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Analysis of the Profitability of Energy Storage for RES in an Equilibrium Model of the Power Market

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1 Sammendrag

Motivasjonen bak denne oppgaven er å anvende komplementaritetsbetingelser til å analysere bruksområder for energilagring. Det har blitt videreutviklet en deterministisk modell av et kraftmarked basert på tidligere prosjektoppgave [1] ved å integrere energilager i modellen. Denne modellen består av produsenter, etterspørsel, fornybar produksjon, systemoperatør, regulator, energilager, energimarked og kapasitetsmekanismer. Perfekt konkurranse har vært en forutsetning. En oversikt over modellen kan finnes i Figur 1.

Styrken til denne måten å modellere på har vist seg å være at hver enkelt aktør kan modelleres hver for seg. Optimalitetsbetingelsene utledes for hver aktør og det er viktig at konsistent notasjon brukes på tvers av aktørene. Deretter settes optimalitetsbetingelsene for alle aktørene sammen i modelleringsprogramvaren General Algebraic Modeling System.

Et scenario med store mengder fornybar energi har blitt lagt til grunn for analysene. Målet har vært å analysere hvordan ulike former for energilager fungerer i dette systemet under ulike betingelser. Det har i alt blitt kjørt 38 caser med ulike former for lager og ulike markedsbetingelser. Fire forskjellige typer marked har blitt analysert:

- Rent energimarked
- Strategisk reserve + energimarked
- Kapasitetsmarked + energimarked
- Kapasitetsbetaling (subsidie) + energimarked

En viktig konklusjon er at norsk pumpekraft bidrar til å flytte kapasitet mellom lengre tidsperioder mens batteriteknologi har vist seg å reagere kortsiktig ved å jevne ut prissvingninger. Norsk pumpekraft har vist seg å øke mengden kjernekraft med hele 18.8% og dette skyldes at pumpekraften er i stand til å jevne ut variasjoner i residualetterspørselen slik at betingelsene for kjernekraft bedres betraktelig ved at en høyere last har en kjøretid over 6500 timer.

Når det gjelder energilagrene har det vist seg at kostnadsnivå og deltakelse i kapasitetsmarkedet gir store utslag på installert kapasitet. Dette gjelder spesielt for pumpekraft der en økning i faste kostnader på bare 10% resulterte i null installert kapasitet.

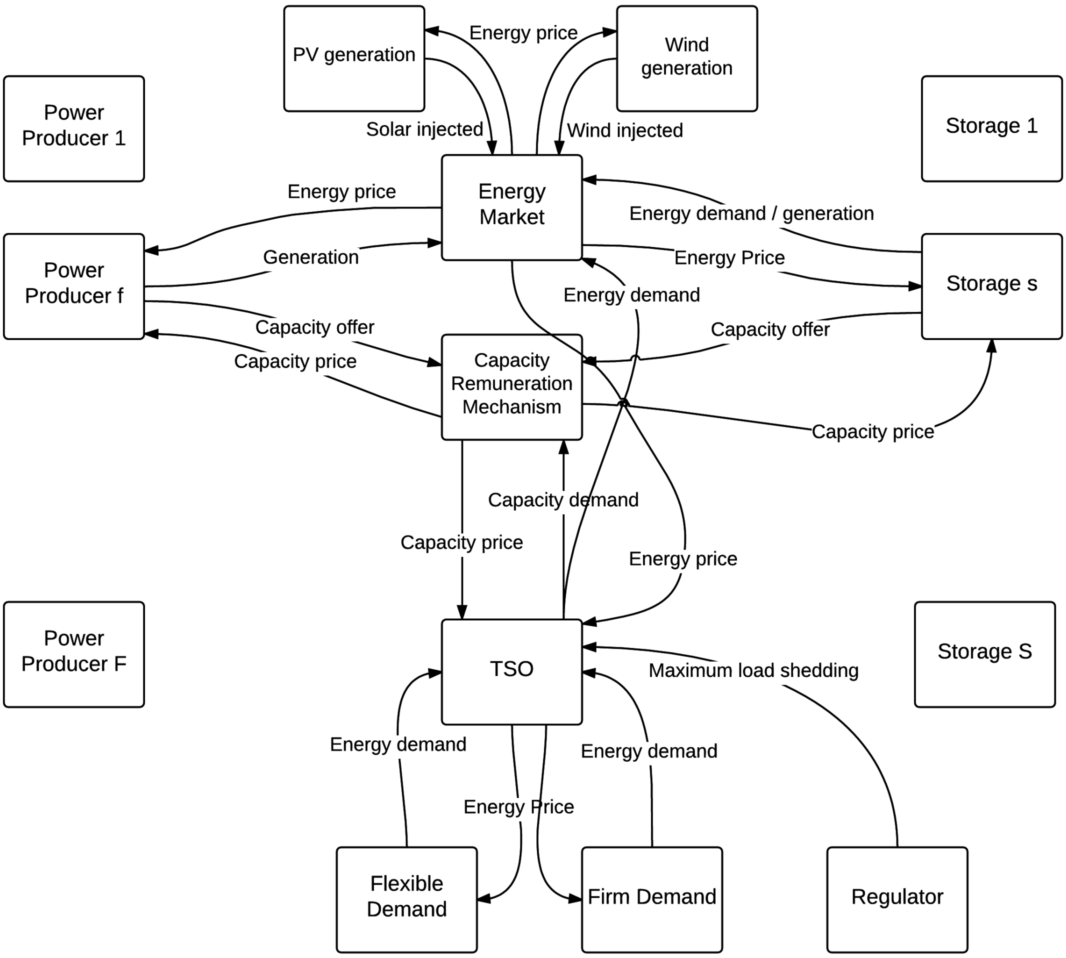

Figure 1: Oversikt over modell

2 Preface

This master's thesis has been carried out as a continuation of the project work "Developing an equilibrium model for the analysis of support schemes in future power systems with large shares of RES"[1]. The work has been done at the department of electrical power engineering at the Norwegian University of Science and Technology as the main part of the course TET4900. The preceding project work was carried out during the fall of 2015 and this master's thesis was carried out during the spring of 2016.

I would like to thank my academic advisor Magnus Korpås at NTNU for the support in general and valuable help provided with scoping the thesis. I would also like to thank my advisor Stefan Jaehnert at SINTEF Energy Research AS for giving valuable feedback on the model development and the insights he provided in general. In addition I would like to thank Martin Kristiansen at NTNU for the technical assistance he provided with the modeling software and Hanspeter Höschle at the Flemish Institute for Technological Research for the help he offered when implementing the model in the preceding project work.

Trondheim, June 8, 2016.

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3 Abstract

The motivation behind this thesis is to utilize complementarity conditions to assess the applications of energy storage in an energy system with high levels of renewable energy sources. A model of a perfectly competitive power market has been developed based on complementarity theory. The model includes firm demand, system operator, power producers and storage units. In addition, four different capacity remuneration schemes have been implemented: Energy only, strategic reserves, capacity market and capacity payment. These models have been subjected to a scenario with high levels of renewable energy in order to assess the impact of energy storage in these circumstances.

The methods used in this work are theoretical and highly dependent on the assumptions and parameters used. The documentation should give a good insight to complementarity modeling in general as well as describing the entire model all the way up to the full mixed complementarity problem formulation.

A large part of this work has consisted of improving the existing model from the project work[1] and develop and integrate the energy storage with the rest of the model.

The findings show that the system can benefit from energy storage options. In general, energy storage will provide better conditions to base load units such as nuclear power. The energy storage will smooth out variations in residual demand and increase the amount of capacity a base load unit can run for a large portion of the year. Utilizing Norwegian hydro reservoirs for pumped hydro applications was found to be the most effective storage unit, increasing the amount of nuclear power by 18.8%. Pumped hydro was found to shift energy on a long-term scale while the battery was found to arbitrage prices on a shorter term.

This thesis can give an insight into which barriers need to be overcome in order to ensure investments in energy storage. For example high fixed costs of the storage and unfavorable conditions compared to thermal plants in a possible capacity remuneration mechanism can be the determining factor resulting in low or no installed storage capacity.

Contents

4 Abbreviations

CCGT Combined-Cycle Gas Turbine

CM Capacity Market

CP Capacity Payment

CRM Capacity Remuneration Mechanism

CS Consumer Surplus

EO Energy Only

ENTSO-E European Network of Transmission System Operators for Electricity

FC Fixed Costs

GAMS General Algebraic Modeling System

KKT Karush-Kuhn-Tucker

MCP Mixed Complementarity Problem

OCGT Open-Cycle Gas Turbine

PHES Pumped Hydro Energy Storage

RES Renewable Energy Sources

SR Strategic Reserve

TSO Transmission System Operator

VC Variable Costs

VOLL Value Of Lost Load

5 Introduction

5.1 Thesis description and motivation

This Master thesis is a continuation of the project work "Developing an Equilibrium Model for the Analysis of Support Schemes in Future Power Systems with Large Shares of RES" [1] which was based on the model described in [7].

The background for this work has been the fact that the renewable energy is expected to increase in the European power system. However, this poses a problem regarding back-up capacity in order to ensure system adequacy when the injected energy from RES is low and demand is high. This introduces the need for capacity remuneration mechanisms (CRMs). Instead of only remunerating the energy produced these market mechanisms aim to compensate power producers and possible storage facilities for the capacity installed. Even if not used, this capacity can be of value to the system in order to prevent deficits because of the intermittent RES.

In this context this thesis applies complementarity theory in order to develop a MCP model suitable for analyzing how different support schemes and technology parameters affects the actors in the system. The main focus of this thesis is implementation and analysis of storage technologies in the model. The goals for this thesis can be summarized as:

- Thorough documentation of the models.
- Implementing energy storage as a new actor in the existing GAMS models.
- Analysis of the decisions for different actors using scenario data from ENTSO-E.
- Assessing the potential role of energy storage technologies as an alternative to thermal backup capacity.

5.2 Modeling Tools

The modeling software that has been used in this thesis is the General Algebraic Modeling System (GAMS). GAMS is a high-level modeling system that is suitable when solving most types of optimization problems depending on the solver that is utilized. For solving Mixed Complementarity Problems the PATH solver has been used. The approach that has been chosen is to represent in-data as an Excel file, then importing this to GAMS. After solving the model, GAMS data have been exported to the relevant variable values in a new excel file. The results files have then been imported to Matlab where the necessary code for generating figures has been implemented. This procedure is represented graphically in figure 2.

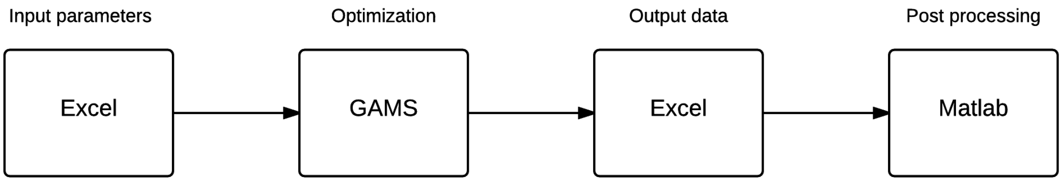


Figure 2: Data processing

The strength of GAMS is that it enables the modeler to focus on the mathematical formulations as most of the code can be written in a mathematical language reducing the need for coding.

The model with energy storage has become complex and this has caused convergence difficulties in the PHES model. This is the reason for reducing the resolution by representing the year with 4380 periods instead of 8760 (one period in the model equals two hours). However, modeling two storage technologies at the same time has not been possible due to too long solution times and failure to converge.

6 Theory

6.1 Energy Management

A power system has a demand side and a supply side and the role of the power market is to make sure these parts meet in an efficient manner. The basic function of the power market is to make sure supply match demand in every hour of the year. Electricity as a commodity has the following features [14, p. 12-13]:

- Continuous flow of energy.
- Electricity is consumed and generated at the same time.
- It is not easy to store in large scale. This option may be expensive.
- The consumption varies during the day and over the year.
- Electricity is very important to most parts of society.
- It is possible to have partial or complete breakdown of the power system due to imbalances. Good operation and planning practices reduces the risk of this.

These aspects lead to the conclusion that power market design is important for the safe operation of a power system. The special features of electricity increases the complexity of the marketplace when operating a power system in a deregulated power market.

In order to balance the grid the consumed power must equal the generated power during each hour. This can be visualized in figure 3. This balancing act becomes increasingly challenging when the amount of renewable in energy increase as the renewable production is not controllable. This would mean that the red graph in the figure becomes more variable. As illustrated by the blue graph for energy storage, the storage generates energy when there is a deficit and stores energy when there is a surplus of generation in the system. However, this representation is very simplified. In order to model the operation of storage it is needed to include these units in a model of the energy market. In addition, some parts of the generation can be controlled since there are conventional power plants in the system in addition to the renewable energy sources.

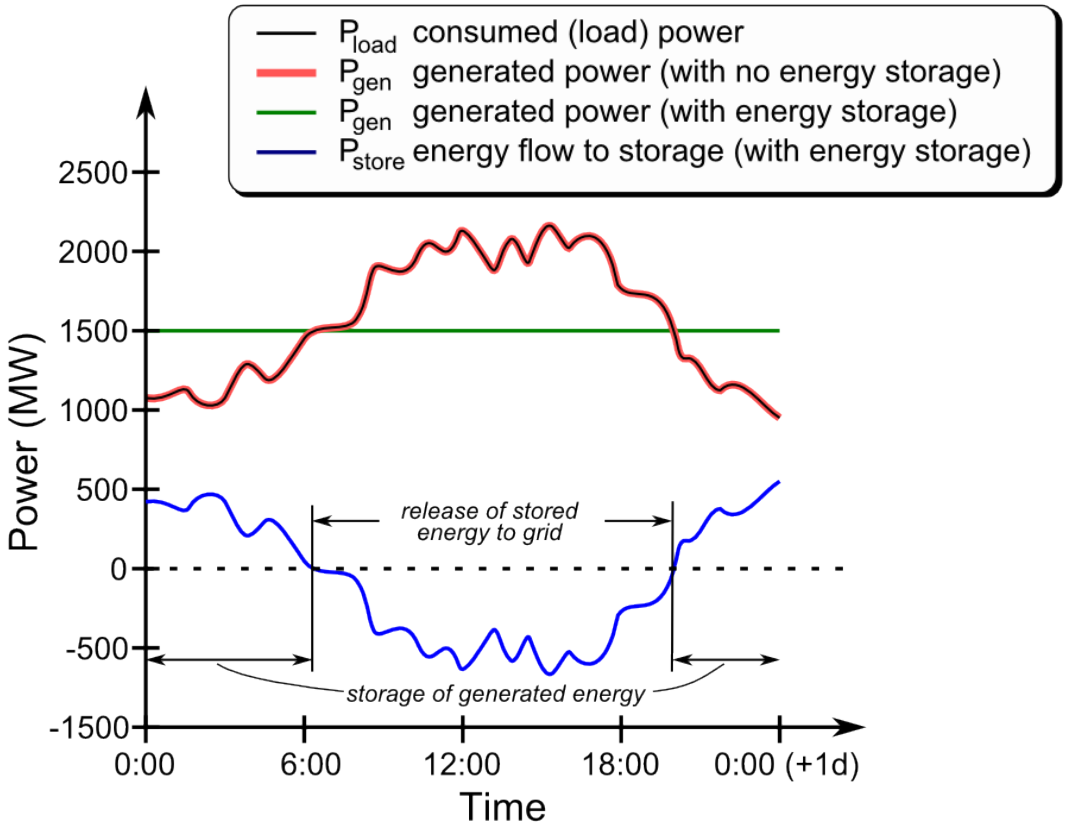


Figure 3: Principle for grid balancing [15]

6.2 Electricity Remuneration Mechanisms

There are several market mechanisms that can balance the energy market. In this thesis the focus will be on a spot market for the energy mechanisms and on capacity remuneration through either strategic reserves or a capacity market.

6.2.1 Energy Based Remuneration

The energy market is remunerating each MWh produced. The obtained price for each MWh varies and is a result of supply and demand each hour of the operating period. This is called a Pool-co market [13] and generating companies compete on the supply side to the entire energy market and not to individual consumers.

6.2.2 Strategic Reserves

A strategic reserve is emergency capacity controlled by a TSO. These reserves are obtained through a strategic reserves market where the TSO is on the demand side and the power producers are on the supply side [10]. Once capacity is contracted through this market the TSO controls it and it is no longer a part of the generation controlled by the supplier.

The strategic reserves lead to an extended supply when the normal generation is not enough. However, this means that the strategic reserves can interact with the market dynamics and inhibit the price incentives necessary for investments. This means that the strategic reserves capacity should only be activated when the system is near an emergency state and only at prices above the highest bid in the market [10].

6.2.3 Capacity Market

A capacity market (also called capacity requirement) is an volume-based mechanism. In addition to the energy market an additional market for the installed capacity is created. In the capacity market the TSO is on the demand side and decides how much capacity should be installed in the system. This provides a new revenue stream to the generation firms and, in contrast to the strategic reserves market, the capacity is operated by the individual firms as usual in the energy market [10].

A capacity market ensures the correct amount of generation capacity by directly controlling it, this means that the investments should be triggered before the system adequacy is insufficient. However, the implementation of a new market is required and this administration can be complex and costly [10].

6.2.4 Capacity Payment

A price-based capacity payment market remunerates the generators according to the capacity installed. The remuneration rate is set by the authorities and can be different for different technologies. RES capacity is typically not remunerated by capacity payments. This scheme is arguably simple and therefore simple to implement. However, the rates can have large impacts on investment decisions. This means that the result can easily be too much or too little capacity installed in the system if the remuneration amount is not set properly [10].

6.3 Complementarity Modeling

This section will describe optimization problems and how the complementarity slackness can be used to derive the optimality conditions.

6.3.1 Optimization Problems

An optimization problem consists of an objective function to be maximized or minimized within one or more constraints. These problems can be both linear and nonlinear, but this thesis will focus on linear problems (LP). A general primal and dual formulation of a LP problem can be found below [11, p.140].

Primal (P):	**Dual (D):**
Max: $z = \mathbf{c}^T * \mathbf{x}$	Min: $w = \mathbf{b}^T * \mathbf{v}$
subject to: $\mathbf{A}*\mathbf{x} \leq \mathbf{b}$	subject to: $\mathbf{A}^T * \mathbf{v} \geq \mathbf{c}$
$\mathbf{x} \geq 0$	$\mathbf{v} \geq 0$

6.3.2 Lagrangian Relaxation

A convenient way to represent optimization problems is by formulating the Lagrangian function of the problem. The Lagrangian is a relaxation of the original problem where the restrictions are incorporated in the objective function as penalty functions. The Lagrangian multiplier assigned to each restriction is the penalty for violating the constraint [11, p.455].

To explain the Lagrangian formulation the general optimization problem is written in a slightly different way in equations 1 and 2[11, p.455]. It should be noted that even though the focus is on linear problems in this thesis the approach described can also be applied to nonlinear problems.

$$\text{Minimize: } f(\mathbf{x}) \tag{1}$$

Subject to:

$$g_i(\mathbf{x}) \geq b_i, i = 1, ..., m \tag{2}$$

The Lagrangian of this problem is formulated in equation 3. All dual variables, v_i, is ≥ 0. These dual variables are the Lagrangian multipliers [11, p.456].

$$\mathcal{L}(\mathbf{x}, \mathbf{v}) = f(\mathbf{x}) + \sum_{i=1}^{m} v_i(b_i - g_i) \quad (3)$$

This Lagrangian function can be differentiated with respect to the decision variables and dual variables in order to obtain the optimality conditions.

6.3.3 Equilibrium Models

A power market model consists of several actors with different objective functions and constraints. Such a model is an example of an equilibrium model. What characterizes the equilibrium state is that all constraints for all actors are satisfied in addition to no actors preferring to change their decision [6]. There are several ways of handling such a problem. However, this thesis will focus on deriving the optimality conditions for each actor and then solving the optimality conditions as a system of equations meaning that the equilibrium is reached when all equations are satisfied.

The derivation of optimality conditions will be done by firs formulating the problem for each actor in the model. Next, the Lagrangian function for each actor will be formulated. From this, the optimality conditions will be derived and the full MCP formulation of the different models will be a summary of these conditions.

6.3.4 Complementarity Conditions

From the optimization problem, the optimality conditions of a linear problem can be expressed as complementary conditions. It is known that if a constraint is not binding, the shadow price of this constraint will have a value of zero. Equations 4 to 6 from Optimization [11, p. 145] describe the optimality conditions for a general LP problem.

$$\text{Primal feasibility: } \mathbf{Ax} \leq \mathbf{b}, \mathbf{x} \leq 0 \quad (4)$$

$$\text{Dual feasibility: } \mathbf{A}^T\mathbf{v} \geq \mathbf{c}, \mathbf{v} \geq 0 \quad (5)$$

$$\text{Complementarity: } \mathbf{v}^T(\mathbf{b} - \mathbf{Ax}) = 0, \mathbf{x}^T(\mathbf{A}^T\mathbf{v} - \mathbf{c}) = 0 \quad (6)$$

These equations show that by finding the primal and the dual of a linear optimization problem the optimality condition can be found as the solution that has both primal and dual feasibility.

One approach to formulate the complementarity slackness constraints is to formulate the Lagrangian for each actor in an equilibrium model and differentiate with respect the decision variables and Lagrangian multipliers and then use the complementarity slackness theorem together with the equality or inequality constraints in the problem [12, p.34]. This is the method that will be used when developing the model in section 7.

6.3.5 Kuhn-Tucker Conditions

Kuhn-Tucker conditions describe the optimality conditions and are derived from the Lagrangian formulation. After the Lagrangian has been formulated the Kuhn-Tucker conditions for a maximization problem are defined as the partial derivatives of the Lagrange function:

- With respect to the nonnegative variables are non-positive [12, p.34] and the complementarity slackness condition [11, p. 145] is fulfilled.
- With respect to free variables are equal to zero [12, p.34].
- With respect to the Lagrange multipliers corresponding to the inequality constraints are nonnegative [12, p.34] and the complementarity slackness condition [11, p. 145] is fulfilled.
- With respect to the Lagrange multipliers corresponding to the equality constraints are equal to zero [12, p.34].

These conditions will be used extensively when the model in this thesis is developed in appendix B.

6.3.6 Karush-Kuhn-Tucker Conditions

The generalized Karush-Kuhn-Tucker (KKT) conditions is essential when formulating nonlinear optimization problems as complementarity problems. KKT conditions is the first order mathematical conditions that has to be satisfied in order to have a optimal solution. From Optimization [11, p. 290] the general KKT conditions are described as shown in equation 7 to 10.

$$\nabla f(x) = \sum_{i=1}^{m} v_i * \nabla g_i(x) \tag{7}$$

$$v_i \geq 0, i = 1, ..., m \tag{8}$$

$$g_i(x) \leq b_i, i = 1, ..., m \tag{9}$$

$$v_i(b_i - g_i(x)) = 0, i = 1, ...m \tag{10}$$

If we have a nonlinear problem with both equality constraints and inequality constraints of both types, we can always reformulate the problem to one of the standard forms and then express the complementarity constraints or the KKT conditions as above. The KKT conditions forms the basis for defining and solving the system as a MCP. However, the model applied in this thesis will not use the KKT conditions as the problems are linear.

6.3.7 Mixed Complementarity Problems

The optimality conditions that has been derived can be represented as a MCP problem [5]. What have been explained previously in this section can be used to form a wide range of problems characterized as mixed complementarity problems (MCP). The complementarity slackness formulation can be used to model the KKT optimality conditions of nonlinear problems and LP optimization problems. There is no specific optimization problem to be solved but the optimality conditions has been derived and these can be solved to obtain the optimal solution to the full model. This means that for example a market with several actors that have different objective functions can be formulated as a complementarity problem in order to generate a solution that is optimal for all actors.

The general mathematical formulation of an inequality constrained and equality constrained complementarity problem is described in equation 11 and 12 [5]:

NCP: Given a function F: $\mathbf{R}^n \rightarrow \mathbf{R}^n$, find z $\in \mathbf{R}^n$ such that:

$$0 \leq F(z) \perp z \geq 0 \tag{11}$$

NE: Given a function F: $\mathbf{R}^n \rightarrow \mathbf{R}^n$, find z $\in \mathbf{R}^n$ such that:

$$F(z) = 0 \tag{12}$$

Equation 11 expresses that one of the two inequalities is to be satisfied as an equality so that the complementarity condition shown in equation 13 is satisfied.

$$z_i * F_i(z) = 0 \tag{13}$$

Based on these complementarity problems a general mixed complementarity problem is defined as[5]:

MCP: Given lower bounds $l \in \{\mathbf{R} \cup \{-\infty\}\}^n$, upper bounds $u \in \{\mathbf{R} \cup \{\infty\}\}^n$ and a function F: $\mathbf{R}^n \rightarrow \mathbf{R}^n$, find $z \in \mathbf{R}^n$ such that precisely one of the following holds for each $i \in \{1, ..., n\}$:

$$F_i(z) = 0 \text{ and } l_i \leq z_i \leq u_i \tag{14}$$

$$F_i(z) > 0 \text{ and } z_i = l_i \tag{15}$$

$$F_i(z) < 0 \text{ and } z_i = u_i \tag{16}$$

7 Methodology

Figure 4 shows a general outline of the model that has been implemented. The model is a MCP equilibrium model, which was described in section 6.3. The strength of using complementarity theory is that the restrictions and optimality conditions of each actor can be derived separate from the rest of the model and then all of these conditions can be put together in the modeling software (GAMS). This means that a complex problem can be broken down to smaller pieces, it also means that the modeling of one actor can be changed without having to redevelop the entire model. However, this requires the modeler to be very diligent regarding the use of correct notation for all parts of the model in order for everything to fit together when implementing. The models are annualized with a time step of two hours in order to keep the solution time at a reasonable level.

This section will describe each model and the optimization problem for each actor under this market structure. Further, the Lagrangian of the different actors will be presented in appendix B based on the optimization problems in this section. From this, the optimality conditions will be derived based on the complementarity slackness condition that were described in section 6.3.4. The MCP formulation will be presented in this section and this will be based on the derivations in appendix B.

The coupling between the different market actors are the energy and capacity markets. For example, the power producers perceive the market price for energy as a parameter. However, the market price for energy is calculated as the dual value of the energy balance equation in the market mechanism.

The market actors seek to optimize their objective function and are modeled in four different markets:

- Energy market
- Energy market and volume-based strategic reserves auction
- Energy market and volume-based capacity market
- Energy market and price-based capacity market

In addition, different levels of storage involvement in the capacity market and sensitivity to fixed costs will be analyzed.

Nomenclature of the symbols used in this section can be found in appendix A. All variables are nonnegative.

The complementarity conditions based on the relations derived in appendix B will

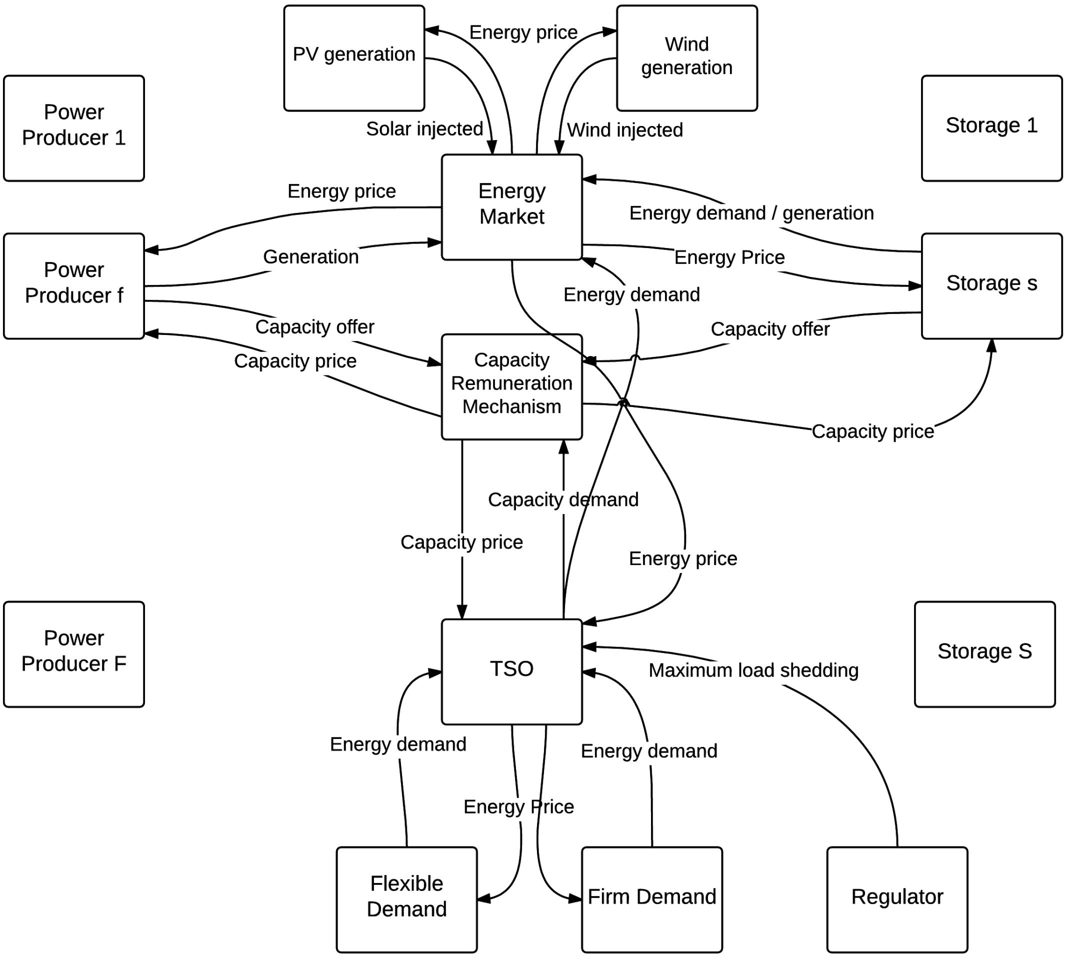


Figure 4: Overview of the model

be formulated so that these can be written into the modeling software (GAMS). This means that all equations should be ≥ 0 or $=$ relations and the sign $\perp$ relates equation with the dual variable and means "complementary to". For details about how the different conditions have been derived the reader is referred to appendix B which follows the same structure as this section.

7.1 Energy Only Model

7.1.1 Power Producers

The objective function for firms operating in an energy market can be found in equation 17. This shows that the firms decides generation each hour and the installed capacity based on their variable costs, fixed costs and the market price. The only remuneration is through the energy market. Equation 18 is the only restriction that applies to the firm in this case and states that the firm can not produce more any given hour than the installed capacity. This means that the installed capacity in the beginning of the period influences all operating hours in that period.

$$\forall f : \text{Maximize: } \pi_f = \sum_{h=1}^{H} (\lambda_h - VC_f) * T * gen_{f,h} - FC_f * cap_f^{inst} \tag{17}$$

Subject to:

$$\forall f, \forall h : -gen_{f,h} + cap_f^{inst} \geq 0 \tag{18}$$

Based on the optimality conditions of this problem the conditions for a solution that is optimal for the power producers are shown in equation 19 to 21.

$$\forall f, \forall h : -\lambda_h * T + VC_f * T + \mu_{f,h} \geq 0 \perp gen_{f,h} \geq 0 \tag{19}$$

$$\forall f : FC_f - \sum_{h=1}^{H} \mu_{f,h} \geq 0 \perp cap_f^{inst} \geq 0 \tag{20}$$

$$\forall f, \forall h : cap_f^{inst} - gen_{f,h} \geq 0 \perp \mu_{f,h} \geq 0 \tag{21}$$

Equation 19 describes how generation is triggered. Generation is increased in the case that the price is high enough to cover variable osts and scarcity rent for generation. As shown in equation 20 installed capacity is triggered if the added scarcity rents for generation is high enough to cover the fixed costs of investment. μ is the dual variable of equation 18 and is interpreted as the scarcity rent for generation. If a firm is producing at the limit the scarcity rent will have a positive value in order to ensure the restriction is satisfied, limiting the firm from producing more.

7.1.2 TSO

The objective function of the TSO is to maximize consumer surplus. This is shown in equation 22. The only decision variable is how much load should be shed in each hour.

$$\text{Maximize: CS} = \sum_{h=1}^{H} ((P^{MAX} - \lambda_h) * (DEM_h - ls_h)) * T \tag{22}$$

Since the demand is a parameter, it can be removed. This simplifies the equation to:

$$\text{Maximize: } \sum_{h=1}^{H} (\lambda_h - P^{MAX}) * ls_h * T \tag{23}$$

Subject to:

$$RS^{ls} * \sum_{h=1}^{H} DEM_h - \sum_{h=1}^{H} ls_h \geq 0 \tag{24}$$

Equation 23 shows how the TSO decides when and if load shedding is exercised. It is clear that for a market price below the VOLL the TSO will not shed any load, but if the market price is at the VOLL load shedding will be used in order to limit it from getting higher. Equation 24 limits the total amount of load shedding to the specified share of total demand.

The optimality conditions of this problem gives the complementarity formulation for the TSO in equations 25 and 26.

$$\forall h : -\lambda_h * T + P^{MAX} * T + \alpha \geq 0 \perp ls_h \geq 0 \tag{25}$$

$$RS^{ls} * \sum_{h=1}^{H} DEM_h - \sum_{h=1}^{H} ls_h \geq 0 \perp \alpha \geq 0 \tag{26}$$

Condition 25 describes that load shedding is triggered if the market price is above P^{MAX}. However, if restriction 24 is binding, α will assume a positive value as described by equation 26. This will allow an increase in the market price above the maximum market price in order to keep the amount of load shed at the maximum level.

7.1.3 Energy Storage

The energy storage decides how much energy should be stored and generated each hour of the operating period. Profit is obtained by arbitrage, buying when the price is low and selling when the price is high. In addition, the storage decides how much capacity in MW and MWh to install and there are fixed costs associated with these capacities.

$$\forall s : \text{Maximize: } \pi_s = \sum_{h=1}^{H} (gen_{s,h} - store_{s,h}) * T * \lambda_h - FC_s^{cap} * cap_s^{inst} - FC_s^{en} * en_s^{inst} \tag{27}$$

Subject to:

$$\forall s, h = 1 : en_{s,\frac{H}{T}}^{stored} * L_s + store_{s,1} * SL_s * T - gen_{s,1} * T - en_{s,1}^{stored} \geq 0 \tag{28}$$

$$\forall s, \forall h > 1 : en_{s,h-1}^{stored} * L_s + store_{s,h} * SL_s * T - gen_{s,h} * T - en_{s,h}^{stored} \geq 0 \tag{29}$$

$$\forall s, \forall h : en_s^{inst} - en_{s,h}^{stored} \geq 0 \tag{30}$$

$$\forall s, \forall h : cap_s^{inst} - gen_{s,h} - store_{s,h} \geq 0 \tag{31}$$

The objective function of the storage units is to maximize the profit. This can be found in equation 27. Equation 29 keeps track of the amount stored and states that the amount stored at the end of an hour is the amount stored in the end of the previous hour plus the amount stored during the hour subtracted the amount generated during the hour and the losses due to converting and storing the energy. In addition, restriction 28 is round coupling the problem so that the hour before the first hour is the last hour. There are only converter losses associated with storing the energy, this is represented by the parameter SL_s which therefore represents both storing and generation losses. The loss associated with having one MWh of energy stored for one hour is L_s. Equation 30 limits the amount of stored energy any given hour to the installed energy capacity and 31 ensures that the energy stored and generated each hour is within the storage's capacity limits. Since the storage never generates and stores during the same hour this can be expressed as one equation instead of two.

