Impacts of Time-Varying Electricity Rates on Forward Contract Scheduling of DisCos

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***Abstract*—Time-varying electricity rates enable demand-side potentials, which provide an opportunity for distribution companies (DisCos) to hedge against the financial risk imposed by volatile spot market prices and uncertain customers' load. In particular, time-varying rates can be effective alternatives for at least a portion of costly forward contracts. This paper establishes a stochastic framework to determine optimal forward market purchases under time-varying rates. Various electricity rating strategies with different time intervals covering flat, time-of-use, and real-time pricing schemes are considered. The objective of the framework is to maximize DisCo's expected profit while the exposure risk is restricted to a predetermined level. The risk is modeled using the conditional value at risk approach. The elastic behavior of demand is taken into account via the price elasticity matrix model. The proposed framework is formulated as a mixed-integer linear programming problem which can be easily solved through commercially available solvers. The effectiveness of the developed methodology is examined through comprehensive case studies based on real data from Finland. A detailed comparison on the scheduling of forward contracts under different rating strategies is also provided.**

***Index Terms*—Demand response, distribution company, forward contract scheduling, risk management, stochastic programming, time-varying electricity rate.**

NOMENCLATURE

Indices and Sets:

bl, B	Index and set of time blocks.
d, D	Index and set of days.
h, h', H	Indices and set of hours.
f_b, F_b	Index and set of base-load forward contracts.
f_p, F_p	Index and set of peak-load forward contracts.
ω, Ω	Index and set of spot price and load scenarios.

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Parameters and Constants:

$b_{d,h}^{\text{peak}}$	Binary indicator, 1 if hour h at day d is in peak period, 0 otherwise.
$b_{bl,h}$	Binary indicator, 1 if hour h belongs to time block bl, 0 otherwise.
$E_{h,h'}$	Electricity load elasticity at hour h in response to electricity rate at hour h'.
$L_{\omega,d,h}^{flat}$	Electricity load under flat rating at scenario ω, day d, and hour h.
M	Very large number.
α	Confidence level used in CVaR calculation.
β	Risk weight.
λ_{service}	Service-related part of electricity rate.
$\lambda_{\omega,d,h}$	Electricity rate under RTP rating at scenario ω, day d, and hour h.
λ_{bl}	Electricity rate under TOU rating at block bl.
λ^{flat}	Electricity rate under flat rating.
$\rho_{\omega,d,h}^{\text{spot}}$	Spot price at scenario ω, day d, and hour h.
$\rho_{f_b}^{\text{base}}$	Price of the base-load forward contract f_b.
$\rho_{f_p}^{\text{peak}}$	Price of the peak-load forward contract f_p.
π_ω	Probability of scenario ω.

Functions and Variables:

$b_{f_b}^{\text{base}}$	Binary variable, 1 if base-load forward contract f_b is signed, 0 otherwise.
$b_{f_b}^{\text{peak}}$	Binary variable, 1 if peak-load forward contract f_b is signed, 0 otherwise.
C^{spot}	Expected cost of spot market purchases.
C_ω^{spot}	Expected cost of spot market purchases.
C^{forward}	Total cost of forward purchases.
CVaR	Conditional value at risk.
Rev	Expected DisCo's revenue.
Rev_ω	DisCo's revenue at scenario ω.
Prof	Expected DisCo's profit.
Prof_ω	DisCo's profit at scenario ω.
$L_{\omega,d,h}$	Electricity load at scenario ω, day d, and hour h.

$P_{\omega,d,h}^{\text{spot}}$ Spot purchases at scenario ω, day d, and hour h.

$P_{f_b}^{\text{base}}$ Power purchased from the base-load contract f_b.

$P_{f_p}^{\text{peak}}$ Power purchased from the peak-load contract f_p.

η_ω, ξ Auxiliary variables used in CVaR calculation.

Acronyms:

ARMA Autoregressive moving average.

CVaR Conditional value at risk.

Disco Distribution company.

GAMS General algebraic modeling system.

MILP Mixed-integer linear programming.

PEM Price elasticity matrix.

RTP Real-time pricing.

TOU Time of use.

I. Introduction

MANY distribution companies (DisCos) all over the world buy electricity from competitive spot markets with volatile prices to meet the electricity requirements of their customers. DisCos also sign fixed-price forward contracts to cope with the financial risk associated with volatile spot prices and uncertain loads [1]. Forward contracts, despite their positive impacts on risk mitigation, decrease DisCo's expected profit due to higher average prices. Time-varying rating strategies can be an effective alternative for costly forward contracts.

This paper aims at evaluating the impact of time-varying rating on reliance on expensive forward contracts. This paper provides an integrated midterm framework for a DisCo to optimally sign forward contracts. Electricity-rating schemes considered in this paper include flat, time-of-use (TOU), and real-time pricing (RTP) strategies. The objective of the presented framework is to maximize DisCo's expected profit while exposure risk is restricted to a given level.

A. Approach

The presented framework is based on scenario-based stochastic programming [2]. Uncertainty on spot price and load is considered through the time-series auto-regressive moving-average (ARMA) approach [3], [4], which enables generating a set of scenarios for upcoming spot prices and loads. The set of scenarios is reduced via a *fast forward* scenario reduction technique to alleviate computational burden.

