ANALYSIS OF THE ROLE OF ENERGY STORAGE IN POWER MARKETS WITH STRATEGIC PLAYERS

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Abstract

Earlier research studies the impact of implementing energy storages in power systems, both operation and planning. Additionally, the possibility of reducing the effects of imperfect competition is also analyzed. To the author's knowledge, this paper is the first theoretical approach in analyzing the effects of a strategic behaving energy storage in a power market with imperfect competition.

The power market is modelled as a day-a-head energy only market with agents representing the energy storage units, the power production units and the consumers. Both energy storages and power producers can possibly operate with strategic behavior. The problems are formulated as either a Mixed Complementarity Problem (MCP) or a Mathematical Problem with Equilibrium Constraints (MPEC). In order to obtain a realistic representation of the market and the variability of renewable energy, restrictions on storage and production capacity are simulated.

Keywords: Energy Markets, Market Power, Energy Storage, MPEC, MCP, Equilibrium Modeling.

Introduction

Description and motivation

Renewable energy sources have lately gained increasing attention in the energy sector due to their vast potential in reducing the dependence on fossil fuels. There has been an increased call for the technology development of renewable energy sources because of the issues regarding climate change concerns as well as consumer efforts. Energy sources such as wind and solar are considered as climate friendly, but the drawbacks of these sources are the variable and uncertain level of electricity generation. The variability of these sources leads to the deployment of energy storage as a potential source for flexibility in future energy systems.

A MicroGrid represent a scaled-down version of the power system. The system can be operated in isolation and be self-supplied – or be connected to the main grid. Smart communication between the grids participations can contribute to local interaction utilizing available flexibility on consumers' premises. At the same time, aggregator companies can achieve influential market power, causing an economic inefficient utilization of the flexibility in the MicroGrid.

Modeling power markets is challenging, combining the physical laws of electricity and the interaction between the market participants creates complex scenarios. To determine the potential role of energy storage in the energy system of the future, it is important to examine economic impacts in developing such systems. There have been conducted several studies on how energy storage can be utilized in an effective way in a power system. A common feature on these studies is the assumption of perfect competition, which suggests that all market players operate as price takers (Ventosa, et al., 2005).

Assuming perfect competition implies that the market participants expect that they have no influence on the market price, which is not always the case. As a result of this, the assumption may limit the reliability of the outcome of a power market to some extent. Hence, the role of strategic players on energy storage should be further examined.

Modeling Tools

General Algebraic Modelling System (GAMS) is the modelling tool applied in this paper. GAMS is a high-level modelling system for optimization and mathematical programming. The system is tailored for complex, large scale modelling applications, and allows to build large models that can be reformulated for new model instances.

For the MCP, the Path solver has been applied, and for the MPEC, KNITRO 10.0 are used.

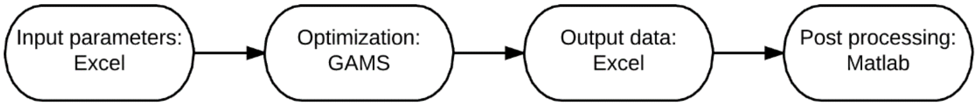

Figure 1 Data processing

Input parameters are exported from Excel to GAMS where the optimization problem gets solved. The results from the problem are exported to a new Excel file, which is further exported to Matlab for post-processing of the data.

Theory

Power Market

The power market is the arena where the supply and demand side meet. Each representative has their objective, and together the representatives find a joint solution, also known as a market equilibrium. The overall purpose of arranging a market is to seek for an efficient allocation of resources.

Electricity systems comprise several physical challenges compared to other commodity markets. The electricity has to be consumed and generated at the same time, requiring a continuous flow of energy. Moreover, the consumption has significant seasonal and intra-day variations, whereas the production cost of conventional energy has an increasing marginal cost as well as capacity constraints. The capacity of storing a large amount of energy is also highly restricted and expensive. However, electricity is still considered as inevitable for most of the society. The lack of flexibility in both production and consumption will, therefore, be potentially abused by firms excreting market power in a deregulated energy market.

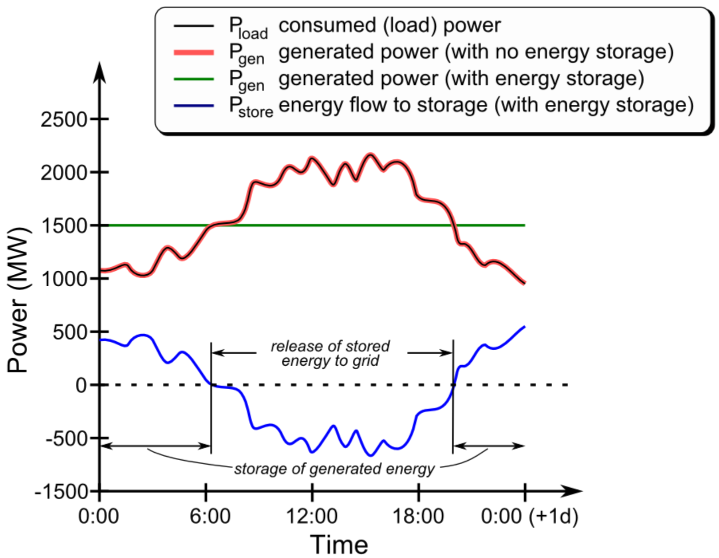

Figure 2 Balancing demand and supply *(Wikichesteredit, 2017)*

Figure 2 Balancing demand and supply , shows a simplistic and illustrative view of the balance of the consumption and production, with and without the possibility of storing energy. The increasing penetration of renewables will amplify the variation in generation profile, the red graph. Moreover, the blue graph represents the operation of an energy storage; this illustrates the benefits; the energy can be stored at low prices and excess capacity, oppositely the storage will generate power at high demand.

The Cournot Game

In an oligopolistic market structure, there are a small number of competing firms. Under this structure, the firms recognize their impact on the market and will exercise market power to maximize profits.

The most applied market structure for modeling imperfect competition in power markets is Cournot competition (Ventosa, et al., 2005). Each firm i faces a cost function $C_i(q_i)$, where q_i is the quantity produced by the firm. $p(q)$ represent the inverse demand curve, where $q = \sum_i^n q_i$ is the consumed quantity and equation (1) is firm i`s profit.

$$\Pi_i = p(q) \cdot q_i - C_i(q_i) \tag{1}$$

Assuming perfect information, each firm knows the competing firms' response to every possible strategy. The Cournot firms supply a quantity which is the best response to every other firm's known strategy. By the deriving, the reaction functions of each firm, the Cournot game gets solved analytically.

The Cournot game can be represented as a duopoly game with two symmetric firms A and B, facing the inverse demand curve, equation, and a constant marginal cost of production c. Their profit functions are given by:

$$\Pi_A = p(q_A + q_B) \cdot q_A - C_A(q_A) \tag{2}$$

$$\Pi_B = p(q_A + q_B) \cdot q_B - C_B(q_B) \tag{3}$$

Maximizing each individual profit Π_i with respect to the supplied quantity, q_i:

$$\frac{\partial \Pi_A}{\partial q_A} = a - \ 2b \cdot q_A - b \cdot q_B - c = 0 \tag{4}$$

$$\frac{\partial \Pi_B}{\partial q_B} = a - \ 2b \cdot q_B - b \cdot q_A - c = 0 \tag{5}$$

By inserting equations (4) into equation (5). and solve for q_A and q_B, the firms' reaction functions are then:

$$q_A^*(q_B) = \frac{a-c}{2b} - \frac{q_B}{2} \tag{6}$$

$$q_B^*(q_A) = \frac{a-c}{2b} - \frac{q_A}{2} \tag{7}$$

Note that the reaction functions are decreasing as the competitor increases its supply. For this symmetric Cournot game, the market equilibrium is:

$$(q_A^*,\ q_B^*, p^*) = \left(\frac{a-c}{3b}, \frac{a-c}{3b}, \frac{a+2c}{3}\right) \tag{8}$$

The equilibrium of the game is a Nash equilibrium, which is an intersection of the two reaction functions. In equilibrium, none of the players have any economic incentive to change their output. Nash equilibriums are therefore considered as strong and realistic to hold.

Complementarity Modeling

After the deregulation of energy markets complementarity modeling has gained an increasing popularity in search for a robust modeling approach of strategic behavior to aid decision-makers. Complementarity modeling generalizes linear programs (LP), convex nonlinear programs (NLP) and convex quadratic programs (QP). The optimality constraints of the problems are given by the

Karush-Kuhn-Tucker (KKT) conditions from the Lagrangian relaxation of the different agents' optimization problem.

Equilibrium

A market consist of several actors with different objectives and constraints. When all actors' restrictions are satisfied and no actors prefer to change their strategy, the marked are in an equilibrium. This paper will focus on deriving the optimality conditions by formulating each actor optimization problem and Lagrangian function.

Complementarity

The optimality conditions of a LP can be expressed as complementary conditions. A LP on its primal and dual form is presented below:

Primal	**Dual**
$max\, z = \boldsymbol{c}^T \cdot \boldsymbol{x}$	$min\, w = \boldsymbol{b}^T \cdot \boldsymbol{v}$
$s.t{:}\ \boldsymbol{A} \cdot \boldsymbol{x} \leq \boldsymbol{b}$	$s.t{:}\ \boldsymbol{A}^T \cdot \boldsymbol{v} \geq \boldsymbol{c}$
$\boldsymbol{x} \geq \boldsymbol{0}$	$\boldsymbol{v} \geq \boldsymbol{0}$

If a constraint is not binding, the value of one unit extra capacity, shadow price, is zero. By finding the regions for primal and dual feasibility of the optimization problem, eq. 1-2,

$$Primal{:}\ \boldsymbol{A} \cdot \boldsymbol{x} \leq \boldsymbol{b}, \boldsymbol{x} \geq \boldsymbol{0} \tag{9}$$
$$Dual{:}\ \boldsymbol{A}^T \cdot \boldsymbol{v} \geq \boldsymbol{c}, \boldsymbol{v} \geq \boldsymbol{0} \tag{10}$$

the optimality condition are the solution where both the primal and the dual are feasible, eq. 11.

$$Complementarity{:}\ \boldsymbol{v}^T \cdot (\boldsymbol{b} - \boldsymbol{A}\boldsymbol{x}) = 0, \boldsymbol{x}^T \cdot (\boldsymbol{A}^T\boldsymbol{v} - \boldsymbol{c}) = 0 \tag{11}$$

When formulating the Lagrangian function of an agent's optimization problem and differentiating it with respect to the agents decision variables and Lagrange multiples, and applying the complementarity slackness theorem together with constraints of the problem, the optimality constraints are derived (Mikuláˇs Luptáˇcik, u.d.).