The optimality conditions for the storage are derived from this problem and can be found in equation 32 to 41.

$$\forall s, \forall h : -\lambda_h * T + \zeta_{s,h} * T + \mu_{s,h} \geq 0 \perp gen_{s,h} \geq 0 \tag{32}$$

$$\forall s, \forall h : \lambda_h * T - \zeta_{s,h} * SL_s * T + \mu_{s,h} \geq 0 \perp store_{s,h} \geq 0 \tag{33}$$

$$\forall s : FC_s^{cap} - \sum_{h=1}^{H} \mu_{s,h} \geq 0 \perp cap_s^{inst} \geq 0 \tag{34}$$

$$\forall s : FC_s^{en} - \sum_{h=1}^{H} \iota_{s,h} \geq 0 \perp en_s^{inst} \geq 0 \tag{35}$$

$$\forall s, \forall h < \frac{H}{T} : -\zeta_{s,h+1} * L_s + \zeta_{s,h} + \iota_{s,h} \geq 0 \perp en_{s,h}^{stored} \geq 0 \tag{36}$$

$$\forall s, h = \frac{H}{T} : -\zeta_{s,1} * L_s + \zeta_{s,\frac{H}{T}} + \iota_{s,\frac{H}{T}} \geq 0 \perp en_{s,\frac{H}{T}}^{stored} \geq 0 \tag{37}$$

$$\forall s, h = 1 : en_{s,\frac{H}{T}}^{stored} * L_s + store_{s,1} * SL_s * T - gen_{s,1} * T - en_{s,1}^{stored} \geq 0 \perp \zeta_{s,1} \geq 0 \tag{38}$$

$$\forall s, \forall h > 1 : en_{s,h-1}^{stored} * L_s + store_{s,h} * SL_s * T - gen_{s,h} * T - en_{s,h}^{stored} \geq 0 \perp \zeta_{s,h} \geq 0 \tag{39}$$

$$\forall s, \forall h > 1 : en_s^{inst} - en_{s,h}^{stored} \geq 0 \perp \iota_{s,h} \geq 0 \tag{40}$$

$$\forall s, \forall h : cap_s^{inst} - gen_{s,h} - store_{s,h} \geq 0 \perp \mu_{s,h} \geq 0 \tag{41}$$

Equation 32 is the condition that generation is triggered if the market price covers the value of stored energy and the scarcity rent for converter capacity. Next, equation 33 describes that energy is stored if the value of stored energy (subtracted converter losses) is at least enough to cover the market price and scarcity rent for converter capacity. Equation 34 is the condition that converter capacity is triggered if the scarcity rents for converter capacity is enough to recover the fixed costs. Similarly, equation 35 is the condition that installed storage energy is triggered if the scarcity rents for energy covers the fixed costs. Further, energy is stored if the value of stored energy the next hour (subtracted losses) is at least the value of stored energy this hour added scarcity rent for energy capacity this hour according to equation 36 to 37.

Equation 38 and 39 is the energy balance for the storage unit and the dual value of this equation is the value of stored energy. This can be interpreted as a generalization of the water value for a hydro power plant. The value of stored energy is determined by several factors including but not limited to current and future market price, fixed costs, losses and decisions by other actors in the system.

The scarcity rent for energy capacity will be positive if the amount of stored energy is at the capacity of the storage unit, according to equation 40. Equation 41 shows that the scarcity rent of converter capacity will be positive if the storage unit is operating at the installed converter capacity. This can either be due to the storage generating or storing energy at the limit of the converter capacity. Due to the converter losses associated with the converting process the storage will never store and generate during the same hour.

7.1.4 Energy Market

The energy market is a energy balance each hour of the operating period. This can be found in equation 42. The generation from firms and storage added to the injected solar and wind production must be more than the demand subtracted load shedding.

$$\forall h : \sum_{f=1}^{F} gen_{f,h} + \sum_{s=1}^{S} (gen_{s,h} - store_{s,h}) + INJ_h^{solar} + INJ_h^{wind} \geq DEM_h - ls_h \quad (42)$$

The energy price is calculated by applying the complementarity slackness theorem [11, p. 145] on equation 42 with λ as the dual variable as stated in equation 43. This means that the energy market will increase the market price until the condition is satisfied.

$$\forall h : \sum_{f=1}^{F} gen_{f,h} + \sum_{s=1}^{S} (gen_{s,h} - store_{s,h}) + INJ_h^{solar} + INJ_h^{wind} - DEM_h + ls_h \geq 0 \perp \lambda_h \geq 0 \quad (43)$$

7.2 Strategic Reserves Model

The SR model includes the SR market as a new source of remuneration for the actors in the system. However, if a firm decides to contract capacity to the strategic reserves the control of this capacity is moved to the TSO.

7.2.1 Power Producers

The objective function for a firm participating in a strategic reserves auction in addition to the energy market can be found in equation 44. This is identical to the EO profit except the last term that remunerates the firm according to the price for capacity and the strategic reserve capacity the firm offers to the capacity market.

$$\forall f : \text{Maximize: } \pi_f = \sum_{h=1}^{H} (\lambda_h - VC_f) * gen_{f,h} * T - FC_f * cap_f^{inst} + \gamma * cap_f^{sr} \quad (44)$$

Subject to:

$$\forall f, \forall h : -gen_{f,h} + cap_f^{inst} - cap_f^{sr} \geq 0 \quad (45)$$

$$\forall f : -cap_f^{sr} + cap_f^{inst} \geq 0 \quad (46)$$

Equation 45 ensures that the firms can only operate the capacity installed that is not offered to the strategic reserves auction. This is because the strategic reserves capacity is controlled by the TSO. Equation 46 restrict the firms from offering more capacity to the auction than their installed capacity.

Based on the first order conditions of this problem the optimality conditions for the power producers can be found in equations 47 to 51.

$$\forall f : \forall h : -\lambda_h * T + VC_f * T + \mu_{f,h} \geq 0 \perp gen_{f,h} \geq 0 \quad (47)$$

$$\forall f : FC_f - \sum_{h=1}^{H} \mu_{f,h} - \theta_f \geq 0 \perp cap_f^{inst} \geq 0 \quad (48)$$

$$\forall f : -\gamma + \sum_{h=1}^{H} \mu_{f,h} + \theta_f \geq 0 \perp cap_f^{sr} \geq 0 \tag{49}$$

$$\forall f, \forall h : cap_f^{inst} - gen_{f,h} - cap_f^{sr} \geq 0 \perp \mu_{f,h} \geq 0 \tag{50}$$

$$\forall f : cap_f^{inst} - cap_f^{sr} \geq 0 \perp \theta_f \geq 0 \tag{51}$$

Similarly to the EO model, generation is triggered if the market price is high enough to cover the variable costs and scarcity rent for generation as can be found in equation 47. Equation 48 shows that installed capacity can be triggered through scarcity rent for generation or scarcity rent for strategic reserves. According to equation 51 the scarcity rent for strategic reserves will have a positive value if all the installed capacity is used as strategic reserves. Further, equation 49 is the condition that the firms will offer capacity to the strategic reserves if the price for capacity covers scarcity rents for generation and the scarcity rent for strategic reserves. Lastly, equation 50 shows that scarcity rents for generation will be positive if all the installed capacity is utilized as more generation requires more installed capacity.

7.2.2 TSO and Demand

It is assumed that the consumers pay for the remuneration through the strategic reserves auction. This means that the objective function has to take these costs into account when optimizing consumer surplus. This can be found as the second term in equation 52. The last term ensures that the strategic reserve is activated before load shedding occurs by adding the small difference ϵ to the market price. The decision variables for the TSO is load shedding, generation from the strategic reserves and capacity demand in the strategic reserves market.

$$\text{Maximize: CS} = \sum_{h=1}^{H} (\lambda_h - P^{MAX}) * ls_h * T - \gamma * dem^{cap} + \sum_{h=1}^{H} (\lambda_h - P^{MAX} + \epsilon) * gen_h^{sr} * T \tag{52}$$

Subject to:

$$RS^{ls} * \sum_{h=1}^{H} DEM_h - \sum_{h=1}^{H} ls_h \geq 0 \tag{53}$$

$$\sum_{f=1}^{F}(cap_f^{inst} - cap_f^{sr}) + \sum_{s=1}^{S} CF_s * (cap_s^{inst} - cap_s^{sr}) + dem^{cap} - RS^{cap} * DEM^{MAX} \geq 0 \quad (54)$$

$$\forall h : \sum_{f=1}^{F} cap_f^{sr} + \sum_{s=1}^{S} CF_s * cap_s^{sr} - gen_h^{sr} \geq 0 \quad (55)$$

Restriction 53 is the load shedding constraint, equal to the EO model. Equation 54 determines how much capacity the TSO demands in order to satisfy the capacity margin set by the regulator. The last restriction 55 limits the TSO from using more strategic reserves than the contracted amount with the possibility of giving storage capacity less than 100% credit for the capacity offered by tuning the value of CF_s. This is to be used when analyzing cases when for instance only a fraction of the capacity offered by battery storage units are relied upon due to the limited time this storage can operate.

Further, the optimality conditions for the TSO are summarized in equations 56 to 61.

$$\forall h : -\lambda_h * T + P^{MAX} * T + \alpha \geq 0 \perp ls_h \geq 0 \quad (56)$$

$$\forall h : -\lambda_h * T + P^{MAX} * T - \epsilon * T + \delta_h \geq 0 \perp gen_h^{sr} \geq 0 \quad (57)$$

$$RS^{ls} * \sum_{h=1}^{H} DEM_h - \sum_{h=1}^{H} ls_h \geq 0 \perp \alpha \geq 0 \quad (58)$$

$$\gamma - \beta \geq 0 \perp dem^{cap} \geq 0 \quad (59)$$

$$\sum_{f=1}^{F}(cap_f^{inst} - cap_f^{sr}) + \sum_{s=1}^{S} CF_s * (cap_s^{inst} - cap_s^{sr}) + dem^{cap} - RS^{cap} * DEM^{MAX} \geq 0 \perp \beta \geq 0 \quad (60)$$

$$\forall h : \sum_{f=1}^{F} cap_f^{sr} + \sum_{s=1}^{S} CF_s * cap_s^{sr} - gen_h^{sr} \geq 0 \perp \delta_h \geq 0 \quad (61)$$

The load shedding decision described by equation 56 is equal to the EO model. In the SR model the TSO also has the option of using the strategic reserves described by equation 57 which is triggered just before load shedding occurs by introducing the price difference ϵ. Capacity demand is triggered if the marginal cost of the capacity reserve margin is above capacity price according to equation 59. The marginal cost of the capacity reserve margin is determined according to equation 60 which is the mechanism that ensures that the total installed capacity in the system will satisfy the regulation requirement. Finally, equation 61 is the condition that the scarcity rent for strategic reserves will take a positive value during the hours that the strategic reserves is producing at the limit.

7.2.3 Energy Storage

The objective function for storage units operating in this model can be found in equation 62. The last term is added to represent the remuneration from offering capacity to the strategic reserves. However, this capacity can be discredited by the factor CF_s to account for the limited time the storage can operate as a producer compared to a traditional power plant.

$$\forall s : \text{Maximize: } \pi_s = \sum_{h=1}^{H}(gen_{s,h} - store_{s,h}) * \lambda_h * T - FC_s^{cap} * cap_s^{inst} - FC_s^{en} * en_s^{inst} + \gamma * cap_s^{sr} * CF_s \quad (62)$$

Subject to:

$$\forall s, h = 1 : en_{s,\frac{H}{T}}^{stored} * L_s + store_{s,1} * T * SL_s - gen_{s,1} * T - en_{s,1}^{stored} \geq 0 \quad (63)$$

$$\forall s, \forall h > 1 : en_{s,h-1}^{stored} * L_s + store_{s,h} * T * SL_s - gen_{s,h} * T - en_{s,h}^{stored} \geq 0 \quad (64)$$

$$\forall s, \forall h : en_s^{inst} - en_{s,h}^{stored} \geq 0 \quad (65)$$

$$\forall s, \forall h : cap_s^{inst} - gen_{s,h} - store_{s,h} - cap_s^{sr} \geq 0 \quad (66)$$

$$\forall s : cap_s^{inst} - cap_s^{sr} \geq 0 \quad (67)$$

Equations 63 to 65 is equal to the EO model. Equation 66 is modified to remove the capacity offered to the strategic reserves from the storage units. Equation 67 limits the storage units from offering more capacity to the strategic reserves than the installed capacity.

The MCP formulation of the energy storage technologies are based on the optimality conditions of this problem and can be found in equations 68 to 79.

$$\forall s, \forall h : -\lambda_h * T + \zeta_{s,h} * T + \mu_{s,h} \geq 0 \perp gen_{s,h} \geq 0 \tag{68}$$

$$\forall s, \forall h : \lambda_h * T - \zeta_{s,h} * T * SL_s + \mu_{s,h} \geq 0 \perp store_{s,h} \geq 0 \tag{69}$$

$$\forall s : FC_s^{cap} - \sum_{h=1}^{H} \mu_{s,h} - \theta_s \geq 0 \perp cap_s^{inst} \geq 0 \tag{70}$$

$$\forall s : FC_s^{en} - \sum_{h=1}^{H} \iota_{s,h} \geq 0 \perp en_s^{inst} \geq 0 \tag{71}$$

$$\forall s : -\gamma * CF_s + \sum_{h=1}^{H} \mu_{s,h} + \theta_s \geq 0 \perp cap_s^{sr} \geq 0 \tag{72}$$

$$\forall s, \forall h < \frac{H}{T} : -\zeta_{s,h+1} * L_s + \zeta_{s,h} + \iota_{s,h} \geq 0 \perp en_{s,h}^{stored} \geq 0 \tag{73}$$

$$\forall s, h = \frac{H}{T} : -\zeta_{s,1} * L_s + \zeta_{s,\frac{H}{T}} + \iota_{s,\frac{H}{T}} \geq 0 \perp en_{s,\frac{H}{T}}^{stored} \geq 0 \tag{74}$$

$$\forall s, h = 1 : en_{s,\frac{H}{T}}^{stored} * L_s + store_{s,1} * T * SL_s - gen_{s,1} * T - en_{s,1}^{stored} \geq 0 \perp \zeta_{s,1} \geq 0 \tag{75}$$

$$\forall s, \forall h > 1 : en_{s,h-1}^{stored} * L_s + store_{s,h} * T * SL_s - gen_{s,h} * T - en_{s,h}^{stored} \geq 0 \perp \zeta_{s,h} \geq 0 \tag{76}$$

$$\forall s, \forall h : en_s^{inst} - en_{s,h}^{stored} \geq 0 \perp \iota_{s,h} \geq 0 \tag{77}$$

$$\forall s, \forall h : cap_s^{inst} - gen_{s,h} - store_{s,h} - cap_s^{sr} \geq 0 \perp \mu_{s,h} \geq 0 \quad (78)$$

$$\forall s : cap_s^{inst} - cap_s^{sr} \geq 0 \perp \theta_s \geq 0 \quad (79)$$

Equation 68, 69, 73, 74, 75 and 76 is equal to the EO model. This is reasonable as the strategic reserves auction does not interfere with operation of the unit once capacity has been determined. Further, equation 71 and 77 is equal to the EO model because no mechanism for remunerating energy capacity has been considered.

Equation 70 shows that in addition to the scarcity rents for converter capacity, the fixed costs of converter capacity can also be covered by the scarcity rent for strategic reserves. Equation 72 is the condition that the storage unit will provide capacity to the strategic reserves if the (possibly reduced) price for capacity is enough to cover scarcity rents for converter capacity and the scarcity rent for strategic reserves. Note that the scarcity rent for strategic reserves will only be positive if all the capacity is used as strategic reserves according to equation 79. Finally, the capacity offered to the strategic reserves is subtracted in equation 78 and this can change the scarcity rent for converter capacity.

7.2.4 Energy Market

The energy market includes the generation from the strategic reserves in addition to the terms from the EO model. This means that this option should be used by the TSO before load shedding occurs.

$$\forall h : \sum_{f=1}^{F} gen_{f,h} + \sum_{s=1}^{S} (gen_{s,h} - store_{s,h}) + gen_h^{sr} + INJ_h^{solar} + INJ_h^{wind} \geq DEM_h - ls_h \quad (80)$$

The energy price is calculated by applying the complementarity slackness theorem [11, p. 145] on equation 80 with λ as the dual variable:

$$\forall h : \sum_{f=1}^{F} gen_{f,h} + \sum_{s=1}^{S} (gen_{s,h} - store_{s,h}) + gen_h^{sr} + INJ_h^{solar} + INJ_h^{wind} - DEM_h + ls_h \geq 0 \perp \lambda_h \geq 0 \quad (81)$$

7.2.5 Strategic Reserves Market

$$\sum_{f=1}^{F} cap_f^{sr} + \sum_{s=1}^{S}(cap_s^{sr} * CF_s) - dem^{cap} \geq 0 \tag{82}$$

According to the complementarity slackness theorem [11, p. 145] the optimality conditions of equation 82 is formulated in equation 83 for the SR auction with γ as the dual variable.

$$\sum_{f=1}^{F} cap_f^{sr} + \sum_{s=1}^{S}(cap_s^{sr} * CF_s) - dem^{cap} \geq 0 \perp \gamma \geq 0 \tag{83}$$

7.3 Capacity-Based Capacity Market Model

In the CM model, the CRM is a capacity market. The market provides a new remuneration mechanism separate from the energy market to the power producers and can be used by the TSO to trigger investments to cover future capacity need and ensure system adequacy.

7.3.1 Power Producers

Equation 84 is the objective function for the power producers when they participate in a volume-based capacity market. The firms are remunerated according to the energy they supply and the capacity they install.

$$\forall f : \text{Maximize: } \pi_f = \sum_{h=1}^{H}(\lambda_h - VC_f) * gen_{f,h} * T - FC_f * cap_f^{inst} + \gamma * cap_f^{cm} \tag{84}$$

Subject to:

$$\forall f, \forall h : -gen_{f,h} + cap_f^{inst} \geq 0 \tag{85}$$

$$\forall f : -cap_f^{cm} + cap_f^{inst} \geq 0 \tag{86}$$

Different from the strategic reserves, the firms are allowed to operate the capacity that is offered to the capacity market. This can be found in equation 85 which is equal to the restriction for the energy only market. Equation 86 is similar to the SR model and states that the firm can not offer more capacity to the market than it has installed.

The MCP conditions for the conventional power producers can be found in equations 87 to 91.

$$\forall f, \forall h : -\lambda_h * T + VC_f * T + \mu_{f,h} \geq 0 \perp gen_{f,h} \geq 0 \quad (87)$$

$$\forall f : FC_f - \sum_{h=1}^{H} \mu_{f,h} - \theta_f \geq 0 \perp cap_f^{inst} \geq 0 \quad (88)$$

$$\forall f : -\gamma + \theta_f \geq 0 \perp cap_f^{cm} \geq 0 \quad (89)$$

$$\forall f, \forall h : cap_f^{inst} - gen_{f,h} \geq 0 \perp \mu_{f,h} \geq 0 \quad (90)$$

$$\forall f : cap_f^{inst} - cap_f^{cm} \geq 0 \perp \theta_f \geq 0 \quad (91)$$

Equation 87 describes how generation is triggered and is similar to the other models. The installed capacity is triggered if the scarcity rents for generation and scarcity rent for capacity covers the fixed costs according to equation 88. Equation 89 describes that capacity offers to the capacity market are triggered if the capacity price is at least the scarcity rent for capacity. However, as can be found in equation 90 and 91, the firms can still operate the capacity that is offered to the capacity market.

7.3.2 TSO and Demand

In the capacity-based capacity market, the capacity is not controlled by the TSO. The TSO only ensures that there is enough capacity in the system to satisfy the regulatory requirements. This is done through the capacity market and the objective function consist of the term from the energy only model in addition to the cost of capacity in the second term in equation 92.

$$\text{Maximize: CS} = \sum_{h=1}^{H} (\lambda_h - P^{MAX}) * ls_h * T - \gamma * dem^{cap} \quad (92)$$

Subject to:

$$RS^{ls} * \sum_{h=1}^{H} DEM_h - \sum_{h=1}^{H} ls_h \geq 0 \tag{93}$$

$$dem^{cap} - RS^{cap} * DEM^{MAX} \geq 0 \tag{94}$$

Restriction 93 is the load shedding constraint equal to the previous models. Restriction 94 ensures that the TSO demands enough capacity to satisfy the capacity margin set by the regulator.

The MCP conditions for the TSO can be found in equations 95 to 98 and are from the first order conditions of this problem.

$$\forall h : -\lambda_h * T + P^{MAX} * T + \alpha \geq 0 \perp ls_h \geq 0 \tag{95}$$

$$\gamma - \beta \geq 0 \perp dem^{cap} \geq 0 \tag{96}$$

$$RS^{ls} * \sum_{h=1}^{H} DEM_h - \sum_{h=1}^{H} ls_h \geq 0 \perp \alpha \geq 0 \tag{97}$$

$$dem^{cap} - RS^{cap} * DEM^{MAX} \geq 0 \perp \beta \geq 0 \tag{98}$$

This is similar to the SR model. However, equation 98 is simpler. In this model the demanded capacity is the entire capacity requirement in the system. This means that the marginal cost of the capacity reserve margin is the dual value of this restriction.

7.3.3 Energy Storage

The objective function for storage units operating in this market can be found in equation 99. In addition to the remuneration from the energy market the storage can be remunerated in the capacity market for the installed amount of capacity. However, the participation in the CRM can be reduced if the term CF_s is less than 1 to account for the limited period the storage unit can supply power in comparison to a conventional power producer.

$$\forall s: \text{Maximize: } \pi_s = \sum_{h=1}^{H}(gen_{s,h} - store_{s,h}) * T * \lambda_h - FC_s^{cap} * cap_s^{inst} - FC_s^{en} * en_s^{inst} + \gamma * cap_s^{cm} * CF_s \quad (99)$$

Subject to:

$$\forall s, h = 1 : en^{stored}_{s,\frac{H}{T}} * L_s + store_{s,1} * T * SL_s - gen_{s,1} * T - en^{stored}_{s,1} \geq 0 \quad (100)$$

$$\forall s, \forall h > 1 : en^{stored}_{s,h-1} * L_s + store_{s,h} * T * SL_s - gen_{s,h} * T - en^{stored}_{s,h} \geq 0 \quad (101)$$

$$\forall s, \forall h : en_s^{inst} - en^{stored}_{s,h} \geq 0 \quad (102)$$

$$\forall s, \forall h : cap_s^{inst} - gen_{s,h} - store_{s,h} \geq 0 \quad (103)$$

$$\forall s : cap_s^{inst} - cap_s^{cm} \geq 0 \quad (104)$$

Restriction 101 is the same energy balance between hours as previously. Also equal to the other models, restriction 102 states that the storage can not keep more energy than the installed amount and 103 limits the amount of stored or generated any given hour. Restriction 104 is the condition that the storage units can not provide more capacity to the capacity market than the installed capacity.

The first order conditions of this problem describes how the energy storage behaves in this market and the MCP formulation can be found in equations 105 to 116.

$$\forall s, \forall h : -\lambda_h * T + \zeta_{s,h} * T + \mu_{s,h} \geq 0 \perp gen_{s,h} \geq 0 \quad (105)$$

$$\forall s, \forall h : \lambda_h * T - \zeta_{s,h} * T * SL_s + \mu_{s,h} \geq 0 \perp store_{s,h} \geq 0 \quad (106)$$

$$\forall s : FC_s^{cap} - \sum_{h=1}^{H} \mu_{s,h} - \theta_s \geq 0 \perp cap_s^{inst} \geq 0 \quad (107)$$

$$\forall s : FC^{en}_s - \sum_{h=1}^{H} \iota_{s,h} \geq 0 \perp en^{inst}_s \geq 0 \tag{108}$$

$$\forall s : -\gamma * CF_s + \theta_s \geq 0 \perp cap^{cm}_s \geq 0 \tag{109}$$

$$\forall s, \forall h < \frac{H}{T} : -\zeta_{s,h+1} * L_s + \zeta_{s,h} + \iota_{s,h} \geq 0 \perp en^{stored}_{s,h} \geq 0 \tag{110}$$

$$\forall s, h = \frac{H}{T} : -\zeta_{s,1} * L_s + \zeta_{s,\frac{H}{T}} + \iota_{s,\frac{H}{T}} \geq 0 \perp en^{stored}_{s,\frac{H}{T}} \geq 0 \tag{111}$$

$$\forall s, h = 1 : en^{stored}_{s,\frac{H}{T}} * L_s + store_{s,1} * T * SL_s - gen_{s,1} * T - en^{stored}_{s,1} \geq 0 \perp \zeta_{s,1} \geq 0 \tag{112}$$

$$\forall s, \forall h > 1 : en^{stored}_{s,h-1} * L_s + store_{s,h} * T * SL_s - gen_{s,h} * T - en^{stored}_{s,h} \geq 0 \perp \zeta_{s,h} \geq 0 \tag{113}$$

$$\forall s, \forall h : en^{inst}_s - en^{stored}_{s,h} \geq 0 \perp \iota_{s,h} \geq 0 \tag{114}$$

$$\forall s, \forall h : cap^{inst}_s - gen_{s,h} - store_{s,h} \geq 0 \perp \mu_{s,h} \geq 0 \tag{115}$$

$$\forall s : cap^{inst}_s - cap^{cm}_s \geq 0 \perp \theta_s \geq 0 \tag{116}$$

Equations 105, 106, 110, 111, 112 and 113 is equal to the EO model because the capacity market does not interfere with the operation of the unit when capacity has been determined. Equations 108 and 114 are equal to the other models because the capacity market do not interfere with the energy installed.

The installed converter capacity is, according to equation 107 triggered if the scarcity rents for converter capacity and scarcity rent for the capacity is high enough to cover fixed costs. Equation 109 describes that offered capacity to the capacity market is triggered if the (possibly reduced) price for capacity covers the scarcity rent for capacity. Note the difference between the CM and SR model, the capacity remuneration does not need to cover the scarcity rents for converter capacity because the full capacity is still operated by the storage unit in the CM model. This can be studied in equation 115 which does not change when capacity is offered to the capacity market as was the case in the SR model. Equation 116 shows that the scarcity rent for capacity will take a positive value if all the installed capacity is offered to the capacity market.

7.3.4 Energy Market

The energy market mechanism is equal to the mechanism for the EO model. The MCP condition is repeated in equation 117.

$$\forall h : \sum_{f=1}^{F} gen_{f,h} + \sum_{s=1}^{S} (gen_{s,h} - store_{s,h}) + INJ_h^{solar} + INJ_h^{wind} - DEM_h + ls_h \geq 0 \perp \lambda_h \geq 0 \tag{117}$$

7.3.5 Capacity Market

The capacity market balance can be found in equation 118 which states that the amount provided by conventional producers and storage units should be at least the capacity demanded by the TSO. The capacity from the storage unit can be lower than the actual amount provided by tuning the value the parameter CF_s in order to account for the limited time storage units can generate power when compared with conventional power plants that rely on fuel.

$$\sum_{f=1}^{F} cap_f^{cm} + \sum_{s=1}^{S} cap_s^{cm} * CF_s - dem^{cap} \geq 0 \tag{118}$$

According to the complementarity slackness theorem [11, p. 145] the optimality condition of equation 118 are formulated in equation 119 with γ as the dual variable of equation 118.

$$\sum_{f=1}^{F} cap_f^{cm} + \sum_{s=1}^{S} cap_s^{cm} * CF_s - dem^{cap} \geq 0 \perp \gamma \geq 0 \tag{119}$$

7.4 Price-Based Capacity Market Model

The price-based capacity market model remunerates the capacity based on a subsidy for the installed capacity.

7.4.1 Power Producers

The objective function of the power producers is to maximize the profit and can be found in equation 120. In addition to the energy remuneration the subsidy *cp* from the capacity market is introduced to remunerate the installed amount of capacity.

$$\forall f : \text{Maximize: } \pi_f = \sum_{h=1}^{H} (\lambda_h - VC_f) * gen_{f,h} * T - FC_f * cap_f^{inst} + cp * cap_f^{inst} \quad (120)$$

Subject to:

$$\forall f, \forall h : -gen_{f,h} + cap_f^{inst} \geq 0 \quad (121)$$

The only restriction that applies to the producer is, similar to the EO model, the limitation of not generating more power than the installed capacity in equation 121.

Based on the optimality conditions of the problem, the decisions of the conventional power producers are formulated as MCP conditions in equations 122 to 124.

$$\forall f, \forall h : -\lambda_h * T + VC_f * T + \mu_{f,h} \geq 0 \perp gen_{f,h} \geq 0 \quad (122)$$

$$\forall f : FC_f - cp - \sum_{h=1}^{H} \mu_{f,h} \geq 0 \perp cap_f^{inst} \geq 0 \quad (123)$$

$$\forall f, \forall h : cap_f^{inst} - gen_{f,h} \geq 0 \perp \mu_{f,h} \geq 0 \quad (124)$$

The conditions for the producer in the CP model are almost equal to the EO model. The difference is that the installed capacity is triggered if the scarcity rents and the capacity payment cover the fixed cost as shown in equation 123. The introduction of the capacity payment shows that the firm has a new source of income and that this may increase investments.

7.4.2 TSO and Demand

The price-based capacity market subsidizes each MW of installed capacity. This subsidy is paid by the consumers and results in an extra cost added to the TSO's objective function of maximizing the consumer surplus shown in equation 125.

$$\text{Maximize: CS} = \sum_{h=1}^{H}(\lambda_h - P^{MAX}) * ls_h * T - \sum_{f=1}^{F}(cp * cap_f^{inst}) - \sum_{s=1}^{S}(cp * cap_s^{inst} * CF_s) \tag{125}$$

Subject to:

$$RS^{ls} * \sum_{h=1}^{H} DEM_h - \sum_{h=1}^{H} ls_h \geq 0 \tag{126}$$

The only restriction to the TSO is the load shedding constraint that can be found in equation 126.

From the first order conditions, the MCP conditions for the TSO are formulated in equations 127 and 128.

$$\forall h : -\lambda_h * T + P^{MAX} * T + \alpha \geq 0 \perp ls_h \geq 0 \tag{127}$$

$$RS^{ls} * \sum_{h=1}^{H} DEM_h - \sum_{h=1}^{H} ls_h \geq 0 \perp \alpha \geq 0 \tag{128}$$

The conditions for the TSO is equal to the EO model. However, the TSO has to pay the capacity payment as shown in the objective function. The MCP conditions does not change because the subsidy is not determined by the TSO, but by the capacity payment market.

7.4.3 Energy Storage

The objective function for the storage units is to maximize the profit as found in equation 129. Compared to the EO model the subsidy is introduced in the last term and this can be credited by the full amount of the installed capacity or parts of the capacity installed by tuning the value of CF_s in the interval 0 to 1.

$$\forall s: \text{Maximize: } \pi_s = \sum_{h=1}^{H}(gen_{s,h} - store_{s,h}) * T * \lambda_h - FC_s^{cap} * cap_s^{inst} - FC_s^{en} * en_s^{inst} + cp * cap_s^{inst} * CF_s \quad (129)$$

Subject to:

$$\forall s, h = 1: en_{s,\frac{H}{T}}^{stored} * L_s + store_{s,1} * T * SL_s - gen_{s,1} * T - en_{s,1}^{stored} \geq 0 \quad (130)$$

$$\forall s, \forall h > 1: en_{s,h-1}^{stored} * L_s + store_{s,h} * T * SL_s - gen_{s,h} * T - en_{s,h}^{stored} \geq 0 \quad (131)$$

$$\forall s, \forall h: en_s^{inst} - en_{s,h}^{stored} \geq 0 \quad (132)$$

$$\forall s, \forall h: cap_s^{inst} - gen_{s,h} - store_{s,h} \geq 0 \quad (133)$$

The restrictions for this actor are equal to EO model. This is because the new income stream is added in the objective function without any restrictions added.

The MCP conditions are formulated in equations 134 to 143.

$$\forall s, \forall h: -\lambda_h * T + \zeta_{s,h} * T + \mu_{s,h} \geq 0 \perp gen_{s,h} \geq 0 \quad (134)$$

$$\forall s, \forall h: \lambda_h * T - \zeta_{s,h} * T * SL_s + \mu_{s,h} \geq 0 \perp store_{s,h} \geq 0 \quad (135)$$

$$\forall s: FC_s^{cap} - cp * CF_s - \sum_{h=1}^{H} \mu_{s,h} \geq 0 \perp cap_s^{inst} \geq 0 \quad (136)$$

$$\forall s: FC_s^{en} - \sum_{h=1}^{H} \iota_{s,h} \geq 0 \perp en_s^{inst} \geq 0 \quad (137)$$

$$\forall s, \forall h < \frac{H}{T}: -\zeta_{s,h+1} * L_s + \zeta_{s,h} + \iota_{s,h} \geq 0 \perp en_{s,h}^{stored} \geq 0 \quad (138)$$

$$\forall s, h = \frac{H}{T} : -\zeta_{s,1} * L_s + \zeta_{s,\frac{H}{T}} + \iota_{s,\frac{H}{T}} \geq 0 \perp en^{stored}_{s,\frac{H}{T}} \geq 0 \quad (139)$$

$$\forall s, h = 1 : en^{stored}_{s,\frac{H}{T}} * L_s + store_{s,1} * T * SL_s - gen_{s,1} * T - en^{stored}_{s,1} \geq 0 \perp \zeta_{s,1} \geq 0 \quad (140)$$

$$\forall s, \forall h > 1 : en^{stored}_{s,h-1} * L_s + store_{s,h} * T * SL_s - gen_{s,h} * T - en^{stored}_{s,h} \geq 0 \perp \zeta_{s,h} \geq 0 \quad (141)$$

$$\forall s, \forall h : en^{inst}_s - en^{stored}_{s,h} \geq 0 \perp \iota_{s,h} \geq 0 \quad (142)$$

$$\forall s, \forall h : cap^{inst}_s - gen_{s,h} - store_{s,h} \geq 0 \perp \mu_{s,h} \geq 0 \quad (143)$$

The CP model is very similar to the EO model. This is due to the simplicity of this mechanism. The capacity payment reduces the fixed costs of the storage units. Equation 136 shows that installed capacity is triggered if the (possibly reduced) capacity payment and the scarcity rents for converter capacity is enough to cover the fixed costs. This is the only modification when compared to the EO model.