The developed framework determines spot and forward purchases under various rating strategies so that the expected profit is maximized at a given risk level. Risk is modeled via the conditional value at risk (CVaR) approach which is a popular risk measure in finance [5], [6]. CVaR denotes the expected profit of a given percent of the most severe scenarios. The risk measure is integrated into the developed framework as a constraint which enforces the risk within a reasonable level. Also, it is assumed that customers are price sensitive and their elastic behavior is captured through the price elasticity matrix (PEM) model [7]. The resulting optimization problem is in the mixed-integer linear programming (MILP) format and its solution is efficiently obtained through commercially available software packages [8], [9].

B. Literature Review and Contributions

A brief review of the literature on portfolio optimization of a DisCo, which seeks higher profit as well as lower risk, is discussed here. An analytical approach for the optimal purchase allocation and demand bidding has been developed in [10]. The results show that although the average price of the spot market is lower than that of the forward contracts, the purchase is not fully allocated in spot market when risk is considered. A risk-constrained least-cost problem has been solved in [11] for determining the optimal share of forward contracts and spot market purchases. A midterm portfolio optimization has been developed in [12] with the goal of profit maximization and risk management. A contract portfolio optimization model has been proposed in [13] wherein the multistage stochastic optimization approach is employed to minimize the expected procurement cost subject to a set of risk constraints. A set of Pareto-optimal tradeoffs between the expected cost and exposure risk has been derived in [14] for a DisCo, which can procure energy from the forward contracts and the spot market. In [15] and [16], a risk-constrained stochastic optimization model has been developed to design energy procurement strategies and selling prices so that the expected profit is maximized at a given risk level. A similar problem has been solved in [17] wherein the resulting nonlinear model is converted into an equivalent MILP problem that can be easily solved through available commercial software. The reviewed studies, despite a tendency toward time-varying rates, have used time-invariant rates.

A stochastic optimization model has been proposed in [18] wherein the contracts on supply and customer sides are designed so that the profit is maximized while risk is maintained at a given level. Although the TOU rating strategy with two different prices for peak and off-peak periods has been employed in [18], elastic behavior of demand in response to selling prices has not been modeled in that paper. A stochastic decision framework to determine the optimal electricity procurement policy and TOU rates has been proposed in [19] wherein the elastic behavior of customers to the TOU rates has also been considered. However, the presented framework is in the mixed-integer nonlinear format that may face convergence problems.

The model presented in this paper is significantly different from any other forward contracting model since: 1) this paper proposes a forward contracting framework for a DisCo under time-varying rates; 2) various electricity rating strategies, including flat, TOU, and RTP schemes are considered in this paper; 3) this paper provides a comprehensive comparison among the impacts of TOU and RTP schemes on DisCo's profit and exposure risk; 4) the elastic behavior of demand in response to time-varying prices is considered in the presented

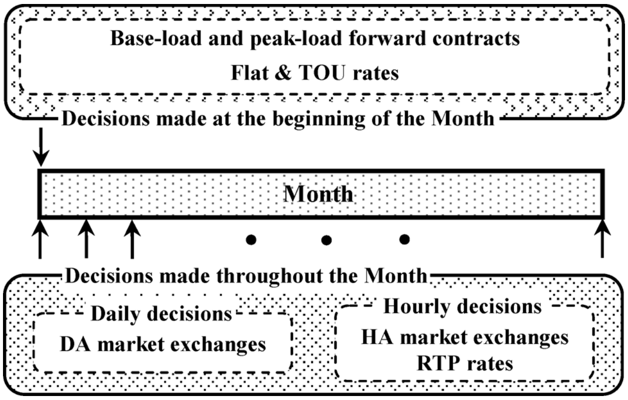

Fig. 1. Monthly decision framework for DisCos.

model; and 5) the developed model is in MILP format in which optimality of the solution is ensured.

C. Paper Organization

This paper is organized as follows. The decision framework, uncertainty characterization, and risk measure are described in Section II. The proposed formulation is presented in Section III. The simulation results are thoroughly discussed in Section IV. Finally, concluding remarks are addressed in Section V.

II. Theoretical Basics

A. Decision Framework

This paper intends to determine the optimal forward contracting decisions for a DisCo under various electricity-rating strategies. The NORDIC electricity market provides market participants with monthly, quarterly, and yearly forward contracts. Without loss of generality, this paper optimizes the decisions over a single month. Meanwhile, forward contracts of the NORDIC market are two fold: base-load contracts (i.e., continuous supply) and peak-load contracts (i.e., continuous supply from 8 A.M. to 8 P.M. on weekdays). Both base-load and peak-load forward contracts are selected and signed at the beginning of the month.

As mentioned heretofore, several rating schemes, including flat, TOU, and RTP strategies are considered in this paper. Clearly, flat and TOU rates are set at the beginning of a month, while RTP rates are set throughout the month on an hourly basis. The decision framework is pictorially shown in Fig. 1. As can be seen, besides the mentioned decisions, the amount of power exchanged in day-ahead and real-time markets is also determined throughout the month. In this figure, the arrows point to the period of decision making (decisions in the upper box are made at the beginning of the month and decisions in the lower box are made frequently within the month). For the sake of simplification, day-ahead and real-time markets are merged into a single market, known as spot market hereinafter.