In this paper all agents' optimization problems are either convex LP or convex NLP.

KKT

The KKT conditions are the optimality requirements of the first order conditions for a solution in nonlinear programming. By allowing inequality constraints, the KKT approach is a generalization of the Lagrange multipliers approach to nonlinear programming. In this section, the necessary and sufficient conditions will be presented.

The standard form formulation of a nonlinear optimization program is given below:

$$max\, f(\boldsymbol{x}) \tag{12}$$
$$s.t{:}\ \forall i{:}\ g_i(\boldsymbol{x}) \leq b_i \tag{13}$$
$$\boldsymbol{x} \geq 0 \tag{14}$$

Vector $\boldsymbol{x} = (\boldsymbol{x}_1, x_2, \ldots, x_{\boldsymbol{n}})$ is the solution vector to the nonlinear program, where $f(\boldsymbol{x})$ is the objective function and $g_i(\boldsymbol{x})$ constraints. Table 1 Necessary and sufficient conditions for optimality summarizes the necessary and sufficient conditions for optimality of the program.

$\boldsymbol{Problem}$	$\boldsymbol{Necessary\ Conditions\ for\ Optimality}$	$\boldsymbol{Also\ Sufficent\ if}$
$One - variable\ unconsstrained$	$\frac{df}{dx} = 0$	$f(x)\ concave$
$Multivariable\ unconstrained$	$\frac{df}{dx_j} = 0 \quad (j = 1,2, \ldots, n)$	$f(\boldsymbol{x})\ concave$
$Constrained, nonnegativity\ constraints\ only$	$\frac{df}{dx_j} = 0 \quad (j = 1,2, \ldots, n)$ $or\ \leq 0\ if\ x_j = 0$	$f(\boldsymbol{x})\ concave$
$General\ constrained\ problem$	$Karush - Kuhn - Tucker\ conditions$	$f(\boldsymbol{x})\ concave\ and$ $g_i(\boldsymbol{x})\ convex\ for$ $(i = 1,2, \ldots, m)$

Table 1 Necessary and sufficient conditions for optimality *(Hiller & Liberman, 2010)*

Theorem. (Hiller & Liberman, 2010) Assume that $f(\boldsymbol{x})$, $g_1(\boldsymbol{x})$, $g_2(\boldsymbol{x})$, . . ., $g_m(\boldsymbol{x})$ are differentiable functions satisfying certain regularity conditions. Then $\mathbf{x}^* = (x_1^*, x_2^*, \ldots, x_n^*)$ can be an optimal solution for the nonlinear programming problem only if there exist m numbers $u_1, u_2, \ldots, u_m$ such that all the following KKT conditions are satisfied:

$$\forall j: \frac{\partial f}{\partial x_j} - \sum_{i=1}^{m} u_i \frac{\partial g_i}{\partial x_j} \leq 0, at\ \boldsymbol{x} = \boldsymbol{x}^* \tag{15}$$

$$\forall j: x_j^* \left(\frac{\partial f}{\partial x_j} - \sum_{i=1}^{m} u_i \frac{\partial g_i}{\partial x_j} \right) = 0, at\ \boldsymbol{x} = \boldsymbol{x}^* \tag{16}$$

$$\forall i: g_i(x^*) - b_i \leq 0 \tag{17}$$

$$\forall i: u_i \cdot [g_i(x^*) - b_i] = 0 \tag{18}$$

$$\forall j: x_j^* \geq 0 \tag{19}$$

$$\forall i: u_i \geq 0 \tag{20}$$

Corollary. Assume that $f(\boldsymbol{x})$ is a concave function and that $g_1(\boldsymbol{x})$, $g_2(\boldsymbol{x})$, . . ., $g_m(\boldsymbol{x})$ are convex functions (i.e., this problem is a convex programming problem), where all these functions satisfy the regularity conditions. Then $\mathbf{x}^* = (x_1^*, x_2^*, \ldots, x_n^*)$ is an optimal solution if and only if all the conditions of the theorem are satisfied.

In special cases the problem can be solved analytically, if a closed-form solution can be derived. Generating a solution from the KKT conditions are usually done through an optimization algorithm and solved by numerically methods.

Mixed Complementarity Problems

Mixed Complementarity Problems (MCP) consist of equality, inequality and complementarity constraints. MCPs does not have any form of an object function, only constraints. Convex linear and non-linear problems can be expressed and solved as a MCP

The MCP formulation is particularly dexterous when solving multiplayer games using mathematical modelling. It is different from standard optimization techniques as MCPs is solved by satisfying all optimality requirements given by the KKT conditions to the problem, Figure 3 MCP, structure . The solution of a MCP formulation generates the optimal solution for all players in a multi-player game simultaneously by determining the value of each complementarity variable with respect to its complementarity constraint.

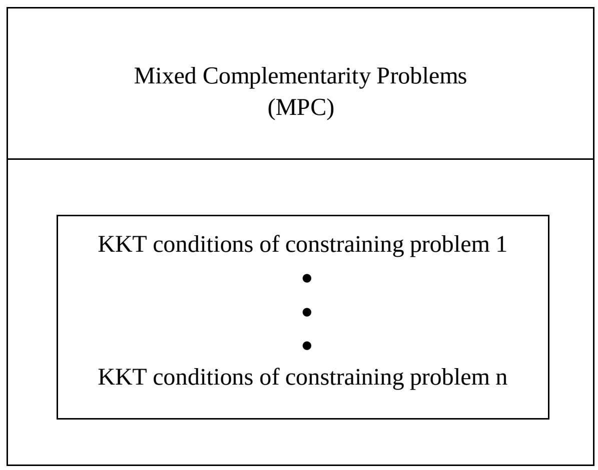

Figure 3 MCP, structure *(Gabriel, et al., 2013)*

By defining the Lagrangian function to each player, each player's individual optimization problem, and deriving the optimality conditions, the MCP are formulated. The KKT conditions of the multi-player game represents the optimization for all players in the equilibrium problem.

Mathematical Programs with Equilibrium Constraints

Mathematical Programs with Equilibrium Constraints (MPEC) are a model class where the object function is one single players' optimization problem subject to own constraints and the optimality constraints from other equilibrium problems,

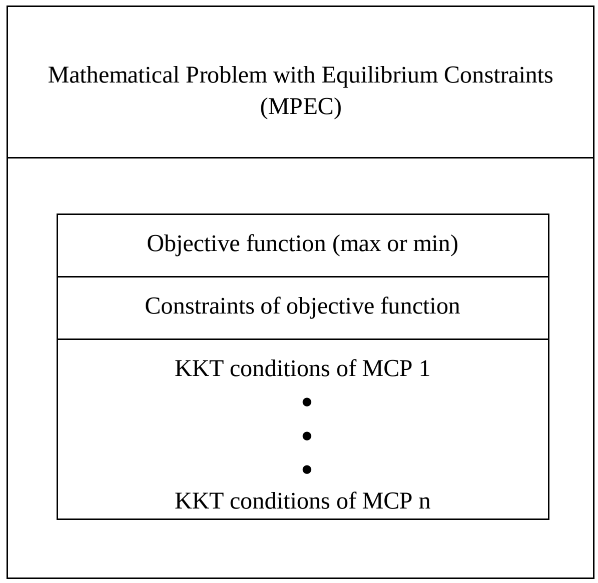

Figure 4 MPEC structure *(Gabriel, et al., 2013)*

The MPEC formulation is often used for bi-level games, as under Stackelberg competition (Gabriel, et al., 2013). The objective function of the Stackelberg leader will be the top-level, where the bottom-level will be the optimality constraints of the rest of the market participants. The leader plays the optimal strategy knowing how the rest of the market will react to the played strategy.

MPECs are difficult and computationally challenging to find a unique optimal solution, as a result of the problem in general are non-convex and non-differentiable, and the FOCs are not sufficient for optimality. (Midthun, 2007)

Methodology

Modelling power markets is challenging, combining the physical laws of electricity and the interactions between the market participants creates complex scenarios. In this chapter, the models are explained in detail. Each agents' optimality constraints are derived by applying complementarity theory. Generating firms and energy storage companies change their behaviour in the various scenarios, which is explained in the relevant subsections.

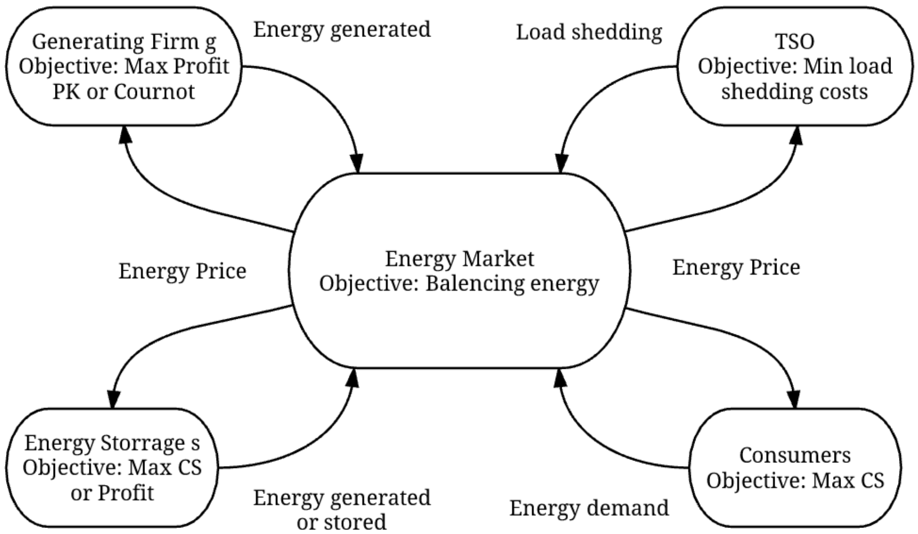

Figure 5 Model illustration, with agents' objective and decision variables

Declaration

Sets:
$g \in G$: *Set of generating firms*
$s \in S$: *Set of storage units*
$h \in H$: *Set of hours*

