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CO_2-intensive power generation and REDD-based emission offsets with a benefit sharing mechanism

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Contents

Abstract

We propose and explore financial instruments supporting programs for reducing emissions from deforestation and forest degradation (FI-REDD). Within a microeconomic framework we model interactions between an electricity producer (EP), electricity consumer (EC), and forest owner (FO). To keep their profit at a maximum, the EP responds to increasing CO_2 prices by adjusting electricity quantities generated by different technologies and charging a higher electricity price to the EC. The EP can hedge against future high (uncertain) CO_2 prices by employing FI-REDD: they can purchase an amount of offsets under an unknown future CO_2 price and later, when the CO_2 price is discovered, decide how many of these offsets to use for actually offsetting emissions and sell the rest on the market, sharing the revenue with the FO. FI-REDD allows for optional consumption of emission offsets by the EP (any amount up to the initially contracted volume is allowed), and includes a benefit sharing mechanism between the EP and FO as it regards unused offsets.

The modeling results indicate that FI-REDD might help avoid bankruptcy of CO_2-intensive producers at high levels of CO_2 prices and therefore serve as a stabilizing mechanism during the transition of energy systems to greener technologies. The analytical results demonstrate the limits for potential market size explained by existing uncertainties. We illustrated that when suppliers and consumers of REDD offsets have asymmetric information on future CO_2 prices, benefit sharing increases the contracted REDD offsets quantity.

Acknowledgments

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1 Introduction

This paper is devoted to the elaboration of financial instruments supporting the Reduced Emissions from Deforestation and Degradation (REDD+) mechanisms [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. Our approach differs in several ways. Firstly, we consider the case when the energy producer has market power – the ability to reduce the 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 doesn't 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 constructed a microeconomic model of interaction between the forest owner (REDD-supplier), electricity producer, and electricity consumer. In the proposed partial equilibrium modeling framework the CO_2 prices are exogenous. The decision-making process of the electricity producer (under condition of 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 can set the price for electricity above his marginal cost according to a demand function. Recent studies suggest that energy companies possess a certain degree of market 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

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the electricity prices for the consumer (increase), and, hence, some financial instruments might be implemented today in order to be prepared for uncertain CO_2 prices in the future [3]. We propose and explore financial instruments supporting 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 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 higher (lower) prices the electricity producer (forest owner) will not want to engage in the contract. In case when parties can agree on the *fair price*, the problem is then to find the maximum amount of REDD offsets which can be contracted. A similar approach in a different problem setup is considered in the paper [11], where the authors developed a newsvendor model to determine the optimal price and volume of CCS contracts to maximize the expected profit of a storage operator.

The idea of benefit sharing is important within the REDD context [12]. We propose a benefit-sharing mechanism that is activated in the case when the 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. We show that for this benefit sharing mechanism there is an equilibrium amount of REDD offsets up to which the *fair prices* coincide, meaning that the deal takes place. We prove that for larger amounts of REDD offsets the desired price of the electricity producer (buyer) is lower than the price of the forest owner (seller), meaning that for these larger amounts the deal is not possible. The paper considers mathematical constructions and properties of the proposed financial instrument. Analytical results presented in the paper are illustrated by a numerical case study based on realistic data for regional electricity production. The modeling results indicate that financial instruments supporting REDD might help avoid bankruptcy of CO_2-intensive producers at high price levels of CO_2 and, therefore, serve as a stabilizing mechanism during the transition of energy systems to greener technologies.

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 the emissions reduction and raising electricity price is constructed for any 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. Based on the comparison of expected profits with and without contracting REDD offsets the electricity producer evaluates his *fair (indifference) price* for each amount of offsets. Similarly, the forest owner – the seller of REDD offsets – calculates his *fair price*. We 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, or (ii) to emit less and share the benefit with the forest owner.

2.1 Notations

In our model the electricity producer uses n technologies that vary 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 (MWh);

$Q = Q(\boldsymbol{x}) = \sum_{i=1}^{n} a_i \sum_{j=1}^{24} x_{ij}$ 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 4.1);

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

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

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 the profit component Π_e and emissions E does not directly depend on price p, however, they are indirectly determined by the technological possibilities of the electricity producer.

We assume that the hourly profile changes proportionally to the aggregate demand (see [3] and section 4.1 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).

In our modeling framework we consider the electricity producer as a profit-maximizing decision maker. 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 $P^e(Q(\boldsymbol{x_1^*}(p))$.

2.2 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 [3]. It is also consistent with results of larger scale modeling [13].

Remark 1. *Under assumption 1 for every* CO_2 *price* $p \in [0, \tilde{p}]$ *there exists a unique emissions level* $\hat{E}(p) = E(\boldsymbol{x_1^*}(p))$ *corresponding to maximum profit* $\hat{\Pi}(p)$*.*

Remark 2. *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.*

Based on the Assumption 1 we prove the following lemma.