B. Uncertainty Characterization

A DisCo usually faces two major sources of uncertainty, namely, spot market prices and the customers' load. These uncertainties are taken into account in the proposed framework through the stochastic programming method [2]. In this method, decision variables are determined considering the value of the objective over the set of possible scenarios. Here, a scenario is the sequence of hourly spot prices and loads in the future. A set of possible scenarios is generated through the time-series ARMA model. An ARMA model establishes a linear relationship between the future and past values of the spot prices and loads. The coefficients of the model are obtained so that an acceptable fit to historical data is achieved. Once possible scenarios are generated, the optimization problem is solved such that the expected value of objective over all scenarios is optimized. Since the generated scenarios cover only a small fraction of the possible scenarios for the future, the accuracy of the resulting solution is improved as the number of generated scenarios increases. However, a large number of scenarios may result in a very large optimization problem. This difficulty is tackled in this paper by decreasing the initial set of scenarios to a tractable set via a *fast forward* scenario reduction technique [20]. The fast forward technique iteratively picks the scenarios so that the probability distance between the original and reduced sets is minimized.

C. Risk Measure

Several techniques have been developed for risk management, including minimum variance, value at risk, and CVaR to name just a few [5], [6]. Among them, CVaR has captured the attention of many researchers especially in the context of portfolio optimization of DisCos [15], [17], [19]. In general, CVaR is the expected loss over a series of most severe events within a given confidence interval. In this paper, CVaR is employed to model the DisCo's profit risk imposed by an uncertain spot price and load. Accordingly, CVaR denotes the expected profit among $(1-\alpha)\times$ 100% scenarios with the lowest profit. CVaR can be formulated as

$$\mathrm{CVaR} = \xi - \frac{1}{1-\alpha}\sum_{\omega\in\Omega}\pi_\omega\,\eta_\omega \tag{1}$$

where

$$\eta_\omega - \xi + \mathrm{Prof}_\omega \geq 0;\quad \forall\omega\in\Omega \tag{2}$$

$$\eta_\omega \geq 0;\quad \forall\omega\in\Omega. \tag{3}$$

In (1)–(3), ζ establishes a threshold to identify $(1-\alpha)\times$ 100% of the worst scenarios. Also, η_ω is the difference between ζ and the network operating cost in $(1-\alpha)\times$ 100% of the worst scenarios and zero otherwise. CVaR is integrated into the developed optimization problem as a constraint to restrict the profit exposure risk to a given level.

III. Developed Framework

This section intends to provide a stochastic forward contracting framework for a DisCo under different rating schemes. Here, various rating strategies with different time steps covering RTP, TOU, and flat rating schemes are considered. To do this, at first, a stochastic model for the optimal power portfolio and risk management under RTP rates is presented. Then, the model is revised for the cases of TOU and flat rates.

The objective function is to maximize the expected profit while exposure risk is restricted to a given level. The expected profit is equal to the expected revenue obtained from selling electricity to customers minus the expected cost of electricity procurement. The procurement cost is further broken up into the cost of purchasing energy from the forward contracts and expected spot market cost/revenue. Therefore, complete objective function is described as

$$\text{Maximize} \quad \text{Prof} = \sum_{\omega \in \Omega} \pi_\omega \text{Prof}_\omega \tag{4}$$

where

$$\text{Prof}_\omega = \text{Rev}_\omega - C_\omega^{\text{spot}} - C^{\text{forward}}; \quad \forall \omega \in \Omega. \tag{5}$$

Note that the cost of forward contracts is independent of the scenarios since they are decided at the beginning of the scheduling horizon.

Summing up the revenue in each scenario multiplied by associated occurrence probability over the set of possible scenarios, the expected revenue can be calculated as

$$\text{Rev} = \sum_{\omega \in \Omega} \pi_\omega \text{Rev}_\omega \tag{6}$$

where

$$Rev_\omega = \sum_{d \in D} \sum_{h \in H} L_{\omega,d,h} \lambda_{\omega,d,h}; \quad \forall \omega \in \Omega. \tag{7}$$

The expected spot market cost/revenue is the next term in the objective function. This term involves the expected payments relative to purchasing from the spot market and the expected revenues relative to selling to the spot market. The expected spot cost/revenue is given as

$$C^{\text{spot}} = \sum_{\omega \in \Omega} \pi_\omega C_\omega^{\text{spot}} \tag{8}$$

where

$$C_\omega^{\text{spot}} = \sum_{d \in D} \sum_{h \in H} P_{\omega,d,h}^{\text{spot}} \rho_{\omega,d,h}^{\text{spot}}; \quad \forall \omega \in \Omega. \tag{9}$$

In (9), $P_{\omega,d,h}^{spot}$ can be either positive or negative depending on whether the sum of the forward purchases is either below or above $L_{\omega,d,h}$. The last term in the objective function is the cost of forward purchases. Forward contracts, either base-loads or peak-loads, are characterized by their prices and quantities. For each available forward contract, price is known while quantity is a decision variable in the optimization problem. The cost of purchasing energy from the forward contracts is formulated as

$$C^{\text{forward}} = \sum_{d \in D} \sum_{h \in H} \left[\sum_{f_b \in F_b} P_{f_b}^{\text{base}} \rho_{f_b}^{\text{base}} + \sum_{f_p \in F_p} P_{f_p}^{\text{peak}} \rho_{f_p}^{\text{peak}} b_{d,h}^{\text{peak}} \right]. \tag{10}$$