Parameters:
α [−]: *Cournot parameter*
CL_s [−]: *Converter efficiency*
W_s^{max} [MW]: *Power limits of storage unit s*
E_s^{max} [MWh]: *Energy capacity of storage unit s*
$V_g^{prod.cap}$ [MW]: *Production capacity for generating firm g*
$V_{g,h}^{ren}$ [MW]: *Renewable energy produced by generating firm g at hour h*
P^{cap} [€/MWh]: *Maximum price*
a_h^d [€/MWh]: *Constant benefit coefficient of demand at hour h*
b_h^d [€/MWh^2]: *Linear benefit coefficient of deman at hour h*
$b_{g,h}^c$ [€/MWh^2]: *Linear cost coefficient of generating firm g at hour h*
$c_{g,h}^c$ [€/MWh^3]: *Quadratic cost coefficient of generating firm g at hour h*

Primal Variables:
λ_h[€/MWh] : *Energy price at hour h*
$e_{s,h}^{stored}$[MWh] : *Amount of energy stored in unit s in hour h*
$w_{s,h}^{stored}$ [MWh]: *Energy stored by storage unit s in hour h*
$w_{s,h}^{gen}$ [MWh]: *Generation output of storage unit s in hour h*
$v_{g,h}^{conv}$ [MWh]: *Conventinal generation output by generating firm g in hour h*
ls_h [MWh]: *Amount of load shedding in hour h*
d_h [MWh]: *Demand in hour h*

Dual Variables:
$\xi_{s,h}$[€hMWh]: *Value of one unit of energy by storage s at hour h*
$\iota_{s,h}$[€hMWh]: *Scarcity rent of capacity of storage unit s at hour h*
$\mu_{g,h}$[€hMWh]: *Scarcity rent of capacity for generating firm g in hour h*
$\nu_{s,h}$[€hMW]: *Scarcity rent of converter capacity of storage s at hour h*

Functions:
$MC_{g,h}(v_{g,h}^{conv})$ [€MWh]: *Marginal cost of production for generating firm*

Energy Storage Units

The energy storage units obtain their profits by intra-day arbitrage trade, which implies storing at low prices and generating at higher prices. Equation (21) are each unit's individual storages profit function, where $w_{g,h}^{stored}$, $w_{g,h}^{generated}$ and $e_{s,h}^{stored}$ are the decision variables. The storage units face restrictions on energy capacity, equation (22), and power capacity, equation (23).

Equation (25) and (26) keep track of the energy level in the storage unit. The energy level in a storage unit after a period is the last period's energy level subtracting generated energy or adding the stored energy calibrating for converter losses, $\mathrm{CL_s}$. The energy balanced is round coupled for the set of all hours.

$$\forall s\colon\ max\ \Pi_s{=}\textstyle\sum_{h\in H}\lambda_h\cdot(w_{s,h}^{gen}-w_{s,h}^{stored}) \tag{21}$$

$Subject\ to$:

$$\forall s,\forall h\colon E_s^{max}-e_{s,h}^{stored}\geq 0 \tag{22}$$

$$\forall s,\forall h\colon W_s^{max}-w_{s,h}^{stored}{-}w_{s,h}^{gen}\geq 0 \tag{23}$$

$$\forall s,\forall h=1\colon e_{s,H}^{stored}+CL_s\cdot w_{s,1}^{stored}-w_{s,1}^{gen}-\ e_{s,1}^{stored}\geq 0 \tag{24}$$

$$\forall s,\forall h>1\colon e_{s,h-1}^{stored}+CL_s\cdot w_{s,h}^{stored}-w_{s,h}^{gen}-\ e_{s,h}^{stored}\geq 0 \tag{25}$$

$$\forall s,\forall h\colon w_{s,h}^{gen},w_{s,h}^{stored},e_{s,h}^{stored}\ \geq 0 \tag{26}$$

Price taker

Modelling the storages as price-taking firms will be equivalent to maximizing the consumer surplus. The storage unit will supply energy when the price peaks, highest marginal benefit of consumption, and store energy at low prices when the marginal benefit of consumption

KKT conditions with respect to $w_{s,h}^{gen}$:

$$\forall s,\forall h\colon \lambda_h-\xi_{s,h}+\nu_{s,h}\leq 0 \tag{27}$$

$$\forall s,\forall h\colon w_{s,h}^{gen}\geq 0 \tag{28}$$

$$\forall s,\forall h\colon (\lambda_h-\xi_{s,h}+\nu_{s,h})\cdot\ w_{s,h}^{gen}=0 \tag{29}$$

KKT conditions with respect to $w_{s,h}^{stored}$:

$$\forall s,\forall h\colon\ -\lambda_h+CL_s\cdot\xi_{s,h}-\nu_{s,h}\leq 0 \tag{30}$$

$$\forall s,\forall h\colon w_{s,h}^{stored}\geq 0 \tag{31}$$

$$\forall s,\forall h\colon\left(-\lambda_h+CL_s*\xi_{s,h}-\nu_{s,h}\right)\cdot\ w_{s,h}^{stored}=0 \tag{32}$$

KKT conditions with respect to $e_{s,h}^{stored}$:

All hours, except last

$$\forall s,\forall h<H\colon \xi_{s,h+1}-\xi_{s,h}-\iota_{s,h}\leq 0 \tag{33}$$

$$\forall s,\forall h<H\colon e_{s,h}^{stored}\geq 0 \tag{34}$$

$$\forall s, \forall h < H: (\xi_{s,h+1} - \xi_{s,h} - \iota_{s,h}) \cdot e_{s,h}^{stored} = 0 \tag{35}$$

Last hour

$$\forall s, \forall h = H: \xi_{s,1} - \xi_{s,H} - \iota_{s,H} \leq 0 \tag{36}$$

$$\forall s, \forall h = H: e_{s,H}^{stored} \geq 0 \tag{37}$$

$$\forall s, \forall h < H: (\xi_{s,1} - \xi_{s,H} - \iota_{s,H}) \cdot e_{s,H}^{stored} = 0 \tag{38}$$

KKT conditions with respect to $\xi_{s,h}$:

First hour

$$s, \forall h = 1: \ e_{s,H}^{stored} + CL_s * w_{s,1}^{stored} - w_{s,1}^{generated} - \ e_{s,1}^{stored} \geq 0 \tag{39}$$

$$\forall s, h = 1: \xi_{s,1} \geq 0 \tag{40}$$

$$\forall s, \forall h = 1: \ (e_{s,H}^{stored} + CL_s \cdot w_{s,1}^{stored} - w_{s,1}^{generated} - \ e_{s,1}^{stored}) \ \cdot \xi_{s,1} = 0 \tag{41}$$

Rest of hours

$$\forall s, \forall h > 1: \ e_{s,h-1}^{stored} + CL_s \cdot w_{s,h}^{stored} - w_{s,h}^{generated} - \ e_{s,h}^{stored} \geq 0 \tag{42}$$

$$\forall s, h > 1: \xi_{s,h} \geq 0 \tag{43}$$

$$\forall s, \forall h > 1: \ (e_{s,h}^{stored} + CL_s \cdot w_{s,h}^{stored} - w_{s,h}^{generated} - \ e_{s,h}^{stored}) \cdot \xi_{s,h} = 0 \tag{44}$$

KKT conditions with respect to $\iota_{s,h}$:

$$\forall s, \forall h: E_s^{max} - e_{s,h}^{stored} \geq 0 \tag{45}$$

$$\forall s, \forall h: \iota_{s,h} \geq 0 \tag{46}$$

$$\forall s, \forall h: (E_s^{max} - e_{s,h}^{stored}) \cdot \iota_{s,h} = 0 \tag{47}$$

KKT conditions with respect to $\nu_{s,h}$

$$\forall s, \forall h: W_s^{max} - w_{s,h}^{stored} - w_{s,h}^{generated} \geq 0 \tag{48}$$

$$\forall s, \forall h: \nu_{s,h} \geq 0 \tag{49}$$

$$\forall s, \forall h: (W_s^{max} - w_{s,h}^{stored} - w_{s,h}^{generated}) \cdot \nu_{s,h} = 0 \tag{50}$$

$\xi_{s,h}$, is the value of one unit stored energy hour h for storage unit s. The storages will supply the market as long the value of stored energy exceeds the market price λ_h and the valuation of converting capacity $\nu_{s,h}$, equation (27). On the other hand, the unit will store energy if the relationship is opposite and converter losses are covered, equation (30). Equation (33) – (38) determines the energy level in the storages based on the value of stored energy from time step to time step. The energy balance of the storage is pinned down by the equation from (39) to (44). The last time step is round coupled with the first, ensuring that storages do not generated more energy than it stores. The reaming equations (45) to (50) are the operating constraints on power and energy capacity for the storage units.

Profit maximizing storage unit

When the energy storage unit operates as an arbitrage player with market power, are the model formulated as an MPEC, where the arbitrage player is the top-level problem. The objective function and restriction are the same as earlier, equation (21)-(26). Differently from the price taker strategy is that the storages operator observes a new price for every possible strategy played for storing and generating energy. The energy storages look down at the bottom-level and see all agents' optimality constraints. The arbitrages players maximize the profit function subject to the other players expected behavior.

Power producers

The objective function of the power producers is given by equation (55). According to the rationality assumption, each generating firm g maximizes the firms' profit by supplying a quantity, $v_{g,h}^{conv}$ to the market at price, λ_h. Thus, the firm will earn a profit, found by subtracting the cost of production from revenue for all hours h. The power producers face a capacity constraint on production, as expressed in equation (55).

The firm's optimization problem is given by:

$$\forall g: max\ \Pi_g = \sum_{h \in H} \lambda_h * (V_{g,h}^{ren} + v_{g,h}^{conv}) - C_{g,h}(v_{g,h}^{conv}) \tag{51}$$

$Subject\ to$:

$$\forall g, \forall h: V_g^{prod.cap} - v_{g,h}^{conv} \geq 0 \tag{52}$$

$$\forall g, \forall h: v_{g,h}^{conventinal} \geq 0 \tag{53}$$

$$\forall g: max\ \Pi_g = \sum_{h \in H} \lambda_h * (V_{g,h}^{ren} + v_{g,h}^{conv}) - C_{g,h}(v_{g,h}^{conv}) \tag{54}$$

The production costs are represented by a continuous convex quadratic function, equation (55),

$$C_{g,h}(v_{g,h}^{conv}) = (b_g^c + c_g^c * v_{g,h}^{conv}) \cdot v_{g,h}^{conv} \tag{55}$$

b_g^c is the linear and c_g^c is the quadratic cost parameter. The marginal cost of production for renewable energy is assumed to be zero. Therefore, $V_{g,h}^{renewable}$ is declared as a parameter.

In the Cournot game, generating firms act as price setters. The firms recognizes that their supplied quantity affect the market price. The producers sees the market price as a function of consumers demand, $\lambda_h = a_h^d - b_h^d \cdot d_h$. Therefore, will the firms supply the quantity, which gives them the highest profit due to expected supplied quantity by competitors and the demand elasticity.