7.4.4 Energy Market

The energy market is equal to the EO and CM models and the MCP formulation of this is repeated in equation 144.

$$\forall h : \sum_{f=1}^{F} gen_{f,h} + \sum_{s=1}^{S} (gen_{s,h} - store_{s,h}) + INJ^{solar}_h + INJ^{wind}_h - DEM_h + ls_h \geq 0 \perp \lambda_h \geq 0 \quad (144)$$

7.4.5 Capacity Market

Equation 145 shows the condition that needs to fulfilled by the capacity market and the task of the market is to provide a subsidy that satisfies this relation.

Similar to the other models, the storage capacity can get credit for less capacity than installed by tuning the parameter CF_s.

$$\sum_{f=1}^{F} cap_f^{inst} + \sum_{s=1}^{S} cap_s^{inst} * CF_s - RS^{cap} * DEM^{MAX} \geq 0 \tag{145}$$

The subsidy for capacity is calculated so that the installed capacity is according to the regulation, this is the optimality conditions of equation 145 with cp as the dual variable. The MCP formulation of this remuneration mechanism can be found in 146.

$$\sum_{f=1}^{F} cap_f^{inst} + \sum_{s=1}^{S} cap_s^{inst} * CF_s - RS^{cap} * DEM^{MAX} \geq 0 \perp cp \geq 0 \tag{146}$$

The capacity payment could also be determined politically, by setting a fixed amount of subsidy for each MW installed. The approach would be to discard the MCP condition and fix the capacity payment as a parameter in the model.

7.5 Input Data

Fixed costs have been represented as annual costs and, if needed, these have been calculated by using the annuity formula presented in [2] with an interest rate of 5%. These calculations can be found in appendix C.

7.5.1 Conventional Power Producers

In this model, the parameters that describe a conventional power producer is annual fixed costs per MW installed and variable costs per MWh produced. Four technologies have been modeled and each technology is represented as one firm in the model:

- Firm 1: Nuclear plant
- Firm 2: Hard coal power plant
- Firm 3: Combined cycle gas power plant (CCGT)
- Firm 4: Open cycle gas power plant (OCGT)

Because of the cost profiles of these units, they will take different roles. Nuclear plants need to operate for a large fraction of the hours during the year to be competitive, making it a typical base load unit. On the other hand OCGT units have relatively low fixed costs and high variable costs which makes them competitive at covering peak load. The cost data for these units are gathered from [8] and can be found in table 1. An interest rate of 5% has been used when calculating the annual fixed costs.

Table 1: Technology characteristics for conventional power producers[8]. Annualized values.

	Nuclear	**Hard coal**	**CCGT**	**OCGT**
Referred to as	Firm 1	Firm 2	Firm 3	Firm 4
Fixed costs [kEUR/MW]	280	72	41	16
Marginal costs [EUR/MWh]	3	35	48	150

7.5.2 Renewable Energy Sources

The renewable energy injected into the system is a time series of hourly production injected into the system. The base data has realistic time-series from the COSMO weather model gathered from [8] and these values have been scaled according to the ten-year network development plan by ENTSO-E from 2014 [3]. It was chosen to model Belgium, Germany, Netherlands and France as one area. Based on this the total RES share was found to be 41.49 % of total energy demand in Vision 4 (30.51% wind, 10.98% solar) [3].

7.5.3 Demand

The objective function of the demand is incorporated in the TSO objective function. Thus, the demand is only represented by data input to the TSO. The demand is not price elastic. This means that no matter what the market price is, this demand is constant. However, it is assumed that if the market price is above the value of lost load, the demand prefer to be disconnected instead of paying the market price.

The source for demand data is the 2014 time-series data from ENTSO-E Vision 4 [3]. The data for Belgium, Germany, Netherlands and France were added together in order to model these four countries as one node.

7.5.4 Regulatory Restrictions

The regulator is responsible for system adequacy and puts restrictions on the TSO. This is done in the form of load shedding requirements, capacity margin requirements and maximum market price.

In all cases the maximum load shedding, represented by the parameter RS^{ls}, was chosen to be 3 hours, or 0.034%, of total demand during the year. In the cases with a CRM the capacity margin, represented by RS^{cap}, was chosen to be 110% of maximum demand. The maximum market price was chosen to be 3000 EUR/MWh and assumed to represent the value of lost load.

7.5.5 Storage Units

When modeling pumped hydro energy storage (PHES) the case of Norway acting as a battery was considered. The capacity calculation includes building and maintaining PHES capacity, necessary reinforcement of the grid in Norway and building long-distance interconnections. Further a reasonable assumptions regarding losses has been found to be 80% for the pumping cycle [9]. In addition, a reasonable amount of the maximum storage available was assumed to be 15TWh, which is a minor portion of the Norwegian hydro power capacity. It has been assumed that there is no need to build more reservoir capacity within this limit and the cost per MWh has been set to 0 EUR/MWh and the installed energy variable fixed at 15 TWh.

Lead-acid batteries have also been modeled. These are characterized by optimistic values for fixed costs, durability and efficiency [4]. There is no upper limit on installed capacity.

The annualized parameters for the storage units can be found in table 2 (note that cable includes grid reinforcement) and the calculations can be found in appendix C.

Table 2: Technology characteristics for storage units [4] [9]

	PHES	**Cable**	**PHES + Cable**	**Lead-acid**
Referred to as	-	-	Storage 1	Storage 2
Fixed costs [EUR/MW]	29021	85077	114098	25901
Fixed costs [EUR/MWh]	0	-	0	6475
Efficiency [%]	-	-	80	92
Loss per hour [%/MWh]	0	0	0	0
Maximum Capacity [TWh]	15	-	15	-

8 Results and Discussion

The results in this section is based on the case data that can be found in appendix D and the input parameters. The main focus has been to study storage units subjected to different scenarios:

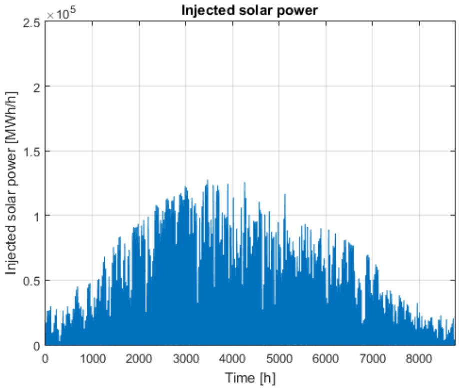
- How does a system with intermittent RES benefit from storage?
- How does the solution change when different types of storage are present?
- How does the presence of storage units influence the investment decisions for traditional power producers?
- How does different CRMs influence the storage units?
- Which conditions are necessary to enable investments in storage?
- Which conditions influence the operation of the storage?
- How does participation in CRMs influence the storage units?

8.1 Load and Injected RES

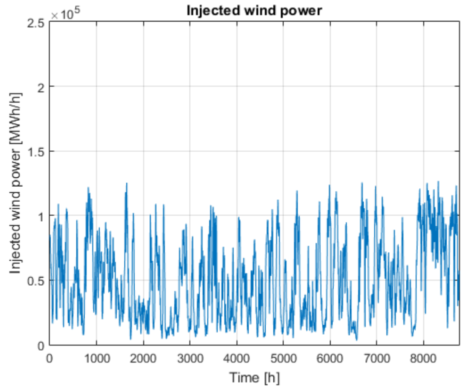
The demand and injected renewable energy is modeled as a fixed time-series of input data. Figure 5 gives an insight to the nature of these data.

Figure 5c shows that the demand is variable, but not with extreme variations. There are variations throughout the day and seasonal variations during the year. Solar and wind power injection can be found in Figure 5a and 5b. From this it is evident that the solar injection varies both short term and seasonal with the largest production during the summer. The wind power is more equally distributed throughout the year, but with large short term variations. The reason that the injected RES is fixed, even if the prices are very low is because variable costs are zero or close to zero. This means that RES plants will produce whenever the energy is available.

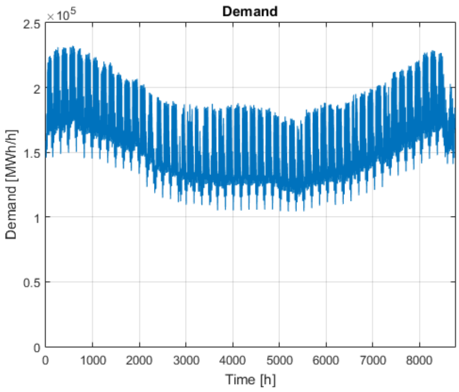
In order to capture the effect of solar and wind injection on the system the residual demand can be found in figure 5d. This is the demand subtracted wind and solar energy. In comparison to the demand curve in figure 5c there is a general downward shift and larger variations. During some hours there are negative residual demand due to RES injection exceeding the demand. Without storage solutions in place this energy will be lost. The large variability is also challenging system adequacy as the power plants in the system need to supply the power necessary to cover residual demand. For example, it has previously been found that the profitability of nuclear plants is challenged when large shares of RES are included [1].



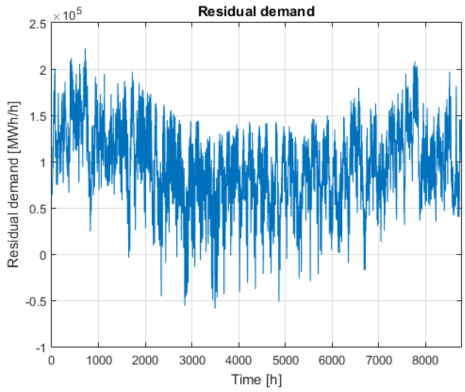
(a) Injected Solar



(b) Injected Wind



(c) Demand



(d) Residual Demand

Figure 5: Demand and injected RES

Figure 6 shows the load duration curves generated when sorting the data in figure 5c and 5d from largest to lowest. The downward shift is due to RES injection. This change is unfavorable for the nuclear plants as will be explained further in section 8.2. Another observation that can be made from figure 6 is that the maximum residual demand is almost as high as the maximum demand. This means that the injected solar and wind power does not lead to much decrease in the capacity requirement that need to be covered by thermal plants or storage units.

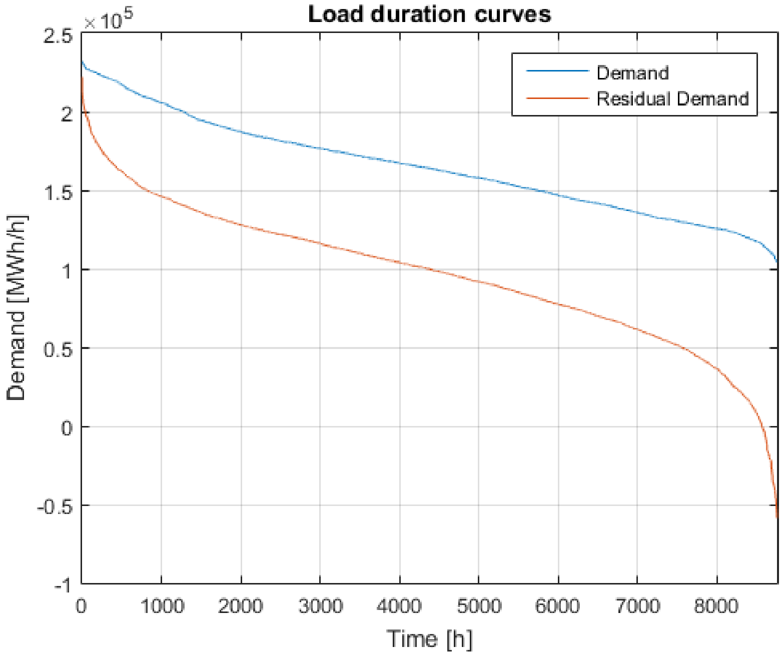


Figure 6: Load Duration Curves

8.2 Cost Characteristics

This section will be the first simple approach to assess optimal running time for the techologies. The cost functions in figure 7 reveal the condition for when one technology is preferred over other technologies. The intersection between load shedding and OCGT shows the amount of hours needed for the OCGT technology to have a lower cost than load shedding. The result is that for the five hours with highest load, load shedding is preferred to OCGT as OCGT need to operate for longer than five hours in order to have a lower cost than load shedding. This, of course, assumes that the load shedding price of 3000 EUR/MWh is the value of lost load. This point determines the number of hours with price spikes.

Proceeding to the intersection between the total cost of OCGT and CCGT shows that crossing approximately 240 hours the load should be served by CCGT instead of OCGT and load shedding. This means that the approximately 240 hours with highest load should be served by OCGT and load shedding while CCGT has lower cost for load levels that last for longer than this amount of hours.

The next intersection, between CCGT and Hard Coal, shows that Hard Coal plants will be preferred for levels of residual demand that last for approximately 2390 hours and more.

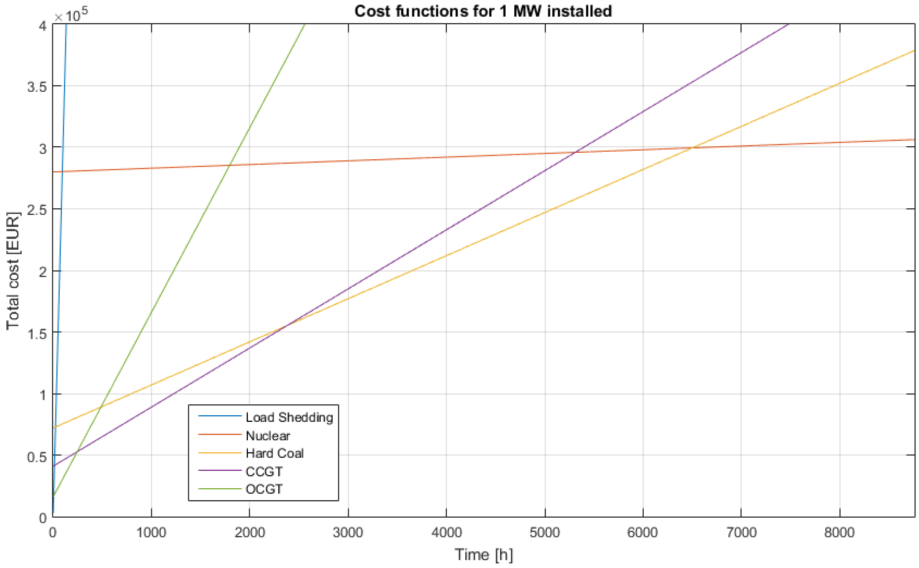


Figure 7: Cost functions for different technologies

The last intersection of the cost functions shows that nuclear power will serve the base load that exceed approximately 6500 hours. Renewable energy can be modeled as a technology that has zero variable costs and high fixed cost. If the number of hours with zero residual demand increase so that the base load does not exceed 6500 hours, there will be no nuclear power in this model.

From this it can be argued that the storage units will buy when there is a surplus of energy and sell when there is a deficit in order to gain a profit from the differences in prices. This means that the load will be increased during the hours with low or negative residual demand. The effect of this is anticipated to more favorable conditions for the nuclear power plants since more load will be lasting for at least 6500 hours of the year.

8.3 Capacity

The installed capacity is a decision variable in this model. This means that the individual producers and storage units will decide their capacity while assuming they can not influence the market price. However, this is because the model is built on the assumption of perfect competition and market power could be a topic for further analysis. Selected capacity data from appendix D have been expressed in figure 8. Each subfigure represent one of the different CRMs and in each subfigure three cases have been considered: No storage, PHES and Battery. The CRM results shown in this figure is the cases with full CRM participation (capacity factor = 1). PHES and Battery has not been modeled simultaneously due to the computational challenges previously mentioned.

First, it is clear that the total installed capacity is higher in the CRM cases (figure 8b, 8c and 8d) than in the Energy Only model (figure 8a). This is due to the presence of a capacity market with a reliability standard, RS^{cap}, requiring the total installed capacity to be at least 110% of maximum demand. The effect is that the CRM ensures that the capacity is at least the specified amount by providing the correct incentives through the CRM. This results in zero load shedding when a CRM is implemented as there are more capacity in the system than the maximum residual demand (see appendix D).

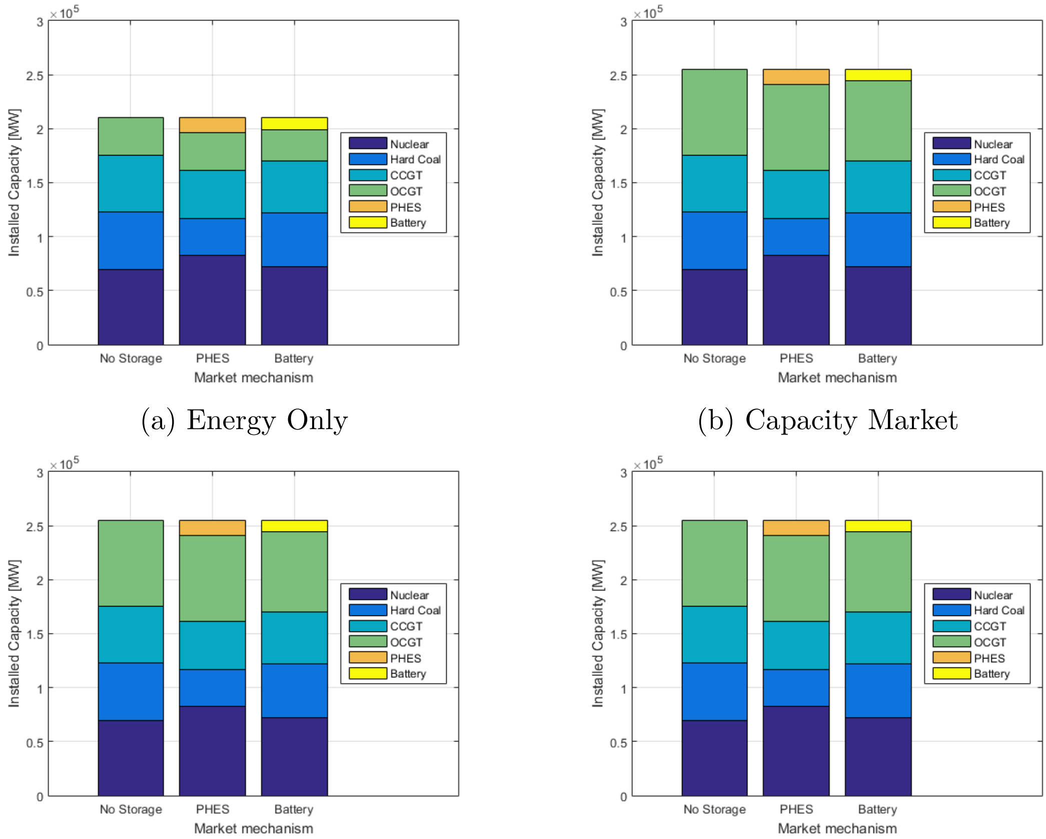
If the case with no storage is studied it is evident that OCGT is the only technology that increases to fulfill the capacity requirement in the CRM cases. This is because the EO solution is the best from a theoretical point of view and that the OCGT unit is the least costly unit that can fulfill the capacity requirement when this restriction is added. This means that the installed PHES and Battery capacity was not influenced by the CRM as long as the storage units participated in the CRM on the same terms as the thermal plants (CF = 1).

The data in figure 8a can be found in table 3. This reveals how the decisions regarding installed capacity change in this system when different forms of energy storage is introduced. In fact, analysis of the SR, CM and CP cases revealed the same changes. This is tied to the fact that the CRM only influenced the OCGT by increasing the amount of OCGT capacity to fulfill the capacity requirement.

Table 3: EO Comparison of Capacity

	No Storage	PHES	Battery
Installed capacity: Nuclear [MW]	69 786	82 933 (+18.8%)	72 434 (+3.8%)
Installed capacity: Coal [MW]	53 292	33 934 (-36.3%)	49 296 (-7.5%)
Installed capacity: CCGT [MW]	52 222	44 347 (-15.1%)	48 626 (-6.9%)
Installed capacity: OCGT [MW]	34 939	34 939 (+0%)	28 982 (-17.0%)
Installed capacity: PHES [MW]	0	14 087	0
Installed capacity: Battery [MW]	0	0	10 902

Nuclear power increases in both the PHES and Battery cases. The increase is much more profound in the PHES case and this can partly be explained by larger storage capacity in the PHES case than in the battery case. Actually, the increase in nuclear power is nearly the same as the PHES capacity. In addition, the results suggests that the battery is more favorable for Coal and CCGT while PHES giving



(a) Energy Only

(b) Capacity Market

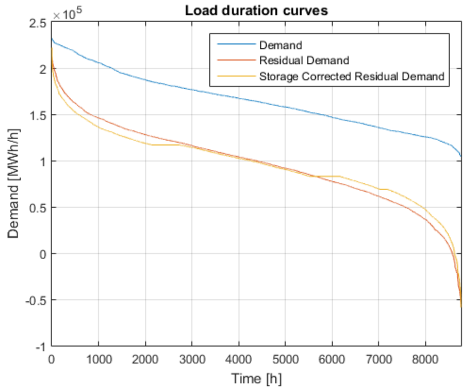
(c) Strategic Reserves

(d) Capacity Payment

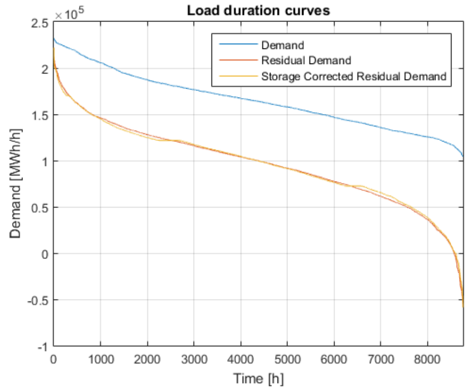
Figure 8: Installed Capacity

more favorable conditions for nuclear power. The main difference between PHES and battery storage is the much lower energy cost for the PHES case giving a larger reservoir capacity and the result is more load that last for at least 6500 hours. This is the crucial factor determining the amount of nuclear power in the system as explained by the cost curves in the previous section.

The impact of storage on residual demand can be studied in Figure 9. This reveal that storage will even out the residual demand, giving better conditions for base load units such as nuclear power. The increase between residual demand and storage corrected residual demand at the 6500 hour mark is the reason for the increase in nuclear power. Comparing Figures 9a and 9b the load-shifting properties of PHES is clearly illustrated. Even corrected for storage, Figure 9 shows that the peak residual load is almost unaffected by the storage units. Further, the amount of lost energy, meaning negative residual demand, is not much affected by the storage units. Still, PHES performs better than battery storage by reducing the amount of lost energy more relative to the battery.



(a) EO: Residual Demand with PHES



(b) EO: Residual Demand with Battery

Figure 9: Residual Demand Corrected for Storage

8.4 Prices and Storage Operation

The price-duration curves for three cases can be found in figure 10. With no storage, the price levels are based on which thermal unit acts as the peaking unit. For example, as can be found in figure 10a, the price is at 150 EUR for approximately 240 hours. This reflects the optimal amount of hours a OCGT unit should be operated as a peaking unit before the CCGT will be less costly as previously explained by the cost functions. A very low price of 3 EUR occurs when the nuclear plant is the peaking unit because of a load that is lower than the installed nuclear capacity. The duration with prices above 3 EUR is approximately 6500 hours and this is, according to the cost function for nuclear plants that was previously explained, the number of hours a nuclear plant need to operate at full capacity in order to be competitive.

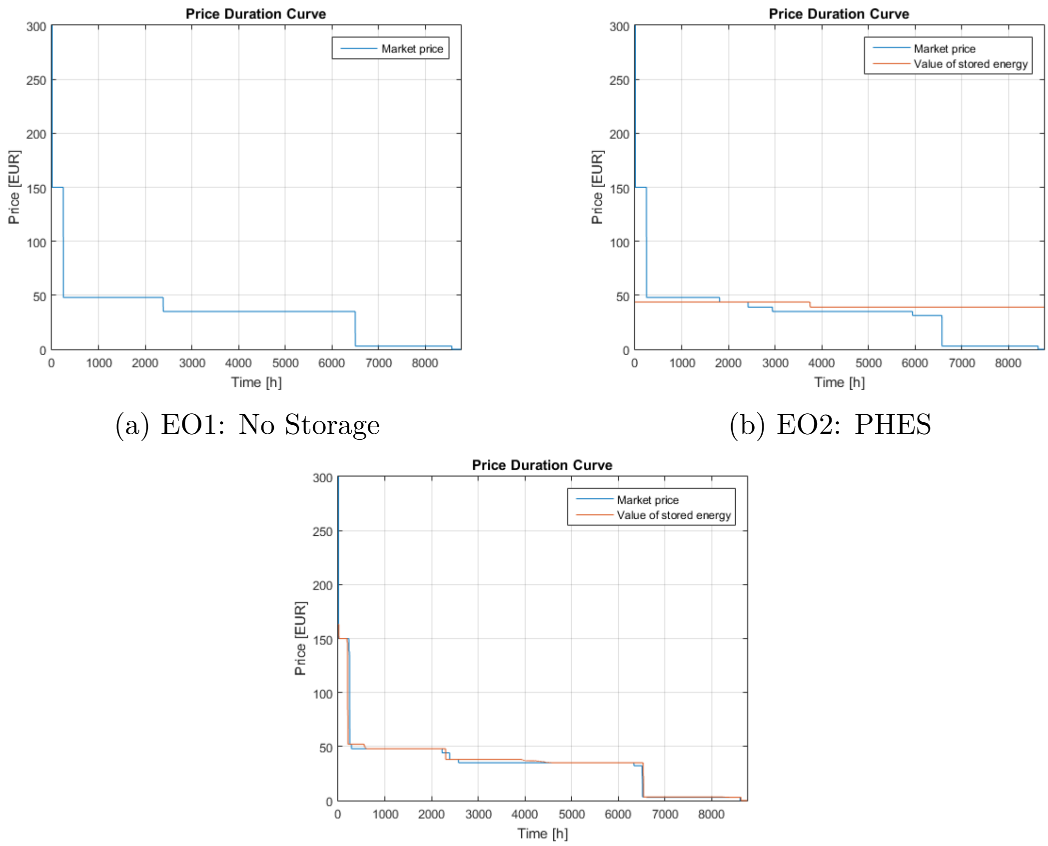
Further, figure 10b and 10c shows that storage units introduces more price levels to the price-duration curve. These occur because of the interaction of the storage units with the market. A closer look at figure 10b reveal that two price levels are formed by the PHES between 48 EUR (CCGT) and 35 EUR (Coal) and one price level is formed between 35 EUR (Coal) and 3 EUR (Nuclear). The two additional price levels between 48 EUR and 35 EUR are present because of the storage unit's marginal cost, or value of stored energy (water value), change depending on a large number of factors. In this example it is 43.75 EUR in the deficit season and 39.06 EUR in the surplus season. This means that the market price need to be at least this value in order for the PHES to produce. Notice the dependence on time of year. For example, keeping all else constant, a PHES plant will require a lower price if the reservoir is close to full than if it is near empty in order to produce. This is different from the thermal plants which will be willing to produce whenever they can recover the variable costs.

The lower price level introduced by the PHES plant is present because the willingness to store power is dependent on market price. The lowest value of stored energy observed is 39.06 EUR and occurs during the surplus season. In order for the PHES plant to be willing to store energy during the surplus season the PHES plant need to pay less than 39.06 EUR per MWh of stored energy as the losses are associated with the storing process and not the generation process. If the losses (20%) are subtracted the lower water value (39.06 EUR) the result is the maximum price in order for PHES to be willing to store power (31.25 EUR). This calculation match the results in figure 10b. The same link between the water value in the deficit season (43.75 EUR) and the hard coal producers (35 EUR) can be found. This means that PHES will be willing to sell for 43.75 EUR if it can buy this energy for no more than 35 EUR.

In order to explain the PHES willingness to buy power the example of nuclear power acting as the peaking unit is considered. This only occurs during the very low load periods as the residual demand is less than the installed nuclear capacity. As was explained, PHES will require a price of at most 31.25 EUR in order to be willing to buy from the nuclear plant. However, the nuclear producer want the price to be as high as possible to increase profits. When these two actors meet on the marketplace the result is a price that is exactly at the buyer's limit of 31.25 EUR.

The price-duration curve for the battery can be found in figure 10c. This shows that, as was also the case with PHES, the battery introduces more price levels in the system. However, the number of levels introduced by the battery is more than with PHES and this can be attributed to the inherent short term operation decisions for batteries. For the battery, value of stored energy follows the market price much closer than the PHES case. This too can be attributed to the short term operation of a battery since it has a relatively large converter capacity in relation to storage size when compared to PHES. All in all, this means that the operation of a battery as depicted is strongly dependent on short term market conditions. The opposite is the case for PHES where the water value can be dependent on market conditions several months in the past/future.

To investigate the differences in the PHES and battery cases the balance for these storage units during the year can be found in figure 11. These figures describe the season-shifting properties of PHES while the battery is having more short term



(a) EO1: No Storage

(b) EO2: PHES

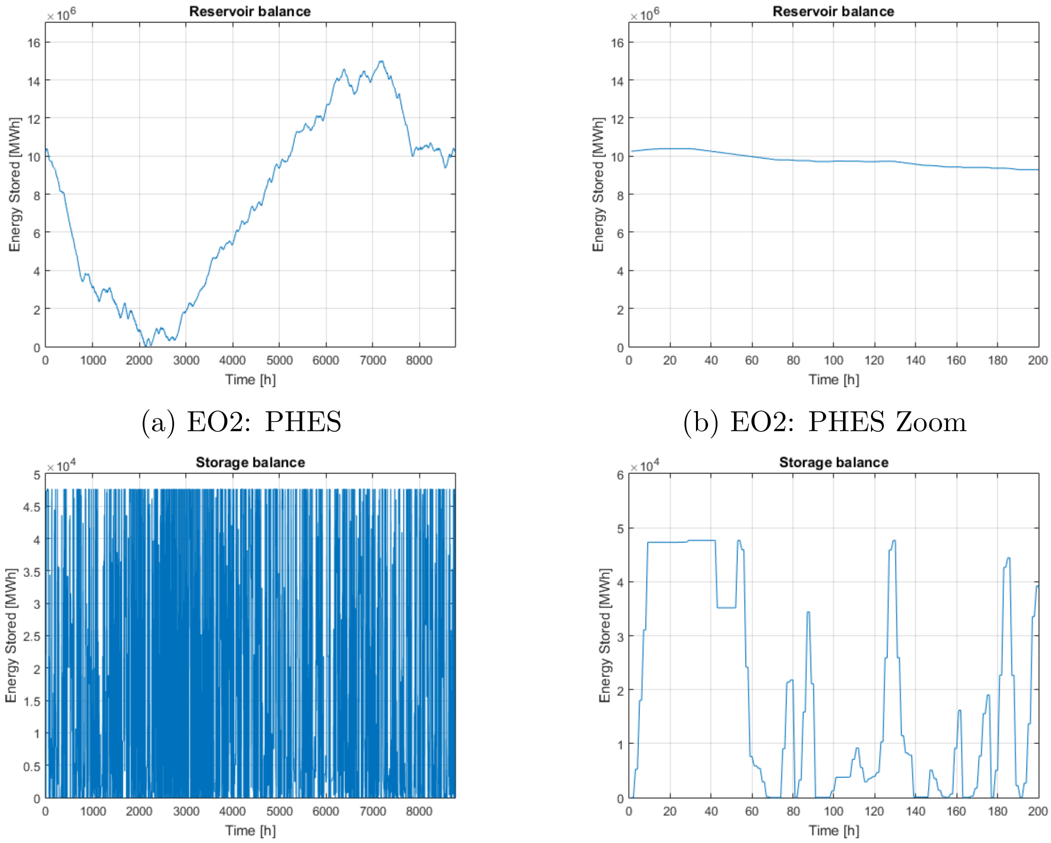
(c) EO3: Battery

Figure 10: Price Duration Curves

applications.

PHES reservoir balance in figure 11a suggests that approximately hour 2150 to hour 7150 is the filling season with a long term increase in the balance during this period. However, some depletion of the reservoir is still allowed during this period in order to arbitrage when the market price is giving favorable conditions. Another observation is that the reservoir is completely filled and completely empty at some point during the year. This is due to the deterministic nature of the model and no risk associated with doing this. A more realistic model would never completely empty the reservoir as there would be multiple inflow and market scenarios and uncertainty to take into account.

Figure 11c does not provide a lot of detail but indicate many cycles of filling and emptying of the battery during the year. The first 200 hours of both PHES and battery storage can be found in figures 11b and 11d. this shows that during



(a) EO2: PHES

(b) EO2: PHES Zoom

(c) EO3: Battery

(d) EO3: Battery Zoom

Figure 11: Energy Stored

the first 200 hours the PHES has a steady decrease of stored energy during this period while the battery is operated completely differently. Figure 11d shows that the battery makes decisions in order to arbitrage on the short term market price fluctuations.

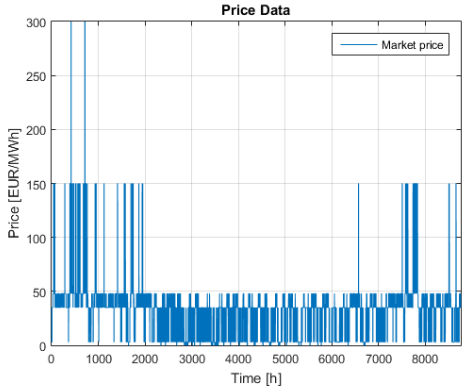
When the models were computed the PHES cases took more time and did not always give an accurate solution. The battery cases had no such problems. This is linked to the long term decisions by the PHES. The season-shifting properties seem to create a problem that is harder to solve. For example, the decisions during hour 50 will affect hour 1050 in the PHES model. This is not necessary the case for the battery since the storage is filled and emptied many times during the year. If the battery has found that it should be completely full during hour h, this means that hour h-1 and hour h+1 will be decoupled since the level in hour h is known. The PHES only has one hour with empty and one hour with full reservoir during the year, resulting in many more time steps between the decoupling for PHES than for the battery storage.

Figure 12 is the time-series of the market price and the value of stored energy (λ and ζ). The value of stored energy is interpreted as the water value if the storage unit is a PHES plant. The SR model results in equal figures while the CM and CP cases are equal, but not with the price spikes above 150 EUR/MWh. This can be studied further in [1].

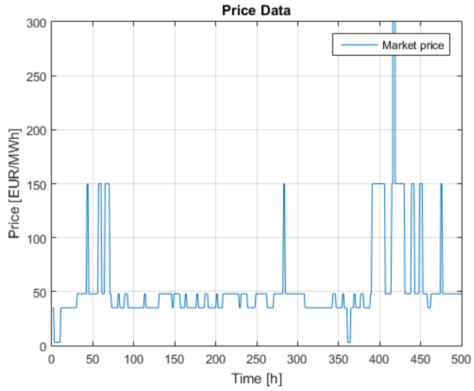
The large reservoir in the PHES case results in a water value that does not fluctuate much during the year, this can be observed in figure 12c. This is explained by the seasonal behavior of PHES since the water value is determined as a result of the entire model for the whole planning horizon. The opposite is observed for the battery in figure 12e. This shows that the value of stored energy fluctuates very much and is more affected by short-term conditions. This is linked to the battery arbitraging short term price differences.