In competitive electricity markets, the level of the risk borne by DisCos has increased substantially. The extreme volatility of the spot market prices, besides load uncertainties, can result in financial distress of DisCos. This situation has forced DisCos to incorporate risk measures into their decision making and procurement strategy development. As discussed earlier, the risk aversion of DisCo is considered by limiting the profit volatility using CVaR. CVaR can be calculated from (1)–(3). The following constraint is incorporated into the developed model to restrict the profit exposure risk to a given level:

$$\text{CVaR} \geq \beta \times \text{Prof}. \tag{11}$$

Expression (11) prevents the DisCo from purchasing/selling large quantities from/to the volatile spot market, thereby reducing exposure risk. In (11), the risk weight models the tradeoff between DisCo's expected profit and its risk exposure. β can take any value between $(-\infty, 1]$ depending on DisCo's willingness to take risk. A risk-averse DisCo picks a weight close to 1 to hedge against the risk. A risktaker DisCo, on the other hand, selects a small weight in the hope of achieving a higher profit. Since detailed explanation on how to determine an appropriate risk weight is beyond the scope of this paper, its value is assumed to be known here. Interested readers are referred to [5] and [6] for a more detailed explanation on risk determination.

The DisCo is obliged to serve electricity consumption of its customers. The energy balance constraint ensures that the amount of the electricity procured from different options is equal to the customers' demand in each time period and each scenario. The energy balance constraint is as

$$L_{\omega,d,h} = P_{\omega,d,h}^{\text{spot}} + \sum_{f_b \in F_b} P_{f_b}^{\text{base}} + \sum_{f_p \in F_p} P_{f_p}^{\text{peak}} b_{d,h}^{\text{peak}}; \quad \forall \omega \in \Omega, \forall d \in D, \forall h \in H. \tag{12}$$

Forward contracts are usually traded at a minimum contract size. For example, in the NORDIC electricity market, the amount of power traded in each forward contract must be at least one megawatt [21]. Clearly, the amount of power agreed in each forward contract is bounded by an upper limit too. The following constraints guarantee that the amount of power procured from each single forward contract is within the corresponding upper and lower limits,

$$b_{f_b}^{\text{base}} \underline{P_{f_b}^{\text{base}}} \leq P_{f_b}^{\text{base}} \leq b_{f_b}^{\text{base}} \overline{P_{f_b}^{\text{base}}}; \quad \forall f_b \in F_b \tag{13}$$

$$b_{f_p}^{\text{peak}} \underline{P_{f_p}^{\text{peak}}} \leq P_{f_p}^{\text{peak}} \leq b_{f_p}^{\text{peak}} \overline{P_{f_p}^{\text{peak}}}; \quad \forall f_p \in F_p \tag{14}$$

where $\bar{\cdot}$ and $\underline{\cdot}$ mean upper and lower bounds, respectively.

As stated in preceding sections, elastic behavior of customers in response to selling prices is modeled through the PEM model. Price elasticity of the customers' load in each period and each scenario can be formulated as

$$L_{\omega,d,h} = L_{\omega,d,h}^{flat} \times \left(1 + \sum_{h' \in H} E_{h,h'} \frac{\lambda_{\omega,d,h'} - \lambda^{\text{flat}}}{\lambda^{\text{flat}}}\right); \quad \forall \omega \in \Omega, \forall d \in D, \forall h \in H. \tag{15}$$

Note that the elasticity matrix is assumed as an input parameter for the problem proposed in this paper.

The total cost of generating and delivering electricity and, hence, the electricity rates consist of two parts: energy-related costs and service-related costs. The energy-related cost is determined based on the intricate trading activities performed in the wholesale market; hence, it is highly volatile. However, the service-related cost is associated with delivering, metering, and billing services which do not vary throughout time. The service related cost can be modeled via a constant value, that is, λ_{service}. However, the share of energy-related cost depends on the implemented rating strategy. In case of the flat rating scheme, the electricity rate offered to customers is equal to the average cost of energy over the scheduling horizon plus λ_{service} as

$$\lambda^{\text{flat}} = \frac{\sum_{\omega\in\Omega}\sum_{d\in D}\sum_{h\in H}\pi_\omega \rho^{\text{spot}}_{\omega,d,h} L^{\text{flat}}_{\omega,d,h}}{\sum_{\omega\in\Omega}\sum_{d\in D}\sum_{h\in H}\pi_\omega} + \lambda_{\text{service}}. \tag{16}$$

On the other hand, when RTP strategy is applied, the energy-related part reflects the spot market prices. So, it is assumed that hourly spot prices plus λ_{service} are offered to the customers as

$$\lambda_{\omega,d,h} = \rho^{\text{spot}}_{\omega,d,h} + \lambda_{\text{service}}; \quad \forall\omega\in\Omega, \forall d\in D, \forall h\in H. \tag{17}$$

It is worth mentioning that the considered pricing strategy is a pure RTP wherein the total risk of the uncertain spot prices is imposed to customers. There are also several combined pricing strategies wherein the customers pay flat or time-of-use prices for a portion of their demand and settle the other portion based on varying real-time prices. These pricing strategies are generally referred to as the multiple-part RTP. Evidently, multiple-part RTP prices are more desirable for risk-averse customers. A detailed description on multiple-part RTP prices can be found in [22].

The optimization problem described by (1)–(17) is of MILP type and can be effectively solved via available commercial software packages. In this optimization problem, decision variables include the forward contract agreements and spot market purchases.