Lemma 1. *For any* $\boldsymbol{x} \in \boldsymbol{X}$ *(6), such that* $E(\boldsymbol{x}) \neq E(\boldsymbol{x_1^*}(p))$*, the following inequality holds for all* $p \in (0, \tilde{p}]$*:*

$$\Pi_e(\boldsymbol{x_1^*}(p)) - E(\boldsymbol{x_1^*}(p))p > \Pi_e(\boldsymbol{x}) - E(\boldsymbol{x})p. \tag{11}$$

The proof is given in the Appendix A.1.

Lemma 1 has the following meaning. If we fix CO_2 price p and select an arbitrary mix of technologies $\boldsymbol{x}$ satisfying the hourly demand, such that the corresponding emissions differ from optimal emissions for the price p, then this mix $\boldsymbol{x}$ is not optimal for the electricity producer in the sense of profit maximization.

2.3 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, contracted REDD offsets would allow offsetting CO_2 emissions in the future. A forest owner is supplying REDD offsets. Let us note that we are not taking into account additional factors in the payoff of the forest owner, e.g. the 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 [14] following a discrete probability distribution:

$$\{p_l, w_l\}, \quad l = 1, .., m, \quad \sum_{l=1}^{m} w_l = 1, \quad p_l \in [0, \tilde{p}], \quad w_l \in (0, 1], \tag{12}$$

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

A problem is divided into two stages: at the first stage 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. $E^0 = \hat{E}(0)$.

At the second stage they face a realization of uncertain CO_2 price. 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) in 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 supplied (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 in the decision-making problem of the electricity producer compared to the case without REDD (see Problem 1).

Problem 2 (with REDD offsets)**.** *Given the feasibility domain* $\boldsymbol{X}$ *(6), CO_2 price distribution* $\{p_l, w_l\}$ *(12) 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*:*

$$\underset{\boldsymbol{x}\in\boldsymbol{X}}{\text{maximize}}\, \Pi^R(\boldsymbol{x}, p_l), \tag{13}$$

where

$$\Pi^R(\boldsymbol{x}, p_l) = \Pi_e(\boldsymbol{x}) - p_l\big[E(\boldsymbol{x}) - \mathcal{E}\big]_+ + \delta p_l\big[\mathcal{E} - E(\boldsymbol{x})\big]_+. \tag{14}$$

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 $\boldsymbol{x}_{\boldsymbol{2}}^{\boldsymbol{*}}(p_l)$ – solution to (13) – generates the maximum profit with REDD: $\hat{\Pi}^R(p_l) = \Pi^R(\boldsymbol{x}_{\boldsymbol{2}}^{\boldsymbol{*}}(p_l), p_l)$ at a particular CO_2 price p_l. We denoted by the symbol $E^R(p_l) = \big[\mathcal{E} - E(\boldsymbol{x}_{\boldsymbol{2}}^{\boldsymbol{*}}(p_l))\big]_+$ the corresponding amount of emission offsets returned to the forest owner.

In our model we assume that the electricity producer and forest owner are both risk neutral and, therefore, we deal with expected values:

$$\mathbb{E}\hat{\Pi}^R(\mathcal{E}, \delta) = \sum_{l=1}^{m} \hat{\Pi}^R(p_l) w_l, \tag{15}$$

$$\mathbb{E}\hat{\Pi} = \sum_{l=1}^{m} \hat{\Pi}(p_l) w_l, \quad \bar{p} = \mathbb{E}p = \sum_{l=1}^{m} p_l w_l.$$

where $\hat{\Pi}(p_l) = \hat{\Pi}(\boldsymbol{x}_{\boldsymbol{1}}^{\boldsymbol{*}}(p_l))$ (9) is solution to the Problem 1 (without REDD) for $p = p_l$, and $\bar{p}$ is the mean CO_2 price.

The discussion below is devoted to the valuation of various amounts of REDD offsets contracted in the first time period under unknown CO_2 price assuming the given distribution (12) and *benefit sharing ratio* $\delta \in [0, 1]$. The forest owner and electricity producer evaluate their *fair (indifference) prices* for the given amount of options. Thus, the forest owner chooses his *fair price* p_F at which he can sell the amount of offsets $\mathcal{E}$ in the first period using the indifference condition:

$$(1 - \delta) \sum_{l=1}^{m} p_l E^R(p_l) w_l + p_F \mathcal{E} = \bar{p}\mathcal{E}, \tag{16}$$

meaning that the forest owner can either sell the emission offsets to the electricity producer in the first period and, possibly, get a profit share in the second period, or keep the offsets and sell them in the second period at the market CO_2 price without engaging in a deal with the electricity producer.