KKT with respect to $v_{g,h}^{conv}$:

$$-\alpha * b_h^d \cdot (v_{g,h}^{conv} + V_{g,h}^{ren}) + MB_h(d_h) - MC_{g,h}(v_{g,h}) - \mu_{g,h} \leq 0 \tag{56}$$

$$\forall g, \forall h: \mu_{g,h} \geq 0 \tag{57}$$

$$\forall g: \left(-\alpha \cdot b_h^d \cdot \left(v_{g,h}^{conv} + V_{g,h}^{ren}\right) + MB_h(d_h) - MC_{g,h}(v_{g,h}) - \mu_{g,h}\right) \cdot v_{g,h}^{conv} = 0 \tag{58}$$

KKT with respect to $\mu_{g,h}$:

$$\forall g: -\alpha * b_h^d \cdot (v_{g,h}^{conv} + V_{g,h}^{ren}) + MB_h(d_h) - MC_{g,h}(v_{g,h}) - \mu_{g,h} \leq 0 \tag{59}$$

$$\forall g: v_{g,h}^{conv} \geq 0 \tag{60}$$

$$\forall g, \forall h: \left(V_g^{prod.cap} - v_{g,h}^{conventinal}\right) \cdot \mu_{g,h} = 0 \tag{61}$$

The parameter α reflects the firms belief in the effects on their profit caused by reducing own supply. In cases of perfect competition α equals zero, and equation (56) - (58) are reduced to:

$$\forall g, \forall h: V_g^{prod.cap} - v_{g,h}^{conventinal} \geq 0 \tag{62}$$

$$\forall g: v_{g,h}^{conv} \geq 0 \tag{63}$$

$$\forall g: \left(MB_h(d_h) - MC_{g,h}(v_{g,h}) - \mu_{g,h}\right) \cdot v_{g,h}^{conv} = 0 \tag{64}$$

Generation is triggered, equation (62), when the consumers' marginal benefit are higher than the sum of marginal cost of production and the scarcity rent on production capacity. The firms will increase its supply until the cost do not cover the marginal benefit of consumption, or restricted by equation (62). Than scarcity rent equals the difference between marginal cost of production and the marginal benefit of consumption.

An α greater than zero represents scenarios where the firms have the possibility of exerting market power. $\alpha \cdot b_h^d \cdot v_{g,h}^{conv}$ in equation (59) causes the restriction to be violated at lower production, $v_{g,h}^{conv}$, relative to the perfect competition case, $\alpha = 0$.

Consumers' marginal benefit $MB_h(d_h)$ is directly affected by the actual consumption, d_h, and indirectly affected by the firms' production decisions $v_{g,h}^{conventinal}$. Since d_h is the sum of supplied quantity by both competing generating firms and storage units, the optimal production is not only a function of the consumer behaviour and production cost, but also as a function of the competing firms' optimal response to own decisions.

Demand Side

Electricity is a normal and strictly homogenous good. The consumers have a decreasing marginal benefit of consumption and the only preference is the price. Equation (65) presents the consumers benefit function and equation (66) the marginal benefit of consumption.

$$B_h(d_h) = \int MB_h(d_h) \tag{65}$$

$$MB_h(d_h) = a_h^d - b_h^d \cdot d_h \tag{66}$$

The consumers are represented by one rational optimization agent, maximizing consumer surplus over all hours, h, thus the total benefit subtracting purchased costs is then:

$$max\ CS = \sum_{h \in H} B_d(d_h) - \lambda_h \cdot d_h \tag{67}$$

$$Subject\ to:$$

$$\forall d: d_h \geq 0 \tag{68}$$

The quantity $d_h$is the decision variable, which is non-negative. The price λ_h are determined by the market clearing where the consumers act as price-takers, with no influence on the price. The consumers will always behave as price-takers in this model. However, consumer behaviour will change through elasticity of demand, the responsiveness to the price.

The KKTs with respect to d_h:

$$\forall h: MB_h(d_h) - \lambda_h \leq 0 \tag{69}$$

$$d_h \geq 0 \tag{70}$$

$$\forall h: (MB_h(d_h) - \lambda_h) \cdot d_h = 0 \tag{71}$$

The consumer will increase its demand d_h as long marginal benefit $MB_h(d_h)$ do not exceeds the market price, λ_h, equation (69).

Transmission System Operator

The Transmission System Operators (TSO) objective is to maximize the consumer surplus and prevent the market price from exceeding the price cap given by the regulators. For market prices below the price cap the TSO will not shed any load. In scenarios where market prices reach the price cap the TSO will prevent the price from increasing further, then load shedding will occur. The amount of load shedding is not limited, and the TSO will only prevent the price of exceeding the given price cap, equation (72).

$$P^{cap} - \lambda_h \geq 0 \tag{72}$$

The complementarity slackness theorem applied on equation (72), where ls_h is the complementarity variable and equation (73)-(75) gives the complementarity restrictions.

$$\forall h: P^{cap} - \lambda_h \geq 0 \tag{73}$$

$$ls_h \geq 0 \tag{74}$$

$$\forall h: (P^{cap} - \lambda_h) * ls_h = 0 \tag{75}$$

Energy Only Market

There are several market structures that can balance the energy market. The marked in this model are an energy only market. Where the firms are remunerated for each MWh supplied for a given hour, with a spot-price determined by the market.

The energy market is driven by the forces of demand and supply, balancing the energy consumed and produced. Equation (76) represents the energy balance of the system for each hour h.

$$\forall h: \sum_{g \in G} (V_{g,h}^{ren} + v_{g,h}^{conv}) + \sum_{s \in S} \left(w_{s,h}^{gen} - w_{s,h}^{stored}\right) + \; ls_h \geq d_h \tag{76}$$

The market price of energy is found by applying the complementarity slackness theorem on equation, where λ_h is the complementarity variable. (Mikuláˇs Luptáˇcik, u.d.) The market will be in equilibrium when the equation of the complementarity restriction, equation (77)-(79), are obeyed. This implies that the price of energy will rise until the demand and supply are balanced, or the price cap is reached and load shedding occurs.

$$\forall h: \left(\sum_{g \in G} (V_{g,h}^{ren} + v_{g,h}^{conv} + \sum_{s \in S} \left(w_{s,h}^{gen} - w_{s,h}^{stored} \right) - ls_h - d_h \right) \geq 0 \tag{77}$$

$$\lambda_h \geq 0 \tag{78}$$

$$\forall h: \left(\sum_{g \in G} (V_{g,h}^{ren} + v_{g,h}^{conv} + \sum_{s \in S} \left(w_{s,h}^{gen} - w_{s,h}^{stored} \right) - ls_h - d_h \right) \cdot \lambda_h = 0 \tag{79}$$

Input

Base Case

Cl_s	$V_{g,h}^{prod.cap}$	W_s^{max}	E_s^{max}	$V_{g,h}^{ren}$	b_h^d	$b_{g,h}^c$	$c_{g,h}^c$	P^{cap}
0,9	10000	10000	10000	0	7	0,2	2	400

Table 2 Parameters

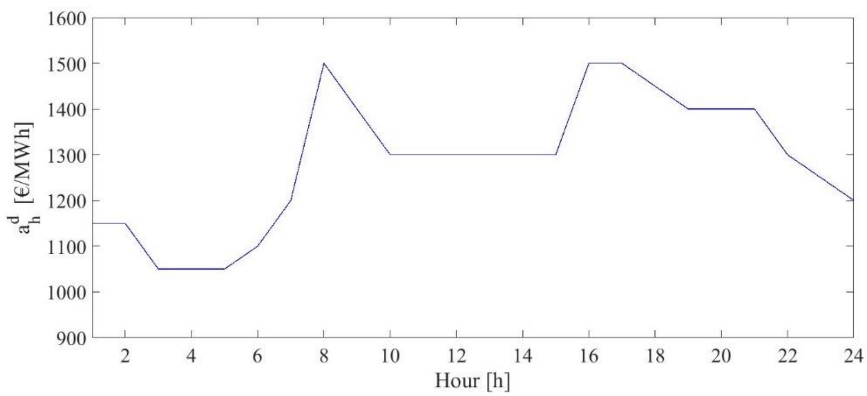

Figure 6 Constant benefit coefficient of demand at hour h

Scarce Production Capacity

$\mathrm{V}_{\mathrm{g,h}}^{\mathrm{prod.cap}}$, $\mathrm{W}_{\mathrm{s}}^{\mathrm{max}}$ and E_s^{max} are the only parameter which changes. The new total production capacity is set to 170 MW and 200 MW for the different cases. The energy storages operation constraints are set to $\mathrm{W}_{\mathrm{s}}^{\mathrm{max}} = 20$ MW and $E_s^{max} = 25\mathrm{MWh}$.

In subsection Shadow prices on production, storage power and storage energy capacity, the different restrictions are presented table 3.

$\mathrm{W}_{\mathrm{s}}^{\mathrm{max}} / E_s^{max}$	$^{0}/_{0}$	$^{10}/_{25}$	$^{15}/_{37.5}$	$^{20}/_{50}$	$^{25}/_{62.5}$	$^{30}/_{75}$

Table 3 Energy storage constraints in subsection Shadow prices on production, storage power and energy capacity

Results

The primary focus of the paper is to study the effects of the energy storage operation and the strategic behavior by the market participants. The following issues will be outlined and further discussed.

- How does imperfect competition affect a power market without energy storages
- How does the energy storage affect the power market when operating as a consumer surplus maximizing agent?
- How does the ownership of the energy storage unit affect the power market

Base Case

The base case is a purely qualitative study, where the goal of the simulations is to prove and target potential outcomes of strategic behavior in the energy market with and without energy storages units. The generating firms and energy storage units are assumed to be symmetric. Hence, the results concerning quantities will be on an aggregate level.

Imperfect Competition and Market Equilibriums

By analyzing the market equilibriums without the possibility of storing energy, a clear evidence of the effects of the strategic behavior by the generating firms appears. The Cournot players have the possibility of exerting market power by reducing the supplied quantity resulting in both higher market price and increased total profit.