So far, an MILP-based model for selecting the optimal forward contracts under the RTP rates was developed. In the following text, the presented model is converted to the optimal forward contracting models under flat and TOU rating strategies by slight modifications.

A. *TOU Rating Strategy*

The RTP scheme is an ideal option since it effectively ties the retail rates to the fluctuating wholesale prices. However, the high cost of installation of a system for communicating real-time rates to customers and the lack of knowledge among customers are major barriers to implement the RTP scheme which makes it impossible in many areas. As an alternative, the TOU scheme divides daytime into two or three time blocks, each of which the electricity rate is proportional to the average cost of generating and delivering power during the respective time periods. TOU rates are determined at the beginning of the scheduling horizon and are valid in all of the days during the horizon. The proposed formulation can be easily converted to a case in which the rates are based on the TOU scheme by considering the following constraints:

$$\lambda_{\omega,d,h} = \sum_{bl\in B} b_{bl,h}\lambda_{bl}; \quad \forall\omega\in\Omega, \forall d\in D, \forall h\in H \tag{18}$$

$$\lambda_{bl} = \frac{\sum_{\omega\in\Omega}\sum_{d\in D}\sum_{h\in H}\pi_\omega b_{bl,h}\rho^{\text{spot}}_{\omega,d,h}}{\sum_{\omega\in\Omega}\sum_{d\in D}\sum_{h\in H}\pi_\omega b_{bl,h}} + \lambda_{\text{service}}; \quad \forall bl\in B \tag{19}$$

where $b_{bl,h}$ equals 1 if hour h belongs to the time block bl and 0 otherwise. Since the electricity rating is not the aim of this paper, $b_{bl,h}$ for all hours and time blocks is assumed to be known. The reformulated version of the optimization problem is still in the MILP format and can be effectively solved via commercially available software packages.

B. *Flat Rating Strategy*

In the flat scheme, the electricity rate offered to customers does not vary during the horizon. The flat rate is equal to the average cost of energy plus the service-related cost. Therefore, the proposed model can be easily converted to a case wherein the rates are based on the flat rating scheme via taking into account the following constraint:

$$\lambda_{\omega,d,h} = \lambda^{\text{flat}}; \quad \forall\omega\in\Omega, \forall d\in D, \forall h\in H. \tag{20}$$

Again, the model is in the MILP format since (20) is linear.

IV. Numerical Study

A. *Input Data*

The performance of the developed framework is illustrated via a case study based on real data from Finland. Here, the focus is on the monthly forward contracting of a DisCo which serves an urban distribution network with a maximum load of 9.4 MW [23]. The decisions made in the following text are on the basis of the offered forward contracts, electricity price, and load in October 2012. The considered DisCo is a price-taker who has no market power. Synonymously, the DisCo's activities do not influence spot and forward markets' prices.

The spot price and load uncertainties are modeled through the scenarios generated using the time-series ARMA approach. The coefficients of the models are estimated via the historical data from January 2010 to December 2011 [24]. Once the models are achieved, two sets of 1000 scenarios are generated for the hourly spot prices and electricity loads within October 2012. To alleviate computational burden, the price and load scenarios are, respectively, reduced to 100 and 10 scenarios. The final price and load scenarios for a typical day are shown in Figs. 2 and 3, respectively. In these figures, black lines represent the expected values.

Combining 100 price scenarios and 10 load scenarios, a joint scenario set of 1000 scenarios is achieved. Note that the probability of each resulting scenario is equal to the product of occurrence probability of the respective price and load scenarios. These scenarios are considered as input data for the following simulations.

To capture the elastic behavior of load in response to the time-varying rates, the self-elasticity and cross-elasticity coefficients of the PEM matrix are set to -0.2 and 0.0087, respectively [7].

The energy-related parts of the electricity rates are determined by considering the generated price scenarios. The service-related part is also set to 20 Euros/MWh. Table I

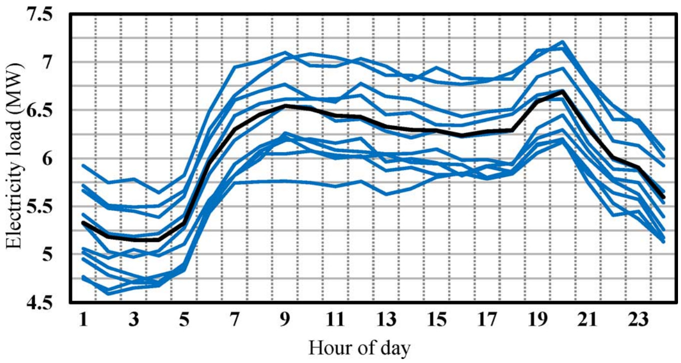

Fig. 2. Scenarios obtained for hourly customers' loads in a typical day.

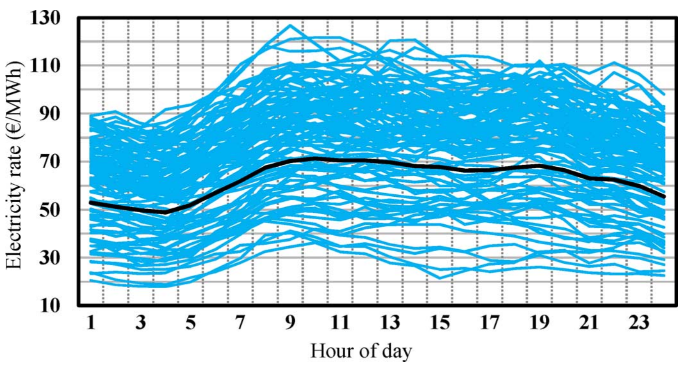

Fig. 3. Scenarios obtained for hourly spot market prices in a typical day.

