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# A Study on Electricity Export Capability of the $\mu$ CHP System with Spot Price

Shi You, Chresten Træholt, Bjarne Poulsen

**Abstract--** When a number of  $\mu$ CHP systems are aggregated as a Virtual Power Plant (VPP), they will be able to participate in the electricity wholesale market with no discrimination compared to conventional large power plants. Hence, this paper investigates the electricity export capability of the  $\mu$ CHP system when the electricity buyback price is given at a value equalizing the dynamic spot price. A  $\mu$ CHP system is modeled with optimized generation, and the marginal price of electricity export for such system is explained. A sensitivity analysis of several key factors, e.g. fuel price, heat to power ratio of the  $\mu$ CHP unit, which influence the export capability of  $\mu$ CHP system, is firstly carried out in the intraday case study, followed by the annual case study which explores the annual system performance. The results show that the electricity export capability of a  $\mu$ CHP system is closely related to its technical parameters, the associated energy price during the trade, as well as the demand profile. Furthermore, the  $\mu$ CHP system running under fluctuating spot price is likely to gain more profit than that running under a fixed electricity export price.

**Index Terms--** marginal price, sensitivity analysis, spot price, Virtual Power Plant,  $\mu$ CHP system

## I. INTRODUCTION

Combined Heat and Power (CHP) plant, representing the distributed energy resources (DER), provides significant reductions in carbon emissions and costs by generating both heat and electricity locally with efficient use of fuel and by offsetting the use of centrally-generated electricity from the grid. In recent years, much interest has been put into producing and deploying  $\mu$ CHP systems for use in small commercial and residential environments as the trend towards a decentralized electricity system with diversified electricity production is becoming more and more apparent [1]-[3]. For small commercial applications, the  $\mu$ CHP devices with tens of kW<sub>el</sub>, which are mainly based on Internal Combustion Engine

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(ICE) technology, have been commercially available for many years. For residential applications, most available  $\mu$ CHP units with several kW<sub>el</sub> are based on Stirling Engine technology. Fuel cell-based  $\mu$ CHP systems are currently thought to be a few years away from large scale deployment [4], they are believed to introduce higher degree of carbon savings due to their high electricity efficiency.

However, similar to other DER units, the  $\mu$ CHP units are often operated independently and lack of efficient participation in the electricity market. The former weakness limits the add-on values of  $\mu$ CHP systems, e.g. providing ancillary services, which could benefit both the power system and the  $\mu$ CHP owners; while the latter weakness results in non-optimized operations of  $\mu$ CHP systems when their operations don't follow the market change which indicates an immediate resource allocation of the energy society.

One of the solutions to the mentioned issues connecting small-scaled DER units like  $\mu$ CHP to the grid is to use a concept so-called Virtual Power Plant (VPP), which could be simply considered as an aggregation approach. The European project CRISP provided a short definition in [5]: A Virtual Power Plant is "an aggregation of DER units dispersed among the network, but controllable as a whole generating system". Other definitions have been provided by the European project FENIX [6] and the European Virtual Fuel Cell Power Plant [7] as well as in many academic papers[8]-[10]. Although the definition of VPP varies as the method of aggregation changes from one to another, it can be basically categorized in two groups: indirect controlled VPP and direct controlled VPP.

Indirect Controlled VPP: uses incentives like variable pricing concerning both generation and consumption to encourage the DER units to decide locally in order to maximize their profit. A VPP organized electricity market could be made available to take care of the energy balance and to create increasing profit margins for DER units as given in Fig. 1. The aggregator, in this case, can not define the behaviors of the DER units by setting target values but can control the DER units by varying the incentives of energy purchasing or consuming on a statistical basis.

Direct Controlled VPP: performs a direct control over its joined DER units based on the acquired information, such as market price, contract types, available transmission capability, from the wholesale electricity market and the grid. The whole group of DER units is thus operated optimally to some extent, depending on the intelligence level of the VPP aggregator.