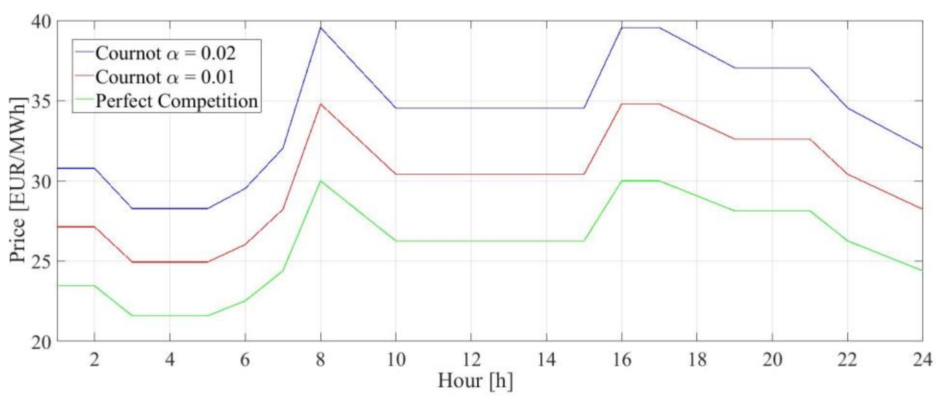

Figure 7 Market price, perfect competition vs. imperfect competition

Figure 7 and Figure 8 shows the price profile and profits over a 24 hour time-series. The firms believe they can affect the market price with a factor of $\alpha * b_h^d$ per unit, when reducing the supplied quantity. An increased α is similar to escalating market power.

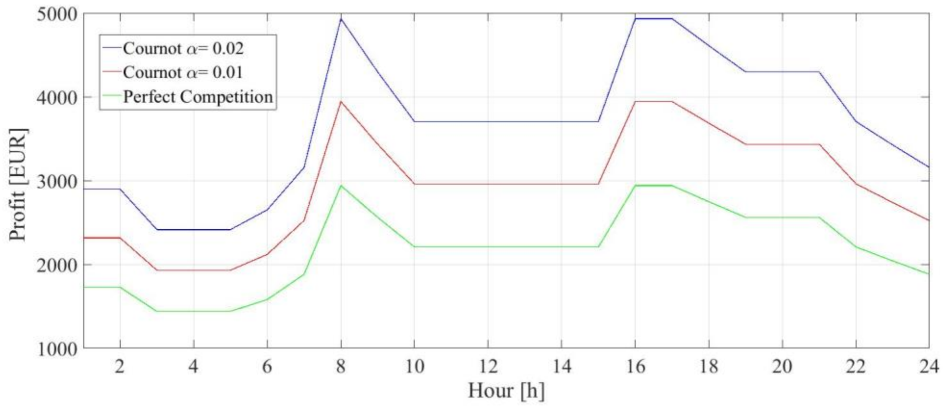

Figure 8 Total profit, perfect competition vs. imperfect competition

The increased market price result in higher profits for the generating firms. The demand curve represents an inverse relationship between the market price and the consumed quantity, the quantity under imperfect competition is as expected at a lower level than under perfect competition, as shown in Figure 9.

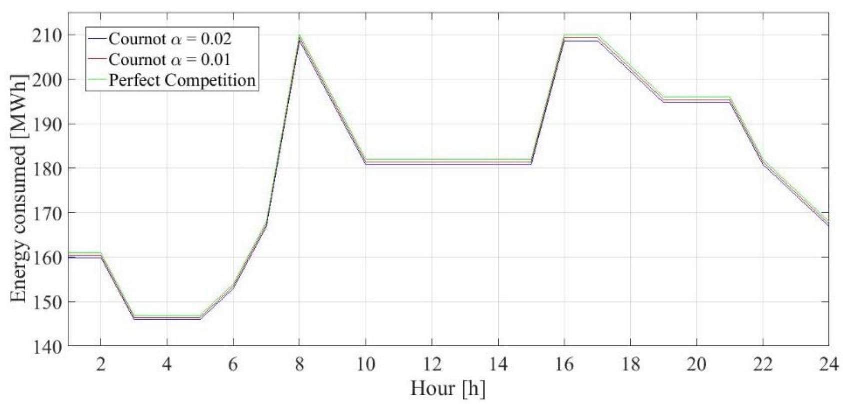

Figure 9 Energy consumed, perfect competition vs. imperfect competition

The elasticity of demand is central for the changes in the market equilibrium. Small changes in quantity will cause large effects on the market price. The Cournot players reduce their quantity by less than 1 %, resulting in a large response on the market price of a 50 % increase in peak-hour. The magnitude of the reaction on price and quantity are therefore reasonable. The elasticity of demand varies on the interval 2 - 3 %, which are considered low but still realistic for a Nordic power market (Gribkovskaia , 2015).

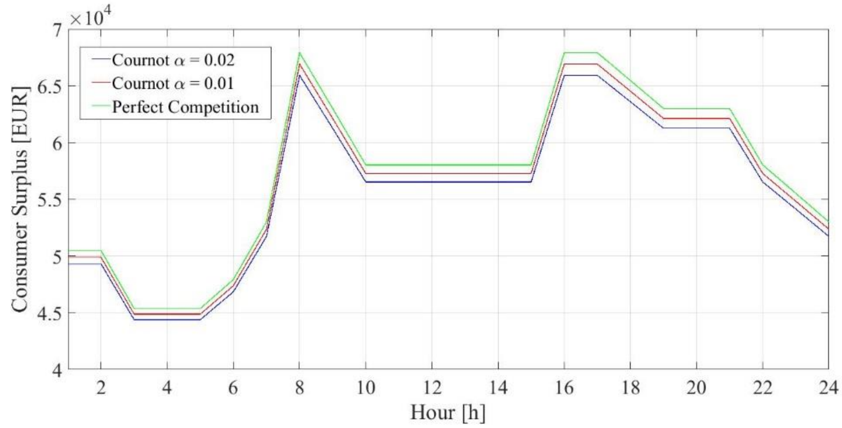

Figure 10 Consumer surplus, perfect competition vs. imperfect competition

During high demand periods, such as hour 8 and hour 16-18, the prices are relatively high compared to the other periods with lower demand. The consumers' utility of consumption is higher in these periods. Figure 10 presents the consumer surplus for each hour under different strategies by the firms. The preferences of the consumer lead to intra-day variations in price greater than the effects of market power.

The increased profits and the reduced consumer surplus has only a marginal impact on total social economical welfare. Despite the deviation from the perfect competition equilibrium, the new equilibriums are in the neighbourhood of the optimal solution. Nevertheless, there have been large welfare transfers from the consumers to the producers due to the market power.

Energy Storage Units and Market Equilibriums

Introducing the possibility of storing energy in the model affected the market equilibrium. The effects are analysed in a perfectly competitive market with energy storage units maximizing consumer surplus.

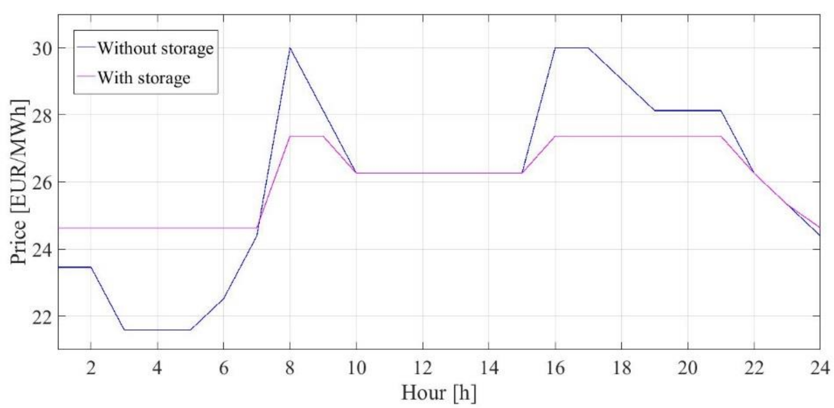

Figure 11 Market price, with and without energy storage

Figure 11 presents the price-profile for a 24-hour simulation with and without energy storages. The price-profile without energy storages shows significant price volatility compared the scenario with energy storages. When energy storage is utilized the intra-day price relationship, minimum price divided by maximum price increases from 0.72 to 0.9. The energy storages are not bounded by its respective power and energy constraints since the relation between min and max price equals the net efficiency of the storage unit.

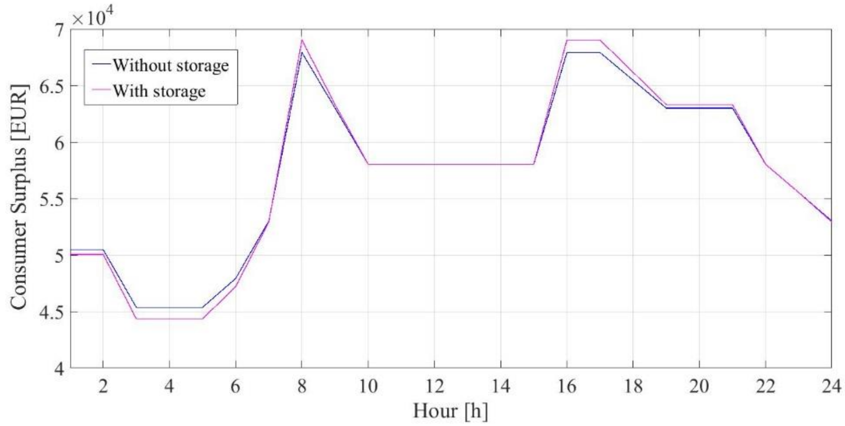

Figure 12 Consumer surplus, with and without energy storage

The energy storage shifts the consumption to the hours where the utility of consumption is at its peak. The consumers prefer higher consumption in peak-demand hours instead of high total quantity of consumption. Figure 12 presents the hour-by-hour consumer surplus, the total consumer surplus is higher when energy storages are installed.

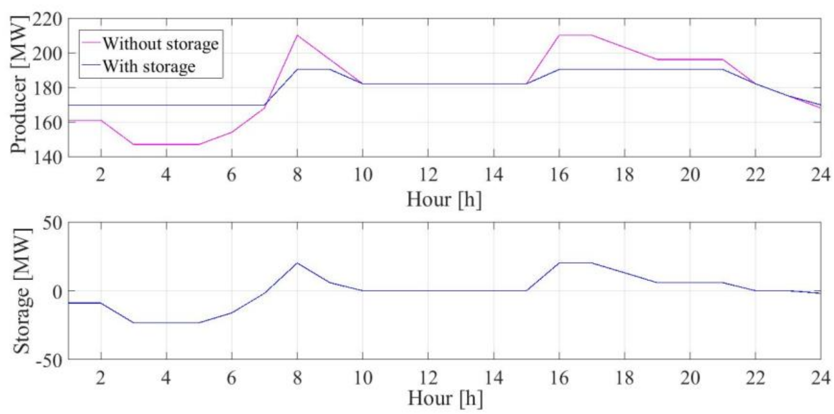

Figure 13 Producer and storage load profiles

The generating firms face a quadratic cost function, where the marginal cost of production is rising. The cost of storing is the market-price or margianal-cost of production adjusted for losses. In the base case, there are savings in shifting the production from high-demand to low-demand hours. The savings are relatively small, 0.4 %. Although the quantitative effect is little, the effect is still significant. The savings in production cost depend only on the slope of the production cost curve. In cases where the marginal cost curve is steeper, the utilization of the storage unit would increase.