It can also be observed that the battery is dampening price fluctuations more than the PHES. This is emphasized when the resolution is increased in figures 12b, 12d and 12f showing only the first 500 hours of the year. Figure 12d shows that the water value is constant during the first 500 hours and that the market price is fluctuating more than with a battery as can be found in figure 12f. It can also be observed that the value of stored energy have several different levels during the first 500 hours for the battery.

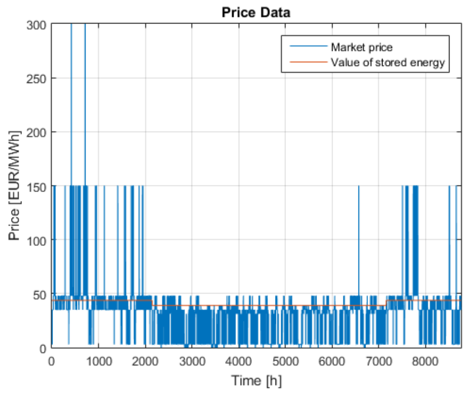
In order to explain this it can be assumed that the PHES divides the year in two periods: filling season and depletion season. During the filling season, the PHES will normally avoid generation of power. This means that if the prices are too high during the filling season the PHES will wait until the market price is lower to fill the reservoir. However, the storage unit will generate during the filling season if the prices are high enough as previously quantified. The situation is different for the storage as this unit have a more short term approach to the arbitrage between high and low prices. Since the battery operate with a higher efficiency for the storage cycle than PHES (92% vs. 80%) this unit does not require as high price differences in order to gain a profit. This means that if the price is high one hour the battery will generate and then it can switch to storing mode the next hour if the price is low enough and this short term decision making is the reason behind a more stable market price in the battery case.



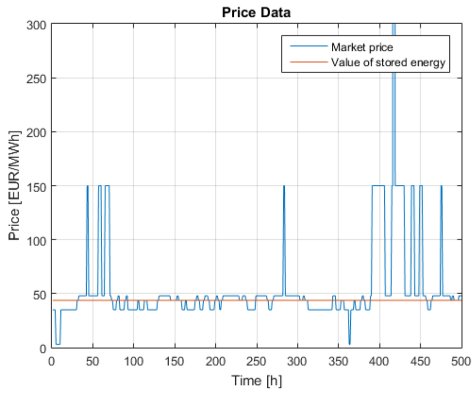
(a) EO1: No Storage



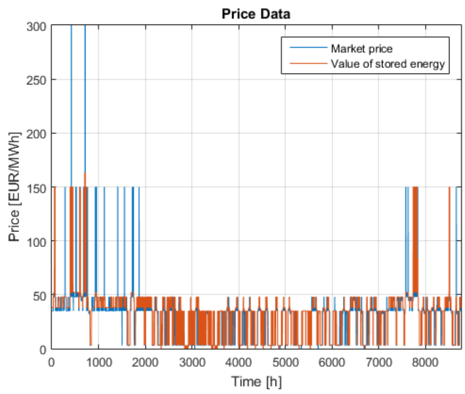
(b) EO1: No Storage Zoom



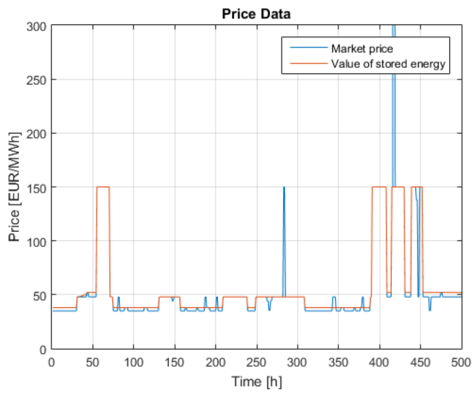
(c) EO2: PHES



(d) EO2: PHES Zoom



(e) EO3: Battery



(f) EO3: Battery Zoom

Figure 12: Price Data

8.5 Storage Participation in CRM

Storage units can provide power for a limited period of time until the storage is depleted. This is in contrast to thermal plants that rely on fuel and can produce power as long as the fuel is available. Because of this drawback, it can be reasonable to give storage units less favorable conditions in the CRMs than thermal plants. The purpose of this subsection is to study different levels of credit factors (CF). As have been explained in section 7, the parameter CF can be varied between 0 and 1 in order to model the storage participation in a CRM from 0 to 100%.

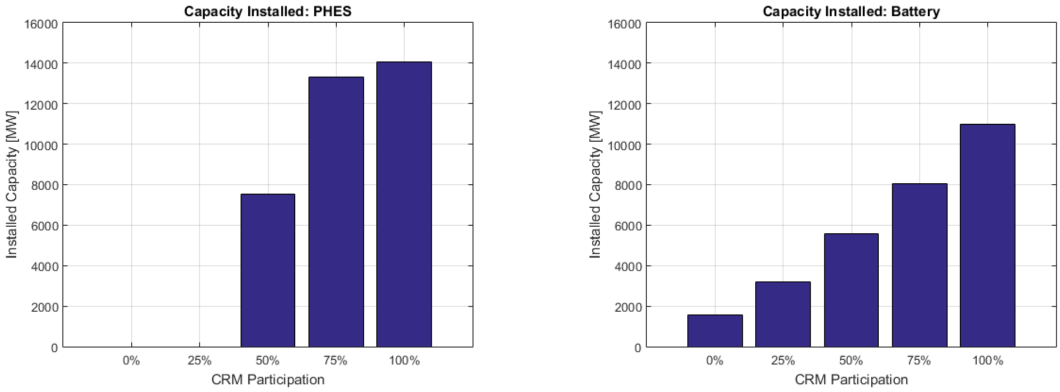
The CM model has been used to study the impact of different levels of CF. In addition, the SR and CP models has also been run with a CF at 0 and 1. Regarding the CM model, both PHES and battey has been calculated with a 0%, 25%, 50%, 75% and 100% credit factor.

Installed capacity for the storage units with different credit factors can be found in figure 13. From this it can be argued that participation in a potential CRM is important for energy storage. Since the storage units participate in a market together with the thermal plants, the reduced remuneration from the capacity market is a huge drawback on the competitiveness of this unit.

Decisions for PHES with different credit factors in the CRM can be found in figure 13a. This shows that with 0% and 25% participation in the CRM the result is zero installed capacity. A credit factor of approximately 50% is necessary to get some PHES capacity in the system. This indicates that PHES is not very profitable with the parameters chosen in this study. This is confirmed by the case EO17 which can be found in appendix D. In EO17, the fixed cost for PHES were increased by 10% in the EO model and this resulted in zero installed capacity. This suggests that small increases in cost or less favorable market conditions is enough to make the PHES uncompetitive.

Installed capacity for the battery storage can be found in figure 13b. This shows a more linear relation between the credit factor and the installed capacity than in the PHES case. Even a credit factor of 0% results in some capacity being installed. From this it can be argued that if the credit factor is 50%, the installed capacity will be about half of what it is if the credit factor is 100%. The size of the battery storage for different credit factors can be found in figure 14 and follows the same pattern as the installed capacity.

The social welfare have been calculated for the different CM cases and can be found in table 4. The differences are small between the different levels of credit factor. This is because the total surplus is mainly determined by the consumer surplus and the storage only have a minor impact on prices which in turn affect



(a) PHES (b) Battery

Figure 13: CM: CF Effect on Capacity

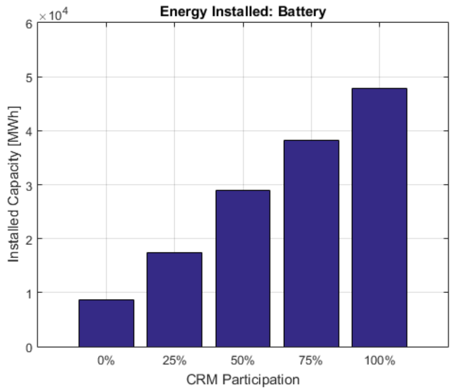


Figure 14: CM: CF Effect on Energy

the consumer surplus. However, an interesting pattern is observed: For PHES the total surplus increases if the credit factor is increased, but the opposite is true for battery storage. This finding suggests that, in order to obtain the best socio-economic solution, PHES should be included in the CRM, but not the battery. This may be because the battery limit periods with very low prices due to surplus of RES, but does not shift the production from the surplus season to the deficit season as is the case with PHES. In appendix D it can be found that PHES actually has some profits. This is contrary to the theory of perfect competition, but can be explained by the fixed storage amount of 15 TWh. If allowed to install any level of storage the amount would be increased until the profit became zero. The load shedding were found to be zero in all CM cases and this is because the capacity requirement were 110% of maximum demand in all cases. However, in real applications with a lower capacity requirement a situation could arise where the peaking unit would be a depleted storage plant. This would then lead to load shedding as the storage plant would not be able to act as the peaking unit after the unit is empty. This model is not likely to yield such a result as it is deterministic, meaning that the storage would preserve the energy in order to arbitrage the high prices in this situation.

Table 4: CM Comparison of Total Surplus [MEUR]

Credit factor	PHES	Battery
100%	4 291 377	4 291 065
75%	4 291 307	4 291 085
50%	4 291 283	4 291 111
25%	4 291 280	4 291 205
0 %	4 291 280	4 291 246

The results from the SR model with and without CRM participation can be found in appendix D. The results in this case were that the credit factor did not influence the decisions for the storage units at all. The reason for this is that only the OCGT units participate in the SR auction in either case since OCGT is the unit with lowest fixed costs in the system.

The CP results with and without CRM participation for the storage units can be found in appendix D. These are similar to the CM results due to the assumption perfect competition that have been done when modeling. Due to the assumptions in these models, the CM and CP models will behave similarly although the market mechanisms are different[1].

The results show that with a credit factor lower than 100% in a CM or CP model, installed capacity for the storage units is less than in the comparable EO cases. Still, the storage units did not get any remuneration in the EO case. This is due to the fact that in the CM case, thermal plants get full remuneration in the CRM and if the storage units do not get full remuneration they will be less competitive than the comparable EO case as in the EO model neither the thermal plants nor the storage units received remuneration for the capacity. It should be emphasized that the installed capacity for storage units will be equal to the EO case if the storage units are given a 100% credit factor.

8.6 Fixed Costs of Storage

The effect of a change in the fixed costs of battery storage can be found in figure 15. This calculation has been performed using the EO model. The fixed costs were varied from -50% and increased by 10% intervals until the result was zero installed capacity. The point that resulted in zero installed capacity was found to be an increase in fixed costs by 40%. From this it can be argued that the battery storage is sensitive to the costs, but not with extreme deviations if the costs are increased or decreased by a relatively small amount.

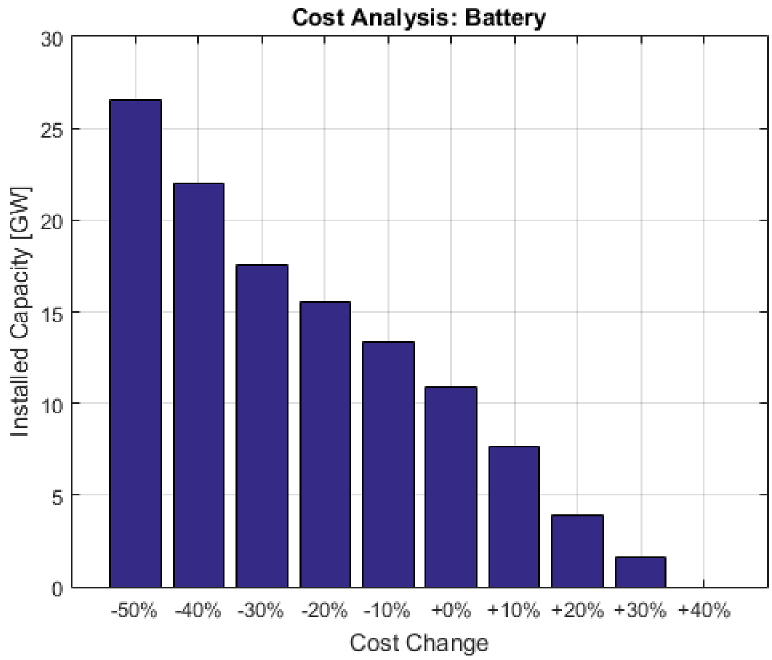


Figure 15: EO: Cost Analysis

The result for PHES was found to be different. As can be found in appendix D, an increase of 10% in the fixed costs resulted in zero installed capacity which suggests that PHES is very sensitive to the fixed costs. However, more calculations with PHES was not performed due to convergence problems.

Another observation made was that the amount of load shedding was reduced when the cost of the battery was reduced. From this it can be argued that cheap batteries can improve system adequacy in a energy-only market. This can be found in appendix D. Another point is that if the fixed costs for battery converter capacity is lower than the thermal unit providing peak power, the battery will take over as the cheapest unit in the system. This means that a possible CRM would increase the storage capacity while having no impact on the thermal units.

9 Conclusions and Further Work

A MCP equilibrium model of a perfectly competitive power market with high levels of RES has been implemented in GAMS. The model includes firm demand, system operator, power producers and storage units. Different CRMs have been modeled and a total of 38 cases representing different market scenarios have been computed from four models: Energy Only, Strategic Reserves, Capacity Market and Capacity Payment. An overview of the cases that have been computed can be found in appendix D with the short description of the cases in the table of contents.

The methods used in this work are theoretical and highly dependent on the assumptions and parameters used and the goal is to give qualitative insights to how market conditions influence the decisions for individual actors with emphasis on energy storage units.

9.1 Conclusions

Based on the case results the following conclusions are drawn. The decisions for the individual actors in the models presented are similar when the same parameters are implemented in different CRMs. This is due to, under the assumption of perfect competition, market actors will seek out the most efficient solution. However, this is only the case when storage units are given a credit factor of 100% in the CRM. A lower credit factor will lead to less installed storage capacity than in the comparable energy only case.

Residual demand was the result of the firm demand subtracted injected solar and injected wind power. This resulted in larger variations in the load that were to be covered by the thermal plants. From the residual demand curve and the load duration curve of residual demand it was found that storage options could be useful, especially to capture the excess energy when RES injection exceeded the firm demand.

When the results from the cases without storage are compared to the solutions that include storage this also influence the thermal plants in the system. For example, the introduction of Norwegian PHES increased the amount of nuclear power in the system with 18.8% while reducing the amount of Coal and CCGT. The same trend was also evident in the battery cases, but not as profound. To conclude this it has been argued that the storage units provide better conditions for the nuclear plants because they smooth over variations. Hence, nuclear plants will be able to operate a higher capacity for at least 6500 hours during the year when compared to the cases without storage.

The operation of PHES and battery is very different. PHES was found to be making operating decisions on a more long-term scale than batteries. Because of the large reservoir in relation to the installed converter capacity, the PHES plants are mainly operated in a manner that shifts the production between the surplus season and the deficit season. The battery had many more cycles during the year than PHES and this is connected to a larger installed converter capacity in relation to the energy installed in addition to a higher efficiency. This resulted in the battery more easily reacting strongly to short therm variations in prices. The difference meant that batteries counteract short term price variations more strongly than the PHES. PHES on the other hand performed better at making the load duration residual demand curve more horizontal.

The credit factor in a capacity market was found to be an important condition in order to ensure the presence of energy storage in the system. However, reduction of the credit factor for PHES was found to be negative for the total surplus while it was positive for batteries. This suggests that batteries does not provide the necessary benefits to be included in a CRM, but this should be verified further. In addition, fixed costs was also found to be an important factor determining the amount of installed storage capacity.

9.2 Further Work

It has been argued that due to the variability of residual demand when large shares of RES are introduced, storage units are useful to ensure system adequacy. However, studies with different levels of RES should be carried out in order to assess how different storage solutions can facilitate integration of RES in the system. One important research question would be "how does the need for storage units change when the share of RES in the system changes?"

This report builds on the assumption of perfect competition. Further studies of this topic could assess how other market assumptions would affect the results.

It has been argued that the installed storage capacity would be influenced by a CRM if the fixed cost of the storage unit had a lower cost than the peaking thermal unit. CRM integration of storage units that compete with peaking power plants could be assessed in further studies.

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A Nomenclature

Sets:

- f ∈ F: Set of conventional power producers
- h ∈ H: Set of hours
- s ∈ S: Set of storage units

Parameters:

- ϵ [1 EUR/MWh]: Price difference between strategic reserve activation and load shedding.
- CF_s [%]: Credit factor for storage units in CRM.
- DEM_h [MWh/h]: Demand data for each hour.
- DEM^{MAX} [MW]: Maximum demand in scenario.
- FC_f [EUR/MW]: Fixed cost for each conventional power producer per year.
- FC_s^{cap} [EUR/MW]: Fixed cost for converter capacity for technology s.
- FC_s^{en} [EUR/MWh]: Fixed cost for storage capacity for technology s.
- INJ_h^{wind} [MWh/h]: Wind energy injected in each hour.
- INJ_h^{solar} [MWh/h]: Solar energy injected in each hour.
- L_s [%]: Storage loss associated with having one MWh of energy stored for a duration of one hour.
- P^{MAX} [EUR/MWh]: Maximum market price.
- RS^{ls} [%]: Reliability standard: Load shed of total demand.
- RS^{cap} [%]: Reliability standard: Reserve margin over maximum demand.
- SL_s [%]: Converter loss for storage technology s.
- T [h]: Length of each timestep.
- VC_f [EUR/MWh]: Variable costs for each conventional power producer.

Variables:

- cap_f^{inst} [MW]: Installed capacity for each conventional power producer f.
- cap_s^{inst} [MW]: Installed capacity for each storage technology s.

- cap_f^{sr} [MW]: Power producer's offered capacity to the strategic reserve.
- cap_s^{sr} [MW]: Storage unit's offered capacity to the strategic reserve.
- cap_f^{cm} [MW]: Power producer's offered capacity to the capacity market.
- cap_s^{cm} [MW]: Storage unit's offered capacity to the capacity market.
- cp [EUR/MW]: CRM price for price based capacity market.
- dem^{cap} [MW]: Demanded capacity in capacity market
- en_s^{inst} [MWh]: Installed storage capacity of storage s.
- $\text{en}_{s,h}^{stored}$ [MWh]: Amount of energy stored in hour h for storage s.
- $\text{gen}_{f,h}$ [MWh/h]: Generation output of power producer f in hour h.
- $\text{gen}_{s,h}$ [MWh/h]: Generation output of storage unit s in hour h.
- gen_h^{sr} [MWh/h]: Generation output from strategic reserve each hour.
- ls_h [MWh/h]: Load shed each hour.
- $\text{store}_{s,h}$ [MWh/h]: Amount of energy stored for storage unit s in hour h.
- π_f [EUR] Profit for power producers.
- π_s [EUR] Profit for storage units.
- α [EUR/MWh]: Price adaption to fulfill load shed standard.
- β [EUR/MW]: Marginal cost of the capacity reserve margin.
- γ [EUR/MW]: Capacity price for volume-based CRM.
- δ_h [EUR/MWh]: Scarcity rent for strategic reserve in each hour.
- $\iota_{s,h}$ [EUR/MWh]: Scarcity rent for storage energy capacity.
- λ_h [EUR/MWh]: Energy price in energy market.
- $\mu_{f,h}$ [EUR/MWh]: Scarcity rent of generation capacity for power producer f in hour h.
- $\mu_{s,h}$ [EUR/MWh]: Scarcity rent of converter capacity for storage unit s in hour h.
- θ_f [EUR/MW]: Scarcity rent for capacity for power producer f.
- θ_s [EUR/MW]: Scarcity rent for capacity for storage unit s.
- $\zeta_{s,h}$ [EUR/MWh]: Value of stored energy.

B Lagrangian and Kuhn-Tucker Conditions

B.1 Energy Only Model

B.1.1 Power Producers

The Lagrangian of the optimization problem in equation 17 and 18 is expressed with μ as the dual variable for equation 18 in equation 147.

$$\forall f : \mathcal{L} = \sum_{h=1}^{H}(\lambda_h - VC_f) * gen_{f,h} * T - FC_f * cap_f^{inst} + \sum_{h=1}^{H} \mu_{f,h} * (cap_f^{inst} - gen_{f,h}) \quad (147)$$

Applying Kuhn-Tucker on the Lagrangian gives the optimality conditions.

With respect to generation:

$$\forall f, \forall h : \lambda_h * T - VC_f * T - \mu_{f,h} \leq 0$$

$$\forall f, \forall h : gen_{f,h} \geq 0$$

$$\forall f, \forall h : (\lambda_h * T - VC_f * T - \mu_{f,h}) * gen_{f,h} = 0$$

With respect to installed capacity:

$$\forall f : -FC_f + \sum_{h=1}^{H} \mu_{f,h} \leq 0$$

$$\forall f : cap_f^{inst} \geq 0$$

$$\forall f : (-FC_f + \sum_{h=1}^{H} \mu_{f,h}) * cap_f^{inst} = 0$$

With respect to μ:

$$\forall f, \forall h : cap_f^{inst} - gen_{f,h} \geq 0$$

$$\forall f, \forall h : \mu_{f,h} \geq 0$$

$$\forall f, \forall h : (cap_f^{inst} - gen_{f,h}) * \mu_{f,h} = 0$$

B.1.2 TSO

The Lagrangian for the TSO problem in an energy only market is formulated in equation 148 with α selected as the dual variable for the load shedding constraint.

$$\mathcal{L} = \sum_{h=1}^{H}(\lambda_h - P^{MAX}) * ls_h * T + \alpha * (RS^{ls} * \sum_{h=1}^{H} DEM_h - \sum_{h=1}^{H} ls_h) \tag{148}$$

Kuhn-Tucker is used to derive the optimality conditions.

With respect to load shedding:

$$\forall h : \lambda_h * T - P^{MAX} * T - \alpha \leq 0$$

$$\forall h : ls_h \geq 0$$

$$\forall h : (\lambda_h * T - P^{MAX} * T - \alpha) * ls_h = 0$$

With respect to α:

$$RS^{ls} * \sum_{h=1}^{H} DEM_h - \sum_{h=1}^{H} ls_h \geq 0$$

$$\alpha \geq 0$$

$$(RS^{ls} * \sum_{h=1}^{H} DEM_h - \sum_{h=1}^{H} ls_h) * \alpha = 0$$

B.1.3 Energy Storage

The Lagrangian of the energy storage operating in an energy only market can be found in equation 149. ζ is chosen as the dual variable for the energy conservation equation, ι is the dual variable for the energy constraint due to installed storage, μ is the dual variable for the capacity constraint due to the limit of the converters installed and κ is the dual variable of the storage level constraint.

$$\begin{aligned}\forall s : \mathcal{L}_s = &\sum_{h=1}^{H}(gen_{s,h} - store_{s,h}) * T * \lambda_h - FC_s^{cap} * cap_s^{inst} - FC_s^{en} * en_s^{inst} \\ &+ \zeta_{s,1}(en_{s,\frac{H}{T}}^{stored} * L_s + store_{s,1} * T * SL_s - gen_{s,1} * T - en_{s,1}^{stored} \\ &+ \sum_{h=2}^{H}\zeta_{s,h}(en_{s,h-1}^{stored} * L_s + store_{s,h} * T * SL_s - gen_{s,h} * T - en_{s,h}^{stored}) \\ &+ \sum_{h=1}^{H}\iota_{s,h} * (en_s^{inst} - en_{s,h}^{stored}) + \sum_{h=1}^{H}\mu_{s,h} * (cap_s^{inst} - gen_{s,h} - store_{s,h})\end{aligned} \tag{149}$$

The optimality conditions to be satisfied in the mixed complementarity model are derived by applying complementarity slackness from the theory section, deriving with respect to each decision variable and dual variable.

With respect to generation:

$$\forall s, \forall h : \lambda_h * T - \zeta_{s,h} * T - \mu_{s,h} \leq 0$$

$$\forall s, \forall h : gen_{s,h} \geq 0$$

$$\forall s, \forall h : (\lambda_h * T - \zeta_{s,h} * T - \mu_{s,h}) * gen_{s,h} = 0$$

With respect to storing energy:

$$\forall s, \forall h : -\lambda_h * T + \zeta_{s,h} * T * SL_s - \mu_{s,h} \leq 0$$

$$\forall s, \forall h : store_{s,h} \geq 0$$

$$\forall s, \forall h : (-\lambda_h * T + \zeta_{s,h} * T * SL_s - \mu_{s,h}) * store_{s,h} = 0$$

With respect to installed capacity:

$$\forall s : -FC_s^{cap} + \sum_{h=1}^{H} \mu_{s,h} \leq 0$$

$$\forall s : cap_s^{inst} \geq 0$$

$$\forall s : (-FC_s^{cap} + \sum_{h=1}^{H} \mu_{s,h}) * cap_s^{inst} = 0$$

With respect to installed energy:

$$\forall s : -FC_s^{en} + \sum_{h=1}^{H} \iota_{s,h} \leq 0$$

$$\forall s : en_s^{inst} \geq 0$$

$$\forall s : (-FC_s^{en} + \sum_{h=1}^{H} \iota_{s,h}) * en_s^{inst} = 0$$

With respect to stored energy:

Hours except last:

$$\forall s, \forall h < \frac{H}{T} : \zeta_{s,h+1} * L_s - \zeta_{s,h} - \iota_{s,h} \leq 0$$

$$\forall s, \forall h < \frac{H}{T} : en_{s,h}^{stored} \geq 0$$

$$\forall s, \forall h < \frac{H}{T} : (\zeta_{s,h+1} * L_s - \zeta_{s,h} - \iota_{s,h}) * en_{s,h}^{stored} = 0$$

Last hour:

$$\forall s, h = \frac{H}{T} : \zeta_{s,1} * L_s - \zeta_{s,\frac{H}{T}} - \iota_{s,\frac{H}{T}} \leq 0$$

$$\forall s, h = \frac{H}{T} : en^{stored}_{s,h} \geq 0$$

$$\forall s, h = \frac{H}{T} : (\zeta_{s,1} * L_s - \zeta_{s,\frac{H}{T}} - \iota_{s,\frac{H}{T}} + \kappa_s) * en^{stored}_{s,\frac{H}{T}} = 0$$

With respect to ζ:

First hour:

$$\forall s, h = 1 : en^{stored}_{s,\frac{H}{T}} * L_s + store_{s,1} * T * SL_s - gen_{s,1} * T - en^{stored}_{s,1} \geq 0$$

$$\forall s, h = 1 : \zeta_{s,1} \geq 0$$

$$\forall s, h = 1 : (en^{stored}_{s,\frac{H}{T}} * L_s + store_{s,1} * T * SL_s - gen_{s,1} * T - en^{stored}_{s,1}) * \zeta_{s,1} = 0$$

Rest of hours:

$$\forall s, \forall h > 1 : en^{stored}_{s,h-1} * L_s + store_{s,h} * T * SL_s - gen_{s,h} * T - en^{stored}_{s,h} \geq 0$$

$$\forall s, \forall h > 1 : \zeta_{s,h} \geq 0$$

$$\forall s, \forall h > 1 : (en^{stored}_{s,h-1} * L_s + store_{s,h} * T * SL_s - gen_{s,h} * T - en^{stored}_{s,h}) * \zeta_{s,h} = 0$$

With respect to ι:

$$\forall s, \forall h : en^{inst}_{s} - en^{stored}_{s,h} \geq 0$$

$$\forall s, \forall h : \iota_{s,h} \geq 0$$

$$\forall s, \forall h : (en^{inst}_{s} - en^{stored}_{s,h}) * \iota_{s,h} = 0$$

With respect to μ

$$\forall s, \forall h : cap_s^{inst} - gen_{s,h} - store_{s,h} \geq 0$$

$$\forall s, \forall h : \mu_{s,h} \geq 0$$

$$\forall s, \forall h : (cap_s^{inst} - gen_{s,h} - store_{s,h}) * \mu_{s,h} = 0$$

B.2 Strategic Reserves Model

B.2.1 Power Producers

The Lagrangian of the optimization problem in equation 44, 45 and 46 can be found in equation 150. μ is the dual variable of equation 45 and θ is the dual variable for equation 46

$$\forall f : \mathcal{L} = \sum_{h=1}^{H} (\lambda_h - VC_f) * gen_{f,h} * T - FC_f * cap_f^{inst} + \gamma * cap_f^{sr} + \sum_{h=1}^{H} \mu_{f,h} * (cap_f^{inst} - gen_{f,h} - cap_f^{sr}) + \theta_f * (cap_f^{inst} - cap_f^{sr}) \quad (150)$$

Applying Kuhn-Tucker gives the optimality conditions.

With respect to generation:

$$\forall f : \forall h : \lambda_h * T - VC_f * T - \mu_{f,h} \leq 0$$

$$\forall f : \forall h : gen_{f,h} \geq 0$$

$$\forall f : \forall h : (\lambda_h * T - VC_f * T - \mu_{f,h}) * gen_{f,h} = 0$$

With respect to installed capacity:

$$\forall f: -FC_f + \sum_{h=1}^{H} \mu_{f,h} + \theta_f \leq 0$$

$$\forall f: cap_f^{inst} \geq 0$$

$$\forall f: (-FC_f + \sum_{h=1}^{H} \mu_{f,h} + \theta_f) * cap_f^{inst} = 0$$

With respect to capacity offered to the strategic reserve:

$$\forall f: \gamma - \sum_{h=1}^{H} \mu_{f,h} - \theta_f \leq 0$$

$$\forall f: cap_f^{sr} \geq 0$$

$$\forall f: (\gamma - \sum_{h=1}^{H} \mu_{f,h} - \theta_f) * cap_f^{sr} = 0$$

With respect to μ:

$$\forall f, \forall h: cap_f^{inst} - gen_{f,h} - cap_f^{sr} \geq 0$$

$$\forall f, \forall h: \mu_{f,h} \geq 0$$

$$\forall f, \forall h: (cap_f^{inst} - gen_{f,h} - cap_f^{sr}) * \mu_{f,h} = 0$$

With respect to θ:

$$\forall f: cap_f^{inst} - cap_f^{sr} \geq 0$$

$$\forall f: \theta_f \geq 0$$

$$\forall f: (cap_f^{inst} - cap_f^{sr}) * \theta_f = 0$$

B.2.2 TSO

The Lagrangian of the TSO operating in an energy market and a strategic reserves market can be found in equation 151. α is the dual variable of the load shedding constraint, β is the dual variable of the capacity constraint and δ is the dual variable for the generation constraint for strategic reserves.

$$\mathcal{L} = \sum_{h=1}^{H}(\lambda_h - P^{MAX}) * ls_h * T - \gamma * dem^{cap} + \sum_{h=1}^{H}(\lambda_h - P^{MAX} + \epsilon) * gen_h^{sr} * T$$
$$+ \alpha * (RS^{ls} * \sum_{h=1}^{H} DEM_h - \sum_{h=1}^{H} ls_h)$$
$$+\beta*(\sum_{f=1}^{F}(cap_f^{inst} - cap_f^{sr}) + CF_s * \sum_{s=1}^{S}(cap_s^{inst} - cap_s^{sr}) + dem^{cap} - RS^{cap} * DEM^{MAX})$$
$$+ \sum_{h=1}^{H} \delta_h * (\sum_{f=1}^{F} cap_f^{sr} + \sum_{s=1}^{S} cap_s^{sr} * CF_s - gen_h^{sr}) \quad (151)$$

The optimality conditions are found by applying Kuhn-Tucker.

