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Fair pricing of REDD-based emission offsets under risk preferences and benefit sharing

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Abstract

We consider risk-aware forest owners and electricity producers evaluating the Reduced Emissions from Deforestation and Degradation (REDD)-based offsets with a benefit-sharing mechanisms under uncertain CO_2 prices. For a range of CO_2 prices and respective risks perceived by the forest owner (seller) and electricity producer (buyer), we apply a model of fair (indifference) pricing. Parties' risk preferences are reflected by exponential utility functions. The potentially contracted amounts of REDD offsets are analyzed under various risk preferences and for different benefit sharing opportunities. Our results show that a risk-averse attitude considerably increases the contracted amounts of REDD offsets (compared to risk-neutral case) and, therefore, creates a higher potential for REDD implementation. We demonstrate possible situations, when parties could agree on a certain range of REDD contracts, *e.g.* smaller amounts of REDD offsets are traded for higher prices, and larger amounts – for lower prices, although contracting a moderate amount at a moderate price is impossible. The suggested benefit sharing mechanism can help increase contracted offset amounts. Our modeling results highlight two ways to promote higher REDD participation: (i) increasing risk aversion of the energy producers, and (ii) implementing the mechanism of benefit/risk sharing between the REDD consumer and supplier.

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1 Introduction

This paper elaborates on the development of financial instruments that support Reduced Emissions from Deforestation and Degradation (REDD) [1, 2, 3]. In the papers [4, 5] decision-making of the price-taking electricity producers consists of choosing between investing in research and development (R&D) to implement new technologies (carbon capture and storage (CCS) modules) and buying REDD options. We explore a similar idea of employing REDD for offsetting emissions of electricity producers by setting a new problem with a few distinctive features. Firstly, we consider the case when an energy producer has a market power – the ability to reduce production output and charge higher electricity prices to consumers. Thus, in the face of uncertain CO_2 prices the electricity producer with market power has more flexibility compared to the price-taking energy producer. Secondly, the electricity producer in our model is a medium-term decision maker: he does not change his technology portfolio by decommissioning CO_2-intensive plants and building new power plants (which would be a long-term investment). The optimization model works with two time steps: initial (low) CO_2 price and future (uncertain) CO_2 price. This simplified rather conceptual modeling approach is justified, because a dynamic model would require additional information about the future which is not available at the moment: CO_2 price formation process, REDD offsets acceptance on the market, etc. For the same reason we focus on the direct contracting of REDD offsets between the forest owner and electricity producer, and do not consider market modeling.

We construct a microeconomic model of interaction between the forest owner (REDD supplier), electricity producer (REDD offsets consumer), and electricity consumer. In the proposed partial equilibrium modeling framework CO_2 prices are exogenous and uncertain. The decision-making process of the electricity producer (under a condition of an existing or absent CO_2 tax/price) consists of (see, *e.g.*, [6, 7]): (i) choosing power plant load factors to minimize the cost given the hourly electricity demand profile and installed capacities of particular power generation technologies; and (ii) choosing an electricity price to maximize the profit based on the demand function indicating consumers' sensitivity to electricity prices.

The electricity producer in the model has market power meaning that he has the possibility of setting a price for electricity above his marginal cost according to a demand function. Recent studies suggest that energy companies possess a certain degree of market

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power [6, 8, 9]. We apply a constant elasticity demand function [10] in the model. The elevating CO_2 price might impact not only the profits of the electricity producer (decrease), but also the electricity prices for the consumer (increase), and, hence, some financial instruments might be implemented today in order to be prepared for the uncertain CO_2 prices in the future [3]. We propose and explore financial instruments supporting the REDD program. On the supply side of the REDD-based emission offsets we model a forest owner who decided to preserve the forest and sell respectively generated REDD-based emission offsets (further – REDD offsets). The focus of our analysis is on how the forest owner and the electricity producer evaluate their *fair prices* for different amounts of REDD offsets. In the paper the fairness of the price is understood in the sense of parties' indifference of whether to engage in contracting a given amount of REDD offsets or not. The *fair price* of the electricity producer (forest owner) means that for a higher (lower) price the electricity producer (forest owner) will not want to engage in the contract. In case the parties can agree on a *fair price*, the problem is to find a range of REDD offsets' amounts which can be contracted.

Risk preferences play an important role in the model of fair pricing. Here we employ exponential utility functions to reflect parties' risk attitudes. The exponential utility admits all types of *risk preferences*: risk-taking, risk-neutral, and risk-averse.

The idea of benefit sharing is important within the REDD context [11]. We propose a *benefit sharing mechanism* that is activated in the case when electricity producer emits less than the amount of REDD offsets contracted in the first period (without CO_2 price); in this case the unused amount of REDD offsets is shared with the forest owner.

The paper considers mathematical constructions and properties of a proposed financial instrument. Analytical results presented in the paper are illustrated by a numerical case study based on realistic data for regional electricity production. Modeling results show how *risk preferences* of the electricity producer and forest owner, combined with the *benefit sharing mechanism*, impact the *fair prices* and contracted amounts of REDD offsets. Our key findings signal that higher REDD participation can be achieved through increasing the parties' risk aversion and activating the benefit sharing mechanism.

2 Modeling Framework

In this section, firstly, we present a model of an electricity producer with market power operating without contracting REDD offsets. The decision-making of the electricity producer consists in choosing a technological mix in order to meet the hourly demand and to maximize profit. The optimal response in terms of emissions' reduction and raising electricity prices is constructed for any future CO_2 price. Secondly, we introduce a two-period model for REDD offsets contracting. Given the distribution of uncertain CO_2 prices in the second period, the electricity producer solves in the first period the problem of expected profit maximization for various amounts of contracted REDD offsets. In general, the electricity producer maximizes utility – a function of his profits. In our study we apply the exponential utility function, that fits well with our modeling framework. In the first time period, based on the comparison of maximum expected utilities with and without contracting REDD offsets, the electricity producer evaluates his *fair (indifference) price* for each amount of offsets that they could potentially buy. Similarly, the forest owner – the seller of REDD offsets – calculates his *fair price*, based on the exponential utility reflecting his risk preferences. We also introduce the benefit sharing mechanism and solve the optimization problem of the electricity producer, who has two options: either (i) to emit more than available REDD offsets purchasing the CO_2 offsets on the market to cover excess of their emissions, or (ii) to emit less and share the benefits from selling the excess of offsets at a market price with the forest owner.

2.1 Notations

In our model the electricity producer uses n technologies varying in costs (US$/MWh, excluding emission costs) and emission factors (ton of CO_2/MWh). Let us introduce the following notations:

$a_i, i = 1, .., n$ are installed capacities (MW);

v_i are variable costs (US$/MWh);

$d_j, j = 1, .., 24$ is hourly average demand (MW);

$\boldsymbol{x} = \{x_{ij}\}, i =, 1.., n,\ j = 1, .., 24,$ is a matrix of hourly load factors (controls, ratio between 0 and 1);

$\boldsymbol{q}(\boldsymbol{x}) = (q_1, ., q_{24}) = \{\sum_{i=1}^{n} a_i x_{ij}\}$ is a vector of hourly outputs (MW);

$Q = Q(\boldsymbol{x}) = \sum_{i=1}^{n} a_i \sum_{j=1}^{24} x_{ij}$ is aggregate daily production (MWh);

P^e is electricity price (US$/MWh);

$D^{-1} : P^e = D^{-1}(Q)$ is inverse demand function (see Section 3.1);

ε_i are emission factors (ton of CO_2/MWh);

p is CO_2 price (US$/ton of CO_2).