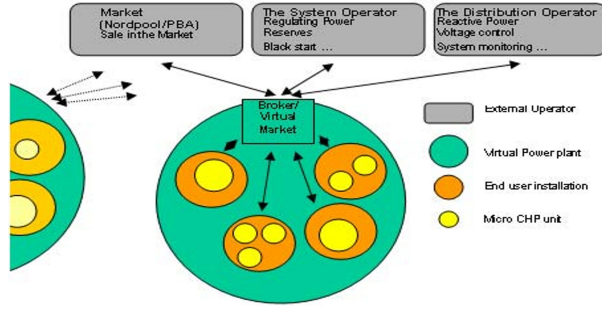


Fig. 1. A structure for market-based Virtual Power Plant

Disregarding the uncertainty introduced by varying aggregation approaches, small DER units like the  $\mu$ CHP are yet believed to have more efficient market participation through VPP in the future. Based on the varying market price, the price-responsiveness of these units would benefit both themselves and the grid operator. For instance, high electricity market prices that imply insufficient energy supplies will be attractive for  $\mu$ CHP units to generate more electricity and sell it back to the grid which in turn alleviates a critical situation.

The paper investigates the electricity export capability of the  $\mu$ CHP system under the VPP scheme, meaning the electricity buyback price is given at a value equalizing the dynamic market price. A  $\mu$ CHP system with optimized generation was modeled in Section II, while the marginal price of electricity export for such system is also explained in the same section. Section III shows the result of a case study, wherein the  $\mu$ CHP system model applied with spot market price is utilized to meet the demand of a multi-family house. The intraday analysis including sensitivity studies on specific factors and the annual analysis on system electrical performance are both done in this part, respectively. Section IV concludes the paper.

## II. MODEL OF A $\mu$ CHP SYSTEM WITH COST MINIMIZATION

In Fig. 2 a model of the relevant  $\mu$ CHP system, modified from [11], is presented. A multi-family house installed with a  $\mu$ CHP unit and the auxiliary units, e.g. boiler and heat tank, interacts with other energy entities. Primary fuels like natural gas or oils are supplied by the fuel supplier and electricity is fed in by the utility company. The excessive electricity produced by the system is bought by a local VPP at the spot market price. The symbols of all the energy flows depicted in Fig. 2 and the accompanying prices are shown in Table I, noticing that they are all none-negative.

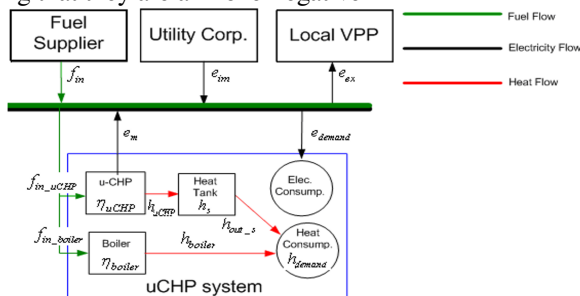


Fig. 2. Model of a  $\mu$ CHP system for a multi-family house

TABLE I  
LIST OF SYMBOLS IN  $\mu$ CHP SYSTEM MODEL

$t_i, i = 1 \dots n$	A specific time slot and the total number of time intervals in one optimization period
$f_{in}(t_i) \cdot P_{ng}(t_i)$	Total primary fuel input (kWh) for the system and its price (€/kWh) at $t_i$
$f_{max\_uCHP}, f_{max\_boiler}$	Maximum fuel input (kWh) for $\mu$ CHP and boiler respectively
$f_{in\_boiler}(t_i), h_{boiler}(t_i)$	Fuel input (kWh) for boiler and its thermal generation (kWh) at $t_i$
$f_{in\_uCHP}(t_i), \alpha(t_i)$	Fuel input (kWh) for $\mu$ CHP unit and the heat to power ratio of the unit at $t_i$
$\eta_{boiler}(t_i), \eta_{uCHP}(t_i)$	Total energy generation efficiency of boiler and $\mu$ CHP unit in % at $t_i$
$h_s(t_i), h_{out\_s}(t_i), h_{s\_max}$	The heat stored (kWh) in heat tank at the end of $t_i$ , heat output (kWh) of heat tank at $t_i$ and the maximum storage capability of heat tank (kWh)
$e_{uCHP}(t_i), h_{uCHP}(t_i)$	Electrical production (kWh) and thermal production (kWh) of $\mu$ CHP unit at $t_i$
$e_{ex}(t_i), P_{ex}(t_i)$	Exported electricity (kWh) and its price (€/kWh) at $t_i$
$e_{im}(t_i), P_{im}(t_i)$	Imported electricity (kWh) and its price (€/kWh) at $t_i$
$h_{demand}(t_i), e_{demand}(t_i)$	Electrical demand (kWh) and thermal demand (kWh) at $t_i$
$C_{marginal}(t_i)$	The marginal price (kWh) for electricity export at $t_i$
$Cost(t_i)$	System cost (€) for $t_i$