With respect to load shedding:

$$\forall h : \lambda_h * T - P^{MAX} * T - \alpha \leq 0 \quad (152)$$

$$\forall h : ls_h \geq 0 \quad (153)$$

$$\forall h : (\lambda_h * T - P^{MAX} * T - \alpha) * ls_h = 0 \quad (154)$$

With respect to generation from the strategic reserves:

$$\forall h : \lambda_h * T - P^{MAX} * T + \epsilon * T - \delta_h \leq 0 \quad (155)$$

$$\forall h : gen_h^{sr} \geq 0 \quad (156)$$

$$\forall h : (\lambda_h * T - P^{MAX} * T + \epsilon * T - \delta_h) * gen_h^{sr} = 0 \quad (157)$$

With respect to demanded capacity:

$$-\gamma + \beta \leq 0$$

$$dem^{cap} \geq 0$$

$$(-\gamma + \beta) * dem^{cap} = 0$$

With respect to α:

$$RS^{ls} * \sum_{h=1}^{H} DEM_h - \sum_{h=1}^{H} ls_h \geq 0 \tag{158}$$

$$\alpha \geq 0 \tag{159}$$

$$(RS^{ls} * \sum_{h=1}^{H} DEM_h - \sum_{h=1}^{H} ls_h) * \alpha = 0 \tag{160}$$

With respect to β:

$$\sum_{f=1}^{F}(cap_f^{inst} - cap_f^{sr}) + CF_S * \sum_{s=1}^{S}(cap_s^{inst} - cap_s^{sr}) + dem^{cap} - RS^{cap} * DEM^{MAX} \geq 0 \tag{161}$$

$$\beta \geq 0 \tag{162}$$

$$(\sum_{f=1}^{F}(cap_f^{inst} - cap_f^{sr}) + CF_S * \sum_{s=1}^{S}(cap_s^{inst} - cap_s^{sr}) + dem^{cap} - RS^{cap} * DEM^{MAX}) * \beta = 0 \tag{163}$$

With respect to δ:

$$\forall h : \sum_{f=1}^{F} cap_f^{sr} + CF_S * \sum_{s=1}^{S} cap_s^{sr} - gen_h^{sr} \geq 0 \tag{164}$$

$$\forall h : cap_s^{sr} \geq 0 \tag{165}$$

$$\forall h : (\sum_{f=1}^{F} cap_f^{sr} + CF_S * \sum_{s=1}^{S} cap_s^{sr} - gen_h^{sr}) * \delta_h = 0 \tag{166}$$

B.2.3 Energy Storage

$$\begin{aligned} \forall s : \mathcal{L}_s = \sum_{h=1}^{H} (gen_{s,h} - store_{s,h}) * T * \lambda_h - FC_s^{cap} * cap_s^{inst} - FC_s^{en} * en_s^{inst} + \gamma * cap_s^{sr} * CF_s \\ + \zeta_{s,1}(en_{s,\frac{H}{T}}^{stored} * L_s + store_{s,1} * T * SL_s - gen_{s,1} * T - en_{s,1}^{stored}) \\ + \sum_{h=2}^{H} \zeta_{s,h}(en_{s,h-1}^{stored} * L_s + store_{s,h} * T * SL_s - gen_{s,h} * T - en_{s,h}^{stored}) + \sum_{h=1}^{H} \iota_{s,h} * (en_s^{inst} - en_{s,h}^{stored}) \\ + \sum_{h=1}^{H} \mu_{s,h} * (cap_s^{inst} - gen_{s,h} - store_{s,h} - cap_s^{sr}) + \theta_s * (cap_s^{inst} - cap_s^{sr}) \end{aligned} \tag{167}$$

With respect to generation:

$$\forall s, \forall h : \lambda_h * T - \zeta_{s,h} * T - \mu_{s,h} \leq 0$$

$$\forall s, \forall h : gen_{s,h} \geq 0$$

$$\forall s, \forall h : (\lambda_h * T - \zeta_{s,h} * T - \mu_{s,h}) * gen_{s,h} = 0$$

With respect to storing energy:

$$\forall s, \forall h : -\lambda_h * T + \zeta_{s,h} * T * SL_s - \mu_{s,h} \leq 0$$

$$\forall s, \forall h : store_{s,h} \geq 0$$

$$\forall s, \forall h : (-\lambda_h * T + \zeta_{s,h} * T * SL_s - \mu_{s,h}) * store_{s,h} = 0$$

With respect to installed capacity:

$$\forall s : -FC_s^{cap} + \sum_{h=1}^{H} \mu_{s,h} + \theta_s \leq 0$$

$$\forall s : cap_s^{inst} \geq 0$$

$$\forall s : (-FC_s^{cap} + \sum_{h=1}^{H} \mu_{s,h} + \theta_s) * cap_s^{inst} = 0$$

With respect to installed energy:

$$\forall s : -FC_s^{en} + \sum_{h=1}^{H} \iota_{s,h} \leq 0$$

$$\forall s : en_s^{inst} \geq 0$$

$$\forall s : (-FC_s^{en} + \sum_{h=1}^{H} \iota_{s,h}) * en_s^{inst} = 0$$

With respect to capacity offered to the strategic reserves:

$$\forall s : \gamma * CF_s - \sum_{h=1}^{H} \mu_{s,h} - \theta_s \leq 0$$

$$\forall s : cap_s^{sr} \geq 0$$

$$\forall s : (\gamma * CF_s - \sum_{h=1}^{H} \mu_{s,h} - \theta_s) * cap_s^{sr} = 0$$

With respect to the amount of stored energy: Hours except last:

$$\forall s, \forall h < \frac{H}{T} : \zeta_{s,h+1} * L_s - \zeta_{s,h} - \iota_{s,h} \leq 0$$

$$\forall s, \forall h < \frac{H}{T} : en_{s,h}^{stored} \geq 0$$

$$\forall s, \forall h < \frac{H}{T} : (\zeta_{s,h+1} * L_s - \zeta_{s,h} - \iota_{s,h}) * en^{stored}_{s,h} = 0$$

Last hour:

$$\forall s, h = \frac{H}{T} : \zeta_{s,1} * L_s - \zeta_{s,\frac{H}{T}} - \iota_{s,\frac{H}{T}} \leq 0$$

$$\forall s, h = \frac{H}{T} : en^{stored}_{s,h} \geq 0$$

$$\forall s, h = \frac{H}{T} : (\zeta_{s,1} * L_s - \zeta_{s,\frac{H}{T}} - \iota_{s,\frac{H}{T}}) * en^{stored}_{s,\frac{H}{T}} = 0$$

With respect to ζ:

First hour:

$$\forall s, h = 1 : en^{stored}_{s,\frac{H}{T}} * L_s + store_{s,1} * T * SL_s - gen_{s,1} * T - en^{stored}_{s,1} \geq 0$$

$$\forall s, h = 1 : \zeta_{s,1} \geq 0$$

$$\forall s, h = 1 : (en^{stored}_{s,\frac{H}{T}} * L_s + store_{s,1} * T * SL_s - gen_{s,1} * T - en^{stored}_{s,1}) * \zeta_{s,1} = 0$$

Rest of hours:

$$\forall s, \forall h > 1 : en^{stored}_{s,h-1} * L_s + store_{s,h} * T * SL_s - gen_{s,h} * T - en^{stored}_{s,h} \geq 0$$

$$\forall s, \forall h > 1 : \zeta_{s,h} \geq 0$$

$$\forall s, \forall h > 1 : (en^{stored}_{s,h-1} * L_s + store_{s,h} * T * SL_s - gen_{s,h} * T - en^{stored}_{s,h}) * \zeta_{s,h} = 0$$

With respect to ι:

$$\forall s, \forall h : en^{inst}_{s} - en^{stored}_{s,h} \geq 0$$

$$\forall s, \forall h : \iota_{s,h} \geq 0$$

$$\forall s, \forall h : (en_s^{inst} - en_{s,h}^{stored}) * \iota_{s,h} = 0$$

With respect to μ:

$$\forall s, \forall h : cap_s^{inst} - gen_{s,h} - store_{s,h} - cap_s^{sr} \geq 0$$

$$\forall s, \forall h : \mu_{s,h} \geq 0$$

$$\forall s, \forall h : (cap_s^{inst} - gen_{s,h} - store_{s,h} - cap_s^{sr}) * \mu_{s,h} = 0$$

With respect to θ:

$$\forall s : cap_s^{inst} - cap_s^{sr} \geq 0$$

$$\forall s : \theta_s \geq 0$$

$$\forall s : (cap_s^{inst} - cap_s^{sr}) * \theta_s = 0$$

B.3 Capacity-Based Capacity Market Model

B.3.1 Power Producers

The Lagrangian for the producer in a volume-based capacity market can be found in equation 168 with μ as the dual variable for equation 85 and θ as the dual variable for equation 86.

$$\forall f : \mathcal{L} = \sum_{h=1}^{H} (\lambda_h - VC_f) * gen_{f,h} * T - FC_f * cap_f^{inst} + \gamma * cap_f^{cm} + \sum_{h=1}^{H} \mu_{f,h} * (cap_f^{inst} - gen_{f,h}) + \theta_f (cap_f^{inst} - cap_f^{cm}) \quad (168)$$

Kuhn-Tucker is applied to obtain the optimality conditions.

With respect to generation:

$$\forall f, \forall h : \lambda_h * T - VC_f * T - \mu_{f,h} \leq 0$$

$$\forall f, \forall h : gen_{f,h} \geq 0$$

$$\forall f, \forall h : (\lambda_h * T - VC_f * T - \mu_{f,h}) * gen_{f,h} = 0$$

With respect to installed capacity:

$$\forall f : -FC_f + \sum_{h=1}^{H} \mu_{f,h} + \theta_f \leq 0$$

$$\forall f : cap_f^{inst} \geq 0$$

$$\forall f : (-FC_f + \sum_{h=1}^{H} \mu_{f,h} + \theta_f) * cap_f^{inst} = 0$$

With respect to capacity offered to the capacity market:

$$\forall f : \gamma - \theta_f \leq 0$$

$$\forall f : cap_f^{cm} \geq 0$$

$$\forall f : (\gamma - \theta_f) * cap_f^{cm} = 0$$

With respect to μ:

$$\forall f, \forall h : cap_f^{inst} - gen_{f,h} \geq 0$$

$$\forall f, \forall h : \mu_{f,h} \geq 0$$

$$\forall f, \forall h : (cap_f^{inst} - gen_{f,h}) * \mu_{f,h} = 0$$

With respect to θ:

$$\forall f : cap_f^{inst} - cap_f^{cm} \geq 0$$

$$\forall f : \theta_f \geq 0$$

$$\forall f : (cap_f^{inst} - cap_f^{cm}) * \theta_f = 0$$

B.3.2 TSO

The Lagrangian formulation for the TSO operating in an energy market and capacity market is shown in equation 169.

$$\begin{aligned} \mathcal{L} = &\sum_{h=1}^{H} (\lambda_h - P^{MAX}) * ls_h * T - \gamma * dem^{cap} \\ &+ \alpha * (RS^{ls} * \sum_{h=1}^{H} DEM_h - \sum_{h=1}^{H} ls_h) + \beta * (dem^{cap} - RS^{cap} * DEM^{MAX}) \end{aligned} \tag{169}$$

The optimality conditions are obtained by applying Kuhn-Tucker.

With respect to load shedding:

$$\forall h : \lambda_h * T - P^{MAX} * T - \alpha \leq 0$$

$$\forall h : ls_h \geq 0$$

$$\forall h : (\lambda_h * T - P^{MAX} * T - \alpha) * ls_h = 0$$

With respect to demanded capacity:

$$-\gamma + \beta \leq 0$$

$$dem^{cap} \geq 0$$

$$(-\gamma + \beta) * dem^{cap} = 0$$

With respect to α:

$$RS^{ls} * \sum_{h=1}^{H} DEM_h - \sum_{h=1}^{H} ls_h \geq 0$$

$$\alpha \geq 0$$

$$(RS^{ls} * \sum_{h=1}^{H} DEM_h - \sum_{h=1}^{H} ls_h) * \alpha = 0$$

With respect to β:

$$dem^{cap} - RS^{cap} * DEM^{MAX} \geq 0$$

$$\beta \geq 0$$

$$(dem^{cap} - RS^{cap} * DEM^{MAX}) * \beta = 0$$

B.3.3 Energy Storage

$$\forall s : \mathcal{L}_s = \sum_{h=1}^{H}(gen_{s,h} - store_{s,h}) * T * \lambda_h - FC_s^{cap} * cap_s^{inst} - FC_s^{en} * en_s^{inst} + \gamma * cap_s^{cm} * CF_s$$
$$+ \zeta_{s,1}(en_{s,\frac{H}{T}}^{stored} * L_s + store_{s,1} * T * SL_s - gen_{s,1} * T - en_{s,1}^{stored})$$
$$+ \sum_{h=2}^{H} \zeta_{s,h}(en_{s,h-1}^{stored} * L_s + store_{s,h} * T * SL_s - gen_{s,h} * T - en_{s,h}^{stored}) + \sum_{h=1}^{H} \iota_{s,h} * (en_s^{inst} - en_{s,h}^{stored})$$
$$+ \sum_{h=1}^{H} \mu_{s,h} * (cap_s^{inst} - gen_{s,h} - store_{s,h}) + \theta_s * (cap_s^{inst} - cap_s^{cm}) \quad (170)$$

With respect to generation:

$$\forall s, \forall h : \lambda_h * T - \zeta_{s,h} * T - \mu_{s,h} \leq 0$$

$$\forall s, \forall h : gen_{s,h} \geq 0$$

$$\forall s, \forall h : (\lambda_h * T - \zeta_{s,h} * T - \mu_{s,h}) * gen_{s,h} = 0$$

With respect to storing energy:

$$\forall s, \forall h : -\lambda_h * T + \zeta_{s,h} * T * SL_s - \mu_{s,h} \leq 0$$

$$\forall s, \forall h : store_{s,h} \geq 0$$

$$\forall s, \forall h : (-\lambda_h * T + \zeta_{s,h} * T * SL_s - \mu_{s,h}) * store_{s,h} = 0$$

With respect to installed capacity:

$$\forall s : -FC_s^{cap} + \sum_{h=1}^{H} \mu_{s,h} + \theta_f \leq 0$$

$$\forall s : cap_s^{inst} \geq 0$$

$$\forall s : (-FC_s^{cap} + \sum_{h=1}^{H} \mu_{s,h} + \theta_f) * cap_s^{inst} = 0$$

With respect to installed energy:

$$\forall s : -FC_s^{en} + \sum_{h=1}^{H} \iota_{s,h} \leq 0$$

$$\forall s : en_s^{inst} \geq 0$$

$$\forall s : (-FC_s^{en} + \sum_{h=1}^{H} \iota_{s,h}) * en_s^{inst} = 0$$

With respect to capacity offered to the capacity market:

$$\forall s : \gamma * CF_s - \theta_f \leq 0$$

$$\forall s : cap_s^{cm} \geq 0$$

$$\forall s : (\gamma * CF_s - \theta_f) * cap_s^{cm} = 0$$

With respect to amount of stored energy:

Hours except last:

$$\forall s, \forall h < \frac{H}{T} : \zeta_{s,h+1} * L_s - \zeta_{s,h} - \iota_{s,h} \leq 0$$

$$\forall s, \forall h < \frac{H}{T} : en_{s,h}^{stored} \geq 0$$

$$\forall s, \forall h < \frac{H}{T} : (\zeta_{s,h+1} * L_s - \zeta_{s,h} - \iota_{s,h}) * en_{s,h}^{stored} = 0$$

Last hour:

$$\forall s, h = \frac{H}{T} : \zeta_{s,1} * L_s - \zeta_{s,\frac{H}{T}} - \iota_{s,\frac{H}{T}} \leq 0$$

$$\forall s, h = \frac{H}{T} : en^{stored}_{s,h} \geq 0$$

$$\forall s, h = \frac{H}{T} : (\zeta_{s,1} * L_s - \zeta_{s,\frac{H}{T}} - \iota_{s,\frac{H}{T}}) * en^{stored}_{s,\frac{H}{T}} = 0$$

With respect to ζ:

First hour:

$$\forall s, h = 1 : en^{stored}_{s,\frac{H}{T}} * L_s + store_{s,1} * T * SL_s - gen_{s,1} * T - en^{stored}_{s,1} \geq 0$$

$$\forall s, h = 1 : \zeta_{s,1} \geq 0$$

$$\forall s, h = 1 : (en^{stored}_{s,\frac{H}{T}} * L_s + store_{s,1} * T * SL_s - gen_{s,1} * T - en^{stored}_{s,1}) * \zeta_{s,1} = 0$$

Rest of hours:

$$\forall s, \forall h > 1 : en^{stored}_{s,h-1} * L_s + store_{s,h} * T * SL_s - gen_{s,h} * T - en^{stored}_{s,h} \geq 0$$

$$\forall s, \forall h > 1 : \zeta_{s,h} \geq 0$$

$$\forall s, \forall h > 1 : (en^{stored}_{s,h-1} * L_s + store_{s,h} * T * SL_s - gen_{s,h} * T - en^{stored}_{s,h}) * \zeta_{s,h} = 0$$

With respect to ι:

$$\forall s, \forall h : en^{inst}_{s} - en^{stored}_{s,h} \geq 0$$

$$\forall s, \forall h : \iota_{s,h} \geq 0$$

$$\forall s, \forall h : (en^{inst}_{s} - en^{stored}_{s,h}) * \iota_{s,h} = 0$$

With respect to μ:

$$\forall s, \forall h : cap_s^{inst} - gen_{s,h} - store_{s,h} \geq 0$$

$$\forall s, \forall h : \mu_{s,h} \geq 0$$

$$\forall s, \forall h : (cap_s^{inst} - gen_{s,h} - store_{s,h}) * \mu_{s,h} = 0$$

With respect to θ:

$$\forall s : cap_s^{inst} - cap_s^{cm} \geq 0$$

$$\forall s : \theta_s \geq 0$$

$$\forall s : (cap_s^{inst} - cap_s^{cm}) * \theta_s = 0$$

B.4 Price-Based Capacity Market Model

B.4.1 Power Producers

The optimization problem for the producer participating in an energy market and capacity payment market is represented as a Lagrangian in equation 171. Also here, μ is used as the dual for the generation limit constraint.

$$\forall f : \mathcal{L} = \sum_{h=1}^{H} (\lambda_h - VC_f) * gen_{f,h} * T - FC_f * cap_f^{inst} + cp * cap_f^{inst} + \sum_{h=1}^{H} \mu_{f,h} * (cap_f^{inst} - gen_{f,h}) \quad (171)$$

The optimality conditions are derived by applying Kuhn-Tucker.

With respect to generation:

$$\forall f, \forall h : \lambda_h * T - VC_f * T - \mu_{f,h} \leq 0$$

$$\forall f, \forall h : gen_{f,h} \geq 0$$

$$\forall f, \forall h : (\lambda_h * T - VC_f * T - \mu_{f,h}) * gen_{f,h} = 0$$

With respect to installed capacity:

$$\forall f : -FC_f + cp + \sum_{h=1}^{H} \mu_{f,h} \leq 0$$

$$\forall f : cap_f^{inst} \geq 0$$

$$\forall f : (-FC_f + cp + \sum_{h=1}^{H} \mu_{f,h}) * cap_f^{inst} = 0$$

With respect to μ:

$$\forall f, \forall h : cap_f^{inst} - gen_{f,h} \geq 0$$

$$\forall f, \forall h : \mu_{f,h} \geq 0$$

$$\forall f, \forall h : (cap_f^{inst} - gen_{f,h}) * \mu_{f,h} = 0$$

B.4.2 TSO

$$\mathcal{L} = \sum_{h=1}^{H} (\lambda_h - P^{MAX}) * ls_h * T - \sum_{f=1}^{F} (cp * cap_f^{inst}) - \sum_{s=1}^{S} (cp * cap_s^{inst} * CF_s) + \alpha * (RS^{ls} * \sum_{h=1}^{H} DEM_h - \sum_{h=1}^{H} ls_h) \quad (172)$$

Kuhn-Tucker is used to derive the optimality conditions.

With respect to load shedding:

$$\forall h : \lambda_h * T - P^{MAX} * T - \alpha \leq 0$$

$$\forall h : ls_h \geq 0$$

$$\forall h : (\lambda_h * T - P^{MAX} * T - \alpha) * ls_h = 0$$

With respect to α:

$$RS^{ls} * \sum_{h=1}^{H} DEM_h - \sum_{h=1}^{H} ls_h \geq 0$$

$$\alpha \geq 0$$

$$(RS^{ls} * \sum_{h=1}^{H} DEM_h - \sum_{h=1}^{H} ls_h) * \alpha = 0$$

B.4.3 Energy Storage

$$\begin{aligned}\forall s : \mathcal{L}_s = \sum_{h=1}^{H} (gen_{s,h} - store_{s,h}) * T * \lambda_h - FC_s^{cap} * cap_s^{inst} - FC_s^{en} * en_s^{inst} + cp * cap_s^{inst} * CF_s \\ + \zeta_{s,1}(en_{s,\frac{H}{T}}^{stored} * L_s + store_{s,1} * T * SL_s - gen_{s,1} * T - en_{s,1}^{stored}) \\ + \sum_{h=2}^{H} \zeta_{s,h}(en_{s,h-1}^{stored} * L_s + store_{s,h} * T * SL_s - gen_{s,h} * T - en_{s,h}^{stored}) \\ + \sum_{h=1}^{H} \iota_{s,h} * (en_s^{inst} - en_{s,h}^{stored}) + \sum_{h=1}^{H} \mu_{s,h} * (cap_s^{inst} - gen_{s,h} - store_{s,h}) \quad (173)\end{aligned}$$

With respect to generation:

$$\forall s, \forall h : \lambda_h * T - \zeta_{s,h} * T - \mu_{s,h} \leq 0$$

$$\forall s, \forall h : gen_{s,h} \geq 0$$

$$\forall s, \forall h : (\lambda_h * T - \zeta_{s,h} * T - \mu_{s,h}) * gen_{s,h} = 0$$

With respect to storing energy:

$$\forall s, \forall h : -\lambda_h * T + \zeta_{s,h} * T * SL_s - \mu_{s,h} \leq 0$$

$$\forall s, \forall h : store_{s,h} \geq 0$$

$$\forall s, \forall h : (-\lambda_h * T + \zeta_{s,h} * T * SL_s - \mu_{s,h}) * store_{s,h} = 0$$

With respect to installed capacity:

$$\forall s : -FC_s^{cap} + cp * CF_s + \sum_{h=1}^{H} \mu_{s,h} \leq 0$$

$$\forall s : cap_s^{inst} \geq 0$$

$$\forall s : (-FC_s^{cap} + cp * CF_s + \sum_{h=1}^{H} \mu_{s,h}) * cap_s^{inst} = 0$$

With respect to installed energy:

$$\forall s : -FC_s^{en} + \sum_{h=1}^{H} \iota_{s,h} \leq 0$$

$$\forall s : en_s^{inst} \geq 0$$

$$\forall s : (-FC_s^{en} + \sum_{h=1}^{H} \iota_{s,h}) * en_s^{inst} = 0$$

With respect to amount of energy stored:

Hours except last:

$$\forall s, \forall h < \frac{H}{T} : \zeta_{s,h+1} * L_s - \zeta_{s,h} - \iota_{s,h} \leq 0$$

$$\forall s, \forall h < \frac{H}{T} : en^{stored}_{s,h} \geq 0$$

$$\forall s, \forall h < \frac{H}{T} : (\zeta_{s,h+1} * L_s - \zeta_{s,h} - \iota_{s,h}) * en^{stored}_{s,h} = 0$$

Last hour:

$$\forall s, h = \frac{H}{T} : \zeta_{s,1} * L_s - \zeta_{s,\frac{H}{T}} - \iota_{s,\frac{H}{T}} \leq 0$$

$$\forall s, h = \frac{H}{T} : en^{stored}_{s,h} \geq 0$$

$$\forall s, h = \frac{H}{T} : (\zeta_{s,1} * L_s - \zeta_{s,\frac{H}{T}} - \iota_{s,\frac{H}{T}}) * en^{stored}_{s,\frac{H}{T}} = 0$$

With respect to ζ:

First hour:

$$\forall s, h = 1 : en^{stored}_{s,\frac{H}{T}} * L_s + store_{s,1} * T * SL_s - gen_{s,1} * T - en^{stored}_{s,1} \geq 0$$

$$\forall s, h = 1 : \zeta_{s,1} \geq 0$$

$$\forall s, h = 1 : (en^{stored}_{s,\frac{H}{T}} * L_s + store_{s,1} * T * SL_s - gen_{s,1} * T - en^{stored}_{s,1}) * \zeta_{s,1} = 0$$

Rest of hours:

$$\forall s, \forall h > 1 : en^{stored}_{s,h-1} * L_s + store_{s,h} * T * SL_s - gen_{s,h} * T - en^{stored}_{s,h} \geq 0$$

$$\forall s, \forall h > 1 : \zeta_{s,h} \geq 0$$

$$\forall s, \forall h > 1 : (en_{s,h-1}^{stored} * L_s + store_{s,h} * T * SL_s - gen_{s,h} * T - en_{s,h}^{stored}) * \zeta_{s,h} = 0$$

With respect to ι:

$$\forall s, \forall h : en_s^{inst} - en_{s,h}^{stored} \geq 0$$

$$\forall s, \forall h : \iota_{s,h} \geq 0$$

$$\forall s, \forall h : (en_s^{inst} - en_{s,h}^{stored}) * \iota_{s,h} = 0$$

With respect to μ

$$\forall s, \forall h : cap_s^{inst} - gen_{s,h} - store_{s,h} \geq 0$$

$$\forall s, \forall h : \mu_{s,h} \geq 0$$

$$\forall s, \forall h : (cap_s^{inst} - gen_{s,h} - store_{s,h}) * \mu_{s,h} = 0$$

C Fixed cost Calculations

The annual cost of an investment is found by applying equation 174[2]. Payment Factor will be denoted PF.

$$\text{Payment Factor}_{r,n} = \frac{r}{1-(1+r)^{-n}} \tag{174}$$

The interest rate is r and number of years for the investment is n. The interest rate will be 5% for all calculations.

C.1 HVDC Cable

The investment cost for long distance cable has been found to be 1153 EUR/kW. This investment has a lifetime of 40 years [9].

From a 5% interest rate and 40 years the resulting PF is computed in equation

$$PF_{5,40} = \frac{0.05}{1-(1+0.05)^{-40}} = 0.058278161 \tag{175}$$

The yearly capital cost was from this found to be 67.195 EUR/kW, or 67195 EUR/MW.

C.2 Grid reinforcement

An additional 30% of the cable cost is needed to cover the grid reinforcement need from this extra interconnection capacity. However, this investment has a lifetime of 70 years.

$$PF_{5,70} = \frac{0.05}{1-(1+0.05)^{-70}} = 0.051699153 \tag{176}$$

The yearly capital cost was from this found to be 17.883 EUR/kW, or 17883 EUR/MW.

C.3 PHES

The investment cost for PHES capacity has been found to be 400 EUR/kW and an additional 0.75% of this is needed each year to cover maintenance need. This investment has a lifetime of 30 years [9].

From a 5% interest rate and 30 years the resulting PF is computed in equation

$$PF_{5,30} = \frac{0.05}{1 - (1 + 0.05)^{-30}} = 0.065051435 \tag{177}$$

The yearly capital cost of the initial investment was found by multiplying the initial investment by the PF and was found to be 26 EUR/kW. An additional 3 EUR/kW was added due to the maintenance need and the total yearly cost of investment was found to be 29021 EUR/MW.

C.4 Lead-acid batteries

The investment cost for Li-ion capacity has been found to be 200 EUR/kW and 50 EUR/kWh. This investment has a lifetime of 10 years [4].

From a 5% interest rate and 10 years the resulting PF is computed in equation

$$PF_{5,10} = \frac{0.05}{1 - (1 + 0.05)^{-10}} = 0.129504575 \tag{178}$$

The yearly capital cost of the initial investment was found by multiplying the initial investment by the PF and was found to be 25901 EUR/MW and 6475 EUR/MWh.

D Case results

D.1 Energy Only Model

D.1.1 EO1: No storage

Table 5: EO1 capacity

	Absolute	Share of system total [%]
Total installed capacity [MW]	210240	100.00
Total installed capacity: Producers [MW]	210240	100.00
Installed capacity: Nuclear [MW]	69786	33.19
Installed capacity: Coal [MW]	53292	25.35
Installed capacity: CCGT [MW]	52222	24.84
Installed capacity: OCGT [MW]	34939	16.62
Total installed capacity: Storage units [MW]	0	0.00
Installed capacity: PHES [MW]	0	0.00
Installed capacity: Battery [MW]	0	0.00
Total installed energy [MWh]	0	0.00
Installed energy: PHES [MWh]	0	0.00
Installed energy: Battery [MWh]	0	0.00

Table 6: EO1 surplus

	Absolute [EUR]	Share of system total [%]
Total Surplus	4292170314831	100.00
Producer surplus	0	0.00
Storage surplus	0	0.00
Consumer surplus	4275319944071	99.61
Solar surplus	5043608049	0.12
Wind surplus	11806762711	0.28
Surplus: Nuclear	0	0.00
Surplus: Coal	0	0.00
Surplus: CCGT	0	0.00
Surplus: OCGT	0	0.00
Surplus: PHES	0	0.00
Surplus: Battery	0	0.00

Table 7: EO1 revenues

	Absolute [EUR]	Share of system total [%]
Total revenues	39291840486	100.00
Total capacity-based revenues	0	0.00
Total energy-based revenues	39291840486	100.00
Producers: Total revenues	39291840486	100.00
Storage units: Total revenues	0	0.00
Producers: Capacity-based revenues	0	0.00
Producers: Energy-based revenues	39291840486	100.00
Storage units: Capacity-based revenues	0	0.00
Storage units: Energy-based revenues	0	0.00
Nuclear: Total revenues	21186657258	53.92
Nuclear: Capacity-based revenues	0	0.00
Nuclear: Energy-based revenues	21186657258	53.92
Coal: Total revenues	12351108983	31.43
Coal: Capacity-based revenues	0	0.00
Coal: Energy-based revenues	12351108983	31.43
CCGT: Total revenues	4697826790	11.96
CCGT: Capacity-based revenues	0	0.00
CCGT: Energy-based revenues	4697826790	11.96
OCGT: Total revenues	1056247455	2.69
OCGT: Capacity-based revenues	0	0.00
OCGT: Energy-based revenues	1056247455	2.69
PHES: Total revenues	0	0.00
PHES: Capacity-based revenues	0	0.00
PHES: Energy-based revenues	0	0.00
Battery: Total revenues	0	0.00
Battery: Capacity-based revenues	0	0.00
Battery: Energy-based revenues	0	0.00

Table 8: EO1 misc

	Value	Unit
Load shedding	26547	MWh
Load shedding	0.00367904	% of total demand
Load shedding	4	number of hours

D.1.2 EO2: PHES

Table 9: EO2: Capacity

	Absolute	Share of system total [%]
Total installed capacity [MW]	210240	100.00
Total installed capacity: Producers [MW]	196153	93.30
Installed capacity: Nuclear [MW]	82933	39.45
Installed capacity: Coal [MW]	33934	16.14
Installed capacity: CCGT [MW]	44347	21.09
Installed capacity: OCGT [MW]	34939	16.62
Total installed capacity: Storage units [MW]	14087	6.70
Installed capacity: PHES [MW]	14087	6.70
Installed capacity: Battery [MW]	0	0.00
Total installed energy [MWh]	15000000	100.00
Installed energy: PHES [MWh]	15000000	100.00
Installed energy: Battery [MWh]	0	0.00

Table 10: EO2: Surplus

	Absolute [EUR]	Share of system total [%]
Total Surplus	4292267150445	100.00
Producer surplus	-1	0.00
Storage surplus	70273235	0.00
Consumer surplus	4275236287111	99.60
Solar surplus	5043245738	0.12
Wind surplus	11917344361	0.28
Surplus: Nuclear	-1	0.00
Surplus: Coal	1	0.00
Surplus: CCGT	0	0.00
Surplus: OCGT	0	0.00
Surplus: PHES	70273235	0.00
Surplus: Battery	0	0.00

Table 11: EO2: Revenues

	Absolute [EUR]	Share of system total [%]
Total revenues	39687193828	100.00
Total capacity-based revenues	0	0.00
Total energy-based revenues	39687193828	100.00
Producers: Total revenues	37573545848	94.67
Storage units: Total revenues	2113647981	5.33
Producers: Capacity-based revenues	0	0.00
Producers: Energy-based revenues	37573545848	94.67
Storage units: Capacity-based revenues	0	0.00
Storage units: Energy-based revenues	2113647981	5.33
Nuclear: Total revenues	25213120255	63.53
Nuclear: Capacity-based revenues	0	0.00
Nuclear: Energy-based revenues	25213120255	63.53
Coal: Total revenues	7714771351	19.44
Coal: Capacity-based revenues	0	0.00
Coal: Energy-based revenues	7714771351	19.44
CCGT: Total revenues	3589406786	9.04
CCGT: Capacity-based revenues	0	0.00
CCGT: Energy-based revenues	3589406786	9.04
OCGT: Total revenues	1056247455	2.66
OCGT: Capacity-based revenues	0	0.00
OCGT: Energy-based revenues	1056247455	2.66
PHES: Total revenues	2113647981	5.33
PHES: Capacity-based revenues	0	0.00
PHES: Energy-based revenues	2113647981	5.33
Battery: Total revenues	0	0.00
Battery: Capacity-based revenues	0	0.00
Battery: Energy-based revenues	0	0.00

Table 12: EO2: Misc

	Value	Unit
Load shedding	26547	MWh
Load shedding	0.00367904	% of total demand
Load shedding	4	number of hours

D.1.3 EO3: Battery

Table 13: EO3: Capacity

	Absolute	Share of system total [%]
Total installed capacity [MW]	210240	100.00
Total installed capacity: Producers [MW]	199338	94.81
Installed capacity: Nuclear [MW]	72434	34.45
Installed capacity: Coal [MW]	49296	23.45
Installed capacity: CCGT [MW]	48626	23.13
Installed capacity: OCGT [MW]	28982	13.79
Total installed capacity: Storage units [MW]	10902	5.19
Installed capacity: PHES [MW]	0	0.00
Installed capacity: Battery [MW]	10902	5.19
Total installed energy [MWh]	47651	100.00
Installed energy: PHES [MWh]	0	0.00
Installed energy: Battery [MWh]	47651	100.00

Table 14: EO3: Surplus

	Absolute [EUR]	Share of system total [%]
Total Surplus	4291953695330	100.00
Producer surplus	0	0.00
Storage surplus	0	0.00
Consumer surplus	4275279431202	99.61
Solar surplus	4958145640	0.12
Wind surplus	11716118489	0.27
Surplus: Nuclear	0	0.00
Surplus: Coal	0	0.00
Surplus: CCGT	0	0.00
Surplus: OCGT	0	0.00
Surplus: PHES	0	0.00
Surplus: Battery	0	0.00

Table 15: EO3: Revenues

	Absolute [EUR]	Share of system total [%]
Total revenues	39511403753	100.00
Total capacity-based revenues	0	0.00
Total energy-based revenues	39511403753	100.00
Producers: Total revenues	38605647199	97.71
Storage units: Total revenues	905756553	2.29
Producers: Capacity-based revenues	0	0.00
Producers: Energy-based revenues	38605647199	97.71
Storage units: Capacity-based revenues	0	0.00
Storage units: Energy-based revenues	905756553	2.29
Nuclear: Total revenues	22002616670	55.69
Nuclear: Capacity-based revenues	0	0.00
Nuclear: Energy-based revenues	22002616670	55.69
Coal: Total revenues	11368934266	28.77
Coal: Capacity-based revenues	0	0.00
Coal: Energy-based revenues	11368934266	28.77
CCGT: Total revenues	4320888907	10.94
CCGT: Capacity-based revenues	0	0.00
CCGT: Energy-based revenues	4320888907	10.94
OCGT: Total revenues	913207356	2.31
OCGT: Capacity-based revenues	0	0.00
OCGT: Energy-based revenues	913207356	2.31
PHES: Total revenues	0	0.00
PHES: Capacity-based revenues	0	0.00
PHES: Energy-based revenues	0	0.00
Battery: Total revenues	905756553	2.29
Battery: Capacity-based revenues	0	0.00
Battery: Energy-based revenues	905756553	2.29

Table 16: EO3: Misc

	Value	Unit
Load shedding	26547	MWh
Load shedding	0.00367904	% of total demand
Load shedding	4	number of hours

D.1.4 EO4: Battery, energy cost half

Table 17: EO4: Capacity

	Absolute	Share of system total [%]
Total installed capacity [MW]	210240	100.00
Total installed capacity: Producers [MW]	192008	91.33
Installed capacity: Nuclear [MW]	74238	35.31
Installed capacity: Coal [MW]	45298	21.55
Installed capacity: CCGT [MW]	48067	22.86
Installed capacity: OCGT [MW]	24405	11.61
Total installed capacity: Storage units [MW]	18231	8.67
Installed capacity: PHES [MW]	0	0.00
Installed capacity: Battery [MW]	18231	8.67
Total installed energy [MWh]	121296	100.00
Installed energy: PHES [MWh]	0	0.00
Installed energy: Battery [MWh]	121296	100.00

Table 18: EO4: Surplus

	Absolute [EUR]	Share of system total [%]
Total Surplus	4291823552745	100.00
Producer surplus	0	0.00
Storage surplus	0	0.00
Consumer surplus	4275180158555	99.61
Solar surplus	4877829787	0.11
Wind surplus	11765564403	0.27
Surplus: Nuclear	0	0.00
Surplus: Coal	0	0.00
Surplus: CCGT	0	0.00
Surplus: OCGT	0	0.00
Surplus: PHES	0	0.00
Surplus: Battery	0	0.00