2.2 Model description

For each matrix of load factors $\boldsymbol{x}$ the profit of the electricity producer in the absence of CO_2 price is calculated as follows:

$$\Pi_e(\boldsymbol{x}) = R(\boldsymbol{x}) - C(\boldsymbol{x}), \tag{1}$$

where

$$R(\boldsymbol{x}) = P^e\big(Q(\boldsymbol{x})\big)Q(\boldsymbol{x}), \tag{2}$$

is the revenue, and

$$C(\boldsymbol{x}) = \sum_{i=1}^{N} v_i a_i \sum_{j=1}^{24} x_{ij} + F_c, \tag{3}$$

is the cost function. A constant fixed cost component, F_c, is not included in the optimization problem, and is used only for profit calculation.

For each CO_2 price p a production scenario $\boldsymbol{x}$ generates corresponding emissions:

$$E(\boldsymbol{x}) = \sum_{i=1}^{n} \varepsilon_i a_i \sum_{j=1}^{24} x_{ij}, \tag{4}$$

and the total profit of the electricity producer is calculated as follows:

$$\Pi(\boldsymbol{x}, p) = \Pi_e(\boldsymbol{x}) - E(\boldsymbol{x})p. \tag{5}$$

We will assume that the CO_2 price belongs to a segment $p \in [0, \tilde{p}]$. Let us note that profit component Π_e and emissions E do not directly depend on price p, however, they are indirectly determined by the technological possibilities of the electricity producer.

We assume that hourly profile changes proportionally to the aggregate demand (see [3] and section 3.1 for details) and introduce the feasibility domain $\boldsymbol{X}$, which contains all technological mixes (controls) satisfying the hourly demand:

$$\boldsymbol{X} = \{\boldsymbol{x} : x_{ij} \in [0, 1] \quad \text{and} \quad \boldsymbol{q}(\boldsymbol{x}) \geq \frac{Q(\boldsymbol{x})}{Q^0}\boldsymbol{d^0}\}, \tag{6}$$

where $\boldsymbol{d^0} = (d_1^0, .., d_{24}^0)$ and Q^0 are, respectively, the initial hourly and daily aggregate demands (at zero CO_2 price).

For convenience, let us first consider the electricity producer as a profit maximizing decision maker, and afterwards introduce his utility (as a function of profit). The profit maximization problem is formulated as follows.

Problem 1 (without REDD offsets)**.** *Given the feasibility domain* $\boldsymbol{X}$ *(6), for every* CO_2 *price* p *the electricity producer maximizes his profit (5):*

$$\underset{\boldsymbol{x}\in\boldsymbol{X}}{\text{maximize}}\,\Pi(\boldsymbol{x}, p). \tag{7}$$

Let us denote a solution to the Problem 1 – the optimal technological mix – by the symbol $\boldsymbol{x_1^*} = \boldsymbol{x_1^*}(p)$ for any price $p \in [0, \tilde{p}]$. Then, by definition of $\boldsymbol{x_1^*}$ for any $\boldsymbol{x} \in \boldsymbol{X}$ (6) the following inequality holds:

$$\Pi(\boldsymbol{x_1^*}, p) \geq \Pi(\boldsymbol{x}, p). \tag{8}$$

Let us denote by the symbol $\hat{\Pi}(p)$ the maximum profit at price p:

$$\hat{\Pi}(p) = \Pi(\boldsymbol{x_1^*}(p), p) = \Pi_e(\boldsymbol{x_1^*}(p)) - E(\boldsymbol{x_1^*}(p))p. \tag{9}$$

The corresponding electricity price is calculated as $P^e(Q(\boldsymbol{x_1^*}(p))$.

2.3 Assumptions for modeling

In our study we assume the following properties of optimal profit $\hat{\Pi}(p)$ (9) and emissions $\hat{E}(p) = E(\boldsymbol{x_1^*}(p), p)$ with respect to CO_2 price.

Assumption 1. *The optimal profit and optimal emissions achieve their maxima at zero* CO_2 *price,* $p = 0$*, and are continuous strictly declining functions with respect to growing* p*:*

$$\hat{\Pi}(p) \downarrow, \quad \hat{E}(p) \downarrow, \quad \textit{when} \quad p \uparrow. \tag{10}$$

This assumption is straightforward in the provided modeling framework as the power generation technologies are fixed (see also [3]). It is consistent with the results of larger scale modeling [12] in the short and medium term.

Remark 1. *Assumption 1 basically restricts the consideration of electricity producers to those unfavorably (negatively) affected by an emerging* CO_2 *price. Those who can potentially benefit from it, e.g. due to a competitive advantage, are not considered here. This situation is beyond the scope of this paper, which is focused on the problem of* CO_2*-intensive power generation.*

2.4 Modeling REDD-based offsets under uncertainty

High CO_2 price decreases the profit of the electricity producer. This negative effect as such can be amplified by uncertainty about the future CO_2 price levels and lead to an excessive risk. To hedge against that the emitter can engage in contracting REDD offsets before the information about CO_2 price is revealed, so that contracted REDD offsets could allow offsetting CO_2 emissions in the future. Let us note that we are not taking into account additional factors in the payoff of a REDD supplier (forest owner), *e.g.* opportunity of deforesting and selling the wood. We assume that the forest owner decided to keep the forest for generating REDD offsets.

Let the future CO_2 price be an uncertain variable [13] following a discrete probability distribution:

$$\{p_l, w_l\}, \quad l = 1,..,m, \quad \sum_{l=1}^{m} w_l = 1, \quad p_l \in [0, \tilde{p}], \quad w_l \in (0, 1], \tag{11}$$

where w_l stands for probability, and realizations of possible prices are $p_i \neq p_j$, if $i \neq j$.

A problem is divided into two stages (time periods): in the first stage the forest owner and electricity producer negotiate an amount $\mathcal{E} \in (0, E^0]$ of REDD offsets and their price. Here E^0 is the maximum amount of emissions – generated by the electricity producer at zero CO_2 price, *i.e.* $E^0 = \hat{E}(0)$.

In the second stage they face the realization of uncertain CO_2 prices. At each realization of the CO_2 price the electricity producer can either use all REDD offsets (by emitting more or equal to the previously contracted amount $\mathcal{E}$), or emit less than $\mathcal{E}$ and share the benefit with the forest owner from selling the rest (unused offsets) on the market (at a market price p).

Benefit sharing mechanism The electricity producer and forest owner, when selling offsets on the market, get shares of the market price δ and $(1 - \delta)$ respectively, so that:

- If $\delta = 1$, the electricity producer has the right to sell the offsets in the second period at a market price without sharing the profit with forest owner.
- If $\delta = 0$, the electricity producer can only use the contracted REDD credits to offset the factual amount of his emissions and the unused credits are returned (without compensation) back to the forest owner, *i.e.* no resale by the electricity producer is possible on the market. The profit from unused offsets goes entirely to the forest owner.
- If $0 < \delta < 1$, the electricity producer faces a trade-off between emitting more and, hence, using more of the contracted REDD credits for offsetting their emissions versus sharing the profit with the forest owner from selling the offsets at the market price.