TABLE I
ELECTRICITY RATES UNDER FLAT AND TOU RATING SCHEMES

Pattern	Period	TOU rate [€/MWh]	Flat rate [€/MWh]
On-peak	7am-8pm	67.1779	
Shoulder	5am-7am 8pm-12am	59.8752	59.7736
Off-peak	12am-5am	53.1390	

provides the information on the electricity rates offered to customers under flat and TOU rating schemes.

Although base-load and peak-load forward contracts are possible in the NORDIC electricity market, almost all forward exchanges are in the form of base-load contracts. Accordingly, only a base-load contract with the price of 44.74 Euros/MWh is considered in the simulations. This price is selected based on the forward contracts offered for October 2012. The lower bound of the considered contract is set to 1 MW.

The confidence level is set to 0.95. The MILP problem formulated earlier is solved via the general algebraic modeling system (GAMS) environment on a 2.53-GHz processor with 2-GB RAM.

B. Simulation Results

This section quantifies the impacts of different rating strategies on DisCo's forward decisions.

1) Flat Rating Strategy: This case is a comparison benchmark to demonstrate the impacts of applying time-varying rates. In this case, customers pay the same rate for the electricity they

TABLE II
FLAT RATING STRATEGY: PROCUREMENT STRATEGY

Risk weight	Forward purchase [MWh]	Expected spot purchases [MWh]
0.2	1746.9	2649.2
0.4	2381.8	2014.3
0.6	2960.9	1435.2
0.8	3492.0	904.1

TABLE III
FLAT RATING STRATEGY: FINANCIAL ASPECTS

Risk weight	Expected revenue [€]	Expected cost [€]	Expected profit [€]	CVaR [€]
0.2	236 689	168 487	68 202	13 640
0.4	236 689	171 641	65 048	26 019
0.6	236 689	174 517	62 173	37 304
0.8	236 689	177 154	59 535	47 628

consume at any time and, therefore, they have no monetary incentive to modify their usage profile. Table II gives the DisCo's procurement strategy for different risk weights.

According to the results, the reliance on forward contracts increases as concern over risk increases. In contrast, the share of spot market purchases decreases with increasing the value of risk weight. For example, the share of forward purchases increases by 35% when the risk weight is increased from 0.2 to 0.4.

Table III provides the financial aspects of the procurement strategies given in Table II. As can be seen, expected revenue remains unchanged for different risk weights while the expected cost increases as the weight increases. This is because of the higher average price of forward contracts which are preferred more when larger risk weights are selected. Accordingly, the expected profit earned by the DisCo decreases as its concern on the risk and, hence, its reliance on forward contracts increases. Despite their negative impacts on expected profit, forward contracts are effective in risk management since profit-exposure risk decreases significantly as the share of forward purchases increases.

2) TOU Rating Strategy: This case simulates a situation in which the TOU rates with three blocks (given in Table I) are offered to customers. The resulting procurement strategies are given in Table IV. Similar to the first case, promotions of the forward and spot purchases are increasing and decreasing with risk weight. However, the amount of energy procured from the forward market is slightly lower in this case compared to that of the first case. For instance, applying the TOU rates has reduced the forward purchases by about 5.78% when the risk weight is 0.2.

The financial aspects of the aforemetioned procurement strategies are given in Table V. Owing to the results, reliance on the spot market decreases as concern on risk increases, resulting in lower expected profit and exposure risk. It is interesting to see the DisCo benefits from the TOU rates since the expected profit is increased and the exposure risk is decreased.

3) RTP Rating Strategy: In this case, the DisCo releases the electricity rates on the basis of the RTP scheme wherein upcoming prices are announced for one hour ahead of time.

TABLE IV
TOU RATING STRATEGY: PROCUREMENT STRATEGY

Risk weight	Forward purchase [MWh]	Expected spot purchases [MWh]
0.2	1666.2	2729.9
0.4	2321.9	2074.2
0.6	2919.7	1476.4
0.8	3467.8	928.3

TABLE V
TOU RATING STRATEGY: FINANCIAL ASPECTS

Risk weight	Expected revenue [€]	Expected cost [€]	Expected profit [€]	CVaR [€]
0.2	237 994	167 563	70 432	14 086
0.4	237 994	170 819	67 175	26 870
0.6	237 994	173 788	64 206	38 524
0.8	237 994	176 510	61 484	49 187

TABLE VI
RTP RATING STRATEGY: PROCUREMENT STRATEGY

Risk weight	Forward purchase [MWh]	Expected spot purchases [MWh]
0.2	0	4396.1
0.4	0	4396.1
0.6	0	4396.1
0.8	0	4396.1

Since the rates are more dynamic compared to those of the TOU scheme, demand response is expected to be more effective in this case. The electricity procurement strategies under the RTP rating associated with different risk weights are given in Table VI. As can be seen, DisCos prefer to procure their electricity needs only from the spot market when the RTP rates are offered to customers. The key explanation for this observation is that the RTP rates put the entire risk of volatile spot prices on customers and, hence, the DisCo is no longer forced to sign the expensive forward contracts. As mentioned earlier, the considered pricing strategy is a pure RTP wherein the total risk of the wholesale price uncertainties is born by customers. Multiple-part RTP schemes may enable balancing the risk between customers and DisCos in a fair manner.