Table 19: EO4: Revenues

	Absolute [EUR]	Share of system total [%]
Total revenues	39558371509	100.00
Total capacity-based revenues	0	0.00
Total energy-based revenues	39558371509	100.00
Producers: Total revenues	38078528466	96.26
Storage units: Total revenues	1479843042	3.74
Producers: Capacity-based revenues	0	0.00
Producers: Energy-based revenues	38078528466	96.26
Storage units: Capacity-based revenues	0	0.00
Storage units: Energy-based revenues	1479843042	3.74
Nuclear: Total revenues	22563028080	57.04
Nuclear: Capacity-based revenues	0	0.00
Nuclear: Energy-based revenues	22563028080	57.04
Coal: Total revenues	10470315883	26.47
Coal: Capacity-based revenues	0	0.00
Coal: Energy-based revenues	10470315883	26.47
CCGT: Total revenues	4256589752	10.76
CCGT: Capacity-based revenues	0	0.00
CCGT: Energy-based revenues	4256589752	10.76
OCGT: Total revenues	788594751	1.99
OCGT: Capacity-based revenues	0	0.00
OCGT: Energy-based revenues	788594751	1.99
PHES: Total revenues	0	0.00
PHES: Capacity-based revenues	0	0.00
PHES: Energy-based revenues	0	0.00
Battery: Total revenues	1479843042	3.74
Battery: Capacity-based revenues	0	0.00
Battery: Energy-based revenues	1479843042	3.74

Table 20: EO4: Misc

	Value	Unit
Load shedding	26547	MWh
Load shedding	0.00367904	% of total demand
Load shedding	4	number of hours

D.1.5 EO5: Battery, energy cost double

Table 21: EO5: Capacity

	Absolute	Share of system total [%]
Total installed capacity [MW]	210240	100.00
Total installed capacity: Producers [MW]	210240	100.00
Installed capacity: Nuclear [MW]	69786	33.19
Installed capacity: Coal [MW]	53292	25.35
Installed capacity: CCGT [MW]	52222	24.84
Installed capacity: OCGT [MW]	34939	16.62
Total installed capacity: Storage units [MW]	0	0.00
Installed capacity: PHES [MW]	0	0.00
Installed capacity: Battery [MW]	0	0.00
Total installed energy [MWh]	0	0.00
Installed energy: PHES [MWh]	0	0.00
Installed energy: Battery [MWh]	0	0.00

Table 22: EO5: Surplus

	Absolute [EUR]	Share of system total [%]
Total Surplus	4292170314831	100.00
Producer surplus	0	0.00
Storage surplus	0	0.00
Consumer surplus	4275319944071	99.61
Solar surplus	5043608049	0.12
Wind surplus	11806762711	0.28
Surplus: Nuclear	0	0.00
Surplus: Coal	0	0.00
Surplus: CCGT	0	0.00
Surplus: OCGT	0	0.00
Surplus: PHES	0	0.00
Surplus: Battery	0	0.00

Table 23: EO5: Revenues

	Absolute [EUR]	Share of system total [%]
Total revenues	39291840486	100.00
Total capacity-based revenues	0	0.00
Total energy-based revenues	39291840486	100.00
Producers: Total revenues	39291840486	100.00
Storage units: Total revenues	0	0.00
Producers: Capacity-based revenues	0	0.00
Producers: Energy-based revenues	39291840486	100.00
Storage units: Capacity-based revenues	0	0.00
Storage units: Energy-based revenues	0	0.00
Nuclear: Total revenues	21186658621	53.92
Nuclear: Capacity-based revenues	0	0.00
Nuclear: Energy-based revenues	21186658621	53.92
Coal: Total revenues	12351107626	31.43
Coal: Capacity-based revenues	0	0.00
Coal: Energy-based revenues	12351107626	31.43
CCGT: Total revenues	4697826784	11.96
CCGT: Capacity-based revenues	0	0.00
CCGT: Energy-based revenues	4697826784	11.96
OCGT: Total revenues	1056247455	2.69
OCGT: Capacity-based revenues	0	0.00
OCGT: Energy-based revenues	1056247455	2.69
PHES: Total revenues	0	0.00
PHES: Capacity-based revenues	0	0.00
PHES: Energy-based revenues	0	0.00
Battery: Total revenues	0	0.00
Battery: Capacity-based revenues	0	0.00
Battery: Energy-based revenues	0	0.00

Table 24: EO5: Misc

	Value	Unit
Load shedding	26547	MWh
Load shedding	0.00367904	% of total demand
Load shedding	4	number of hours

D.1.6 EO6: Battery, converter cost half

Table 25: EO6: Capacity

	Absolute	Share of system total [%]
Total installed capacity [MW]	211896	100.00
Total installed capacity: Producers [MW]	196628	92.79
Installed capacity: Nuclear [MW]	72912	34.41
Installed capacity: Coal [MW]	48388	22.84
Installed capacity: CCGT [MW]	47947	22.63
Installed capacity: OCGT [MW]	27380	12.92
Total installed capacity: Storage units [MW]	15268	7.21
Installed capacity: PHES [MW]	0	0.00
Installed capacity: Battery [MW]	15268	7.21
Total installed energy [MWh]	69288	100.00
Installed energy: PHES [MWh]	0	0.00
Installed energy: Battery [MWh]	69288	100.00

Table 26: MEO6: Surplus

	Absolute [EUR]	Share of system total [%]
Total Surplus	4291974550469	100.00
Producer surplus	0	0.00
Storage surplus	0	0.00
Consumer surplus	4275200266516	99.61
Solar surplus	4979144948	0.12
Wind surplus	11795139006	0.27
Surplus: Nuclear	0	0.00
Surplus: Coal	0	0.00
Surplus: CCGT	0	0.00
Surplus: OCGT	0	0.00
Surplus: PHES	0	0.00
Surplus: Battery	0	0.00

Table 27: EO6: Revenues

	Absolute [EUR]	Share of system total [%]
Total revenues	39485736966	100.00
Total capacity-based revenues	0	0.00
Total energy-based revenues	39485736966	100.00
Producers: Total revenues	38396771482	97.24
Storage units: Total revenues	1088965483	2.76
Producers: Capacity-based revenues	0	0.00
Producers: Energy-based revenues	38396771482	97.24
Storage units: Capacity-based revenues	0	0.00
Storage units: Energy-based revenues	1088965483	2.76
Nuclear: Total revenues	22153405257	56.10
Nuclear: Capacity-based revenues	0	0.00
Nuclear: Energy-based revenues	22153405257	56.10
Coal: Total revenues	11154034568	28.25
Coal: Capacity-based revenues	0	0.00
Coal: Energy-based revenues	11154034568	28.25
CCGT: Total revenues	4227160805	10.71
CCGT: Capacity-based revenues	0	0.00
CCGT: Energy-based revenues	4227160805	10.71
OCGT: Total revenues	862170853	2.18
OCGT: Capacity-based revenues	0	0.00
OCGT: Energy-based revenues	862170853	2.18
PHES: Total revenues	0	0.00
PHES: Capacity-based revenues	0	0.00
PHES: Energy-based revenues	0	0.00
Battery: Total revenues	1088965483	2.76
Battery: Capacity-based revenues	0	0.00
Battery: Energy-based revenues	1088965483	2.76

Table 28: EO6: Misc

	Value	Unit
Load shedding	20228	MWh
Load shedding	0.00280337	% of total demand
Load shedding	2	number of hours

D.1.7 EO7: Battery, converter cost double

Table 29: EO7: Capacity

	Absolute	Share of system total [%]
Total installed capacity [MW]	210240	100.00
Total installed capacity: Producers [MW]	210240	100.00
Installed capacity: Nuclear [MW]	69786	33.19
Installed capacity: Coal [MW]	53292	25.35
Installed capacity: CCGT [MW]	52222	24.84
Installed capacity: OCGT [MW]	34939	16.62
Total installed capacity: Storage units [MW]	0	0.00
Installed capacity: PHES [MW]	0	0.00
Installed capacity: Battery [MW]	0	0.00
Total installed energy [MWh]	0	0.00
Installed energy: PHES [MWh]	0	0.00
Installed energy: Battery [MWh]	0	0.00

Table 30: EO7: Surplus

	Absolute [EUR]	Share of system total [%]
Total Surplus	4292170314831	100.00
Producer surplus	0	0.00
Storage surplus	0	0.00
Consumer surplus	4275319944071	99.61
Solar surplus	5043608049	0.12
Wind surplus	11806762711	0.28
Surplus: Nuclear	0	0.00
Surplus: Coal	0	0.00
Surplus: CCGT	0	0.00
Surplus: OCGT	0	0.00
Surplus: PHES	0	0.00
Surplus: Battery	0	0.00

Table 31: EO7: Revenues

	Absolute [EUR]	Share of system total [%]
Total revenues	39291840486	100.00
Total capacity-based revenues	0	0.00
Total energy-based revenues	39291840486	100.00
Producers: Total revenues	39291840486	100.00
Storage units: Total revenues	0	0.00
Producers: Capacity-based revenues	0	0.00
Producers: Energy-based revenues	39291840486	100.00
Storage units: Capacity-based revenues	0	0.00
Storage units: Energy-based revenues	0	0.00
Nuclear: Total revenues	21186657006	53.92
Nuclear: Capacity-based revenues	0	0.00
Nuclear: Energy-based revenues	21186657006	53.92
Coal: Total revenues	12351109241	31.43
Coal: Capacity-based revenues	0	0.00
Coal: Energy-based revenues	12351109241	31.43
CCGT: Total revenues	4697826784	11.96
CCGT: Capacity-based revenues	0	0.00
CCGT: Energy-based revenues	4697826784	11.96
OCGT: Total revenues	1056247455	2.69
OCGT: Capacity-based revenues	0	0.00
OCGT: Energy-based revenues	1056247455	2.69
PHES: Total revenues	0	0.00
PHES: Capacity-based revenues	0	0.00
PHES: Energy-based revenues	0	0.00
Battery: Total revenues	0	0.00
Battery: Capacity-based revenues	0	0.00
Battery: Energy-based revenues	0	0.00

Table 32: EO7: Misc

	Value	Unit
Load shedding	26547	MWh
Load shedding	0.00367904	% of total demand
Load shedding	4	number of hours

D.1.8 EO8: Battery, fixed costs reduced by 50%

Table 33: EO8: Capacity

	Absolute	Share of system total [%]
Total installed capacity [MW]	214825	100.00
Total installed capacity: Producers [MW]	188315	87.66
Installed capacity: Nuclear [MW]	74650	34.75
Installed capacity: Coal [MW]	43902	20.44
Installed capacity: CCGT [MW]	49492	23.04
Installed capacity: OCGT [MW]	20272	9.44
Total installed capacity: Storage units [MW]	26510	12.34
Installed capacity: PHES [MW]	0	0.00
Installed capacity: Battery [MW]	26510	12.34
Total installed energy [MWh]	173726	100.00
Installed energy: PHES [MWh]	0	0.00
Installed energy: Battery [MWh]	173726	100.00

Table 34: EO8: Surplus

	Absolute [EUR]	Share of system total [%]
Total Surplus	4291864558747	100.00
Producer surplus	0	0.00
Storage surplus	0	0.00
Consumer surplus	4275190316030	99.61
Solar surplus	4856218430	0.11
Wind surplus	11818024288	0.28
Surplus: Nuclear	0	0.00
Surplus: Coal	0	0.00
Surplus: CCGT	0	0.00
Surplus: OCGT	0	0.00
Surplus: PHES	0	0.00
Surplus: Battery	0	0.00

Table 35: EO8: Revenues

	Absolute [EUR]	Share of system total [%]
Total revenues	39541655614	100.00
Total capacity-based revenues	0	0.00
Total energy-based revenues	39541655614	100.00
Producers: Total revenues	37791634105	95.57
Storage units: Total revenues	1750021509	4.43
Producers: Capacity-based revenues	0	0.00
Producers: Energy-based revenues	37791634105	95.57
Storage units: Capacity-based revenues	0	0.00
Storage units: Energy-based revenues	1750021509	4.43
Nuclear: Total revenues	22698332952	57.40
Nuclear: Capacity-based revenues	0	0.00
Nuclear: Energy-based revenues	22698332952	57.40
Coal: Total revenues	10180424281	25.75
Coal: Capacity-based revenues	0	0.00
Coal: Energy-based revenues	10180424281	25.75
CCGT: Total revenues	4277398118	10.82
CCGT: Capacity-based revenues	0	0.00
CCGT: Energy-based revenues	4277398118	10.82
OCGT: Total revenues	635478754	1.61
OCGT: Capacity-based revenues	0	0.00
OCGT: Energy-based revenues	635478754	1.61
PHES: Total revenues	0	0.00
PHES: Capacity-based revenues	0	0.00
PHES: Energy-based revenues	0	0.00
Battery: Total revenues	1750021509	4.43
Battery: Capacity-based revenues	0	0.00
Battery: Energy-based revenues	1750021509	4.43

Table 36: EO8: Misc

	Value	Unit
Load shedding	14369	MWh
Load shedding	0.00199139	% of total demand
Load shedding	2	number of hours

D.1.9 EO9: Battery, fixed costs reduced by 40%

Table 37: EO9: Capacity

	Absolute	Share of system total [%]
Total installed capacity [MW]	213372	100.00
Total installed capacity: Producers [MW]	191334	89.67
Installed capacity: Nuclear [MW]	74650	34.99
Installed capacity: Coal [MW]	44503	20.86
Installed capacity: CCGT [MW]	48632	22.79
Installed capacity: OCGT [MW]	23549	11.04
Total installed capacity: Storage units [MW]	22038	10.33
Installed capacity: PHES [MW]	0	0.00
Installed capacity: Battery [MW]	22038	10.33
Total installed energy [MWh]	132397	100.00
Installed energy: PHES [MWh]	0	0.00
Installed energy: Battery [MWh]	132397	100.00

Table 38: EO9: Surplus

	Absolute [EUR]	Share of system total [%]
Total Surplus	4291898148279	100.00
Producer surplus	0	0.00
Storage surplus	0	0.00
Consumer surplus	4275190399108	99.61
Solar surplus	4942782178	0.12
Wind surplus	11764966993	0.27
Surplus: Nuclear	0	0.00
Surplus: Coal	0	0.00
Surplus: CCGT	0	0.00
Surplus: OCGT	0	0.00
Surplus: PHES	0	0.00
Surplus: Battery	0	0.00

Table 39: EO9: Revenues

	Absolute [EUR]	Share of system total [%]
Total revenues	39544099776	100.00
Total capacity-based revenues	0	0.00
Total energy-based revenues	39544099776	100.00
Producers: Total revenues	37989551881	96.07
Storage units: Total revenues	1554547895	3.93
Producers: Capacity-based revenues	0	0.00
Producers: Energy-based revenues	37989551881	96.07
Storage units: Capacity-based revenues	0	0.00
Storage units: Energy-based revenues	1554547895	3.93
Nuclear: Total revenues	22689980405	57.38
Nuclear: Capacity-based revenues	0	0.00
Nuclear: Energy-based revenues	22689980405	57.38
Coal: Total revenues	10284844947	26.01
Coal: Capacity-based revenues	0	0.00
Coal: Energy-based revenues	10284844947	26.01
CCGT: Total revenues	4275089948	10.81
CCGT: Capacity-based revenues	0	0.00
CCGT: Energy-based revenues	4275089948	10.81
OCGT: Total revenues	739636581	1.87
OCGT: Capacity-based revenues	0	0.00
OCGT: Energy-based revenues	739636581	1.87
PHES: Total revenues	0	0.00
PHES: Capacity-based revenues	0	0.00
PHES: Energy-based revenues	0	0.00
Battery: Total revenues	1554547895	3.93
Battery: Capacity-based revenues	0	0.00
Battery: Energy-based revenues	1554547895	3.93

Table 40: EO9: Misc

	Value	Unit
Load shedding	17277	MWh
Load shedding	0.00239433	% of total demand
Load shedding	2	number of hours

D.1.10 EO10: Battery, fixed costs reduced by 30%

Table 41: EO10: Capacity

	Absolute	Share of system total [%]
Total installed capacity [MW]	211843	100.00
Total installed capacity: Producers [MW]	194302	91.72
Installed capacity: Nuclear [MW]	73943	34.90
Installed capacity: Coal [MW]	46154	21.79
Installed capacity: CCGT [MW]	47377	22.36
Installed capacity: OCGT [MW]	26829	12.66
Total installed capacity: Storage units [MW]	17541	8.28
Installed capacity: PHES [MW]	0	0.00
Installed capacity: Battery [MW]	17541	8.28
Total installed energy [MWh]	96824	100.00
Installed energy: PHES [MWh]	0	0.00
Installed energy: Battery [MWh]	96824	100.00

Table 42: EO10: Surplus

	Absolute [EUR]	Share of system total [%]
Total Surplus	4291894901987	100.00
Producer surplus	0	0.00
Storage surplus	0	0.00
Consumer surplus	4275174767413	99.61
Solar surplus	4942374284	0.12
Wind surplus	11777760290	0.27
Surplus: Nuclear	0	0.00
Surplus: Coal	0	0.00
Surplus: CCGT	0	0.00
Surplus: OCGT	0	0.00
Surplus: PHES	0	0.00
Surplus: Battery	0	0.00

Table 43: EO10: Revenues

	Absolute [EUR]	Share of system total [%]
Total revenues	39516195697	100.00
Total capacity-based revenues	0	0.00
Total energy-based revenues	39516195697	100.00
Producers: Total revenues	38203242399	96.68
Storage units: Total revenues	1312953298	3.32
Producers: Capacity-based revenues	0	0.00
Producers: Energy-based revenues	38203242399	96.68
Storage units: Capacity-based revenues	0	0.00
Storage units: Energy-based revenues	1312953298	3.32
Nuclear: Total revenues	22469716254	56.86
Nuclear: Capacity-based revenues	0	0.00
Nuclear: Energy-based revenues	22469716254	56.86
Coal: Total revenues	10651369209	26.95
Coal: Capacity-based revenues	0	0.00
Coal: Energy-based revenues	10651369209	26.95
CCGT: Total revenues	4221101732	10.68
CCGT: Capacity-based revenues	0	0.00
CCGT: Energy-based revenues	4221101732	10.68
OCGT: Total revenues	861055204	2.18
OCGT: Capacity-based revenues	0	0.00
OCGT: Energy-based revenues	861055204	2.18
PHES: Total revenues	0	0.00
PHES: Capacity-based revenues	0	0.00
PHES: Energy-based revenues	0	0.00
Battery: Total revenues	1312953298	3.32
Battery: Capacity-based revenues	0	0.00
Battery: Energy-based revenues	1312953298	3.32

Table 44: EO10: Misc

	Value	Unit
Load shedding	20335	MWh
Load shedding	0.00281817	% of total demand
Load shedding	2	number of hours

D.1.11 EO11: Battery, fixed costs reduced by 20%

Table 45: EO11: Capacity

	Absolute	Share of system total [%]
Total installed capacity [MW]	210572	100.00
Total installed capacity: Producers [MW]	195041	92.62
Installed capacity: Nuclear [MW]	73848	35.07
Installed capacity: Coal [MW]	46782	22.22
Installed capacity: CCGT [MW]	48270	22.92
Installed capacity: OCGT [MW]	26142	12.41
Total installed capacity: Storage units [MW]	15531	7.38
Installed capacity: PHES [MW]	0	0.00
Installed capacity: Battery [MW]	15531	7.38
Total installed energy [MWh]	85729	100.00
Installed energy: PHES [MWh]	0	0.00
Installed energy: Battery [MWh]	85729	100.00

Table 46: EO11: Surplus

	Absolute [EUR]	Share of system total [%]
Total Surplus	4291816812304	100.00
Producer surplus	0	0.00
Storage surplus	0	0.00
Consumer surplus	4275177624181	99.61
Solar surplus	4888430692	0.11
Wind surplus	11750757431	0.27
Surplus: Nuclear	0	0.00
Surplus: Coal	0	0.00
Surplus: CCGT	0	0.00
Surplus: OCGT	0	0.00
Surplus: PHES	0	0.00
Surplus: Battery	0	0.00

Table 47: EO11: Revenues

	Absolute [EUR]	Share of system total [%]
Total revenues	39544406344	100.00
Total capacity-based revenues	0	0.00
Total energy-based revenues	39544406344	100.00
Producers: Total revenues	38284144704	96.81
Storage units: Total revenues	1260261640	3.19
Producers: Capacity-based revenues	0	0.00
Producers: Energy-based revenues	38284144704	96.81
Storage units: Capacity-based revenues	0	0.00
Storage units: Energy-based revenues	1260261640	3.19
Nuclear: Total revenues	22438013667	56.74
Nuclear: Capacity-based revenues	0	0.00
Nuclear: Energy-based revenues	22438013667	56.74
Coal: Total revenues	10764963587	27.22
Coal: Capacity-based revenues	0	0.00
Coal: Energy-based revenues	10764963587	27.22
CCGT: Total revenues	4255591208	10.76
CCGT: Capacity-based revenues	0	0.00
CCGT: Energy-based revenues	4255591208	10.76
OCGT: Total revenues	825576243	2.09
OCGT: Capacity-based revenues	0	0.00
OCGT: Energy-based revenues	825576243	2.09
PHES: Total revenues	0	0.00
PHES: Capacity-based revenues	0	0.00
PHES: Energy-based revenues	0	0.00
Battery: Total revenues	1260261640	3.19
Battery: Capacity-based revenues	0	0.00
Battery: Energy-based revenues	1260261640	3.19

Table 48: EO11: Misc

	Value	Unit
Load shedding	25220	MWh
Load shedding	0.0034951	% of total demand
Load shedding	4	number of hours

D.1.12 EO12: Battery, fixed costs reduced by 10%

Table 49: EO12: Capacity

	Absolute	Share of system total [%]
Total installed capacity [MW]	210240	100.00
Total installed capacity: Producers [MW]	196931	93.67
Installed capacity: Nuclear [MW]	72966	34.71
Installed capacity: Coal [MW]	48476	23.06
Installed capacity: CCGT [MW]	48158	22.91
Installed capacity: OCGT [MW]	27332	13.00
Total installed capacity: Storage units [MW]	13308	6.33
Installed capacity: PHES [MW]	0	0.00
Installed capacity: Battery [MW]	13308	6.33
Total installed energy [MWh]	62683	100.00
Installed energy: PHES [MWh]	0	0.00
Installed energy: Battery [MWh]	62683	100.00

Table 50: EO12: Surplus

	Absolute [EUR]	Share of system total [%]
Total Surplus	4291896693479	100.00
Producer surplus	0	0.00
Storage surplus	0	0.00
Consumer surplus	4275229599202	99.61
Solar surplus	4933741027	0.11
Wind surplus	11733353250	0.27
Surplus: Nuclear	0	0.00
Surplus: Coal	0	0.00
Surplus: CCGT	0	0.00
Surplus: OCGT	0	0.00
Surplus: PHES	0	0.00
Surplus: Battery	0	0.00

Table 51: EO12: Revenues

	Absolute [EUR]	Share of system total [%]
Total revenues	39529688620	100.00
Total capacity-based revenues	0	0.00
Total energy-based revenues	39529688620	100.00
Producers: Total revenues	38454137366	97.28
Storage units: Total revenues	1075551254	2.72
Producers: Capacity-based revenues	0	0.00
Producers: Energy-based revenues	38454137366	97.28
Storage units: Capacity-based revenues	0	0.00
Storage units: Energy-based revenues	1075551254	2.72
Nuclear: Total revenues	22167322687	56.08
Nuclear: Capacity-based revenues	0	0.00
Nuclear: Energy-based revenues	22167322687	56.08
Coal: Total revenues	11160746858	28.23
Coal: Capacity-based revenues	0	0.00
Coal: Energy-based revenues	11160746858	28.23
CCGT: Total revenues	4255536327	10.77
CCGT: Capacity-based revenues	0	0.00
CCGT: Energy-based revenues	4255536327	10.77
OCGT: Total revenues	870531495	2.20
OCGT: Capacity-based revenues	0	0.00
OCGT: Energy-based revenues	870531495	2.20
PHES: Total revenues	0	0.00
PHES: Capacity-based revenues	0	0.00
PHES: Energy-based revenues	0	0.00
Battery: Total revenues	1075551254	2.72
Battery: Capacity-based revenues	0	0.00
Battery: Energy-based revenues	1075551254	2.72

Table 52: EO12: Misc

	Value	Unit
Load shedding	26547	MWh
Load shedding	0.00367904	% of total demand
Load shedding	4	number of hours

D.1.13 EO13: Battery, fixed costs increased by 10%

Table 53: EO13: Capacity

	Absolute	Share of system total [%]
Total installed capacity [MW]	210240	100.00
Total installed capacity: Producers [MW]	202617	96.37
Installed capacity: Nuclear [MW]	71824	34.16
Installed capacity: Coal [MW]	50470	24.01
Installed capacity: CCGT [MW]	49081	23.35
Installed capacity: OCGT [MW]	31243	14.86
Total installed capacity: Storage units [MW]	7623	3.63
Installed capacity: PHES [MW]	0	0.00
Installed capacity: Battery [MW]	7623	3.63
Total installed energy [MWh]	31280	100.00
Installed energy: PHES [MWh]	0	0.00
Installed energy: Battery [MWh]	31280	100.00

Table 54: EO13: Surplus

	Absolute [EUR]	Share of system total [%]
Total Surplus	4292001053736	100.00
Producer surplus	0	0.00
Storage surplus	0	0.00
Consumer surplus	4275284635370	99.61
Solar surplus	4983897524	0.12
Wind surplus	11732520841	0.27
Surplus: Nuclear	0	0.00
Surplus: Coal	0	0.00
Surplus: CCGT	0	0.00
Surplus: OCGT	0	0.00
Surplus: PHES	0	0.00
Surplus: Battery	0	0.00

Table 55: EO13: Revenues

	Absolute [EUR]	Share of system total [%]
Total revenues	39464176546	100.00
Total capacity-based revenues	0	0.00
Total energy-based revenues	39464176546	100.00
Producers: Total revenues	38806897287	98.33
Storage units: Total revenues	657279259	1.67
Producers: Capacity-based revenues	0	0.00
Producers: Energy-based revenues	38806897287	98.33
Storage units: Capacity-based revenues	0	0.00
Storage units: Energy-based revenues	657279259	1.67
Nuclear: Total revenues	21813028902	55.27
Nuclear: Capacity-based revenues	0	0.00
Nuclear: Energy-based revenues	21813028902	55.27
Coal: Total revenues	11640396322	29.50
Coal: Capacity-based revenues	0	0.00
Coal: Energy-based revenues	11640396322	29.50
CCGT: Total revenues	4376946222	11.09
CCGT: Capacity-based revenues	0	0.00
CCGT: Energy-based revenues	4376946222	11.09
OCGT: Total revenues	976525842	2.47
OCGT: Capacity-based revenues	0	0.00
OCGT: Energy-based revenues	976525842	2.47
PHES: Total revenues	0	0.00
PHES: Capacity-based revenues	0	0.00
PHES: Energy-based revenues	0	0.00
Battery: Total revenues	657279259	1.67
Battery: Capacity-based revenues	0	0.00
Battery: Energy-based revenues	657279259	1.67

Table 56: EO13: Misc

	Value	Unit
Load shedding	26547	MWh
Load shedding	0.00367904	% of total demand
Load shedding	4	number of hours

D.1.14 EO14: Battery, fixed costs increased by 20%

Table 57: EO14: Capacity

	Absolute	Share of system total [%]
Total installed capacity [MW]	210240	100.00
Total installed capacity: Producers [MW]	206369	98.16
Installed capacity: Nuclear [MW]	71072	33.81
Installed capacity: Coal [MW]	51750	24.61
Installed capacity: CCGT [MW]	50839	24.18
Installed capacity: OCGT [MW]	32707	15.56
Total installed capacity: Storage units [MW]	3871	1.84
Installed capacity: PHES [MW]	0	0.00
Installed capacity: Battery [MW]	3871	1.84
Total installed energy [MWh]	15485	100.00
Installed energy: PHES [MWh]	0	0.00
Installed energy: Battery [MWh]	15485	100.00

Table 58: EO14: Surplus

	Absolute [EUR]	Share of system total [%]
Total Surplus	4292058711859	100.00
Producer surplus	0	0.00
Storage surplus	0	0.00
Consumer surplus	4275296030346	99.61
Solar surplus	4997915357	0.12
Wind surplus	11764766156	0.27
Surplus: Nuclear	0	0.00
Surplus: Coal	0	0.00
Surplus: CCGT	0	0.00
Surplus: OCGT	0	0.00
Surplus: PHES	0	0.00
Surplus: Battery	0	0.00

Table 59: EO14: Revenues

	Absolute [EUR]	Share of system total [%]
Total revenues	39391481923	100.00
Total capacity-based revenues	0	0.00
Total energy-based revenues	39391481923	100.00
Producers: Total revenues	39035774581	99.10
Storage units: Total revenues	355707342	0.90
Producers: Capacity-based revenues	0	0.00
Producers: Energy-based revenues	39035774581	99.10
Storage units: Capacity-based revenues	0	0.00
Storage units: Energy-based revenues	355707342	0.90
Nuclear: Total revenues	21580277810	54.78
Nuclear: Capacity-based revenues	0	0.00
Nuclear: Energy-based revenues	21580277810	54.78
Coal: Total revenues	11942931251	30.32
Coal: Capacity-based revenues	0	0.00
Coal: Energy-based revenues	11942931251	30.32
CCGT: Total revenues	4519193463	11.47
CCGT: Capacity-based revenues	0	0.00
CCGT: Energy-based revenues	4519193463	11.47
OCGT: Total revenues	993372057	2.52
OCGT: Capacity-based revenues	0	0.00
OCGT: Energy-based revenues	993372057	2.52
PHES: Total revenues	0	0.00
PHES: Capacity-based revenues	0	0.00
PHES: Energy-based revenues	0	0.00
Battery: Total revenues	355707342	0.90
Battery: Capacity-based revenues	0	0.00
Battery: Energy-based revenues	355707342	0.90

Table 60: EO14: Misc

	Value	Unit
Load shedding	26547	MWh
Load shedding	0.00367904	% of total demand
Load shedding	4	number of hours

D.1.15 EO15: Battery, fixed costs increased by 30%

Table 61: EO15: Capacity

	Absolute	Share of system total [%]
Total installed capacity [MW]	210240	100.00
Total installed capacity: Producers [MW]	208650	99.24
Installed capacity: Nuclear [MW]	70552	33.56
Installed capacity: Coal [MW]	52464	24.95
Installed capacity: CCGT [MW]	51998	24.73
Installed capacity: OCGT [MW]	33637	16.00
Total installed capacity: Storage units [MW]	1590	0.76
Installed capacity: PHES [MW]	0	0.00
Installed capacity: Battery [MW]	1590	0.76
Total installed energy [MWh]	6361	100.00
Installed energy: PHES [MWh]	0	0.00
Installed energy: Battery [MWh]	6361	100.00

Table 62: EO15: Surplus

	Absolute [EUR]	Share of system total [%]
Total Surplus	4292157046545	100.00
Producer surplus	0	0.00
Storage surplus	0	0.00
Consumer surplus	4275307933477	99.61
Solar surplus	5052120582	0.12
Wind surplus	11796992486	0.27
Surplus: Nuclear	0	0.00
Surplus: Coal	0	0.00
Surplus: CCGT	0	0.00
Surplus: OCGT	0	0.00
Surplus: PHES	0	0.00
Surplus: Battery	0	0.00

Table 63: EO15: Revenues

	Absolute [EUR]	Share of system total [%]
Total revenues	39338259085	100.00
Total capacity-based revenues	0	0.00
Total energy-based revenues	39338259085	100.00
Producers: Total revenues	39183104165	99.61
Storage units: Total revenues	155154921	0.39
Producers: Capacity-based revenues	0	0.00
Producers: Energy-based revenues	39183104165	99.61
Storage units: Capacity-based revenues	0	0.00
Storage units: Energy-based revenues	155154921	0.39
Nuclear: Total revenues	21419403034	54.45
Nuclear: Capacity-based revenues	0	0.00
Nuclear: Energy-based revenues	21419403034	54.45
Coal: Total revenues	12120937257	30.81
Coal: Capacity-based revenues	0	0.00
Coal: Energy-based revenues	12120937257	30.81
CCGT: Total revenues	4634785915	11.78
CCGT: Capacity-based revenues	0	0.00
CCGT: Energy-based revenues	4634785915	11.78
OCGT: Total revenues	1007977958	2.56
OCGT: Capacity-based revenues	0	0.00
OCGT: Energy-based revenues	1007977958	2.56
PHES: Total revenues	0	0.00
PHES: Capacity-based revenues	0	0.00
PHES: Energy-based revenues	0	0.00
Battery: Total revenues	155154921	0.39
Battery: Capacity-based revenues	0	0.00
Battery: Energy-based revenues	155154921	0.39

Table 64: EO15: Misc

	Value	Unit
Load shedding	26547	MWh
Load shedding	0.00367904	% of total demand
Load shedding	4	number of hours

D.1.16 EO16: Battery, fixed costs increased by 40%

Table 65: EO16: Capacity

	Absolute	Share of system total [%]
Total installed capacity [MW]	210240	100.00
Total installed capacity: Producers [MW]	210240	100.00
Installed capacity: Nuclear [MW]	69786	33.19
Installed capacity: Coal [MW]	53292	25.35
Installed capacity: CCGT [MW]	52222	24.84
Installed capacity: OCGT [MW]	34939	16.62
Total installed capacity: Storage units [MW]	0	0.00
Installed capacity: PHES [MW]	0	0.00
Installed capacity: Battery [MW]	0	0.00
Total installed energy [MWh]	0	0.00
Installed energy: PHES [MWh]	0	0.00
Installed energy: Battery [MWh]	0	0.00

Table 66: EO16: Surplus

	Absolute [EUR]	Share of system total [%]
Total Surplus	4292170314831	100.00
Producer surplus	0	0.00
Storage surplus	0	0.00
Consumer surplus	4275319944071	99.61
Solar surplus	5043608049	0.12
Wind surplus	11806762711	0.28
Surplus: Nuclear	0	0.00
Surplus: Coal	0	0.00
Surplus: CCGT	0	0.00
Surplus: OCGT	0	0.00
Surplus: PHES	0	0.00
Surplus: Battery	0	0.00

Table 67: EO16: Revenues

	Absolute [EUR]	Share of system total [%]
Total revenues	39291840486	100.00
Total capacity-based revenues	0	0.00
Total energy-based revenues	39291840486	100.00
Producers: Total revenues	39291840486	100.00
Storage units: Total revenues	0	0.00
Producers: Capacity-based revenues	0	0.00
Producers: Energy-based revenues	39291840486	100.00
Storage units: Capacity-based revenues	0	0.00
Storage units: Energy-based revenues	0	0.00
Nuclear: Total revenues	21186657042	53.92
Nuclear: Capacity-based revenues	0	0.00
Nuclear: Energy-based revenues	21186657042	53.92
Coal: Total revenues	12351109205	31.43
Coal: Capacity-based revenues	0	0.00
Coal: Energy-based revenues	12351109205	31.43
CCGT: Total revenues	4697826784	11.96
CCGT: Capacity-based revenues	0	0.00
CCGT: Energy-based revenues	4697826784	11.96
OCGT: Total revenues	1056247455	2.69
OCGT: Capacity-based revenues	0	0.00
OCGT: Energy-based revenues	1056247455	2.69
PHES: Total revenues	0	0.00
PHES: Capacity-based revenues	0	0.00
PHES: Energy-based revenues	0	0.00
Battery: Total revenues	0	0.00
Battery: Capacity-based revenues	0	0.00
Battery: Energy-based revenues	0	0.00