The *benefit sharing ratio* δ is included in the negotiation process between REDD-offsets supplier (forest owner) and consumer (electricity producer) along with the amount of offsets $\mathcal{E}$ and their price.

We assume that the forest owner and electricity producer face the same CO_2 price distribution. The presence of REDD offsets at the second stage of the model leads to the following modification of the Problem 1 (the case without REDD).

Problem 2 (with REDD offsets)**.** *Given the feasibility domain* $\boldsymbol{X}$ *(6),* CO_2 *price distribution* $\{p_l, w_l\}$ *(11), benefit sharing ratio* $\delta \in [0, 1]$*, and amount of REDD offsets* $\mathcal{E} \in (0, E^0]$ *contracted in the first time period the electricity producer solves in the second time period the following profit-maximization problem for every possible future* CO_2 *price* p_l*:*

$$\underset{\boldsymbol{x} \in \boldsymbol{X}}{\text{maximize}}\, \Pi^R(\boldsymbol{x}, p_l), \tag{12}$$

where

$$\Pi^R(\boldsymbol{x}, p_l) = \Pi_e(\boldsymbol{x}) - p_l \big[E(\boldsymbol{x}) - \mathcal{E}\big]_+ + \delta p_l \big[\mathcal{E} - E(\boldsymbol{x})\big]_+. \tag{13}$$

Here $[y]_+ = \max\{y, 0\}$, meaning that the electricity producer can offset his emissions up to the amount $\mathcal{E}$ by using REDD offsets, the rest is sold on the market and the profit is shared with the forest owner.

The optimal technological mix $\boldsymbol{x}_2^*(p_l)$ – solution to (12) – generates the maximum profit with REDD:

$$\hat{\Pi}^R(p_l) = \Pi^R(\boldsymbol{x}_2^*(p_l), p_l), \tag{14}$$

at a particular CO_2 price p_l. We denote by the symbol:

$$E^R(p_l) = \left[\mathcal{E} - E(\boldsymbol{x}_2^*(p_l))\right]_+, \tag{15}$$

the corresponding amount of unused emission offsets that have to be sold on the market generating the profit (to be shared).

2.5 Modeling risk preferences of forest owner and electricity producer

We model *risk preferences* by implementing utility functions. Let us denote by the symbol U_F the utility of the forest owner, and by the symbol U_E – electricity producer's utility. In our model utilities are functions of profits:

$$U_E = U_E(\Pi_E), \quad U_F = U_F(\Pi_F). \tag{16}$$

Here symbol Π_F stands for the profit of the forest owner from selling REDD offsets (to be specified in more detail in section 2.5.2), and Π_E is the profit of electricity producer: $\Pi_E = \Pi$ as in (5) without REDD, and $\Pi_E = \Pi_R$ (13) with REDD. In this paper we deal with exponential utility functions. Thus, electricity producer's utility is given by the function:

$$U_E(\Pi_E) = (1 - e^{-\alpha \Pi_E})/\alpha, \tag{17}$$

where α is a constant parameter that represents the degree of *risk preference*: $\alpha > 0$ for *risk-aversion*, and $\alpha < 0$ for *risk-taking*. Applying L'Hôpital's rule, one can show the following asymptotic property:

$$\lim_{\alpha \to 0} \frac{1 - e^{-\alpha \Pi_E}}{\alpha} = \lim_{\alpha \to 0} \Pi_E e^{-\alpha \Pi_E} = \Pi_E, \tag{18}$$

meaning that when α tends to zero the utility function (17) converges to the *risk-neutral* utility $U_E(\Pi_E) = \Pi_E$. Exponential utility implies constant absolute risk aversion equal to α (see [14]).

2.5.1 Utility maximization by the electricity producer

After the introduction of utility function (17) into the model, the profit maximization Problem 1 (without REDD) (7) and Problem 2 (with REDD) (12) can be substituted, respectively, by the utility maximization problems:

$$\underset{\boldsymbol{x} \in \boldsymbol{X}}{\text{maximize}} \quad U_E(\Pi(\boldsymbol{x}, p_l)), \tag{19}$$

$$\underset{\boldsymbol{x} \in \boldsymbol{X}}{\text{maximize}} \quad U_E(\Pi^R(\boldsymbol{x}, p_l)). \tag{20}$$

Remark 2. *In the case of exponential utility function U_E (17) the solutions to utility maximization problems (19) and (20) coincide with the solutions to the profit maximization problems (7) and (12), respectively.*

The utility function U_E (17) is a strictly increasing with respect to Π_E:

$$\frac{dU_E}{d\Pi_E} = \frac{\alpha e^{-\alpha \Pi_E}}{\alpha} = e^{-\alpha \Pi_E} > 0. \tag{21}$$

Let us consider the case without REDD: $\Pi_E = \Pi$ (5). The monotonicity property (21) by definition means that for all $\boldsymbol{x} \in \boldsymbol{X}$, such that $\Pi(\boldsymbol{x}_1^*, p_l) \geq \Pi(\boldsymbol{x}, p_l)$ (8), we have

$$U_E(\Pi(\boldsymbol{x}_1^*, p_l)) \geq U_E(\Pi(\boldsymbol{x}, p_l)), \tag{22}$$

meaning that $\boldsymbol{x}_1^*(p_l)$ delivers the maximum $U_E(\hat{\Pi}(p_l))$ in (19). The same reasoning is valid for the case with REDD, implying that $\boldsymbol{x}_2^*(p_l)$ is the solution to problem (20).

2.5.2 Utility of the forest owner

The profit at price p_l of the forest owner who does not contract REDD offsets in the first time period is calculated as follows:

$$\Pi_F^O(p_l) = p_l \mathcal{E}, \tag{23}$$

meaning that he keeps all the offsets in the first period and sells them in the second period when the CO_2 price reveals.

His profit when contracting REDD offsets in the first time period (under unknown CO_2 price) is given by the optimal behavior (including benefit sharing) of the electricity producer (see Problem 2):

$$\Pi_F^R(p_l) = (1 - \delta) p_l E^R(p_l) + p_F \mathcal{E}. \tag{24}$$

Recall, that symbol $E^R(p_l) = E^R(\mathcal{E}, \delta)$ (15) denotes emissions shared with the electricity producer in the second period at realization of CO_2 price p_l.

The utility function of the forest owner is given by the similar to (17) equation:

$$U_F(\Pi_F) = (1 - e^{-\beta \Pi_F})/\beta, \tag{25}$$

where β is a constant representing the *risk preferences*. Here profit $\Pi_F = \Pi_F^O$ (23) without REDD in the first time period, and $\Pi_F = \Pi_F^R$ (24) with contracting REDD offsets under uncertainty.

2.5.3 Expected utilities

In order to determine *fair prices* we need to introduce expected utilities. Given the distribution $\{p_l, w_l\}$ (11) of CO_2 price, they are calculated straightforward:

$$\mathbb{E}[U_E(\Pi_E)] = \sum_{l=1}^{m} U_E(\Pi_E(p_l)) w_l, \quad \mathbb{E}[U_F(\Pi_F)] = \sum_{l=1}^{m} U_F(\Pi_F(p_l)) w_l. \tag{26}$$

Remark 3. *If we apply risk-neutral utilities (special cases of (17) when $\alpha \to 0$ and (25) when $\beta \to 0$):*

$$U_E(\Pi_E) = \Pi_E, \quad U_F(\Pi_F) = \Pi_F, \tag{27}$$

then we arrive at the expected mean values (EMV) [13] in (26).