Table VII presents the financial aspects of the mentioned procurement strategies. Clearly, the DisCo's revenue, cost, profit, and exposure risk are independent of the risk weight since the respective procurement strategies are exactly the same. Owing to the results, application of the RTP rates leads to significant benefits for the DisCo in both the expected profit and exposure risk. It can be seen that the expected profit earned by the DisCo increases by 15.94% when the risk weight is set to 0.2. Such an increment in profit along with negligible risk level provides great incentives for DisCos to offer RTP rates.

The DisCo profit for various risk weights in different cases is shown in Fig. 4. Comparing the expected profit associated with different cases reveals that, with a given risk weight, the expected profit obtained via the flat scheme is less than that obtained through the TOU scheme, and the profit earned by using the TOU rates is much lower than that achieved via the RTP rates. This observation is the direct result of the DisCo's reliance

TABLE VII
RTP RATING STRATEGY: FINANCIAL ASPECTS

Risk weight	Expected revenue [€]	Expected cost [€]	Expected profit [€]	CVaR [€]
0.2	237 910	158 839	79 071	71 589
0.4	237 910	158 839	79 071	71 589
0.6	237 910	158 839	79 071	71 589
0.8	237 910	158 839	79 071	71 589

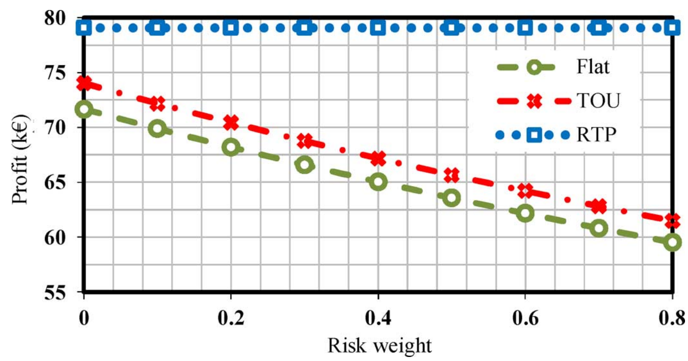

Fig. 4. Expected profit for various risk weights and different rating schemes.

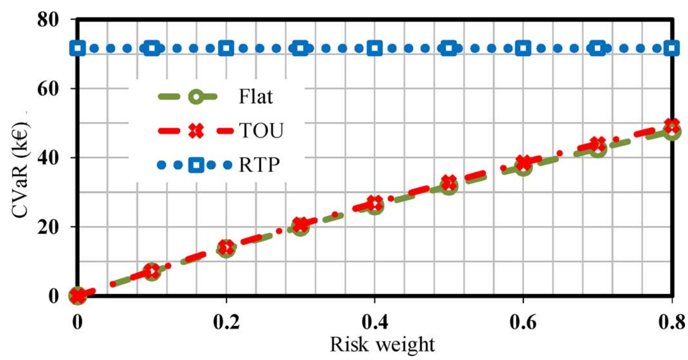

Fig. 5. CVaR for various risk weights and different rating schemes.

on forward purchases when the flat and TOU rates are offered. The other point deserving a specific emphasis is that as concern on risk (risk weight) increases, the superiority of the RTP scheme increases. This is due to the fact that the Disco's reliance on forward purchases increases as the risk weight increases.

Fig. 5 depicts CVaR for various risk weights in different cases. Note that there is an inverse relationship between the exposure risk and CVaR. As can be observed, the DisCo's profit exposure risk decreases as the risk weight increases when the flat and TOU rates are implemented while the risk remains unchanged when the RTP scheme is applied. This is due to the reason that the RTP rates put the total risk of uncertain spot prices on customers. Another key point is that the changes in the DisCo's profit exposure risk caused by applying the TOU rates are negligible. This is due to the fact that TOU rates are determined at the beginning of the scheduling horizon and they cannot respond to spot price variations during the horizon.

Fig. 6 shows the required forward purchases for various risk weights in different cases. As can be seen, implementing the flat and TOU rates, the amount of required forward purchases increases by increasing the risk weight. However, the DisCo requires no forward purchase when the RTP rates are offered to

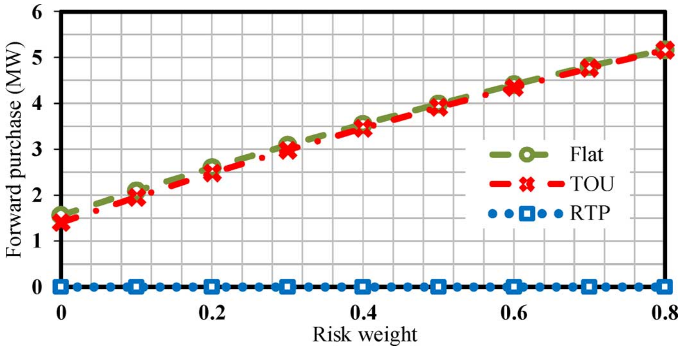

Fig. 6. Forward purchases for various risk weights and different rating schemes.