In this process, a group of equations indicating physical energy balances are given as follows:

Production Balance:

$$f_{in\_boiler}(t_i) \cdot \eta_{boiler}(t_i) = h_{boiler}(t_i) \quad (1)$$

$$f_{in\_uCHP}(t_i) \cdot \eta_{uCHP}(t_i) \cdot \frac{\alpha(t_i)}{1 + \alpha(t_i)} = h_{uCHP}(t_i) \quad (2)$$

$$f_{in\_uCHP}(t_i) \cdot \eta_{uCHP}(t_i) \cdot \frac{1}{1 + \alpha(t_i)} = e_{uCHP}(t_i) \quad (3)$$

Fuel Balance:

$$f_{in\_boiler}(t_i) + f_{in\_uCHP}(t_i) = f_{in}(t_i) \quad (4)$$

Electrical Balance:

$$e_{uCHP}(t_i) + e_{im}(t_i) - e_{ex}(t_i) = e_{demand}(t_i) \quad (5)$$

Thermal Balance:

$$h_{boiler}(t_i) + h_{out\_s}(t_i) = h_{demand}(t_i) \quad (6)$$

Thermal Storage Balance:

$$h_{uCHP}(t_i) + h_s(t_{i-1}) = h_{out\_s}(t_i) + h_s(t_i) \quad (7)$$

Subject to capacity limit of every device:

Capacity limit of boiler:

$$f_{in\_boiler}(t_i) \leq f_{max\_boiler} \quad (8)$$

Capacity limit of  $\mu$ CHP:

$$f_{in\_uCHP}(t_i) \leq f_{max\_uCHP} \quad (9)$$

Storage limit of heat tank:

$$h_s(t_i) \leq h_{s\_max} \quad (10)$$

The object of such system, as in (11), is to minimize the total cost for one optimization period which includes  $n$  time intervals.

$$\sum_{i=1}^n cost(t_i) = \sum_{i=1}^n [f_{in}(t_i) \cdot p_{ng}(t_i) + e_{im}(t_i) \cdot p_{im}(t_i) - e_{ex}(t_i) \cdot p_{ex}(t_i)] \quad (11)$$

By knowing the information regarding both energy prices and demand profiles in advance, the  $\mu$ CHP system is capable of generating a cost-minimized production schedule. The

schedule defines the setting point of each unit within its generation margin at every time interval. The heat demand is met by either  $\mu$ CHP unit or the auxiliary boiler or both, depending on an economic evaluation of the system cost. Heat tank as the thermal storage unit, provides more flexibility to  $\mu$ CHP system during electricity export. In other words, the  $\mu$ CHP system could generate more electricity for export purpose while storing the excessive heat in heat tank in the case of low heat demand but with high electricity export price. In real time, the system follows the schedule and meets its local demand with the least system cost. During this process, several assumptions are made and listed below:

- Precise prediction on energy prices and local demand, this could be possible as long as the VPP has a reliable forecasting system and the optimization period is very close to real time, like 5 minutes ahead;
- Intelligent modules with both computational capabilities and controllability are installed in the system;
- The whole system is lossless;
- Heat dump is not allowed;
- Start up cost and shut down cost are ignored;

The marginal price for electricity export of such system is a time dependent variable. It indicates the price level at which the  $\mu$ CHP system is willing to produce one more unit of electricity for export. It can be derived by comparing the optimized schedules under zero buyback price and marginal price.

When  $P_{ex}(t_i) = 0, \forall i = 1 \dots n$ , the total system cost can be calculated as  $Cost(t^-)$ , indicating the total system cost for previous schedule in one optimization period.

When  $P_{ex}(t_a) = C_{margin}(t_a)$ , and  $P_{ex}(t_i) = 0, \forall i = 1 \dots a-1, a+1 \dots n$ , the total system cost can be calculated again as  $Cost(t^+)$ , indicating the total system cost for the new schedule in the same optimization period.

