. Papaefthimiou, E. Karamanou, S. Papathanassiou, and M. Papadopoulos, "Operating policies for wind-pumped storage hybrid power stations in island grids," *Renewable Power Generation, IET*, vol. 3, pp. 293-307, 2009.

[39] J.-c. CUI, D.-h. LIU, W.-l. LIANG, F. XIE, and H.-y. CHEN, "Analysis on economic and environmental benefit of pumped-storage station [J]," *Electric Power*, vol. 1, p. 002, 2007.

[40] D. K. Khatod, V. Pant, and J. Sharma, "Optimized daily scheduling of wind-pumped hydro plants for a day-ahead electricity market system," in *Power Systems, 2009. ICPS'09. International Conference on*, 2009, pp. 1-6.

[41] K. Tanaka, K. Uchida, K. Ogimi, T. Goya, A. Yona, T. Senjy, T. Funabashi, and C.-H. Kim, "Optimal operation by controllable loads based on smart grid

topology considering insolation forecasted error," *Smart Grid, IEEE Transactions on*, vol. 2, pp. 438-444, 2011.

[42] J.-K. Lung, Y. Lu, W.-L. Hung, and W.-S. Kao, "Modeling and dynamic simulations of doubly fed adjustable-speed pumped storage units," *Energy Conversion, IEEE Transactions on*, vol. 22, pp. 250-258, 2007.

[43] G. Caralis and A. Zervos, "Analysis of the combined use of wind and pumped storage systems in autonomous Greek islands," *Renewable Power Generation, IET*, vol. 1, pp. 49-60, 2007.

[44] F. Gao, A. Hallam, and C.-N. Yu, "Wind generation scheduling with pump storage unit by Collocation method," in *Power & Energy Society General Meeting, 2009. PES'09. IEEE*, 2009, pp. 1-8.

[45] M. D. Hopkins, A. Pahwa, and T. Easton, "Intelligent dispatch for distributed renewable resources," *Smart Grid, IEEE Transactions on*, vol. 3, pp. 1047-1054, 2012.

[46] E. D. Castronuovo and J. P. Lopes, "On the optimization of the daily operation of a wind-hydro power plant," *Power Systems, IEEE Transactions on*, vol. 19, pp. 1599-1606, 2004.

[47] H. Siahkali, M. Mokhtary, and F. Ahmadi, "Fuzzy Modeling of Uncertainties in Generation Scheduling Integrating Wind Farms and Pumped Storage Plants," in *Power and Energy Engineering Conference (APPEEC), 2011 Asia-Pacific*, 2011, pp. 1-5.

[48] P. D. Nguyen Ngoc, T. Pham, S. Bacha, and D. Roye, "Optimal operation for a wind-hydro power plant to participate to ancillary services," in *Industrial Technology, 2009. ICIT 2009. IEEE International Conference on*, 2009, pp. 1-5.

[49] S.-J. Deng, Y. Shen, and H. Sun, "Stochastic Co-optimization for Hydro-Electric Power Generation," *Power Systems Engineering Research Center,* 2004.

[50] C. P. Rodriguez and G. J. Anders, "Bidding strategy design for different types of electric power market participants," *Power Systems, IEEE Transactions on*, vol. 19, pp. 964-971, 2004.

[51] G. Akhtar, A. T. Al-Awami, and M. W. Khalid, "Coordinating emission-aware energy trading with V2G services," in *EUROCON, 2013 IEEE*, 2013, pp. 1293-1298.

[52] R. T. Rockafellar and S. Uryasev, "Optimization of conditional value-at-risk," *Journal of risk*, vol. 2, pp. 21-42, 2000.

[53] J. M. Morales, A. J. Conejo, and J. Pérez-Ruiz, "Short-term trading for a wind power producer," *Power Systems, IEEE Transactions on*, vol. 25, pp. 554-564, 2010.

[54] H. Heitsch and W. Römisch, "Scenario reduction algorithms in stochastic programming," *Computational optimization and applications*, vol. 24, pp. 187-206, 2003.

[55] W. F. Sharpe and G. M. Cooper, "Risk-return classes of New York stock exchange common stocks, 1931-1967," *Financial Analysts Journal*, pp. 46-81, 1972.

[56] A. J. Wood and B. F. Wollenberg, *Power generation, operation, and control*: John Wiley & Sons, 2012.

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