2.5.4 Interpretation of risk preferences

The interpretation of parameter α in (17) is the following. For illustration, let us consider a situation when a decision-maker evaluates his participation in the lottery with two outcomes: he can win 10 mln. with a probability of 0.5, or loose 10 mln. with the same probability. If $\alpha \simeq 0$, the decision-maker's expected utility (26) is zero, meaning that he is indifferent on whether to participate in this lottery, or not. The *risk-taker*'s expected utility (with $\alpha = -0.1$) is 5.43, meaning that he is willing to participate in the lottery. On the contrary, the *risk-averse* person ($\alpha = 0.1$) has an expected utility equal to -5.43, meaning that he prefers to avoid this venture. In a similar manner, the risk preference parameters reflect parties' perception of the uncertain CO_2 price distribution in our model.

In Figure 1 we can see the impact of risk-preferences to the shape of an exponential utility function. Here we depict the functions of profit $U_E(\Pi_E)$ (17), where profit Π_E belongs to the segment from 0 to 4 mln. US\$, determined by our case-study below.

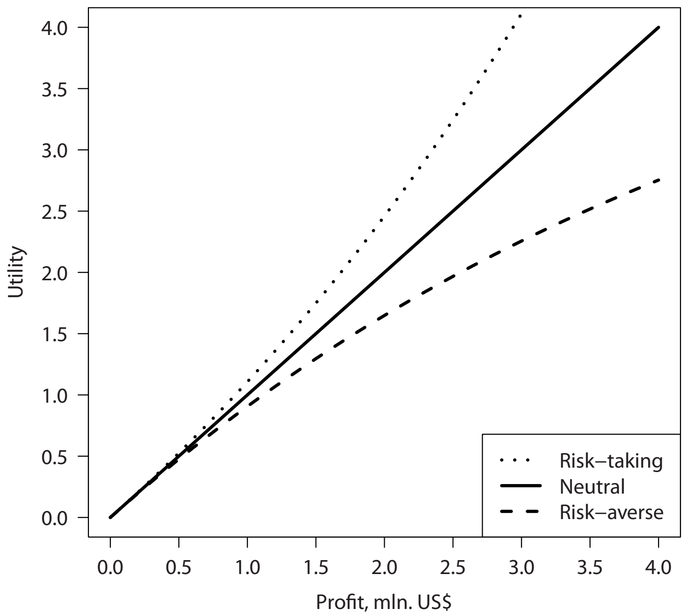

Figure 1: Sensitivity analysis of utility function with respect to *risk preferences* $\alpha = -0.2$ – *risk-taking*, $\alpha \simeq 0$ – *risk-neutral*, $\alpha = 0.2$ – *risk-averse*.

2.6 Fair prices in the model with exponential risk preferences

The discussion below is devoted to valuation of various amounts of REDD offsets contracted in the first time period under unknown CO_2 price assuming the given distribution (11) and a fixed *benefit sharing ratio* $\delta \in [0, 1]$. The forest owner and electricity producer evaluate their *fair (indifference) prices* for the given amount of offsets. The electricity producer derives the price he is willing to pay for the REDD offsets according to his *indifference condition* based on (9) and (14):

$$\mathbb{E}[U_E(\hat{\Pi}(p_l))] = \mathbb{E}[U_E\big(\hat{\Pi}^R(p_l) - p_E\mathcal{E}\big)]. \tag{28}$$

Here p_E is the desired *fair price* of the electricity producer. Let us note, that here we deal with the maximized expected utilities of the electricity producer. The maximum of the utility function's argument and, hence, the maximum of the utility function itself is achieved at solutions $\boldsymbol{x}_2^*(p_l)$ as the term $p_E\mathcal{E}$ is a constant and, hence, it is not included in the optimization (see (12), (19)-(20), and Remark 2). The *indifference condition* (28) means that electricity producer's expected utility stays the same whether the electricity producer participates in REDD, or not.

Substituting exponential utility (17) into equality (28), we simplify it to the following equation with respect to unknown *fair price* p_E:

$$p_E = \frac{1}{\alpha\mathcal{E}}\Big(\ln(\sum_{l=1}^{m} e^{-\alpha\hat{\Pi}(p_l)}w_l) - \ln(\sum_{l=1}^{m} e^{-\alpha\hat{\Pi}^R(p_l)}w_l)\Big). \tag{29}$$

The *indifference condition* for the forest owner means that he chooses his *fair price* p_F in such a way, that his expected utility stays the same no matter if he engages in REDD in the first time period, or not. Hence, the equation takes the form:

$$\mathbb{E}[U_F(\Pi_F^O(p_l))] = \mathbb{E}[U_F(\Pi_F^R(p_l)]. \tag{30}$$

Let us derive the forest owner's *fair price* for REDD offsets by substituting (23)-(25) to (30):

$$p_F = \frac{1}{\beta\mathcal{E}}\Big(\ln(\sum_{l=1}^{m} e^{-\beta(1-\delta)p_l E^R(p_l)}w_l) - \ln(\sum_{l=1}^{m} e^{-\beta p_l\mathcal{E}}w_l)\Big). \tag{31}$$

Thus, for the given CO_2 price distribution $\{p_l, w_l\}, l = 1,..,m$ (11), *benefit sharing ratio* $\delta \in [0,1]$ and amount of offsets $\mathcal{E} \in (0, E^0]$ one derives the *fair prices* of the forest owner p_F (31) and the electricity producer p_E (29). Using equations of the *fair prices*, we can find the volumes of REDD offsets $\mathcal{E}$, for which the deal takes place. Namely, the amount $\mathcal{E}$ can be contracted only if $p_F(\mathcal{E}) \leq p_E(\mathcal{E})$, meaning that the selling price p_F is not higher than the buying price p_E. Functions $p_F = p_F(\mathcal{E})$ and $p_E = p_E(\mathcal{E})$ represent, respectively, risk-adjusted supply and demand curves for REDD offsets.

Remark 4. *The exponential utility function (17) considered in this study possesses the feature of equal buying and selling price of an asset, discussed e.g. in [13].*

If we consider an electricity producer having REDD offsets and wishing to sell them at a *fair price* denoted by p_E^s subject to *indifference equation* inverse to (28):

$$\mathbb{E}[U_F(\hat{\Pi}_E^R(p_l))] = \mathbb{E}[U_F(\hat{\Pi}_E(p_l) + p_E^s\mathcal{E})], \tag{32}$$

we determine that the *fair* <u>*selling*</u> *price* coincides with the *fair* <u>*buying*</u> *price*: $p_E^s = p_E$ (29). The same is valid for the forest owner. It is well known that some other types of utilities do not possess this feature (see, *e.g.* [13], p. 90) [1].

2.7 Analytical solution for risk-neutral case

As discussed above the *risk-neutral* utility is a special case of exponential utility. In the case of *risk-neutral* utilities (27) we analytically find solutions to utility maximizing problems (19)-(20) of the electricity producer depending on the amount of REDD offsets $\mathcal{E} \in (0, E^0]$ and determine the corresponding *fair prices* of the forest owner and electricity producer. This allows us to obtain an analytical estimate of the amount of REDD offsets, that can be contracted.