Once  $Cost(t^-) = Cost(t^+)$ , the marginal price for the specific time interval  $t_a$  can be derived. By repeating this, the marginal prices for all intervals in one optimization period can be found.

For the buyback price at a specific time interval, it doesn't incur any electricity export until it exceeds the corresponding marginal price and further results in a less system cost for the whole optimization period.

In the situation that the optimization period only includes one time interval  $t_i$ , the marginal price equation can be simply derived as follow:

$$\frac{h_{boiler}(t^+)}{\eta_{boiler}(t^+)} \cdot P_{fuel}(t) + \frac{e_{\mu CHP}(t^+) \cdot (1+\alpha)}{\eta_{\mu CHP}(t^+)} \cdot P_{fuel}(t) - \{e_{\mu CHP}(t^+) - e_{\mu CHP}(t^-) - e_m(t^-)\} \cdot C_{marginal}(t) = \frac{h_{boiler}(t^-)}{\eta_{boiler}(t^-)} \cdot P_{fuel}(t) + e_m(t^-) \cdot P_m(t) + \frac{e_{\mu CHP}(t^-) \cdot (1+\alpha)}{\eta_{\mu CHP}(t^-)} \cdot P_{fuel}(t) \quad (12)$$

The right side of (12) depicts the system cost when there is no electricity export since the buyback price is zero. It comprises the boiler cost, the cost for imported electricity as well as the cost for  $\mu$ CHP generation. The left side of (12) describes the updated system cost when electricity export

occurs at the marginal price of  $\mu$ CHP system. From the equation, it's easy to find that the marginal price for electricity export is closely related to the technical parameters of each device and the energy prices involved in the trading process.

The marginal price derived in (12) is different from the value derived when the optimization period consists of many continuous time intervals. It is because the latter situation couples the marginal price for one time interval with the other time intervals. This theoretically leads to a more cost-effective schedule than the one optimizing a single time interval, since the storage capacity at this time interval can be saved for latter use when a higher buyback price is foreseen in the coming time interval.

### III. CASE STUDY

In the case study, the  $\mu$ CHP system is applied to a multi-family house. It aims at explore the export capability of the  $\mu$ CHP system based on the marginal price method given in section II. The annual demand profile for the house is on hourly basis and its average monthly profile is given in Fig. 3. Both intraday and annual analyses concerning the system performance are carried out in this section, wherein an annual hourly spot price from NordPool [12] is assumed to be electricity buyback price. Each optimization period is defined as a day and the time interval is thus considered as an hour. In the intraday analysis, sensitivity study concerning the marginal price of electricity export for the modeled  $\mu$ CHP system is done with three factors,  $P_{ng}$ ,  $\eta_{\mu CHP}$  and  $\alpha$  in both summer day and winter day. Following that, annual economic performance and export performance of such system are evaluated and further compared with the same system running under a fixed buyback price equalizing the average spot price. Values for the parameters used in the case study are given in Table II. Assumption made in section II also applies to the case studies, furthermore several variables are assumed to be fixed as shown in Table II. As a linear optimization problem, GAMS [13] is employed to simulate the process and find out the optimal solution.

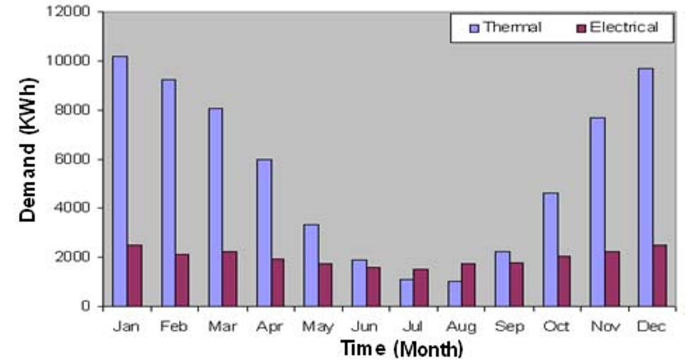


Fig. 3. Demand Profile for Multi-family House

#### A. Intraday Study

The intraday study includes studies on both winter day and summer day. Sensitivity analysis, including 4 scenarios:



system with original settings, system with -10% gas price, system  $\mu$ CHP efficiency equals 88%, system with  $\mu$ CHP unit's heat to power ratio equals one, are carried in winter and summer, respectively. In each scenario, values for all the parameters are cited from TABLE II except for the indicated parameter.