The results in this section so far present only simulations under perfect competition. Under imperfect competition, known as Cournot behavior, the CS maximizing storage unit will influence the market in a similar way as earlier in this subsection Figure 13, shows the same pattern as presented in Figure 14.

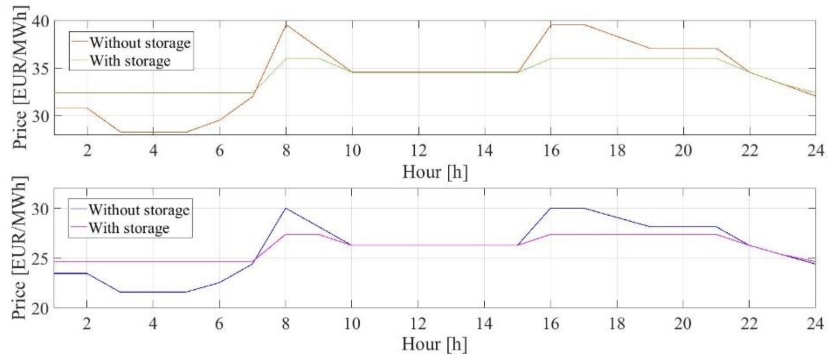

Figure 14 Market price perfect competition vs. imperfect competition with and without energy storage

The energy storage unit stores and generates close to the same amount of energy regardless of the producing firms' behaviour. The utilization of the energy storage is expected to be higher under imperfect competition. However, the constant benefit coefficient a dominates marginal cost of production c in equation (6) and (7), due to the gradual increase in marginal cost of production. This results in approximately the same reduction of supply by the Cournot players each hour. The minimal price divided by the maximum price of the Cournot game intra-day without energy storage is the same as under perfect competition, 0.72. With more rapidly increasing marginal cost for production the operation of the storage will deviate from operations under perfect competition operating generators.

Effects of ownership of the storage units

The storage unit has the advantage of storing energy in periods with low price, and generate at high prices. This technical feature may be used for several purposes, depending on the ownership of the unit. Earlier the energy storage has maximized consumer surplus, this mimics the behaviour of smaller storages owned by the consumer or a perfect competitive market. Other relevant behaviour of the storage is the mimic of an arbitrage player. The arbitrage player is expected to drive the price up and the quantity down in order to maximize own profit at the expense of the consumers. Hence, two different ownerships are assessed; i) consumer oriented, and ii), producer oriented.

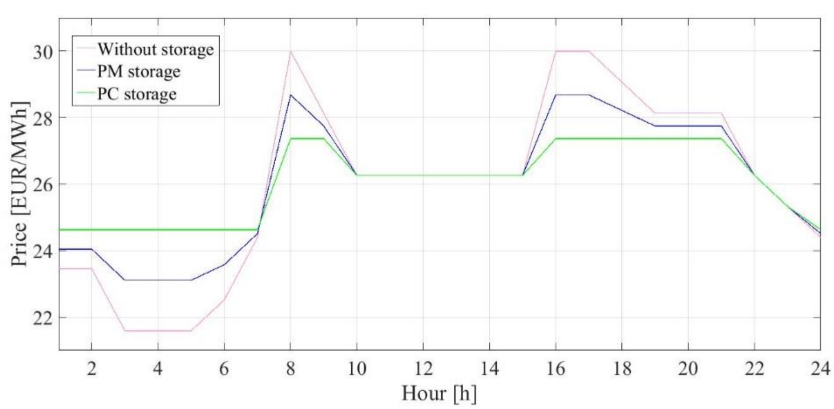

Figure 15 Market price, under different storage operation strategies, profit maximizing (PM) and perfect competitive (PC)

Figure 15 Market price, under different storage operation strategies clarifies the effect on price due to the ownership and behaviour of the storage unit. The arbitrage player (PM) drives up the market price by restricting the supply relative the consumer surplus maximizing storage unit.

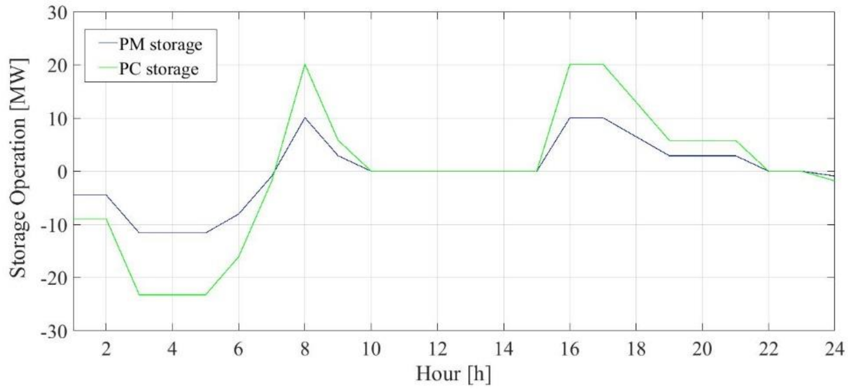

Figure 16 Energy generation by storages, under different storage operation strategies

The operation of the storage units is presented in Figure 16, both strategies have the same pattern of storing at low price hours and generating at high price hours. The total profit for the consumer surplus maximizing agent is in total zero. The storage shifts the intra-day consumption by utilizing the flexibility of the storage.

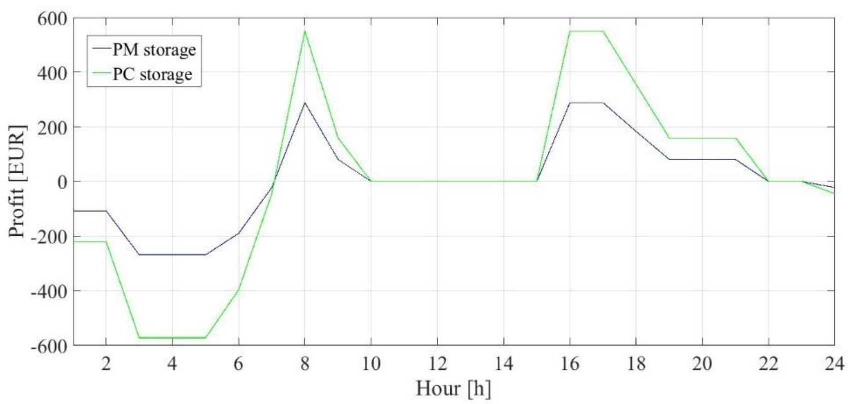

Figure 17 Storage units' profit, under different storage operation strategies

The arbitrage player obtains a positive total profit for the 24 hours. Both storages shift the consumption towards high demand periods. Nevertheless, the arbitrage player drives the price up in high demand periods relative to the consumer surplus maximizing storage. Despite the low level of changes in quantity the price level increases with 4.8% during peak-demand hours.

The effect of the strategic behaviour by the arbitrage player may be considered marginal. In a well-functional power market with high degree of competition and high production capacity, the effects of the arbitrage player will not be considered as potential for distort competition. Nevertheless, the arbitrage player drives the market price upwards. In a micro grid, there is a potential lack of capacity or rapidly increasing marginal cost of production for serving the peak-demand hours. The effect of the arbitrage player behaviour will therefore be reasonable to believe could be increased

Scarce Production Capacity

In this section, the role of the energy storage unit will be further analyzed under restricted generation capacity. Reducing the hourly generation capacities to 200 MW and 170 MW has great impact on the power market. In the perfect competition base case with no storage the peak-generation was 215 MW at hour 8, 16 and 17. Peak-production capacity is now reduced to 80 % and 93% of optimal. The energy storing unit has now an installed power capacity on 20 MW and an energy capacity of 25MWh.

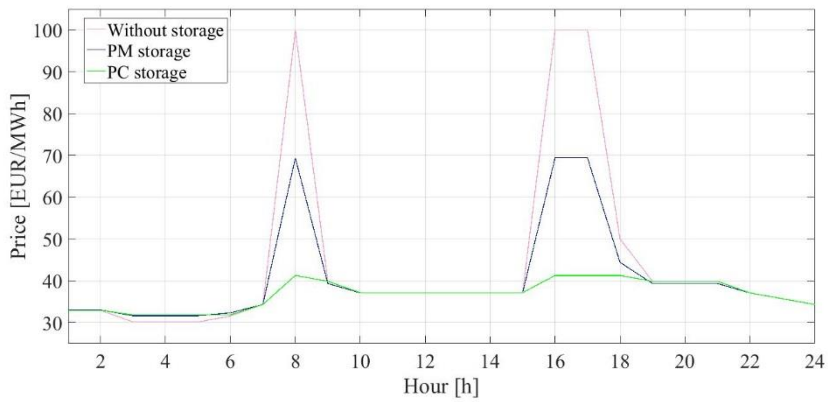

Figure 18 Market prices, under different storage operation strategies and production capacity of 200 MW

The effects caused by the reduction in production capacity are similar for both cases. The reduction of production capacity leads to increased energy prices, as illustrated in Figure 18 and Figure 20. The effect of ownership and strategy outlined in subsection 4.1.3 is present and enlarged as a result of the limited production capacity. Reducing the production capacity to 93 % of optimal effect, results in 70 % increase in energy prices at peak-hour demand caused by the strategic play. The effects of the reduced production capacity are not present when the energy storage maximize consumer surplus.