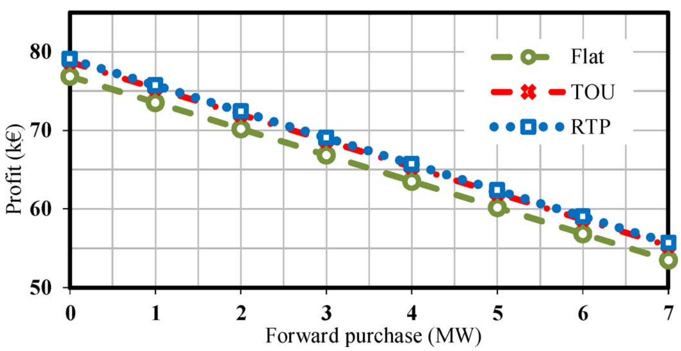

Fig. 7. Expected profit for various forward purchases and different rating schemes.

customers. This is due to the fact that TOU rates are released several months earlier and, hence, they are unable to capture spikes in spot prices. In contrast, by employing the RTP scheme, the level of risk born by DisCos and, hence, forward purchases is negligible since hourly electricity rates reflect hourly spot prices.

The expected profit earned by the DisCo for various forward purchases in different cases is illustrated in Fig. 7. As can be seen, the application of the TOU and RTP rates result in almost identical profits while the flat rating strategy leads to lower profits. This figure emphasizes that the application of TOU rates increases the expected profit earned by DisCos.

Fig. 8 depicts the CVaR associated with different forward purchases in various cases. As can be seen, the application of flat and TOU rates results in almost identical outcomes. In these cases, CVaR exhibits a surprising behavior. It increases as the forward purchases increase from 0 to about 5.5 MW. Thereafter, CVaR decreases again as the forward purchases increase. This is due to the fact that the DisCo has to sell surplus power in the spot market with volatile prices. So it can be concluded that relying too much on forward purchases has negative impacts on the expected profit and exposure risk. Indeed, it can be observed in Figs. 7 and 8 that forward contracts are improper for a DisCo which offers RTP electricity rates to customers.

C. Accuracy Verification

The determination of the number of required scenarios is a challenging issue in scenario-based stochastic programming approaches. Too few scenarios might lead to inaccurate results,

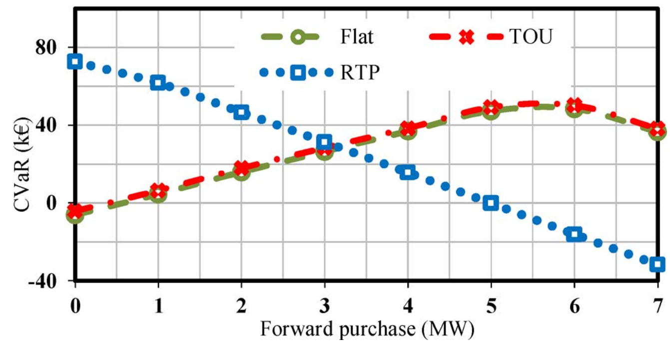

Fig. 8. CVaR for various forward purchases and different rating schemes.

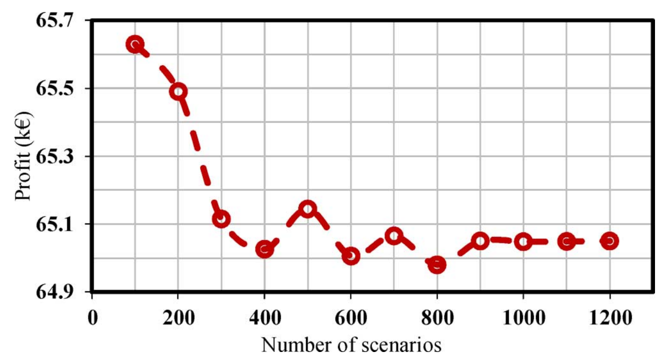

Fig. 9. Evolution of the expected profit versus the number of scenarios.

while too many scenarios may make the problem computationally infeasible. To overcome this issue, the number of adopted scenarios is usually determined through engineering judgments. Evolution of the expected profit versus the number of scenarios under the flat rating scheme when the risk weight is set to 0.4 is plotted in Fig. 9. As can be seen, the expected profit stabilizes in the vicinity of 900 scenarios. Therefore, the accuracy of the results provided in this paper is guaranteed.

V. Conclusion

This paper addressed the forward contracting problem faced by a DisCo under various rating strategies covering flat, TOU, and RTP schemes. The problems were formulated based on the MILP fashion since commercially available solvers guarantee optimality of solutions. The models were applied to a case study based on real data from Finland. The numerical study provided a detailed comparison among the DisCo's revenue, profit, and exposure risk under different rating schemes. Owing to the results, RTP rates provide significant benefits to DisCos. The results emphasize that DisCos no longer require costly forward contracts if they offer RTP rates to customers. The application of RTP rates results in higher profits and much lower exposure risks. This observation is due to the fact that RTP rates put the entire risk of volatile spot prices on customers. However, the benefits provided by the TOU rating scheme are very limited compared to RTP rates. The application of TOU rates results in higher profits but it has no significant impact on exposure risk. The amounts of forward purchases required for risk management are almost identical when electricity rates are based on flat and TOU rating schemes.

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