TABLE II  
LIST OF VALUES FOR PARAMETERS UTILIZED IN CASE STUDY

$f_{\max\_boiler} = 30 \text{ kW}$	Auxiliary boiler
$f_{\max\_uCHP} = 24 \text{ kW}$	$\mu$ CHP unit with internal combustion engine driven by natural gas
$h_{s\_max} = 28 \text{ kWh}$	Heat tank is in size of 500 liters with temperature range 20 °C -70°C
$\eta_{boiler}(t_i) = 85.5\%$	Assumed to be fixed over the year (The peak efficiency of modern $\mu$ CHP unit is around 90%; however 80% is used here since operational conditions with lower efficiency such start up, shut down and partial load are not taken into account in the simulation)
$\eta_{uCHP}(t_i) = 80\%$	
$\alpha(t_i) = 2$	
$P_{ex}(t_i)$	Hourly price from spot market of NordPool
$P_{im}(t_i) = 0.115 \text{ €/kWh}$	Assumed to be constant tariffs over the year
$P_{ng}(t_i) = 0.048 \text{ €/kWh}$	
$h_{demand}(t_i), e_{demand}(t_i)$	Hourly basis

#### Case 1: Winter Day

As given in Fig. 4, the hourly based demand profile in the studied winter day has a very high heat to power ratio. When the parameter settings is kept the same as given in TABLE II, the marginal price for such system is around 0.0677€/kWh in most hours except for hour 18, in which the marginal price is an infinite value. This is because the  $\mu$ CHP system has exerted all its power to meet the peak electrical demand at hour 18, export is thus impossible. Following the peak of spot price, export starts at hour 19 and hour 20, as shown in Fig. 5.