Table 68: EO16: Misc

	Value	Unit
Load shedding	26547	MWh
Load shedding	0.00367904	% of total demand
Load shedding	4	number of hours

D.1.17 EO17: PHES, fixed costs increased by 10%

Table 69: EO17: Capacity

	Absolute	Share of system total [%]
Total installed capacity [MW]	210240	100.00
Total installed capacity: Producers [MW]	210240	100.00
Installed capacity: Nuclear [MW]	69786	33.19
Installed capacity: Coal [MW]	53292	25.35
Installed capacity: CCGT [MW]	52222	24.84
Installed capacity: OCGT [MW]	34939	16.62
Total installed capacity: Storage units [MW]	0	0.00
Installed capacity: PHES [MW]	0	0.00
Installed capacity: Battery [MW]	0	0.00
Total installed energy [MWh]	15000000	100.00
Installed energy: PHES [MWh]	15000000	100.00
Installed energy: Battery [MWh]	0	0.00

Table 70: EO17: Surplus

	Absolute [EUR]	Share of system total [%]
Total Surplus	4292170314831	100.00
Producer surplus	0	0.00
Storage surplus	0	0.00
Consumer surplus	4275319944071	99.61
Solar surplus	5043608049	0.12
Wind surplus	11806762711	0.28
Surplus: Nuclear	0	0.00
Surplus: Coal	0	0.00
Surplus: CCGT	0	0.00
Surplus: OCGT	0	0.00
Surplus: PHES	0	0.00
Surplus: Battery	0	0.00

Table 71: EO17: Revenues

	Absolute [EUR]	Share of system total [%]
Total revenues	39291840486	100.00
Total capacity-based revenues	0	0.00
Total energy-based revenues	39291840486	100.00
Producers: Total revenues	39291840486	100.00
Storage units: Total revenues	0	0.00
Producers: Capacity-based revenues	0	0.00
Producers: Energy-based revenues	39291840486	100.00
Storage units: Capacity-based revenues	0	0.00
Storage units: Energy-based revenues	0	0.00
Nuclear: Total revenues	21186657248	53.92
Nuclear: Capacity-based revenues	0	0.00
Nuclear: Energy-based revenues	21186657248	53.92
Coal: Total revenues	12351108999	31.43
Coal: Capacity-based revenues	0	0.00
Coal: Energy-based revenues	12351108999	31.43
CCGT: Total revenues	4697826784	11.96
CCGT: Capacity-based revenues	0	0.00
CCGT: Energy-based revenues	4697826784	11.96
OCGT: Total revenues	1056247455	2.69
OCGT: Capacity-based revenues	0	0.00
OCGT: Energy-based revenues	1056247455	2.69
PHES: Total revenues	0	0.00
PHES: Capacity-based revenues	0	0.00
PHES: Energy-based revenues	0	0.00
Battery: Total revenues	0	0.00
Battery: Capacity-based revenues	0	0.00
Battery: Energy-based revenues	0	0.00

Table 72: EO17: Misc

	Value	Unit
Load shedding	26547	MWh
Load shedding	0.00367904	% of total demand
Load shedding	4	number of hours

D.2 Strategic Reserves Model

D.2.1 SR1: No Storage

Table 73: SR1: Capacity

	Absolute	Share of system total [%]
Total installed capacity [MW]	255219	100.00
Total installed capacity: Producers [MW]	255219	100.00
Installed capacity: Nuclear [MW]	69786	27.34
Installed capacity: Coal [MW]	53292	20.88
Installed capacity: CCGT [MW]	52222	20.46
Installed capacity: OCGT [MW]	79918	31.31
Total installed capacity: Storage units [MW]	0	0.00
Installed capacity: PHES [MW]	0	0.00
Installed capacity: Battery [MW]	0	0.00
Total installed energy [MWh]	0	0.00
Installed energy: PHES [MWh]	0	0.00
Installed energy: Battery [MWh]	0	0.00

Table 74: SR1: Surplus

	Absolute [EUR]	Share of system total [%]
Total Surplus	4291450748664	100.00
Producer surplus	0	0.00
Storage surplus	0	0.00
Consumer surplus	4274600317863	99.61
Solar surplus	5043681322	0.12
Wind surplus	11806749479	0.28
Surplus: Nuclear	0	0.00
Surplus: Coal	0	0.00
Surplus: CCGT	0	0.00
Surplus: OCGT	0	0.00
Surplus: PHES	0	0.00
Surplus: Battery	0	0.00

Table 75: SR1: Revenues

	Absolute [EUR]	Share of system total [%]
Total revenues	40011499544	100.00
Total capacity-based revenues	719659057	1.80
Total energy-based revenues	39291840486	98.20
Producers: Total revenues	40011499544	100.00
Storage units: Total revenues	0	0.00
Producers: Capacity-based revenues	719659057	1.80
Producers: Energy-based revenues	39291840486	98.20
Storage units: Capacity-based revenues	0	0.00
Storage units: Energy-based revenues	0	0.00
Nuclear: Total revenues	21186657230	52.95
Nuclear: Capacity-based revenues	0	0.00
Nuclear: Energy-based revenues	21186657230	52.95
Coal: Total revenues	12351109017	30.87
Coal: Capacity-based revenues	0	0.00
Coal: Energy-based revenues	12351109017	30.87
CCGT: Total revenues	4697826784	11.74
CCGT: Capacity-based revenues	0	0.00
CCGT: Energy-based revenues	4697826784	11.74
OCGT: Total revenues	1775906513	4.44
OCGT: Capacity-based revenues	719659057	1.80
OCGT: Energy-based revenues	1056247455	2.64
PHES: Total revenues	0	0.00
PHES: Capacity-based revenues	0	0.00
PHES: Energy-based revenues	0	0.00
Battery: Total revenues	0	0.00
Battery: Capacity-based revenues	0	0.00
Battery: Energy-based revenues	0	0.00

Table 76: SR1: Misc

	Value	Unit
Load shedding	0	MWh
Load shedding	0	% of total demand
Load shedding	0	number of hours
SR generation	26547	MWh
SR generation	0.00367904	% of total demand
SR generation	4	number of hours
CRM price	16000	EUR
Capacity demand	44979	MW
Offered capacity: Total	44979	MW
Offered capacity: Nuclear	0	MW
Offered capacity: Coal	0	MW
Offered capacity: CCGT	0	MW
Offered capacity: OCGT	44979	MW
Offered capacity: PHES	0	MW
Offered capacity: Battery	0	MW

D.2.2 SR2: PHES without CRM participation

Table 77: SR2: Capacity

	Absolute	Share of system total [%]
Total installed capacity [MW]	269308	100.00
Total installed capacity: Producers [MW]	255219	94.77
Installed capacity: Nuclear [MW]	82936	30.80
Installed capacity: Coal [MW]	33923	12.60
Installed capacity: CCGT [MW]	44353	16.47
Installed capacity: OCGT [MW]	94007	34.91
Total installed capacity: Storage units [MW]	14090	5.23
Installed capacity: PHES [MW]	14090	5.23
Installed capacity: Battery [MW]	0	0.00
Total installed energy [MWh]	15000000	100.00
Installed energy: PHES [MWh]	15000000	100.00
Installed energy: Battery [MWh]	0	0.00

Table 78: SR2: Surplus

	Absolute [EUR]	Share of system total [%]
Total Surplus	4291322240119	100.00
Producer surplus	4	0.00
Storage surplus	70234250	0.00
Consumer surplus	4274291337392	99.60
Solar surplus	5043362992	0.12
Wind surplus	11917305481	0.28
Surplus: Nuclear	6	0.00
Surplus: Coal	-2	0.00
Surplus: CCGT	0	0.00
Surplus: OCGT	0	0.00
Surplus: PHES	70234250	0.00
Surplus: Battery	0	0.00

Table 79: SR2: Revenues

	Absolute [EUR]	Share of system total [%]
Total revenues	40632705599	100.00
Total capacity-based revenues	945093207	2.33
Total energy-based revenues	39687612391	97.67
Producers: Total revenues	38518312113	94.80
Storage units: Total revenues	2114393486	5.20
Producers: Capacity-based revenues	945093207	2.33
Producers: Energy-based revenues	37573218906	92.47
Storage units: Capacity-based revenues	0	0.00
Storage units: Energy-based revenues	2114393486	5.20
Nuclear: Total revenues	25213996961	62.05
Nuclear: Capacity-based revenues	0	0.00
Nuclear: Energy-based revenues	25213996961	62.05
Coal: Total revenues	7712841730	18.98
Coal: Capacity-based revenues	0	0.00
Coal: Energy-based revenues	7712841730	18.98
CCGT: Total revenues	3590132760	8.84
CCGT: Capacity-based revenues	0	0.00
CCGT: Energy-based revenues	3590132760	8.84
OCGT: Total revenues	2001340662	4.93
OCGT: Capacity-based revenues	945093207	2.33
OCGT: Energy-based revenues	1056247455	2.60
PHES: Total revenues	2114393486	5.20
PHES: Capacity-based revenues	0	0.00
PHES: Energy-based revenues	2114393486	5.20
Battery: Total revenues	0	0.00
Battery: Capacity-based revenues	0	0.00
Battery: Energy-based revenues	0	0.00

Table 80: SR2: Misc

	Value	Unit
Load shedding	0	MWh
Load shedding	0	% of total demand
Load shedding	0	number of hours
SR generation	26547	MWh
SR generation	0.00367904	% of total demand
SR generation	4	number of hours
CRM price	16000	EUR
Capacity demand	59068	MW
Offered capacity: Total	59068	MW
Offered capacity: Nuclear	0	MW
Offered capacity: Coal	0	MW
Offered capacity: CCGT	0	MW
Offered capacity: OCGT	59068	MW
Offered capacity: PHES	0	MW
Offered capacity: Battery	0	MW

D.2.3 SR3: Battery without CRM participation

Table 81: SR3: Capacity

	Absolute	Share of system total [%]
Total installed capacity [MW]	266121	100.00
Total installed capacity: Producers [MW]	255219	95.90
Installed capacity: Nuclear [MW]	72434	27.22
Installed capacity: Coal [MW]	49296	18.52
Installed capacity: CCGT [MW]	48626	18.27
Installed capacity: OCGT [MW]	84863	31.89
Total installed capacity: Storage units [MW]	10902	4.10
Installed capacity: PHES [MW]	0	0.00
Installed capacity: Battery [MW]	10902	4.10
Total installed energy [MWh]	47651	100.00
Installed energy: PHES [MWh]	0	0.00
Installed energy: Battery [MWh]	47651	100.00

Table 82: SR3: Surplus

	Absolute [EUR]	Share of system total [%]
Total Surplus	4291059693810	100.00
Producer surplus	0	0.00
Storage surplus	0	0.00
Consumer surplus	4274385369641	99.61
Solar surplus	4958218912	0.12
Wind surplus	11716105257	0.27
Surplus: Nuclear	0	0.00
Surplus: Coal	0	0.00
Surplus: CCGT	0	0.00
Surplus: OCGT	0	0.00
Surplus: PHES	0	0.00
Surplus: Battery	0	0.00

Table 83: SR3: Revenues

	Absolute [EUR]	Share of system total [%]
Total revenues	40405498164	100.00
Total capacity-based revenues	894094411	2.21
Total energy-based revenues	39511403753	97.79
Producers: Total revenues	39499741611	97.76
Storage units: Total revenues	905756553	2.24
Producers: Capacity-based revenues	894094411	2.21
Producers: Energy-based revenues	38605647199	95.55
Storage units: Capacity-based revenues	0	0.00
Storage units: Energy-based revenues	905756553	2.24
Nuclear: Total revenues	22002616670	54.45
Nuclear: Capacity-based revenues	0	0.00
Nuclear: Energy-based revenues	22002616670	54.45
Coal: Total revenues	11368934266	28.14
Coal: Capacity-based revenues	0	0.00
Coal: Energy-based revenues	11368934266	28.14
CCGT: Total revenues	4320888907	10.69
CCGT: Capacity-based revenues	0	0.00
CCGT: Energy-based revenues	4320888907	10.69
OCGT: Total revenues	1807301768	4.47
OCGT: Capacity-based revenues	894094411	2.21
OCGT: Energy-based revenues	913207356	2.26
PHES: Total revenues	0	0.00
PHES: Capacity-based revenues	0	0.00
PHES: Energy-based revenues	0	0.00
Battery: Total revenues	905756553	2.24
Battery: Capacity-based revenues	0	0.00
Battery: Energy-based revenues	905756553	2.24

Table 84: SR3: Misc

	Value	Unit
Load shedding	0	MWh
Load shedding	0	% of total demand
Load shedding	0	number of hours
SR generation	26547	MWh
SR generation	0.00367904	% of total demand
SR generation	4	number of hours
CRM price	16000	EUR
Capacity demand	55881	MW
Offered capacity: Total	55881	MW
Offered capacity: Nuclear	0	MW
Offered capacity: Coal	0	MW
Offered capacity: CCGT	0	MW
Offered capacity: OCGT	55881	MW
Offered capacity: PHES	0	MW
Offered capacity: Battery	0	MW

D.2.4 SR4: PHES with CRM participation

Table 85: SR4: Capacity

	Absolute	Share of system total [%]
Total installed capacity [MW]	255219	100.00
Total installed capacity: Producers [MW]	241132	94.48
Installed capacity: Nuclear [MW]	82933	32.49
Installed capacity: Coal [MW]	33934	13.30
Installed capacity: CCGT [MW]	44347	17.38
Installed capacity: OCGT [MW]	79918	31.31
Total installed capacity: Storage units [MW]	14087	5.52
Installed capacity: PHES [MW]	14087	5.52
Installed capacity: Battery [MW]	0	0.00
Total installed energy [MWh]	15000000	100.00
Installed energy: PHES [MWh]	15000000	100.00
Installed energy: Battery [MWh]	0	0.00

Table 86: SR4: Surplus

	Absolute [EUR]	Share of system total [%]
Total Surplus	4291547523819	100.00
Producer surplus	0	0.00
Storage surplus	70300152	0.00
Consumer surplus	4274516585364	99.60
Solar surplus	5043290581	0.12
Wind surplus	11917347722	0.28
Surplus: Nuclear	0	0.00
Surplus: Coal	0	0.00
Surplus: CCGT	0	0.00
Surplus: OCGT	0	0.00
Surplus: PHES	70300152	0.00
Surplus: Battery	0	0.00

Table 87: SR4: Revenues

	Absolute [EUR]	Share of system total [%]
Total revenues	40406869489	100.00
Total capacity-based revenues	719659057	1.78
Total energy-based revenues	39687210431	98.22
Producers: Total revenues	38293204906	94.77
Storage units: Total revenues	2113664583	5.23
Producers: Capacity-based revenues	719659057	1.78
Producers: Energy-based revenues	37573545848	92.99
Storage units: Capacity-based revenues	0	0.00
Storage units: Energy-based revenues	2113664583	5.23
Nuclear: Total revenues	25213120256	62.40
Nuclear: Capacity-based revenues	0	0.00
Nuclear: Energy-based revenues	25213120256	62.40
Coal: Total revenues	7714771350	19.09
Coal: Capacity-based revenues	0	0.00
Coal: Energy-based revenues	7714771350	19.09
CCGT: Total revenues	3589406786	8.88
CCGT: Capacity-based revenues	0	0.00
CCGT: Energy-based revenues	3589406786	8.88
OCGT: Total revenues	1775906513	4.40
OCGT: Capacity-based revenues	719659057	1.78
OCGT: Energy-based revenues	1056247455	2.61
PHES: Total revenues	2113664583	5.23
PHES: Capacity-based revenues	0	0.00
PHES: Energy-based revenues	2113664583	5.23
Battery: Total revenues	0	0.00
Battery: Capacity-based revenues	0	0.00
Battery: Energy-based revenues	0	0.00

Table 88: SR4: Misc

	Value	Unit
Load shedding	0	MWh
Load shedding	0	% of total demand
Load shedding	0	number of hours
SR generation	26547	MWh
SR generation	0.00367904	% of total demand
SR generation	4	number of hours
CRM price	16000	EUR
Capacity demand	44979	MW
Offered capacity: Total	44979	MW
Offered capacity: Nuclear	0	MW
Offered capacity: Coal	0	MW
Offered capacity: CCGT	0	MW
Offered capacity: OCGT	44979	MW
Offered capacity: PHES	0	MW
Offered capacity: Battery	0	MW

D.2.5 SR5: Battery with CRM participation

Table 89: SR5: Capacity

	Absolute	Share of system total [%]
Total installed capacity [MW]	255219	100.00
Total installed capacity: Producers [MW]	244316	95.73
Installed capacity: Nuclear [MW]	72434	28.38
Installed capacity: Coal [MW]	49296	19.32
Installed capacity: CCGT [MW]	48626	19.05
Installed capacity: OCGT [MW]	73961	28.98
Total installed capacity: Storage units [MW]	10902	4.27
Installed capacity: PHES [MW]	0	0.00
Installed capacity: Battery [MW]	10902	4.27
Total installed energy [MWh]	47651	100.00
Installed energy: PHES [MWh]	0	0.00
Installed energy: Battery [MWh]	47651	100.00

Table 90: SR5: Surplus

	Absolute [EUR]	Share of system total [%]
Total Surplus	4291234129163	100.00
Producer surplus	0	0.00
Storage surplus	0	0.00
Consumer surplus	4274559804995	99.61
Solar surplus	4958218912	0.12
Wind surplus	11716105257	0.27
Surplus: Nuclear	0	0.00
Surplus: Coal	0	0.00
Surplus: CCGT	0	0.00
Surplus: OCGT	0	0.00
Surplus: PHES	0	0.00
Surplus: Battery	0	0.00

Table 91: SR5: Revenues

	Absolute [EUR]	Share of system total [%]
Total revenues	40231062810	100.00
Total capacity-based revenues	719659057	1.79
Total energy-based revenues	39511403753	98.21
Producers: Total revenues	39325306257	97.75
Storage units: Total revenues	905756553	2.25
Producers: Capacity-based revenues	719659057	1.79
Producers: Energy-based revenues	38605647199	95.96
Storage units: Capacity-based revenues	0	0.00
Storage units: Energy-based revenues	905756553	2.25
Nuclear: Total revenues	22002616670	54.69
Nuclear: Capacity-based revenues	0	0.00
Nuclear: Energy-based revenues	22002616670	54.69
Coal: Total revenues	11368934266	28.26
Coal: Capacity-based revenues	0	0.00
Coal: Energy-based revenues	11368934266	28.26
CCGT: Total revenues	4320888907	10.74
CCGT: Capacity-based revenues	0	0.00
CCGT: Energy-based revenues	4320888907	10.74
OCGT: Total revenues	1632866414	4.06
OCGT: Capacity-based revenues	719659057	1.79
OCGT: Energy-based revenues	913207356	2.27
PHES: Total revenues	0	0.00
PHES: Capacity-based revenues	0	0.00
PHES: Energy-based revenues	0	0.00
Battery: Total revenues	905756553	2.25
Battery: Capacity-based revenues	0	0.00
Battery: Energy-based revenues	905756553	2.25

Table 92: SR5: Misc

	Value	Unit
Load shedding	0	MWh
Load shedding	0	% of total demand
Load shedding	0	number of hours
SR generation	26547	MWh
SR generation	0.00367904	% of total demand
SR generation	4	number of hours
CRM price	16000	EUR
Capacity demand	44979	MW
Offered capacity: Total	44979	MW
Offered capacity: Nuclear	0	MW
Offered capacity: Coal	0	MW
Offered capacity: CCGT	0	MW
Offered capacity: OCGT	44979	MW
Offered capacity: PHES	0	MW
Offered capacity: Battery	0	MW

D.3 Capacity-Based Capacity Market Model

D.3.1 CM1: No Storage

Table 93: CM1: Capacity

	Absolute	Share of system total [%]
Total installed capacity [MW]	255219	100.00
Total installed capacity: Producers [MW]	255219	100.00
Installed capacity: Nuclear [MW]	69786	27.34
Installed capacity: Coal [MW]	53292	20.88
Installed capacity: CCGT [MW]	52222	20.46
Installed capacity: OCGT [MW]	79918	31.31
Total installed capacity: Storage units [MW]	0	0.00
Installed capacity: PHES [MW]	0	0.00
Installed capacity: Battery [MW]	0	0.00
Total installed energy [MWh]	0	0.00
Installed energy: PHES [MWh]	0	0.00
Installed energy: Battery [MWh]	0	0.00

Table 94: CM1: Surplus

	Absolute [EUR]	Share of system total [%]
Total Surplus	4291280476299	100.00
Producer surplus	0	0.00
Storage surplus	0	0.00
Consumer surplus	4274852100413	99.62
Solar surplus	4783129608	0.11
Wind surplus	11645246279	0.27
Surplus: Nuclear	0	0.00
Surplus: Coal	0	0.00
Surplus: CCGT	0	0.00
Surplus: OCGT	0	0.00
Surplus: PHES	0	0.00
Surplus: Battery	0	0.00

Table 95: CM1: Revenues

	Absolute [EUR]	Share of system total [%]
Total revenues	40015481578	100.00
Total capacity-based revenues	4083497880	10.20
Total energy-based revenues	35931983698	89.80
Producers: Total revenues	40015481578	100.00
Storage units: Total revenues	0	0.00
Producers: Capacity-based revenues	4083497880	10.20
Producers: Energy-based revenues	35931983698	89.80
Storage units: Capacity-based revenues	0	0.00
Storage units: Energy-based revenues	0	0.00
Nuclear: Total revenues	21186657258	52.95
Nuclear: Capacity-based revenues	1116582257	2.79
Nuclear: Energy-based revenues	20070075001	50.16
Coal: Total revenues	12351108983	30.87
Coal: Capacity-based revenues	852674391	2.13
Coal: Energy-based revenues	11498434592	28.73
CCGT: Total revenues	4697826790	11.74
CCGT: Capacity-based revenues	835557660	2.09
CCGT: Energy-based revenues	3862269130	9.65
OCGT: Total revenues	1779888548	4.45
OCGT: Capacity-based revenues	1278683572	3.20
OCGT: Energy-based revenues	501204976	1.25
PHES: Total revenues	0	0.00
PHES: Capacity-based revenues	0	0.00
PHES: Energy-based revenues	0	0.00
Battery: Total revenues	0	0.00
Battery: Capacity-based revenues	0	0.00
Battery: Energy-based revenues	0	0.00

Table 96: CM1: Misc

	Value	Unit
Load shedding	0	MW
Load shedding	0	% of total demand
Load shedding	0	number of hours
CRM price	16000	EUR
Capacity demand	255219	MW
Offered capacity: total	255219	MW
Offered capacity: Nuclear	69786	MW
Offered capacity: Coal	53292	MW
Offered capacity: CCGT	52222	MW
Offered capacity: OCGT	79918	MW
Offered capacity: PHES	0	MW
Offered capacity: Battery	0	MW

D.3.2 CM2: PHES without CRM participation

Table 97: CM2: Capacity

	Absolute	Share of system total [%]
Total installed capacity [MW]	255219	100.00
Total installed capacity: Producers [MW]	255219	100.00
Installed capacity: Nuclear [MW]	69786	27.34
Installed capacity: Coal [MW]	53292	20.88
Installed capacity: CCGT [MW]	52222	20.46
Installed capacity: OCGT [MW]	79918	31.31
Total installed capacity: Storage units [MW]	0	0.00
Installed capacity: PHES [MW]	0	0.00
Installed capacity: Battery [MW]	0	0.00
Total installed energy [MWh]	15000000	100.00
Installed energy: PHES [MWh]	15000000	100.00
Installed energy: Battery [MWh]	0	0.00

Table 98: CM2: Surplus

	Absolute [EUR]	Share of system total [%]
Total Surplus	4291280476299	100.00
Producer surplus	0	0.00
Storage surplus	0	0.00
Consumer surplus	4274852100412	99.62
Solar surplus	4783129607	0.11
Wind surplus	11645246279	0.27
Surplus: Nuclear	0	0.00
Surplus: Coal	0	0.00
Surplus: CCGT	0	0.00
Surplus: OCGT	0	0.00
Surplus: PHES	0	0.00
Surplus: Battery	0	0.00

Table 99: CM2: Revenues

	Absolute [EUR]	Share of system total [%]
Total revenues	40015481579	100.00
Total capacity-based revenues	4083497880	10.20
Total energy-based revenues	35931983699	89.80
Producers: Total revenues	40015481579	100.00
Storage units: Total revenues	0	0.00
Producers: Capacity-based revenues	4083497880	10.20
Producers: Energy-based revenues	35931983699	89.80
Storage units: Capacity-based revenues	0	0.00
Storage units: Energy-based revenues	0	0.00
Nuclear: Total revenues	21186657999	52.95
Nuclear: Capacity-based revenues	1116582297	2.79
Nuclear: Energy-based revenues	20070075702	50.16
Coal: Total revenues	12351108240	30.87
Coal: Capacity-based revenues	852674351	2.13
Coal: Energy-based revenues	11498433889	28.73
CCGT: Total revenues	4697826793	11.74
CCGT: Capacity-based revenues	835557660	2.09
CCGT: Energy-based revenues	3862269132	9.65
OCGT: Total revenues	1779888547	4.45
OCGT: Capacity-based revenues	1278683572	3.20
OCGT: Energy-based revenues	501204976	1.25
PHES: Total revenues	0	0.00
PHES: Capacity-based revenues	0	0.00
PHES: Energy-based revenues	0	0.00
Battery: Total revenues	0	0.00
Battery: Capacity-based revenues	0	0.00
Battery: Energy-based revenues	0	0.00

Table 100: CM2: Misc

	Value	Unit
Load shedding	0	MW
Load shedding	0	% of total demand
Load shedding	0	number of hours
CRM price	16000	EUR
Capacity demand	255219	MW
Offered capacity: total	255219	MW
Offered capacity: Nuclear	69786	MW
Offered capacity: Coal	53292	MW
Offered capacity: CCGT	52222	MW
Offered capacity: OCGT	79918	MW
Offered capacity: PHES	0	MW
Offered capacity: Battery	0	MW

D.3.3 CM3: Battery without CRM participation

Table 101: CM3: Capacity

	Absolute	Share of system total [%]
Total installed capacity [MW]	256782	100.00
Total installed capacity: Producers [MW]	255219	99.39
Installed capacity: Nuclear [MW]	70721	27.54
Installed capacity: Coal [MW]	52189	20.32
Installed capacity: CCGT [MW]	51744	20.15
Installed capacity: OCGT [MW]	80565	31.37
Total installed capacity: Storage units [MW]	1563	0.61
Installed capacity: PHES [MW]	0	0.00
Installed capacity: Battery [MW]	1563	0.61
Total installed energy [MWh]	8628	0.00
Installed energy: PHES [MWh]	0	0.00
Installed energy: Battery [MWh]	8628	0.00

Table 102: CM3: Surplus

	Absolute [EUR]	Share of system total [%]
Total Surplus	4291245756585	100.00
Producer surplus	0	0.00
Storage surplus	0	0.00
Consumer surplus	4274830406589	99.62
Solar surplus	4779589024	0.11
Wind surplus	11635760971	0.27
Surplus: Nuclear	0	0.00
Surplus: Coal	0	0.00
Surplus: CCGT	0	0.00
Surplus: OCGT	0	0.00
Surplus: PHES	0	0.00
Surplus: Battery	0	0.00

Table 103: CM3: Revenues

	Absolute [EUR]	Share of system total [%]
Total revenues	40067867650	100.00
Total capacity-based revenues	4083497880	10.19
Total energy-based revenues	35984369770	89.81
Producers: Total revenues	39916830442	99.62
Storage units: Total revenues	151037208	0.38
Producers: Capacity-based revenues	4083497880	10.19
Producers: Energy-based revenues	35833332562	89.43
Storage units: Capacity-based revenues	0	0.00
Storage units: Energy-based revenues	151037208	0.38
Nuclear: Total revenues	21471006436	53.59
Nuclear: Capacity-based revenues	1131535207	2.82
Nuclear: Energy-based revenues	20339471229	50.76
Coal: Total revenues	12052216247	30.08
Coal: Capacity-based revenues	835024505	2.08
Coal: Energy-based revenues	11217191742	28.00
CCGT: Total revenues	4621278060	11.53
CCGT: Capacity-based revenues	827904407	2.07
CCGT: Energy-based revenues	3793373653	9.47
OCGT: Total revenues	1772329699	4.42
OCGT: Capacity-based revenues	1289033760	3.22
OCGT: Energy-based revenues	483295939	1.21
PHES: Total revenues	0	0.00
PHES: Capacity-based revenues	0	0.00
PHES: Energy-based revenues	0	0.00
Battery: Total revenues	151037208	0.38
Battery: Capacity-based revenues	0	0.00
Battery: Energy-based revenues	151037208	0.38

Table 104: CM3: Misc

	Value	Unit
Load shedding	0	MW
Load shedding	0	% of total demand
Load shedding	0	number of hours
CRM price	16000	EUR
Capacity demand	255219	MW
Offered capacity: total	255219	MW
Offered capacity: Nuclear	70721	MW
Offered capacity: Coal	52189	MW
Offered capacity: CCGT	51744	MW
Offered capacity: OCGT	80565	MW
Offered capacity: PHES	0	MW
Offered capacity: Battery	0	MW

D.3.4 CM4: PHES with CRM participation

Table 105: CM4: Capacity

	Absolute	Share of system total [%]
Total installed capacity [MW]	255219	100.00
Total installed capacity: Producers [MW]	241132	94.48
Installed capacity: Nuclear [MW]	82933	32.49
Installed capacity: Coal [MW]	33934	13.30
Installed capacity: CCGT [MW]	44347	17.38
Installed capacity: OCGT [MW]	79918	31.31
Total installed capacity: Storage units [MW]	14087	5.52
Installed capacity: PHES [MW]	14087	5.52
Installed capacity: Battery [MW]	0	0.00
Total installed energy [MWh]	15000000	100.00
Installed energy: PHES [MWh]	15000000	100.00
Installed energy: Battery [MWh]	0	0.00

Table 106: CM4: Surplus

	Absolute [EUR]	Share of system total [%]
Total Surplus	4291377251454	100.00
Producer surplus	0	0.00
Storage surplus	70300152	0.00
Consumer surplus	4274768367913	99.61
Solar surplus	4782738867	0.11
Wind surplus	11755844522	0.27
Surplus: Nuclear	0	0.00
Surplus: Coal	0	0.00
Surplus: CCGT	0	0.00
Surplus: OCGT	0	0.00
Surplus: PHES	70300152	0.00
Surplus: Battery	0	0.00

Table 107: CM4: Revenues

	Absolute [EUR]	Share of system total [%]
Total revenues	40410851524	100.00
Total capacity-based revenues	4083497880	10.10
Total energy-based revenues	36327353644	89.90
Producers: Total revenues	38297186940	94.77
Storage units: Total revenues	2113664583	5.23
Producers: Capacity-based revenues	3858109585	9.55
Producers: Energy-based revenues	34439077355	85.22
Storage units: Capacity-based revenues	225388295	0.56
Storage units: Energy-based revenues	1888276289	4.67
Nuclear: Total revenues	25213120256	62.39
Nuclear: Capacity-based revenues	1326929896	3.28
Nuclear: Energy-based revenues	23886190360	59.11
Coal: Total revenues	7714771350	19.09
Coal: Capacity-based revenues	542943348	1.34
Coal: Energy-based revenues	7171828002	17.75
CCGT: Total revenues	3589406786	8.88
CCGT: Capacity-based revenues	709552770	1.76
CCGT: Energy-based revenues	2879854017	7.13
OCGT: Total revenues	1779888548	4.40
OCGT: Capacity-based revenues	1278683572	3.16
OCGT: Energy-based revenues	501204976	1.24
PHES: Total revenues	2113664583	5.23
PHES: Capacity-based revenues	225388295	0.56
PHES: Energy-based revenues	1888276289	4.67
Battery: Total revenues	0	0.00
Battery: Capacity-based revenues	0	0.00
Battery: Energy-based revenues	0	0.00

Table 108: CM4: Misc

	Value	Unit
Load shedding	0	MW
Load shedding	0	% of total demand
Load shedding	0	number of hours
CRM price	16000	EUR
Capacity demand	255219	MW
Offered capacity: total	255219	MW
Offered capacity: Nuclear	82933	MW
Offered capacity: Coal	33934	MW
Offered capacity: CCGT	44347	MW
Offered capacity: OCGT	79918	MW
Offered capacity: PHES	14087	MW
Offered capacity: Battery	0	MW

D.3.5 CM5: Battery with CRM participation

Table 109: CM5: Capacity

	Absolute	Share of system total [%]
Total installed capacity [MW]	255219	100.00
Total installed capacity: Producers [MW]	244234	95.70
Installed capacity: Nuclear [MW]	72434	28.38
Installed capacity: Coal [MW]	49362	19.34
Installed capacity: CCGT [MW]	48566	19.03
Installed capacity: OCGT [MW]	73872	28.94
Total installed capacity: Storage units [MW]	10985	4.30
Installed capacity: PHES [MW]	0	0.00
Installed capacity: Battery [MW]	10985	4.30
Total installed energy [MWh]	47788	100.00
Installed energy: PHES [MWh]	0	0.00
Installed energy: Battery [MWh]	47788	100.00

Table 110: CM5: Surplus

	Absolute [EUR]	Share of system total [%]
Total Surplus	4291065345098	100.00
Producer surplus	0	0.00
Storage surplus	0	0.00
Consumer surplus	4274812145199	99.62
Solar surplus	4699313340	0.11
Wind surplus	11553886559	0.27
Surplus: Nuclear	0	0.00
Surplus: Coal	0	0.00
Surplus: CCGT	0	0.00
Surplus: OCGT	0	0.00
Surplus: PHES	0	0.00
Surplus: Battery	0	0.00

Table 111: CM5: Revenues

	Absolute [EUR]	Share of system total [%]
Total revenues	40233108683	100.00
Total capacity-based revenues	4083497880	10.15
Total energy-based revenues	36149610803	89.85
Producers: Total revenues	39326038494	97.75
Storage units: Total revenues	907070189	2.25
Producers: Capacity-based revenues	3907744976	9.71
Producers: Energy-based revenues	35418293518	88.03
Storage units: Capacity-based revenues	175752904	0.44
Storage units: Energy-based revenues	731317285	1.82
Nuclear: Total revenues	22002687475	54.69
Nuclear: Capacity-based revenues	1158948490	2.88
Nuclear: Energy-based revenues	20843738985	51.81
Coal: Total revenues	11379243196	28.28
Coal: Capacity-based revenues	789793871	1.96
Coal: Energy-based revenues	10589449324	26.32
CCGT: Total revenues	4310088043	10.71
CCGT: Capacity-based revenues	777054673	1.93
CCGT: Energy-based revenues	3533033370	8.78
OCGT: Total revenues	1634019781	4.06
OCGT: Capacity-based revenues	1181947941	2.94
OCGT: Energy-based revenues	452071840	1.12
PHES: Total revenues	0	0.00
PHES: Capacity-based revenues	0	0.00
PHES: Energy-based revenues	0	0.00
Battery: Total revenues	907070189	2.25
Battery: Capacity-based revenues	175752904	0.44
Battery: Energy-based revenues	731317285	1.82