[1] Let us note that H. Raiffa [13] treats these prices as the prices for which one is willing to buy or sell his participation in the lottery. In our case "no lottery" means that the forest owner (electricity producer) does not participate in REDD.

Theorem 1 (Risk-neutral case)**.** *In the case, when both forest owner and electricity producer are risk-neutral, meaning that their expected utilities are mean values (27), for a given* CO_2 *price distribution* $\{p_l, w_l\}, l = 1, .., m$ *(11) and for any benefit sharing ratio* $\delta \in [0, 1)$ *there exists an amount* $\tilde{\mathcal{E}} \in (0, E^0]$ *of REDD offsets up to which the fair prices of the forest owner* p_F *(31) and of the electricity producer* p_E *(29) coincide and are equal to the expected* CO_2 *price* $\bar{p}$*. This amount equals the minimum optimal quantity of emissions generated by the electricity producer at the maximum possible* CO_2 *price* $\tilde{p} = \max\{p_l\}$*:*

$$p_F = p_E = \bar{p} \quad \textit{for any} \quad \mathcal{E} \leq \tilde{\mathcal{E}}, \quad \delta \in [0, 1], \tag{33}$$

where

$$\tilde{\mathcal{E}} = E(\boldsymbol{x}_{\mathbf{1}}^{*}(\tilde{p})), \quad \bar{p} = \sum_{l=1}^{m} p_l w_l. \tag{34}$$

For any amount of REDD offsets larger than $\tilde{\mathcal{E}}$ *(34) the fair price of the forest owner* p_F *is higher than the fair price of the electricity producer* p_E*:*

$$p_F > p_E \quad \textit{for any} \quad \mathcal{E} > \tilde{\mathcal{E}}, \quad \delta \in [0, 1). \tag{35}$$

The proof is given in the A.1.

Remark 5. *Theorem 1 shows that in the case of a bounded* CO_2 *price distribution, the forest owner and electricity producer can contract any amount* $\mathcal{E} \in (0, \tilde{\mathcal{E}}]$ *of REDD offsets for the fair price* $\bar{p}$*. Thus, in the considered risk-neutral case, only two characteristics of distribution fully determine the solution to the problem: the mean and the highest price.*

The practical consequence following from this result is that – on one hand – the potentially contracted amount is limited by the potentially high future CO_2 price (the higher the price, the lower is the contracted amount). On the other hand, even in the *risk-neutral* case with possibility of a high CO_2 price the contracted amount is non-zero, hinting at the opportunity to practically implement the REDD-based offset instrument featuring a *benefit sharing* approach as considered in this paper.

3 Modeling Results

The analytical solution obtained for the case of *risk-neutral* utilities (27) in the previous section is valid for a broad range of possible model setups in our modeling framework. In order to provide a numerical example and illustrate the impacts of *risk preferences* and *benefit sharing* mechanism on the contracted amount of REDD offsets, we calibrate the model for a realistic case-study, and carry out numeric optimization.

3.1 Data and calibration

Technologies in the model In our illustrative case study a regional electricity producer is operating power plants with the following technologies: coal (pulverized coal steam), combustion turbine (natural gas-fired) and combined cycle gas turbine (CCGT) (see [7]). The corresponding fixed and variable costs, as well as the installed capacities are given in Table 1. The total size of installed capacity (7900 MW) is chosen to illustrate a model at a regional scale, and is roughly equivalent to the installed capacity of Belarus[2].

[2] See International Energy Statistics provided by the U.S. Energy Information Administration (EIA) http://www.eia.gov/cfapps/ipdbproject/

Table 1: Technological data for the case-study. *Sources:* [7, 15, 16].

Technology	Annual fixed cost, thousands of US$/MWy	Variable cost, US$/MWh	Installed Capacity, MW	Emission factors, tons of CO_2/MWh
Coal-fired	224	18.9	3800	1.02
Natural gas-fired combustion turbine	64	55.6	1900	0.55
Natural gas-fired combined cycle	96	39	2200	0.33

Average hourly electricity demand To construct an economically efficient production plan the electricity producer has to determine the combination of technologies to be used hourly during the day in order to satisfy the hourly demand profile. A hypothetical demand profile for an average day of the year is depicted in Figure 2. It features the same shape (peaks) as the regional profiles provided in the literature [17, 18]. The hourly demand values are scaled to match the installed capacity of the electricity producer (as in Table 1). Similar to [18] we use the hourly average demand for each day over a longer period, *e.g.* one year. We estimate the hourly profile change assuming that a change in aggregate demand leads to proportional shifts for every hour of the profile on an average day. Our model works with an average demand profile at the annual scale and provides a higher level of abstraction than the unit commitment (UC) problem (see *e.g.* [19]).

Demand function We assume that the electricity producer has market power in the region, and use a constant elasticity demand curve, that is commonly employed in aggregate energy demand studies [20, 10]. The consumers respond to the change in electricity price P^e by changing the consumption Q according to an aggregate demand function $D(P^e)$, *i.e.*:

$$P^e = D^{-1}(Q) = AQ^{\alpha}, \tag{36}$$

where $A > 0$ is a constant, and $\alpha < 0$ is the constant elasticity of demand. The coefficients of the aggregate demand function in our model are calibrated in such a way that a realistic electricity price (close to European[3] electricity price) is achieved in the solution to an optimization Problem 1. The estimated parameters of the demand function (36) are $A = 1.05 \times 10^5$, $\alpha = -0.612$. These values are consistent with $P^e = 88.8\,$US$/MWh at maximum profit without CO_2 price. The value of elasticity coefficient $\epsilon_d = \frac{1}{\alpha} = -1.63$ is within a plausible range as estimated in the literature (for a set of OECD countries it was found to be within the confidence interval of $-2.3, ..., -0.1$, see, *e.g.* [20]). In our example the profit maximizing quantity is $Q^0 = 103.65\,$GWh/day (which is approximately equal to the average daily electricity consumption in Belarus[4]), and the corresponding profit is $\hat{\Pi}(Q^0) = 1.3\,$bln. US$/year (excluding taxes and depreciation).

Emissions factors For presently operating, coal-fired power plants the cumulative emissions range between 950 and 1250 gCO_2 eq/ kWh [15]. In our study we use a value from

[3]See Quarterly Reports On European Electricity Markets http://ec.europa.eu/energy/en/statistics/market-analysis
[4]See the EIA website: http://www.eia.gov/cfapps/ipdbproject/