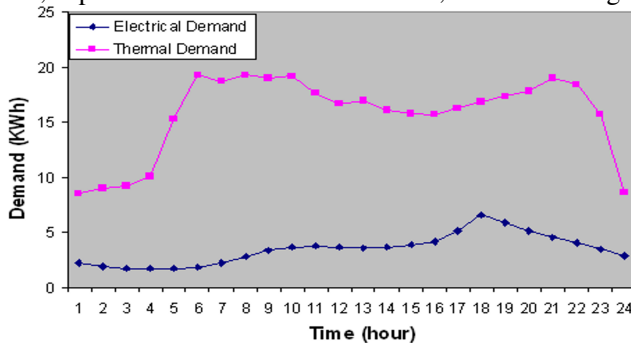


Fig. 4. Demand Profile for Multi-family House in a Winter Day

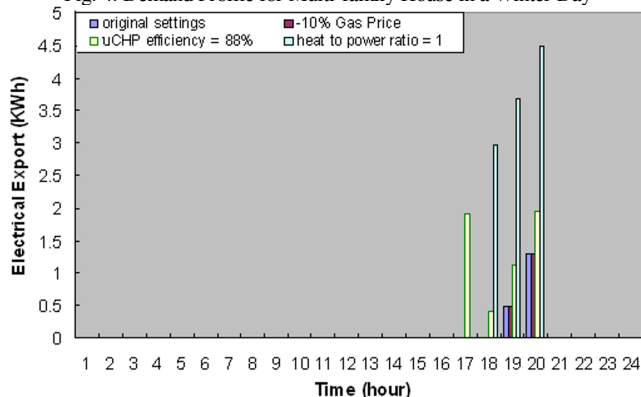


Fig. 5. Electrical Export for Different Scenarios in a Winter Day

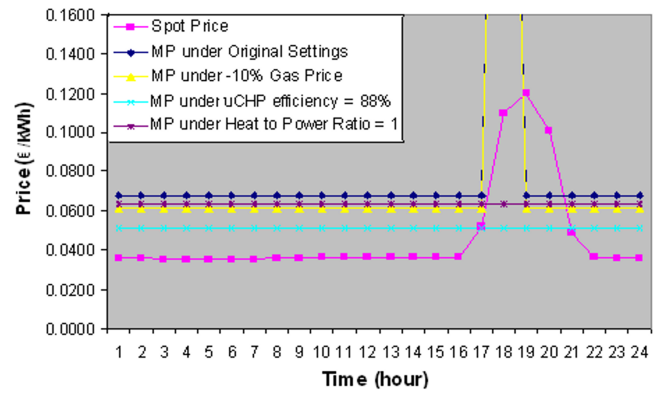


Fig. 6. Marginal Price for Different Scenarios VS Spot Price in a Winter Day

As presented in Fig. 5 and Fig. 6, changes to the parameter settings can cause a deviation of marginal price from the values derived under original system settings. The scenario with  $\mu$ CHP efficiency equals 88% results in the lowest marginal price at 0.0514€/kWh, and this further leads to continuous electricity export from hour 17 to hour 20. The scenario with heat to power ratio of  $\mu$ CHP unit equals 1 has a higher marginal price than the one with lower gas price; however as the electrical efficiency is accordingly increased by 10%, the  $\mu$ CHP unit has more excessive electricity than that of the other scenarios.

#### Case 2: Summer Day

As given in Fig. 7, in contrast to the hourly based demand profile in a winter day, heat to power ratio of the demand in a summer day is less than 1 in most of the time. This results in a lot extra heat when the  $\mu$ CHP system generates electricity. In turn, the extra heat limits the export capability of such system and incurs a pretty high marginal price for electricity export. The marginal price given in Fig. 8, is equal to the electricity import price in all previous scenarios explored in a winter day. This is because varying only one parameter in a reasonable range as before is not enough to incur an efficient electricity production than buying it from the grid. Therefore, another scenario with both increased  $\mu$ CHP efficiency and lowered heat to power ratio of the  $\mu$ CHP unit is conducted. A lower marginal price at 0.1091€/kWh can be derived, as given in Fig 8. However, this is still much higher than the spot price. No electricity is injected back to the grid in this summer day.

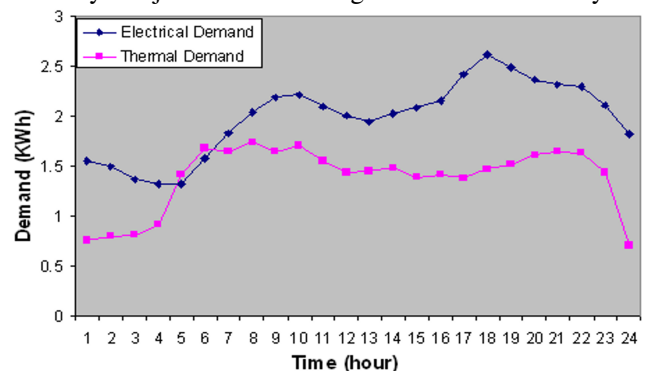


Fig. 7. Demand Profile for Multi-family House in a Summer Day

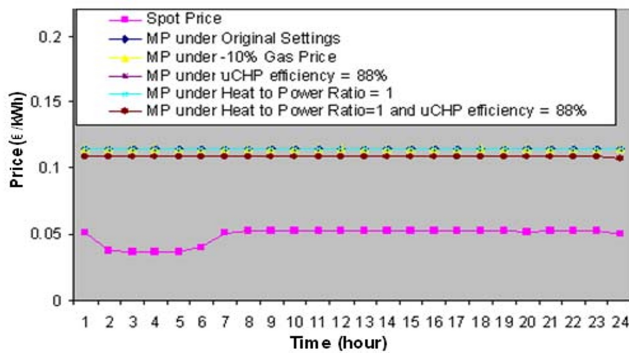


Fig. 8. Marginal Price for Different Scenarios VS Spot Price in a Summer Day

### B. Annual Study

Utilizing the values for parameter given in TABLE II and the annual hourly spot price given in Fig. 9, the optimization process in each day is run through the whole year. Simulated result is given Fig. 10. It shows that such  $\mu$ CHP system can export little electricity in winter and spring. No electricity is exported in summer and fall, since the low heat demand results in relative high marginal prices.