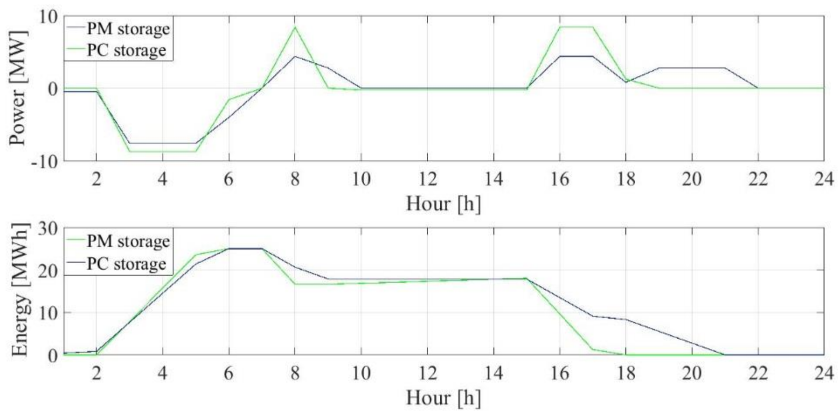

Figure 19 Generation profile and energy level for storage units under different storage operation strategies and production capacity of 200 MW

The generation profile for the two operation strategies are outlined in figure Figure 19. The CS maximizing unit (PC) generates at higher levels at peak-hour visa vi the arbitrage player (PM).

PC storage generates 8.39 MW in hour 8, when the price peaks. To achieve profit the PM storage reduces the amount of generation in hour 8 to 4.37 MW, for then generating 2.77 MW in hour 9. The intra-day price variation makes it profitable generating at hour 9. The PM storage exploits the reduced production capacity in hour 8 to gain excess profit. In hour 9 the PC storage decides to produce since higher generation in hour 16 and 17 will have a negative opportunity cost. The operation of the energy storage will follow the same pattern for the peak-demand in hour 16 and 17. The PC storage generates when the utility of consumption peaks, at the same time the PM storage exploits the reduced production capacity and generate less in peak hours and more when the intra-day price difference exceeds the converter losses.

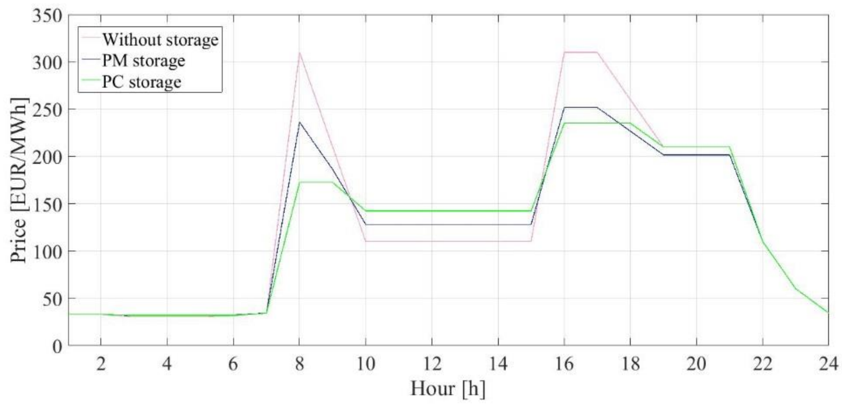

Figure 20 Market prices, under different storage operation strategies and production capacity of 170 MW

A small reduction in production capacity proved to have major effects on operation of the energy storages, and the storages effects on the energy market. With further reduction of capacity, to 170 MW, the effects follow the same pattern and the effects are also enlarged, Figure 20 and Figure 21

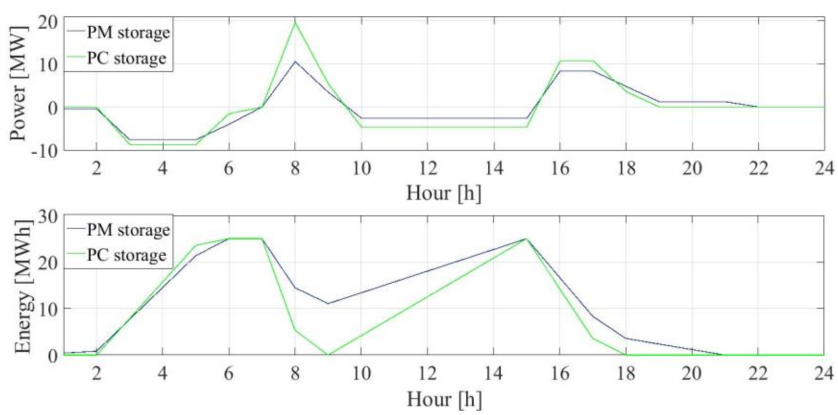

Figure 21 Generation profile and energy level for storage units under different storage operation strategies and production capacity of 170 MW

Between the morning at 8 peak demand and afternoon peak demand 16-17 both storage unit stores energy despite high midday price. The PC storage is constrained by generation (MW) and storing capability (MWh). At the same time the PM storage is only restricted by the capability of storing energy (MWh). In next subsection the valuation of the investment incentives will be discussed. So far, clear evidence is presented of how production flexibility can be advantageously used for gaining excess profit. The consumers are suffering great losses when the energy storage operates as a profit maximizing agent, as shown in Figure 22 Consumer surplus under different storage operations strategies and production capacity of 200 MW and Figure 23 Consumer surplus under different storage operations strategies and production capacity of 170 MW

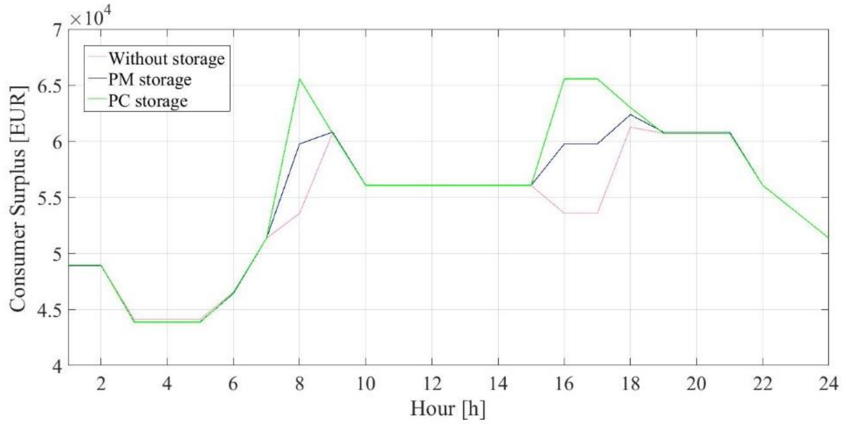

Figure 22 Consumer surplus under different storage operations strategies and production capacity of 200 MW

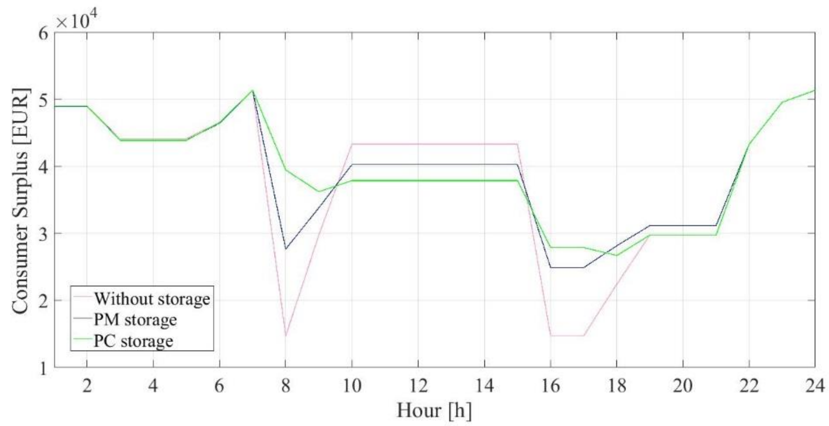

Figure 23 Consumer surplus under different storage operations strategies and production capacity of 170 MW

The consumer surplus in peak demand hours is clearly effected by the strategic behaviour of the energy storage unit.

Shadow prices on production, storage power and energy capacity

The storage energy and power capacity have a major influence on the valuation of future investment. With binding restrictions on generation capacity and storage operations, the shadow price of the capacity constraint represent the value of one unit extra. The shadow price is the measurement of the investment incentive, the highest expected investment cost an agent will except.

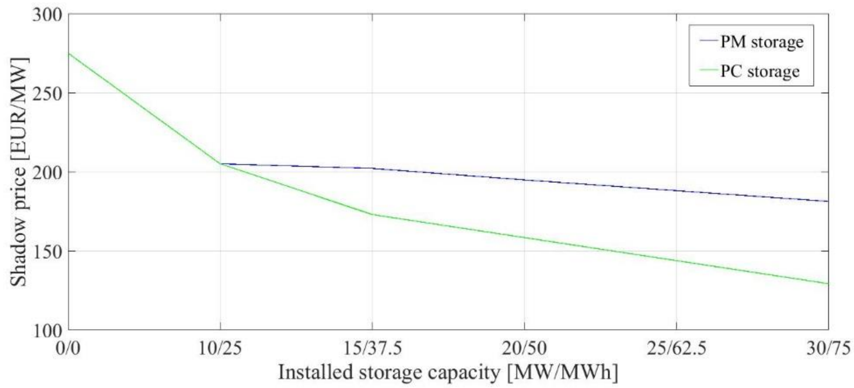

Figure 24 Peak shadow price on production capacity for generators, under different storage operation strategies and generator production capacity of 170 MW

As expected a high initial capacity of the storage will reduce valuation of generation capacity and the incentive to invest. The valuation of generation capacity by the perfectly competitive generators are higher when the energy storage operates as an arbitrage player, as a result of the higher peak-prices. From Figure 24, the incentives for investments increases with reductions in competition and size of existing storages.

The energy storage unit has both restrictions on power generation and energy capacity. The valuation of increased power capacity on storage operation by the arbitrage player are low, although the optimal generation capacity of the producers is reduced to 80 %. The investment incentives on power capacity above 10 MW, 5% of hourly consume in hour 8, are more or less not existing. The investment incentives increase rapidly when the storage unit's capacity declines below 10 MW.

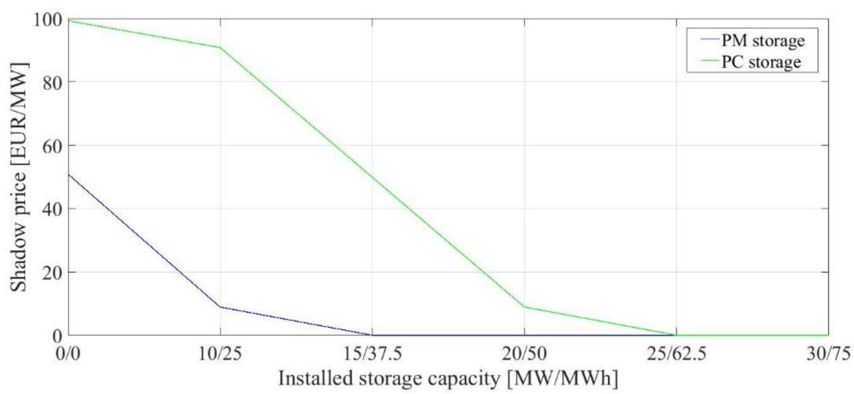

Figure 25 Peak shadow price on storage power capacity, under different storage operation strategies and generator production capacity of 170 MW

The storage with CS maximizing objective values increased power capacity definitely higher than the arbitrage player, Figure 25. Nevertheless, real investment cost for energy storage units as lithium-ion batteries surpass the shadow values of the power capacity for both players. *(Anon., 2016)*

The same pattern of higher valuation of extra capacity is recognized for the energy capacity constraint. PC storage values increased energy capacity significantly higher than the PM storage, as illustrated in figure Figure 26.