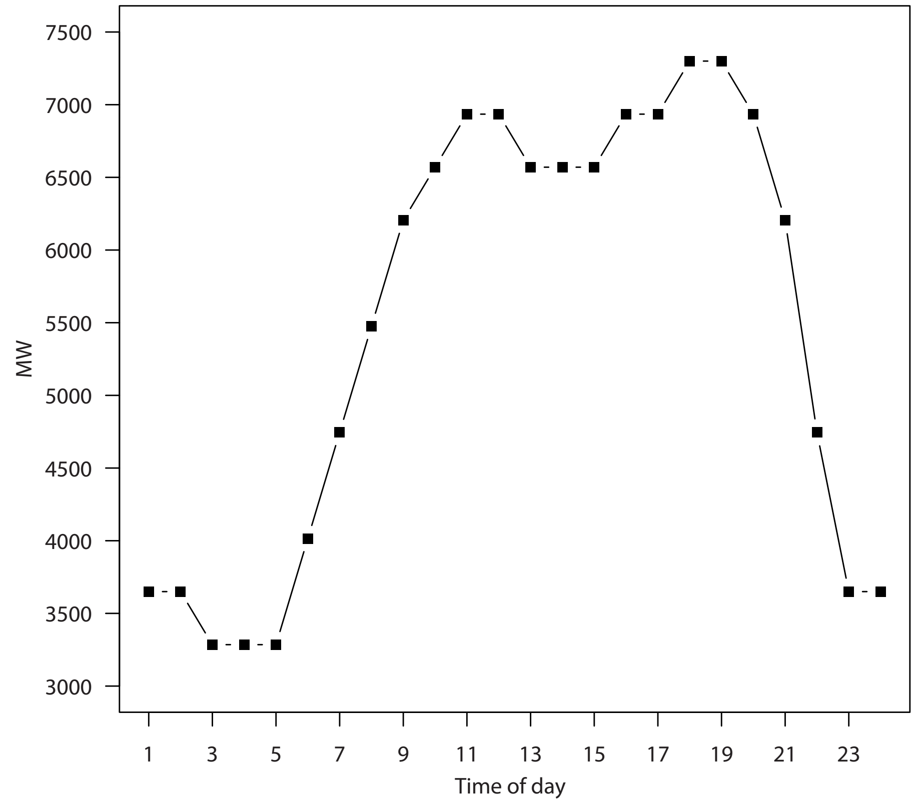

Figure 2: Average hourly electricity demand (based on Figure 1 in [17]).

this interval as given in Table 1. Emissions factors for gas powered plants are taken from [16].

3.2 Numerical results

Simulations were carried out for the discrete (nine points) approximation of a uniform price distribution within the range 0–80 US$/ton of CO_2:

$$p_l = 10(l-1), \quad w_l = \frac{1}{9}, \quad l = 1,..,9. \tag{37}$$

Sizes of REDD-based offset contracts used in the model are within the range $[0, E^0]$, where E^0 is the optimal emission without CO_2 price.

3.2.1 A case of risk-neutral utilities

Let us start with a case of *risk-neutral* utilities (27) (by setting parameters close to zero: $\alpha = 0.001$ in (17), and $\beta = 0.001$ in (25)). In Figure 3 the *fair prices* (29) and (31) with respect to the contracted amount of offsets $\mathcal{E} \leq E^0$ are depicted for the *benefit sharing ratio* $\delta = 0.5$. The plot demonstrates that the maximum amount of emissions offsets for which the deal can take place is $\tilde{\mathcal{E}} = E(\boldsymbol{x}^*(p_9)) = 11.8$ $MtCO_2$/day, *i.e.* 4 $GtCO_2$/year (at the equilibrium *fair price* $\bar{p} = 40$ US$/ton CO_2). That amount the electricity producer emits at the maximum CO_2 price $p_9 = 80$ US$/ton CO_2, while maximizing his profit. For amounts larger than $\tilde{\mathcal{E}}$ the *fair price* of the forest owner is higher than the *fair price* of the electricity producer. This is consistent with the analytical results (33), (35).

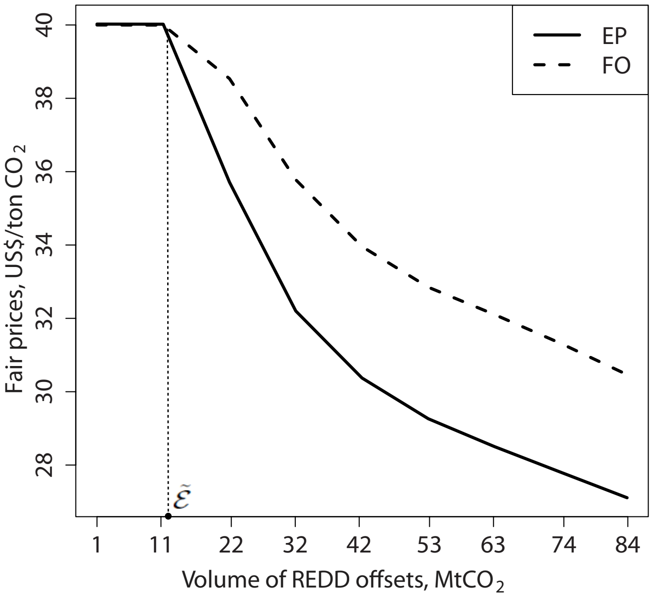

Figure 3: *Fair prices* of the *risk-neutral* electricity producer (EP) and forest owner (FO) depending on the volume of REDD offsets. *Benefit sharing ratio* is $\delta = 0.5$, and future CO_2 price distribution is uniform within the range 0–80 US$/ton CO_2.

In the following sections we keep all model parameters fixed except for the *risk preferences* of the forest owner and electricity producer, by assigning values to parameters α and β, and *benefit sharing ratio* δ.

3.2.2 Sensitivity analysis of fair prices with respect to risk preferences

In Figure 4 we show, how different values of parameter α (risk preferences of the electricity producer) impact the *fair prices* of the electricity producer $p_E = p_E(\mathcal{E})$ (29) for the fixed *benefit sharing ratio* $\delta = 0.5$. The range of parameter $\alpha \in [-0.2, 0.2]$ corresponds to approximately 10 % variation of the *fair price* relative to the *risk-neutral* scenario, $\alpha \simeq 0$ (see Figure 1 with utilities). The plot demonstrates, that the *risk-taking* ($\alpha < 0$) electricity producer is less interested in REDD offsets and, hence, he evaluates these offsets lower than the *risk-neutral* ($\alpha \simeq 0$) electricity producer. Quite the opposite, the *risk-averse* electricity producer ($\alpha > 0$) is ready to pay a higher price for the same amount of REDD offsets.

The sensitivity of a forest owner's *fair prices* is symmetric to the electricity producer's. The *risk-averse* forest owner is charging a lower *fair price*, and the *risk-taking* – a higher *fair price* – compared to the *risk-neutral* behavior. Similarly to the electricity producer the magnitude of change in the forest owner's *fair price* depends on the degree of *risk preference* parameter β.

3.2.3 Impacts of risk preferences on contracted amounts of REDD offsets

Here we consider the *risk-averse* electricity producer and *risk-averse* forest owner by setting their risk preference parameters to positive values: $\alpha = \beta = 0.1$, and also the *risk-taking* forest owner and *risk-taking* electricity producer by setting: $\alpha = \beta = -0.1$.