Table 112: CM5: Misc

	Value	Unit
Load shedding	0	MW
Load shedding	0	% of total demand
Load shedding	0	number of hours
CRM price	16000	EUR
Capacity demand	255219	MW
Offered capacity: total	255219	MW
Offered capacity: Nuclear	72434	MW
Offered capacity: Coal	49362	MW
Offered capacity: CCGT	48566	MW
Offered capacity: OCGT	73872	MW
Offered capacity: PHES	0	MW
Offered capacity: Battery	10985	MW

D.3.6 CM6: PHES with 25% CRM participation

Table 113: CM6: Capacity

	Absolute	Share of system total [%]
Total installed capacity [MW]	255219	100.00
Total installed capacity: Producers [MW]	255219	100.00
Installed capacity: Nuclear [MW]	69786	27.34
Installed capacity: Coal [MW]	53292	20.88
Installed capacity: CCGT [MW]	52222	20.46
Installed capacity: OCGT [MW]	79918	31.31
Total installed capacity: Storage units [MW]	0	0.00
Installed capacity: PHES [MW]	0	0.00
Installed capacity: Battery [MW]	0	0.00
Total installed energy [MWh]	15000000	100.00
Installed energy: PHES [MWh]	15000000	100.00
Installed energy: Battery [MWh]	0	0.00

Table 114: CM6: Surplus

	Absolute [EUR]	Share of system total [%]
Total Surplus	4291280476299	100.00
Producer surplus	0	0.00
Storage surplus	0	0.00
Consumer surplus	4274852100412	99.62
Solar surplus	4783129607	0.11
Wind surplus	11645246279	0.27
Surplus: Nuclear	0	0.00
Surplus: Coal	0	0.00
Surplus: CCGT	0	0.00
Surplus: OCGT	0	0.00
Surplus: PHES	0	0.00
Surplus: Battery	0	0.00

Table 115: CM6: Revenues

	Absolute [EUR]	Share of system total [%]
Total revenues	40015481578	100.00
Total capacity-based revenues	4083497880	10.20
Total energy-based revenues	35931983698	89.80
Producers: Total revenues	40015481578	100.00
Storage units: Total revenues	0	0.00
Producers: Capacity-based revenues	4083497880	10.20
Producers: Energy-based revenues	35931983698	89.80
Storage units: Capacity-based revenues	0	0.00
Storage units: Energy-based revenues	0	0.00
Nuclear: Total revenues	21186657229	52.95
Nuclear: Capacity-based revenues	1116582256	2.79
Nuclear: Energy-based revenues	20070074973	50.16
Coal: Total revenues	12351109018	30.87
Coal: Capacity-based revenues	852674393	2.13
Coal: Energy-based revenues	11498434625	28.73
CCGT: Total revenues	4697826784	11.74
CCGT: Capacity-based revenues	835557659	2.09
CCGT: Energy-based revenues	3862269125	9.65
OCGT: Total revenues	1779888548	4.45
OCGT: Capacity-based revenues	1278683572	3.20
OCGT: Energy-based revenues	501204976	1.25
PHES: Total revenues	0	0.00
PHES: Capacity-based revenues	0	0.00
PHES: Energy-based revenues	0	0.00
Battery: Total revenues	0	0.00
Battery: Capacity-based revenues	0	0.00
Battery: Energy-based revenues	0	0.00

Table 116: CM6: Misc

	Value	Unit
Load shedding	0	MW
Load shedding	0	% of total demand
Load shedding	0	number of hours
CRM price	16000	EUR
Capacity demand	255219	MW
Offered capacity: total	255219	MW
Offered capacity: Nuclear	69786	MW
Offered capacity: Coal	53292	MW
Offered capacity: CCGT	52222	MW
Offered capacity: OCGT	79918	MW
Offered capacity: PHES	0	MW
Offered capacity: Battery	0	MW

D.3.7 CM7: Battery with 25% CRM participation

Table 117: CM7: Capacity

	Absolute	Share of system total [%]
Total installed capacity [MW]	257607	100.00
Total installed capacity: Producers [MW]	254423	98.76
Installed capacity: Nuclear [MW]	71303	27.68
Installed capacity: Coal [MW]	51388	19.95
Installed capacity: CCGT [MW]	51453	19.97
Installed capacity: OCGT [MW]	80278	31.16
Total installed capacity: Storage units [MW]	3184	1.24
Installed capacity: PHES [MW]	0	0.00
Installed capacity: Battery [MW]	3184	1.24
Total installed energy [MWh]	17469	100.00
Installed energy: PHES [MWh]	0	0.00
Installed energy: Battery [MWh]	17469	100.00

Table 118: CM7: Surplus

	Absolute [EUR]	Share of system total [%]
Total Surplus	4291205385527	100.00
Producer surplus	0	0.00
Storage surplus	0	0.00
Consumer surplus	4274834360950	99.62
Solar surplus	4764126406	0.11
Wind surplus	11606898170	0.27
Surplus: Nuclear	0	0.00
Surplus: Coal	0	0.00
Surplus: CCGT	0	0.00
Surplus: OCGT	0	0.00
Surplus: PHES	0	0.00
Surplus: Battery	0	0.00

Table 119: CM7: Revenues

	Absolute [EUR]	Share of system total [%]
Total revenues	40113972914	100.00
Total capacity-based revenues	4083497880	10.18
Total energy-based revenues	36030475034	89.82
Producers: Total revenues	39808298718	99.24
Storage units: Total revenues	305674197	0.76
Producers: Capacity-based revenues	4070761557	10.15
Producers: Energy-based revenues	35737537161	89.09
Storage units: Capacity-based revenues	12736323	0.03
Storage units: Energy-based revenues	292937874	0.73
Nuclear: Total revenues	21649724969	53.97
Nuclear: Capacity-based revenues	1140849608	2.84
Nuclear: Energy-based revenues	20508875361	51.13
Coal: Total revenues	11848953572	29.54
Coal: Capacity-based revenues	822210727	2.05
Coal: Energy-based revenues	11026742845	27.49
CCGT: Total revenues	4563461883	11.38
CCGT: Capacity-based revenues	823251014	2.05
CCGT: Energy-based revenues	3740210869	9.32
OCGT: Total revenues	1746158294	4.35
OCGT: Capacity-based revenues	1284450208	3.20
OCGT: Energy-based revenues	461708086	1.15
PHES: Total revenues	0	0.00
PHES: Capacity-based revenues	0	0.00
PHES: Energy-based revenues	0	0.00
Battery: Total revenues	305674197	0.76
Battery: Capacity-based revenues	12736323	0.03
Battery: Energy-based revenues	292937874	0.73

Table 120: CM7: Misc

	Value	Unit
Load shedding	0	MW
Load shedding	0	% of total demand
Load shedding	0	number of hours
CRM price	16000	EUR
Capacity demand	255219	MW
Offered capacity: total	255219	MW
Offered capacity: Nuclear	71303	MW
Offered capacity: Coal	51388	MW
Offered capacity: CCGT	51453	MW
Offered capacity: OCGT	80278	MW
Offered capacity: PHES	0	MW
Offered capacity: Battery	796	MW

D.3.8 CM8: PHES with 50% CRM participation

Table 121: CM8: Capacity

	Absolute	Share of system total [%]
Total installed capacity [MW]	258981	100.00
Total installed capacity: Producers [MW]	251456	97.09
Installed capacity: Nuclear [MW]	77312	29.85
Installed capacity: Coal [MW]	43655	16.86
Installed capacity: CCGT [MW]	46808	18.07
Installed capacity: OCGT [MW]	83681	32.31
Total installed capacity: Storage units [MW]	7526	2.91
Installed capacity: PHES [MW]	7526	2.91
Installed capacity: Battery [MW]	0	0.00
Total installed energy [MWh]	15000000	100.00
Installed energy: PHES [MWh]	15000000	100.00
Installed energy: Battery [MWh]	0	0.00

Table 122: CM8: Surplus

	Absolute [EUR]	Share of system total [%]
Total Surplus	4291282504889	100.00
Producer surplus	0	0.00
Storage surplus	0	0.00
Consumer surplus	4274833276299	99.62
Solar surplus	4788421545	0.11
Wind surplus	11660807045	0.27
Surplus: Nuclear	0	0.00
Surplus: Coal	0	0.00
Surplus: CCGT	0	0.00
Surplus: OCGT	0	0.00
Surplus: PHES	0	0.00
Surplus: Battery	0	0.00

Table 123: CM8: Revenues

	Absolute [EUR]	Share of system total [%]
Total revenues	40203885089	100.00
Total capacity-based revenues	4083497880	10.16
Total energy-based revenues	36120387209	89.84
Producers: Total revenues	39149724601	97.38
Storage units: Total revenues	1054160488	2.62
Producers: Capacity-based revenues	4023292698	10.01
Producers: Energy-based revenues	35126431903	87.37
Storage units: Capacity-based revenues	60205182	0.15
Storage units: Energy-based revenues	993955306	2.47
Nuclear: Total revenues	23487857146	58.42
Nuclear: Capacity-based revenues	1236992600	3.08
Nuclear: Energy-based revenues	22250864546	55.35
Coal: Total revenues	9909220245	24.65
Coal: Capacity-based revenues	698481735	1.74
Coal: Energy-based revenues	9210738511	22.91
CCGT: Total revenues	3912553480	9.73
CCGT: Capacity-based revenues	748929610	1.86
CCGT: Energy-based revenues	3163623870	7.87
OCGT: Total revenues	1840093729	4.58
OCGT: Capacity-based revenues	1338888754	3.33
OCGT: Energy-based revenues	501204976	1.25
PHES: Total revenues	1054160488	2.62
PHES: Capacity-based revenues	60205182	0.15
PHES: Energy-based revenues	993955306	2.47
Battery: Total revenues	0	0.00
Battery: Capacity-based revenues	0	0.00
Battery: Energy-based revenues	0	0.00

Table 124: CM8: Misc

	Value	Unit
Load shedding	0	MW
Load shedding	0	% of total demand
Load shedding	0	number of hours
CRM price	16000	EUR
Capacity demand	255219	MW
Offered capacity: total	255219	MW
Offered capacity: Nuclear	77312	MW
Offered capacity: Coal	43655	MW
Offered capacity: CCGT	46808	MW
Offered capacity: OCGT	83681	MW
Offered capacity: PHES	3763	MW
Offered capacity: Battery	0	MW

D.3.9 CM9: Battery with 50% CRM participation

Table 125: CM9: Capacity

	Absolute	Share of system total [%]
Total installed capacity [MW]	257994	100.00
Total installed capacity: Producers [MW]	252443	97.85
Installed capacity: Nuclear [MW]	71825	27.84
Installed capacity: Coal [MW]	50698	19.65
Installed capacity: CCGT [MW]	49304	19.11
Installed capacity: OCGT [MW]	80617	31.25
Total installed capacity: Storage units [MW]	5551	2.15
Installed capacity: PHES [MW]	0	0.00
Installed capacity: Battery [MW]	5551	2.15
Total installed energy [MWh]	28897	100.00
Installed energy: PHES [MWh]	0	0.00
Installed energy: Battery [MWh]	28897	100.00

Table 126: CM9: Surplus

	Absolute [EUR]	Share of system total [%]
Total Surplus	4291111422398	100.00
Producer surplus	0	0.00
Storage surplus	0	0.00
Consumer surplus	4274798644195	99.62
Solar surplus	4729378895	0.11
Wind surplus	11583399309	0.27
Surplus: Nuclear	0	0.00
Surplus: Coal	0	0.00
Surplus: CCGT	0	0.00
Surplus: OCGT	0	0.00
Surplus: PHES	0	0.00
Surplus: Battery	0	0.00

Table 127: CM9: Revenues

	Absolute [EUR]	Share of system total [%]
Total revenues	40168308181	100.00
Total capacity-based revenues	4083497880	10.17
Total energy-based revenues	36084810301	89.83
Producers: Total revenues	39655652479	98.72
Storage units: Total revenues	512655702	1.28
Producers: Capacity-based revenues	4039087130	10.06
Producers: Energy-based revenues	35616565348	88.67
Storage units: Capacity-based revenues	44410750	0.11
Storage units: Energy-based revenues	468244953	1.17
Nuclear: Total revenues	21811374334	54.30
Nuclear: Capacity-based revenues	1149192856	2.86
Nuclear: Energy-based revenues	20662181479	51.44
Coal: Total revenues	11670342937	29.05
Coal: Capacity-based revenues	811169594	2.02
Coal: Energy-based revenues	10859173343	27.03
CCGT: Total revenues	4391015507	10.93
CCGT: Capacity-based revenues	788857181	1.96
CCGT: Energy-based revenues	3602158326	8.97
OCGT: Total revenues	1782919701	4.44
OCGT: Capacity-based revenues	1289867499	3.21
OCGT: Energy-based revenues	493052201	1.23
PHES: Total revenues	0	0.00
PHES: Capacity-based revenues	0	0.00
PHES: Energy-based revenues	0	0.00
Battery: Total revenues	512655702	1.28
Battery: Capacity-based revenues	44410750	0.11
Battery: Energy-based revenues	468244953	1.17

Table 128: CM9: Misc

	Value	Unit
Load shedding	0	MW
Load shedding	0	% of total demand
Load shedding	0	number of hours
CRM price	16000	EUR
Capacity demand	255219	MW
Offered capacity: total	255219	MW
Offered capacity: Nuclear	71825	MW
Offered capacity: Coal	50698	MW
Offered capacity: CCGT	49304	MW
Offered capacity: OCGT	80617	MW
Offered capacity: PHES	0	MW
Offered capacity: Battery	2776	MW

D.3.10 CM10: PHES with 75% CRM participation

Table 129: CM10: Capacity

	Absolute	Share of system total [%]
Total installed capacity [MW]	258544	100.00
Total installed capacity: Producers [MW]	245242	94.86
Installed capacity: Nuclear [MW]	82797	32.02
Installed capacity: Coal [MW]	35889	13.88
Installed capacity: CCGT [MW]	43313	16.75
Installed capacity: OCGT [MW]	83243	32.20
Total installed capacity: Storage units [MW]	13302	5.14
Installed capacity: PHES [MW]	13302	5.14
Installed capacity: Battery [MW]	0	0.00
Total installed energy [MWh]	15000000	100.00
Installed energy: PHES [MWh]	15000000	100.00
Installed energy: Battery [MWh]	0	0.00

Table 130: CM10: Surplus

	Absolute [EUR]	Share of system total [%]
Total Surplus	4291307032516	100.00
Producer surplus	0	0.00
Storage surplus	28504646	0.00
Consumer surplus	4274805709956	99.62
Solar surplus	4782751874	0.11
Wind surplus	11690066040	0.27
Surplus: Nuclear	0	0.00
Surplus: Coal	0	0.00
Surplus: CCGT	0	0.00
Surplus: OCGT	0	0.00
Surplus: PHES	28504646	0.00
Surplus: Battery	0	0.00

Table 131: CM10: Revenues

	Absolute [EUR]	Share of system total [%]
Total revenues	40321658303	100.00
Total capacity-based revenues	4083497880	10.13
Total energy-based revenues	36238160423	89.87
Producers: Total revenues	38441526107	95.34
Storage units: Total revenues	1880132195	4.66
Producers: Capacity-based revenues	3923875017	9.73
Producers: Energy-based revenues	34517651090	85.61
Storage units: Capacity-based revenues	159622863	0.40
Storage units: Energy-based revenues	1720509332	4.27
Nuclear: Total revenues	25167411869	62.42
Nuclear: Capacity-based revenues	1324751551	3.29
Nuclear: Energy-based revenues	23842660318	59.13
Coal: Total revenues	7982270973	19.80
Coal: Capacity-based revenues	574231319	1.42
Coal: Energy-based revenues	7408039655	18.37
CCGT: Total revenues	3458747097	8.58
CCGT: Capacity-based revenues	693000954	1.72
CCGT: Energy-based revenues	2765746142	6.86
OCGT: Total revenues	1833096169	4.55
OCGT: Capacity-based revenues	1331891193	3.30
OCGT: Energy-based revenues	501204976	1.24
PHES: Total revenues	1880132195	4.66
PHES: Capacity-based revenues	159622863	0.40
PHES: Energy-based revenues	1720509332	4.27
Battery: Total revenues	0	0.00
Battery: Capacity-based revenues	0	0.00
Battery: Energy-based revenues	0	0.00

Table 132: CM10: Misc

	Value	Unit
Load shedding	0	MW
Load shedding	0	% of total demand
Load shedding	0	number of hours
CRM price	16000	EUR
Capacity demand	255219	MW
Offered capacity: total	255219	MW
Offered capacity: Nuclear	82797	MW
Offered capacity: Coal	35889	MW
Offered capacity: CCGT	43313	MW
Offered capacity: OCGT	83243	MW
Offered capacity: PHES	9976	MW
Offered capacity: Battery	0	MW

D.3.11 CM11: Battery with 75% CRM participation

Table 133: CM11: Capacity

	Absolute	Share of system total [%]
Total installed capacity [MW]	257232	100.00
Total installed capacity: Producers [MW]	249179	96.87
Installed capacity: Nuclear [MW]	71886	27.95
Installed capacity: Coal [MW]	49979	19.43
Installed capacity: CCGT [MW]	49355	19.19
Installed capacity: OCGT [MW]	77960	30.31
Total installed capacity: Storage units [MW]	8052	3.13
Installed capacity: PHES [MW]	0	0.00
Installed capacity: Battery [MW]	8052	3.13
Total installed energy [MWh]	38214	100.00
Installed energy: PHES [MWh]	0	0.00
Installed energy: Battery [MWh]	38214	100.00

Table 134: CM11: Surplus

	Absolute [EUR]	Share of system total [%]
Total Surplus	4291084891749	100.00
Producer surplus	0	0.00
Storage surplus	0	0.00
Consumer surplus	4274812492443	99.62
Solar surplus	4721356680	0.11
Wind surplus	11551042626	0.27
Surplus: Nuclear	0	0.00
Surplus: Coal	0	0.00
Surplus: CCGT	0	0.00
Surplus: OCGT	0	0.00
Surplus: PHES	0	0.00
Surplus: Battery	0	0.00

Table 135: CM11: Revenues

	Absolute [EUR]	Share of system total [%]
Total revenues	40203695055	100.00
Total capacity-based revenues	4083497880	10.16
Total energy-based revenues	36120197175	89.84
Producers: Total revenues	39503162890	98.26
Storage units: Total revenues	700532166	1.74
Producers: Capacity-based revenues	3986868352	9.92
Producers: Energy-based revenues	35516294537	88.34
Storage units: Capacity-based revenues	96629528	0.24
Storage units: Energy-based revenues	603902638	1.50
Nuclear: Total revenues	21834039269	54.31
Nuclear: Capacity-based revenues	1150170623	2.86
Nuclear: Energy-based revenues	20683868647	51.45
Coal: Total revenues	11553402041	28.74
Coal: Capacity-based revenues	799660096	1.99
Coal: Energy-based revenues	10753741945	26.75
CCGT: Total revenues	4401194178	10.95
CCGT: Capacity-based revenues	789682646	1.96
CCGT: Energy-based revenues	3611511532	8.98
OCGT: Total revenues	1714527401	4.26
OCGT: Capacity-based revenues	1247354987	3.10
OCGT: Energy-based revenues	467172414	1.16
PHES: Total revenues	0	0.00
PHES: Capacity-based revenues	0	0.00
PHES: Energy-based revenues	0	0.00
Battery: Total revenues	700532166	1.74
Battery: Capacity-based revenues	96629528	0.24
Battery: Energy-based revenues	603902638	1.50

Table 136: CM11: Misc

	Value	Unit
Load shedding	0	MW
Load shedding	0	% of total demand
Load shedding	0	number of hours
CRM price	16000	EUR
Capacity demand	255219	MW
Offered capacity: total	255219	MW
Offered capacity: Nuclear	71886	MW
Offered capacity: Coal	49979	MW
Offered capacity: CCGT	49355	MW
Offered capacity: OCGT	77960	MW
Offered capacity: PHES	0	MW
Offered capacity: Battery	6039	MW

D.4 Price-Based Capacity Market Model

D.4.1 CP1: No Storage

Table 137: CP1: Capacity

	Absolute	Share of system total [%]
Total installed capacity [MW]	255219	100.00
Total installed capacity: Producers [MW]	255219	100.00
Installed capacity: Nuclear [MW]	69786	27.34
Installed capacity: Coal [MW]	53292	20.88
Installed capacity: CCGT [MW]	52222	20.46
Installed capacity: OCGT [MW]	79918	31.31
Total installed capacity: Storage units [MW]	0	0.00
Installed capacity: PHES [MW]	0	0.00
Installed capacity: Battery [MW]	0	0.00
Total installed energy [MWh]	0	0.00
Installed energy: PHES [MWh]	0	0.00
Installed energy: Battery [MWh]	0	0.00

Table 138: CP1: Surplus

	Absolute [EUR]	Share of system total [%]
Total Surplus	4291280476299	100.00
Producer surplus	0	0.00
Storage surplus	0	0.00
Consumer surplus	4274852100413	99.62
Solar surplus	4783129608	0.11
Wind surplus	11645246279	0.27
Surplus: Nuclear	0	0.00
Surplus: Coal	0	0.00
Surplus: CCGT	0	0.00
Surplus: OCGT	0	0.00
Surplus: PHES	0	0.00
Surplus: Battery	0	0.00

Table 139: CP1: Revenues

	Absolute [EUR]	Share of system total [%]
Total revenues	40015481578	100.00
Total capacity-based revenues	4083497880	10.20
Total energy-based revenues	35931983698	89.80
Producers: Total revenues	40015481578	100.00
Storage units: Total revenues	0	0.00
Producers: Capacity-based revenues	4083497880	10.20
Producers: Energy-based revenues	35931983698	89.80
Storage units: Capacity-based revenues	0	0.00
Storage units: Energy-based revenues	0	0.00
Nuclear: Total revenues	21186657258	52.95
Nuclear: Capacity-based revenues	1116582257	2.79
Nuclear: Energy-based revenues	20070075001	50.16
Coal: Total revenues	12351108983	30.87
Coal: Capacity-based revenues	852674391	2.13
Coal: Energy-based revenues	11498434592	28.73
CCGT: Total revenues	4697826790	11.74
CCGT: Capacity-based revenues	835557660	2.09
CCGT: Energy-based revenues	3862269130	9.65
OCGT: Total revenues	1779888548	4.45
OCGT: Capacity-based revenues	1278683572	3.20
OCGT: Energy-based revenues	501204976	1.25
PHES: Total revenues	0	0.00
PHES: Capacity-based revenues	0	0.00
PHES: Energy-based revenues	0	0.00
Battery: Total revenues	0	0.00
Battery: Capacity-based revenues	0	0.00
Battery: Energy-based revenues	0	0.00

Table 140: CP1: Misc

	Value	Unit
Load shedding	0	MWh
Load shedding	0	% of total demand
Load shedding	0	number of hours
CRM price	16000	EUR

D.4.2 CP2: PHES without CRM participation

Table 141: CP2: Capacity

	Absolute	Share of system total [%]
Total installed capacity [MW]	255219	100.00
Total installed capacity: Producers [MW]	255219	100.00
Installed capacity: Nuclear [MW]	69786	27.34
Installed capacity: Coal [MW]	53292	20.88
Installed capacity: CCGT [MW]	52222	20.46
Installed capacity: OCGT [MW]	79918	31.31
Total installed capacity: Storage units [MW]	0	0.00
Installed capacity: PHES [MW]	0	0.00
Installed capacity: Battery [MW]	0	0.00
Total installed energy [MWh]	15000000	100.00
Installed energy: PHES [MWh]	15000000	100.00
Installed energy: Battery [MWh]	0	0.00

Table 142: CP2: Surplus

	Absolute [EUR]	Share of system total [%]
Total Surplus	4291280476299	100.00
Producer surplus	-1	0.00
Storage surplus	0	0.00
Consumer surplus	4274852100413	99.62
Solar surplus	4783129608	0.11
Wind surplus	11645246279	0.27
Surplus: Nuclear	-1	0.00
Surplus: Coal	-1	0.00
Surplus: CCGT	1	0.00
Surplus: OCGT	0	0.00
Surplus: PHES	0	0.00
Surplus: Battery	0	0.00

Table 143: CP2: Revenues

	Absolute [EUR]	Share of system total [%]
Total revenues	40015481578	100.00
Total capacity-based revenues	4083497880	10.20
Total energy-based revenues	35931983698	89.80
Producers: Total revenues	40015481578	100.00
Storage units: Total revenues	0	0.00
Producers: Capacity-based revenues	4083497880	10.20
Producers: Energy-based revenues	35931983698	89.80
Storage units: Capacity-based revenues	0	0.00
Storage units: Energy-based revenues	0	0.00
Nuclear: Total revenues	21186657199	52.95
Nuclear: Capacity-based revenues	1116582254	2.79
Nuclear: Energy-based revenues	20070074945	50.16
Coal: Total revenues	12351109038	30.87
Coal: Capacity-based revenues	852674394	2.13
Coal: Energy-based revenues	11498434644	28.73
CCGT: Total revenues	4697826793	11.74
CCGT: Capacity-based revenues	835557660	2.09
CCGT: Energy-based revenues	3862269133	9.65
OCGT: Total revenues	1779888548	4.45
OCGT: Capacity-based revenues	1278683572	3.20
OCGT: Energy-based revenues	501204976	1.25
PHES: Total revenues	0	0.00
PHES: Capacity-based revenues	0	0.00
PHES: Energy-based revenues	0	0.00
Battery: Total revenues	0	0.00
Battery: Capacity-based revenues	0	0.00
Battery: Energy-based revenues	0	0.00

Table 144: CP2: Misc

	Value	Unit
Load shedding	0	MWh
Load shedding	0	% of total demand
Load shedding	0	number of hours
CRM price	16000	EUR

D.4.3 CP3: Battery without CRM participation

Table 145: CP3: Capacity

	Absolute	Share of system total [%]
Total installed capacity [MW]	256782	100.00
Total installed capacity: Producers [MW]	255219	99.39
Installed capacity: Nuclear [MW]	70721	27.54
Installed capacity: Coal [MW]	52189	20.32
Installed capacity: CCGT [MW]	51744	20.15
Installed capacity: OCGT [MW]	80565	31.37
Total installed capacity: Storage units [MW]	1563	0.61
Installed capacity: PHES [MW]	0	0.00
Installed capacity: Battery [MW]	1563	0.61
Total installed energy [MWh]	8628	100.00
Installed energy: PHES [MWh]	0	0.00
Installed energy: Battery [MWh]	8628	100.00

Table 146: CP3: Surplus

	Absolute [EUR]	Share of system total [%]
Total Surplus	4291245756585	100.00
Producer surplus	0	0.00
Storage surplus	0	0.00
Consumer surplus	4274830406589	99.62
Solar surplus	4779589024	0.11
Wind surplus	11635760971	0.27
Surplus: Nuclear	0	0.00
Surplus: Coal	0	0.00
Surplus: CCGT	0	0.00
Surplus: OCGT	0	0.00
Surplus: PHES	0	0.00
Surplus: Battery	0	0.00

Table 147: CP3: Revenues

	Absolute [EUR]	Share of system total [%]
Total revenues	40067867650	100.00
Total capacity-based revenues	4083497880	10.19
Total energy-based revenues	35984369770	89.81
Producers: Total revenues	39916830442	99.62
Storage units: Total revenues	151037208	0.38
Producers: Capacity-based revenues	4083497880	10.19
Producers: Energy-based revenues	35833332562	89.43
Storage units: Capacity-based revenues	0	0.00
Storage units: Energy-based revenues	151037208	0.38
Nuclear: Total revenues	21471006436	53.59
Nuclear: Capacity-based revenues	1131535207	2.82
Nuclear: Energy-based revenues	20339471229	50.76
Coal: Total revenues	12052216247	30.08
Coal: Capacity-based revenues	835024505	2.08
Coal: Energy-based revenues	11217191742	28.00
CCGT: Total revenues	4621278060	11.53
CCGT: Capacity-based revenues	827904407	2.07
CCGT: Energy-based revenues	3793373653	9.47
OCGT: Total revenues	1772329699	4.42
OCGT: Capacity-based revenues	1289033760	3.22
OCGT: Energy-based revenues	483295939	1.21
PHES: Total revenues	0	0.00
PHES: Capacity-based revenues	0	0.00
PHES: Energy-based revenues	0	0.00
Battery: Total revenues	151037208	0.38
Battery: Capacity-based revenues	0	0.00
Battery: Energy-based revenues	151037208	0.38

Table 148: CP3: Misc

	Value	Unit
Load shedding	0	MWh
Load shedding	0	% of total demand
Load shedding	0	number of hours
CRM price	16000	EUR

D.4.4 CP4: PHES with CRM participation

Table 149: CP4: Capacity

	Absolute	Share of system total [%]
Total installed capacity [MW]	255219	100.00
Total installed capacity: Producers [MW]	241132	94.48
Installed capacity: Nuclear [MW]	82933	32.49
Installed capacity: Coal [MW]	33934	13.30
Installed capacity: CCGT [MW]	44347	17.38
Installed capacity: OCGT [MW]	79918	31.31
Total installed capacity: Storage units [MW]	14087	5.52
Installed capacity: PHES [MW]	14087	5.52
Installed capacity: Battery [MW]	0	0.00
Total installed energy [MWh]	15000000	100.00
Installed energy: PHES [MWh]	15000000	100.00
Installed energy: Battery [MWh]	0	0.00

Table 150: CP4: Surplus

	Absolute [EUR]	Share of system total [%]
Total Surplus	4291377304478	100.00
Producer surplus	0	0.00
Storage surplus	70276279	0.00
Consumer surplus	4274768434992	99.61
Solar surplus	4782763333	0.11
Wind surplus	11755829873	0.27
Surplus: Nuclear	-1	0.00
Surplus: Coal	1	0.00
Surplus: CCGT	0	0.00
Surplus: OCGT	0	0.00
Surplus: PHES	70276279	0.00
Surplus: Battery	0	0.00

Table 151: CP4: Revenues

	Absolute [EUR]	Share of system total [%]
Total revenues	40410836820	100.00
Total capacity-based revenues	4083497880	10.10
Total energy-based revenues	36327338940	89.90
Producers: Total revenues	38297186940	94.77
Storage units: Total revenues	2113649880	5.23
Producers: Capacity-based revenues	3858109585	9.55
Producers: Energy-based revenues	34439077355	85.22
Storage units: Capacity-based revenues	225388295	0.56
Storage units: Energy-based revenues	1888261585	4.67
Nuclear: Total revenues	25213120256	62.39
Nuclear: Capacity-based revenues	1326929896	3.28
Nuclear: Energy-based revenues	23886190359	59.11
Coal: Total revenues	7714771351	19.09
Coal: Capacity-based revenues	542943348	1.34
Coal: Energy-based revenues	7171828003	17.75
CCGT: Total revenues	3589406786	8.88
CCGT: Capacity-based revenues	709552770	1.76
CCGT: Energy-based revenues	2879854017	7.13
OCGT: Total revenues	1779888548	4.40
OCGT: Capacity-based revenues	1278683572	3.16
OCGT: Energy-based revenues	501204976	1.24
PHES: Total revenues	2113649880	5.23
PHES: Capacity-based revenues	225388295	0.56
PHES: Energy-based revenues	1888261585	4.67
Battery: Total revenues	0	0.00
Battery: Capacity-based revenues	0	0.00
Battery: Energy-based revenues	0	0.00

Table 152: CP4: Misc

	Value	Unit
Load shedding	0	MWh
Load shedding	0	% of total demand
Load shedding	0	number of hours
CRM price	16000	EUR

D.4.5 CP5: Battery with CRM participation

Table 153: CP5: Capacity

	Absolute	Share of system total [%]
Total installed capacity [MW]	255219	100.00
Total installed capacity: Producers [MW]	244234	95.70
Installed capacity: Nuclear [MW]	72434	28.38
Installed capacity: Coal [MW]	49362	19.34
Installed capacity: CCGT [MW]	48566	19.03
Installed capacity: OCGT [MW]	73872	28.94
Total installed capacity: Storage units [MW]	10985	4.30
Installed capacity: PHES [MW]	0	0.00
Installed capacity: Battery [MW]	10985	4.30
Total installed energy [MWh]	47788	100.00
Installed energy: PHES [MWh]	0	0.00
Installed energy: Battery [MWh]	47788	100.00

Table 154: CP5: Surplus

	Absolute [EUR]	Share of system total [%]
Total Surplus	4291065345098	100.00
Producer surplus	0	0.00
Storage surplus	0	0.00
Consumer surplus	4274812145199	99.62
Solar surplus	4699313340	0.11
Wind surplus	11553886559	0.27
Surplus: Nuclear	0	0.00
Surplus: Coal	0	0.00
Surplus: CCGT	0	0.00
Surplus: OCGT	0	0.00
Surplus: PHES	0	0.00
Surplus: Battery	0	0.00

Table 155: CP5: Revenues

	Absolute [EUR]	Share of system total [%]
Total revenues	40233108683	100.00
Total capacity-based revenues	4083497880	10.15
Total energy-based revenues	36149610803	89.85
Producers: Total revenues	39326038494	97.75
Storage units: Total revenues	907070189	2.25
Producers: Capacity-based revenues	3907744976	9.71
Producers: Energy-based revenues	35418293519	88.03
Storage units: Capacity-based revenues	175752904	0.44
Storage units: Energy-based revenues	731317285	1.82
Nuclear: Total revenues	22002687475	54.69
Nuclear: Capacity-based revenues	1158948490	2.88
Nuclear: Energy-based revenues	20843738985	51.81
Coal: Total revenues	11379243196	28.28
Coal: Capacity-based revenues	789793871	1.96
Coal: Energy-based revenues	10589449324	26.32
CCGT: Total revenues	4310088042	10.71
CCGT: Capacity-based revenues	777054673	1.93
CCGT: Energy-based revenues	3533033370	8.78
OCGT: Total revenues	1634019781	4.06
OCGT: Capacity-based revenues	1181947941	2.94
OCGT: Energy-based revenues	452071840	1.12
PHES: Total revenues	0	0.00
PHES: Capacity-based revenues	0	0.00
PHES: Energy-based revenues	0	0.00
Battery: Total revenues	907070189	2.25
Battery: Capacity-based revenues	175752904	0.44
Battery: Energy-based revenues	731317285	1.82

Table 156: CP5: Misc

	Value	Unit
Load shedding	0	MWh
Load shedding	0	% of total demand
Load shedding	0	number of hours
CRM price	16000	EUR