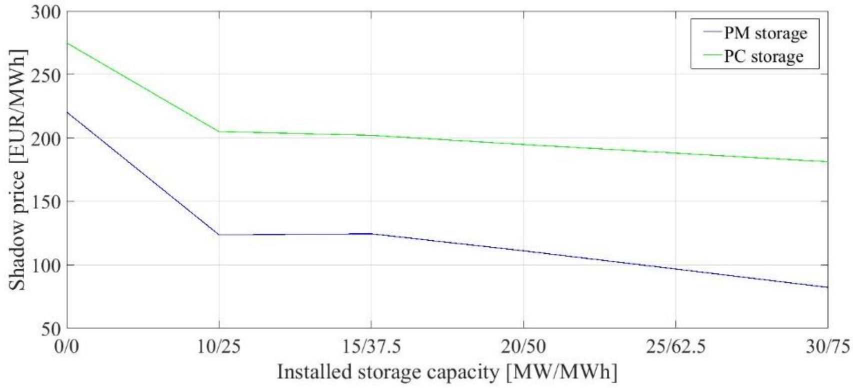

Figure 26 Peak shadow price on storage energy capacity under different storage operation strategies and generator production capacity of 170 MW

There is a clear tendency that under reduced generation capacity that consumers' value increased capacity of both power and energy far more than the PM storage unit.

Discussion

Overall discussion

This section collects and summarizes the major findings in the previous chapter. These will be further discussed, where the role of energy storage in power markets with strategic players will be emphasized. Subsection Imperfect competition and Market Equilibriums clarified the effect of market power on the market by the generators. By reducing the supply quantity, the firms experienced an increase in both price and profit. A small change in supplied quantity caused a great change in price, which is regarded as realistic when considering an inelastic demand. The effect of market power become clearer as the Cournot-parameter α increases. This is in line with earlier studies on imperfect competition. (Willems, 2000)

The intraday price variations get reduced as the energy storage in a perfectly competitive market is introduced. The price variations are reduced to the efficiency of the energy storage. The results are as expected in a perfectly competitive power market without any capacity constraints. Moreover, the price taking storage is placed in a market with a Cournot player, which caused to a reduction in intraday price variations. The fact that the price variations are equal to the efficiency of the energy storage is caused by the lack of capacity constraints for the storage. Earlier studies (Oudalov, et al., 2008) that focus on the optimal size of an energy storage in a power market show similar behavior in trying to equalize the intraday variations, where the storage capacity is at the same time limited because of high investment costs.

The owner's objective of the energy storage determines how the operation develops. Price variations will occur in a market with increasing marginal costs of production, and also with a demand that vary from hour to hour. An energy storage that is owned by the consumers will reduce the intraday price variations until it equals the efficiency. The results are therefore reasonable when the arbitrage player reduce the supply relatively to the consumer-owned energy storage, and by that obtain an increase in profit. In a market without any constraints in production and slowly rising marginal costs during production, the effect of a strategic game is expected to be small, but the effect is still existing. Generally, few researchers have studied this area of expertise related to market power and energy storage. However, the few earlier studies have shown that the energy storage has the effect of reducing the market power of a monopolist (Yujian Ye, et al., 2016). The results in this study also support this conclusion, as the price of the energy market is reduced to during peak-demand hours.

The strategic playing energy storage has the ability to exercise market power and thereby increase own profit. What happens when capacity constraints are introduced to the market? Generally, the role of an energy storage in a power system depends strongly on what kind of power system the energy storage is located. In order to exercise market power, there must be either an increase in marginal costs or restrictions on production. In section Scarce Production Capacity, the generators production capacity is reduced compared to the base case. Thus, there is a clear relationship between reduced production capacity and increased market power. In case of tighter restrictions, the strategic energy storage has the possibility to increase the profit at the expense of the consumers. The shadow prices for the storage capacity are presented. As the strategic playing storage has the desire in reducing the supply, compared to the consumer owned storage, the shadow prices will naturally become lower. Thus, this provides the basis of the fact that the consumers will value a higher capacity in energy storages when the generation capacity is reduced.

Limitations

This section provides an evaluation of the validity of the model and the results. The weaknesses and limitations are therefore highlighted and further discussed.

First of all, the results of the model are highly dependent on the assumptions and the input parameters. The market structures of perfect and imperfect competition are solely assumptions of the state of a power market, which indeed decides the outcome of the model. In order for a strategic playing energy storage to obtain an increase in profit, comparing with a price taking storage, the competitors have to face limitations or increasing marginal costs. The constraints that lead to imperfect competition is central in considering the model itself, but also in evaluating the validity of the results.

The models are simplistic descriptions of a complex reality. Comprehensive extensions of the model can be conducted in order to obtain a more realistic representation of such complex problems. The market is presented with the features of continuous supply and demand curves. However, this representation does not account for the start and stop costs for the production units, which implies non-continuous curves.

The producers' marginal costs are rising, which results to the effect of intraday price variations as the demand will vary during the day. The marginal costs in the presented cases are assumed to be rising, but still increasing in a conservative way. In the base case, the increasing marginal costs provided a possibility for the energy storage to increase its own profit. A steeper curve of the marginal cost would leave the basis of an increase in market power, while a gentler curve would have reduced the possibility. In order to quantify the effect of the market power, a more precise representation of generator portfolio is necessary. It is crucial in considering whether the peak demand will be covered by the renewable energy with low marginal costs or peak power plants with high marginal costs.

The instabilities and variations of renewable energy can result in lack of production capacity during a day at different hours. It has therefore been conducted simulations with restricted production capacity, leading to that market power can be used. The realistic scenarios and the input parameters will then vary in response to the different markets with varying solar and wind conditions.

It is not only conditions on the supply side that determine the effect of market power. The consumers' price sensitivity on the demand play also a central role in the effect of market power. In the presented scenarios, the price elasticity is observed to be 2-3%. This is considered as a low price elasticity, which means that the consumer hardly reduces its power consumption at higher prices. Again, there are huge variations for the different power markets. The models are able to capture such effects, while it is also difficult to verify the results. However, an increase in price elasticity is still realistic in considering other European and American markets (Ros, 2015). Demand response is also expected to be significant in future power markets, both for private consumption and in industries. The process of installing Smart Meters is expected to take place in the entire EU, and this will probably lead to an increase in the consumers' price sensitivity. These representations of the consumers can limit the quality of the quantitative results.

However, there are possibilities for both import and export from other nodes in larger power systems. The transmission will offer the same flexibility as an energy storage would. When the prices are higher, the import will come from the neighbouring node, while in case of lower prices the neighbouring node will be exported to. In case of price variations between the nodes, the power market of the energy storage will be reduced if the possibility of transmission has been present. The lack of transmission provides the possibility for the existence of market power.

Conclusion

An investigation of the role of energy storage in a power market with different market structures has been conducted by modeling and applying complementarity theory. The generators and energy storages are modeled both as price takers and price setters. The effect from both the producers' and the storages' use of market power has been carefully analyzed. Moreover, the role of energy storage has also been modeled in different scenarios with increasing marginal costs in production, with and without constraints on production capacity. The overall objective is thus to study what kind of effects a strategic playing energy storage may provide.

By using complementarity theory, the models have been developed in order to recreate the different market structures. The problems are formulated as Mixed Complementarity Problems (MCP) and Mathematical Problems with Equilibrium Constraints (MPEC), which are solved in the modeling tool General Algebraic Modelling System (GAMS). The input parameters are selected in order to obtain a realistic representation of the market equilibriums

The study revealed that the Cournot producers can reduce the amount of supply, in order to increase own profit. The market equilibrium is designated as a Nash-Equilibrium, which means that none of the players sees any incentives to deviate from their own strategy. As energy storage is introduced to the power system, the intra-day price variations will be reduced.

The role of energy storage is highly affected by the assumptions of the market situation. The strategic playing energy storage exploited the benefit of market power in all the investigated scenarios. The energy storage has the possibility of exerting market power when constraints on production capacity is introduced. The investment incentives of the energy storage showed variations for the different strategies; the size of the incentives became less compared to real investments costs for energy storage technologies. Nevertheless, this is still within the range of realistic future investment costs.

The proposed study has led to the conclusion that the ownership of the energy storage can provide an idea about the effects of power market. The qualitative results show clearly the existence of a strategic behaviour in energy storage, where these effects appear to be realistic. However, the quantitative results are still highly dependent on the models assumptions and input parameters, which should be further considered.

Further Work

The model in this thesis presents a simplistic description of a complex market. Several exciting expansions and scenarios should be further explored. The uncertainty related to the Renewable Energy Sources (RES) may have a major influence in how the energy storage will be operated under different strategies and ownership. The role of RES, in terms of solar and wind, will play an increasing role in the future power system. Hence, exploring this area of expertise is highly relevant.

As stated in the discussion part, one relevant expansion of the model is to include several nodes with transmission constraints. The storage unit will then face new scenarios as the other nodes may supply the same flexibility. The possibility of importing and exporting from other nodes offers the same flexibility as the storage. The potential benefits of future reduction in investment costs in energy storages are; savings as a result of reduced investments and also the scaling of transmission grid that is in favour of investing energy storing systems.

This work has primary focused on the analysis of the supply-side of the power market. However, the demand response becomes highly relevant when Smart-meters are installed. The continuity and availability of information makes it possible for consumers to respond quicker on price incentives, which will lead to increased flexibility of consumption. Thus, introducing representing agents for consumers group will be a realistic and relevant extension of the model.

The analysis is only concentrated on intra-day, 24 hours. Extending the time horizon as well as accounting for the investments in production capacity and energy storages, will take the modelling one step further into a wider understanding of the role of energy storage in power markets with strategic players. However, the extensions of the models are indeed an important way in the search of a realistic representation, but further work should also consider and validate the input parameters in order to obtain an applicable model of the complex problem.

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