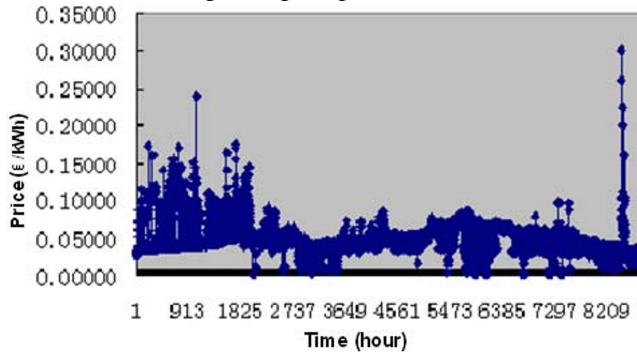


Fig. 9. Hourly Price of NordPool Spot Market in 2006

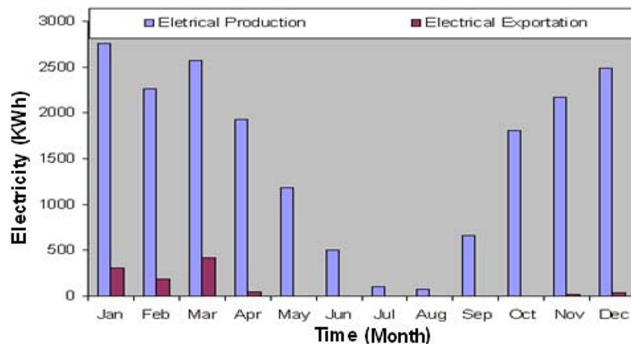


Fig. 10. Annual Electrical Performance of  $\mu$ CHP System under Spot Price

Similar study on the annual electrical performance of  $\mu$ CHP system is done with fixed buyback price. The price is considered to be the average value of spot price, equalizing 0.048€/kWh. As depicted in Fig. 11,  $\mu$ CHP system under such pricing scheme export none electricity to the grid. Although less electricity is produced by  $\mu$ CHP system in such scheme, the annual cost is a little higher than that under the spot price scheme.

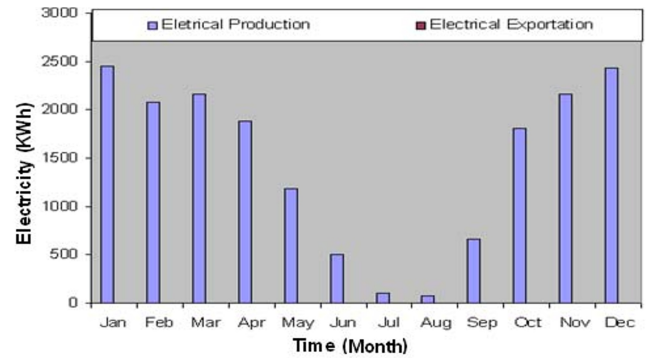


Fig. 11. Annual Electrical Performance of  $\mu$ CHP System under Fixed Price

Table III summarizes the  $\mu$ CHP system performance under different pricing schemes of electricity export. The  $\mu$ CHP system under spot price is found to be with less system cost and more electricity production. In other words, variable export price for electricity may save little for the  $\mu$ CHP owners, but it does incur more exported electricity from such small units. This would ultimately make great contributions to alleviate the inadequacy of electricity supply at critical moments if more  $\mu$ CHP units are deployed efficiently in the power system.

TABLE III  
COMPARISON OF SYSTEM PERFORMANCE UNDER DIFFERENT PRICING SCHEMES

Pricing Scheme	Total Cost (€)	Generated Electricity (kWh)	Exported Electricity (kWh)
Spot Price	4223.6	18521	1037
Fixed Price	4243.6	17484	0

## IV. CONCLUSIONS

This paper investigates the electricity export capability of a  $\mu$ CHP system getting dynamic export price through a Virtual Power Plant. This study provides the foundation for VPP developers and system operators to develop rational pricing schemes, which shall maximize the utilization of DER units in a more efficient way.

Based on the proposed cost-minimized  $\mu$ CHP model, marginal price for electricity export of such system is explained. Case studies demonstrate that the marginal price for a  $\mu$ CHP system is higher than the spot price in most time of the year. However, as the spot price fluctuates dramatically in spring and winter, some electricity can be sold back to the grid in case of a high spot price. In the context of very low heat demand, especially in summer, high marginal price is found when heat dumping is not allowed. The change of marginal price for  $\mu$ CHP systems indicates that such systems would be utilized more efficiently if they were installed at places with high thermal demand during the year.

Variable price for electricity export can exert more electricity from  $\mu$ CHP systems than fixed export price. However, in order to completely use the electricity export capability of  $\mu$ CHP systems especially in summer days, VPP developers may have to develop more effective dynamic pricing schemes rather than using spot price.

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## VI. BIOGRAPHIES

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