For convenience let us denote the maximum contracted amounts by the symbol: $\mathcal{E}_{YZ}$, where Y is a risk preference behavior of the electricity producer taking two values: "a"

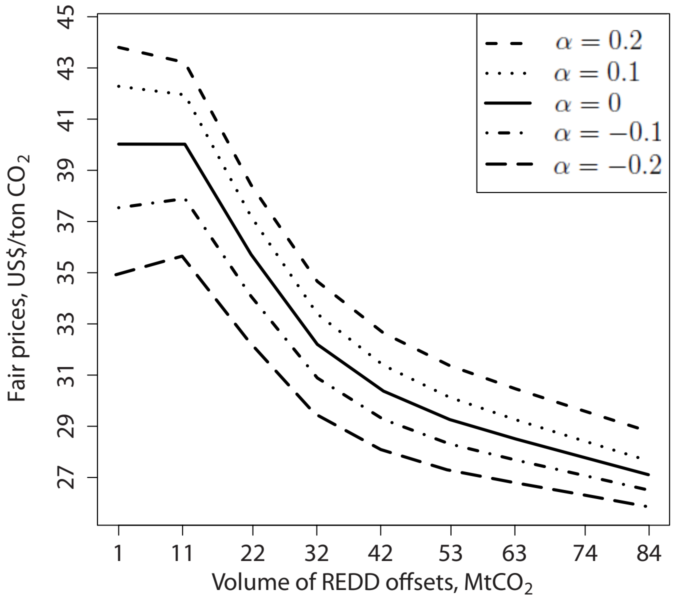

Figure 4: Sensitivity analysis of electricity producer's *fair prices* with respect to his *risk preferences* $\alpha < 0$ – *risk-taking*, $\alpha \simeq 0$ – *risk-neutral*, $\alpha > 0$ – *risk-averse*. *Benefit sharing ratio* is $\delta = 0.5$.

– risk-averse, and "t" – risk-taking, and Z is defined in the same manner for the forest owner.

Figure 5 shows that within the considered set of risk preference parameters the *risk aversion* of the electricity producer enables contracting the REDD offsets (if EP is *risk-taking* the *fair price* curves of EP and FO do not intersect and, hence, there is no agreement on the price and consequently REDD offsets cannot be contracted). The contracted amount when the forest owner is *risk-averse* exceeds the amount when the forest owner is *risk-taking*:

$$\mathcal{E}_{aa} = 19.5 \text{ MtCO}_2 > \mathcal{E}_{at} = 15.9 \text{ MtCO}_2. \tag{38}$$

Both contracted amounts $\mathcal{E}_{aa}$ and $\mathcal{E}_{at}$ are greater than in the *risk-neutral* case (Figure 3). At the same time the *risk-taking* electricity producer in this experiment never agrees on buying any REDD offsets, $\mathcal{E}_{ta} = \mathcal{E}_{tt} = 0$, as his buying price is too low – even lower than than the price set by the *risk-averse* forest owner (Figure 5). In this case and generally if there is a gap between supply and demand prices, public funds could help close the gap and enable emissions offsetting with REDD.

Modeling results presented in this section highlight, that the *risk-averse* behavior of the forest owner and electricity producer lead to an increase of contracted amounts of REDD offsets along with a decrease in price (compare Figures 3 and 5). Obviously, the contracted amount of REDD offsets also depends on the *benefit sharing ratio* δ ($\delta = 0.5$ here).

3.2.4 The role of the benefit sharing mechanism

We consider a situation of the risk-averse electricity producer and forest owner where parameters are set values: $\alpha = 0.2$, $\beta = 0.8$. The plot in Figure 6 shows how the benefit sharing ratio impacts the contracted amounts of REDD offsets. At every value of parameter δ expected utilities of the forest owner and electricity producer stay the same, but the contracted amounts (solid line) and equilibrium prices (dashed line) differ. The

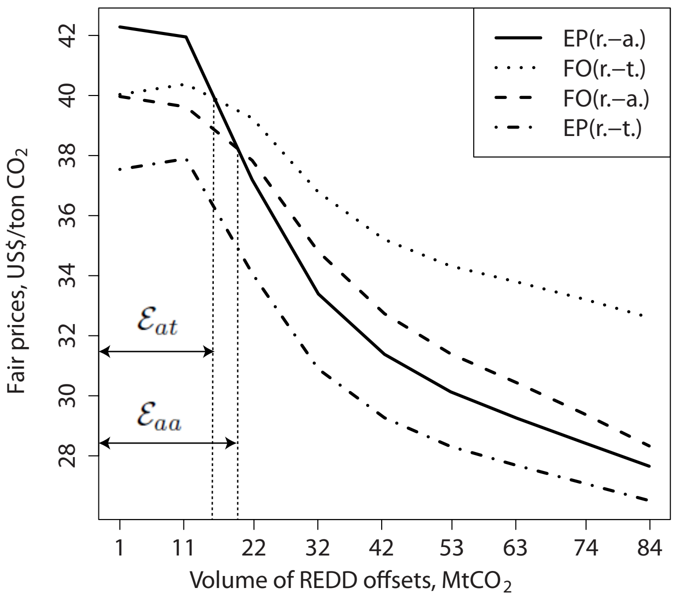

Figure 5: *Fair prices* of electricity producer (EP) and forest owner (FO) depending on the volume of REDD offsets. *Risk-averse* (r.-a.) utilities correspond to $\alpha = \beta = 0.1$, *risk-taking* (r.-t.) to $\alpha = \beta = -0.1$. *Benefit sharing ratio* is $\delta = 0.5$.

nonlinear shape of the plots is explained by nonregularities in searching for the intersection point between the curves of *fair prices* (as in Figure 5). Our modeling results indicate that there is a certain value of *benefit sharing ratio*, $\delta = 0.75$ in our case, which provides the highest possibilities for contracting REDD offsets. Namely, as indicated in Figure 6, at this "optimal" *benefit sharing ratio* the entire amount of REDD offsets 83.9MtCO_2 can be contracted at the lowest price 32.9 US$/ton. In this way, benefit sharing allows to engage in REDD with less investments at the start. The fact that the highest amount can be traded at lowest price generates possibilities for involving more energy producers in REDD.

3.2.5 Multiple ranges of contracted REDD offsets

In conclusion, we would like to illustrate an interesting effect arising from certain combinations of *risk preferences* and *benefit sharing ratio*. In Figure 7 one can see the *fair prices* $p_E = p_E(\mathcal{E})$ (29) and $p_F = p_F(\mathcal{E})$ (31) constructed for the case when both the electricity producer and forest owner are *risk-averse*: $\alpha = \beta = 0.15$, and *benefit sharing ratio* $\delta = 0.5$. In the plot we observe two points of intersection, meaning that either smaller amounts of REDD offsets are contracted $\mathcal{E} \leq \mathcal{E}_{aa}$ for the higher price, or a larger amounts $\mathcal{E} \geq \hat{\mathcal{E}}_{aa}$ – at lower prices. At the same time there is a range of amounts of REDD offsets $\mathcal{E} \in [\mathcal{E}_{aa}, \hat{\mathcal{E}}_{aa}]$, which are not contracted as indicated in Figure 7. In our numerical simulation we observed that this gap vanishes as the *benefit sharing ratio* increases.

4 Conclusions and Policy Implications

According to a recent IEA report [21] a considerable share of total CO_2 emissions (about 80 %) comes from the energy sector. This makes the sector a good candidate for emissions reduction and in particular using REDD. In order to implement REDD mechanism efficiently it is necessary to understand the decision-making process (rational behavior)

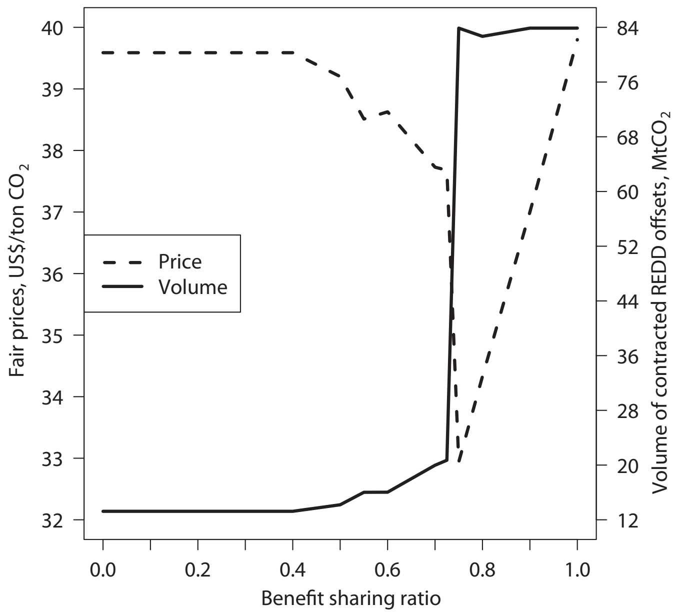

Figure 6: Sensitivity analysis of *fair prices* and contacted amounts of REDD offsets with respect to *benefit sharing ratio*. Forest owner and electricity producer are *risk-averse*: $\alpha = 0.2$, $\beta = 0.08$. Solid line – maximum contracted amounts for each $\delta \in [0, 1]$, dashed line – corresponding equilibrium *fair prices*.

of energy producers – the potential buyers of REDD-based offsets. Our model deals with the medium-term planning of the electricity producer who possesses flexibility in his response to uncertain CO_2 prices. The electricity producer in the model is restricted in exercising market power (raising the electricity price) by the elasticity of demand coming from electricity consumers and is maximizing his utility (function of profit) by optimizing technological mixes in the production. Utility of the forest owner (REDD supplier) is a function of his profits from selling REDD offsets and reflects his risk preferences. In our study we applied an exponential utility function that includes the risk-neutral utility as a special case. The analytical results provided in the paper for the *risk-neutral* utilities show that there is a restricted amount of REDD offsets that can be contracted in this case. Modeling results on the fair pricing under *risk preferences* and active *benefit sharing mechanism* show that *risk-averse* behavior increases the contracted amounts compared to the *risk-neutral* case. In the case where both parties are *risk-taking* no contracts can be made (for any possible amount of REDD offsets) under symmetric information on CO_2 price distribution. We illustrated an important feature of benefit sharing mechanism, which consists in the possibility of choosing optimal *benefit sharing ratio*, allowing to contract the highest amount of REDD offsets at the lowest price.

Thus, in this study we identified two promising approaches to effective REDD implementation in connection to the energy sector: (i) increasing *risk-aversion* of the energy producers, or strengthening the policy signal to allow for exposing a risk-averse behavior, and (ii) activating the *benefit sharing mechanism.* The current delay in REDD implementation can be connected with the fact that energy producers are not able to adequately assess the risks associated with CO_2 prices (explained by the weak policy design). An additional hurdle for REDD development is its future acceptance on carbon markets as illustrated by the case of the European Emission Trading System (EU ETS). The *benefit sharing mechanism* as discussed in our study, could allow the REDD-supplier and con-

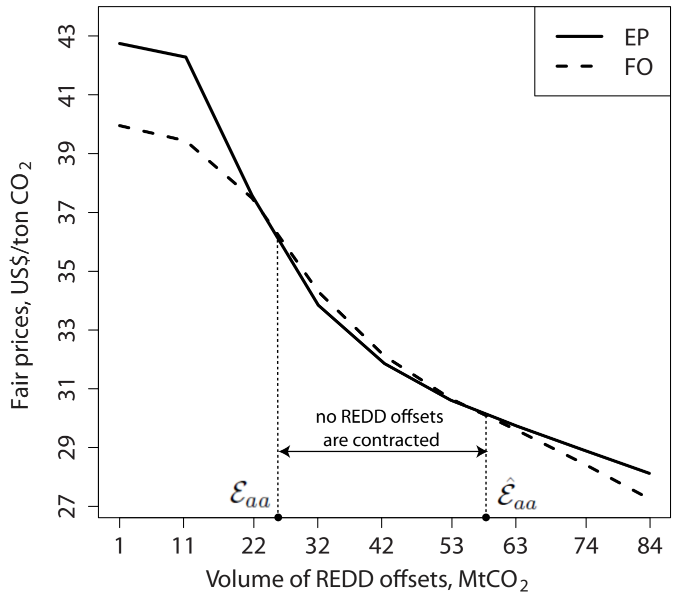

Figure 7: *Fair prices* of the *risk-averse* electricity producer (EP), $\alpha = 0.15$, and *risk-averse* forest owner (FO), $\beta = 0.15$, for *benefit sharing ratio* $\delta = 0.5$.

sumer to have an alternative means of controlling future uncertainty, and hence facilitate REDD implementation at a larger scale. Another mechanism for supporting REDD (although not cost-free) might involve public funds for closing the price gap between REDD demand and supply, especially when other means are not sufficient and the uncertainty as perceived by the parties still remains too high. This is potentially the case where relatively small investments may play a decisive role in enabling REDD.

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A Appendix

A.1 Proof of Theorem 1

Proof. In the case of risk-neutral utilities, the fair prices (29), (31) are calculated as follows:

$$p_F = p_F(\mathcal{E}, \delta) = \bar{p} - (1-\delta)\frac{\sum_{l=1}^{m} p_l E^R(p_l) w_l}{\mathcal{E}}, \tag{39}$$

$$p_E = p_E(\mathcal{E}, \delta) = \frac{\mathbb{E}\hat{\Pi}^R(\mathcal{E}, \delta) - \mathbb{E}\hat{\Pi}}{\mathcal{E}}. \tag{40}$$

According to Assumption 1 the amount $\tilde{\mathcal{E}}$ (34) is emitted by the electricity producer at any price p_l in the distribution (11). Hence, for every $p = p_l$ in the distribution the maximum profit with REDD $\hat{\Pi}^R(p_l)$ differs from the maximum profit without REDD $\hat{\Pi}(p_l)$ (9) by the term $p_l\tilde{\mathcal{E}}$:

$$\hat{\Pi}^R(p_l) = \hat{\Pi}(p_l) + p_l\tilde{\mathcal{E}}. \tag{41}$$

Substituting (41) to the definition of *fair price* of the electricity producer (40) we get:

$$p_E = \frac{\mathbb{E}\hat{\Pi}^R - \mathbb{E}\hat{\Pi}}{\tilde{\mathcal{E}}} = \frac{\mathbb{E}\hat{\Pi} + \mathbb{E}p_l\tilde{\mathcal{E}} - \mathbb{E}\hat{\Pi}}{\tilde{\mathcal{E}}} = \mathbb{E}p_l = \bar{p}. \tag{42}$$

At the same time, in this case no emissions are returned to the forest owner at any CO_2 price. Substituting $E_l^R = 0$ to (39) one gets:

$$p_F = \bar{p}. \tag{43}$$

The same reasoning is valid for any $\mathcal{E} \in (0, \tilde{\mathcal{E}}]$, and, hence, (33) is true.

Based on Assumption 1 we can show that for the amount of REDD offsets $\mathcal{E} \in (\tilde{\mathcal{E}}, E^0]$, there are CO_2 price realizations $p = p_l$ in the distribution (11) (at least $\tilde{p} = \max\{p_l\}$), for which the strict inequality takes place $p_F > p_E$ and, hence, (35) is true. □