Similarly, the electricity producer derives the price he is willing to pay for the REDD offsets according to his indifference condition:

$$\mathbb{E}\hat{\Pi}^R(\mathcal{E}, \delta) - p_E \mathcal{E} = \mathbb{E}\hat{\Pi}. \tag{17}$$

For the given CO_2 price distribution $\{p_l, w_l\}, l = 1, .., m$ (12), *benefit sharing ratio* $\delta \in [0, 1]$ and amount of offsets $\mathcal{E} \in (0, E^0]$ based on the equations (16)-(17) one can derive the *fair prices* for the forest owner p_F and the electricity producer p_E:

$$p_F = p_F(\mathcal{E}, \delta) = \bar{p} - (1 - \delta) \frac{\sum_{l=1}^{m} p_l E^R(p_l) w_l}{\mathcal{E}}, \tag{18}$$

$$p_E = p_E(\mathcal{E}, \delta) = \frac{\mathbb{E}\hat{\Pi}^R(\mathcal{E}, \delta) - \mathbb{E}\hat{\Pi}}{\mathcal{E}}. \tag{19}$$

For a fixed parameter $\delta \in [0, 1]$ equations (18)-(19) represent supply and demand curves for REDD offsets within the suggested benefit sharing approach. Let us note that for $\delta = 1$ (no benefit sharing with REDD supplier) the forest owner and electricity producer agree[1] on any amount $\mathcal{E}$, as:

$$\mathbb{E}\hat{\Pi}^R(\mathcal{E}, \delta = 1) = \bar{p}\mathcal{E} + \mathbb{E}\hat{\Pi}, \quad p_F(\mathcal{E}, \delta = 1) = \bar{p}, \tag{20}$$

and hence $p_F = p_E = \bar{p}$ for any $\mathcal{E}$.

In the next section we discuss what amount they can contract, when the benefit sharing takes place, i.e. for any $\delta \in [0, 1)$.

2.3.1 Decision-making with REDD offsets, benefit sharing mechanism, and known realization of CO_2 price in the second time period.

In order to analyze the behavior of the electricity producer let us consider a certain realization of CO_2 price $p = p_l$ in the second period. Technically, the Problem 2 can be split into two alternative profit-maximizing tasks.

Problem 3 ($E(\boldsymbol{x}) \geq \mathcal{E}$)**.** *Given the feasibility domain $\boldsymbol{X}$ (6) and the amount of REDD offsets $\mathcal{E} \in (0, E^0]$, maximize the profit:*

$$\underset{\boldsymbol{x} \in \boldsymbol{X_3}}{\text{maximize}}\, \Pi_3^R(p, \boldsymbol{x}), \tag{21}$$

where

$$\Pi_3^R(p, \boldsymbol{x}) = \Pi_e(\boldsymbol{x}) - p(E(\boldsymbol{x}) - \mathcal{E}), \tag{22}$$

$$\boldsymbol{X_3} = \boldsymbol{X} \cap \{\boldsymbol{x} : E(\boldsymbol{x}) \geq \mathcal{E}\}. \tag{23}$$

Let us denote the solution to Problem 3 by the symbol $\boldsymbol{x_3^*} = \boldsymbol{x_3^*}(p) \in \boldsymbol{X_3}$. The corresponding maximum profit is given by the relation:

$$\hat{\Pi}_3^R = \hat{\Pi}_3^R(p) = \Pi_e(\boldsymbol{x_3^*}) - p(E(\boldsymbol{x_3^*}) - \mathcal{E}). \tag{24}$$

Problem 4 ($E(\boldsymbol{x}) \leq \mathcal{E}$)**.** *Given the feasibility domain $\boldsymbol{X}$ (6) and the amount of REDD offsets $\mathcal{E} \in (0, E^0]$, maximize the profit:*

$$\underset{\boldsymbol{x} \in \boldsymbol{X_4}}{\text{maximize}}\, \Pi_4^R(p, \boldsymbol{x}), \tag{25}$$

where

$$\Pi_4^R(p, \boldsymbol{x}) = \Pi_e(\boldsymbol{x}) - \delta p(E(\boldsymbol{x}) - \mathcal{E}), \tag{26}$$

$$\boldsymbol{X_4} = \boldsymbol{X} \cap \{\boldsymbol{x} : E(\boldsymbol{x}) \leq \mathcal{E}\}. \tag{27}$$

Let us denote the solution to Problem 4 by the symbol $\boldsymbol{x_4^*} = \boldsymbol{x_4^*}(p) \in \boldsymbol{X_4}$. The corresponding maximum profit is given by the relation:

$$\hat{\Pi}_4^R = \hat{\Pi}_4^R(p) = \Pi_e(\boldsymbol{x_4^*}) - \delta p(E(\boldsymbol{x_4^*}) - \mathcal{E}). \tag{28}$$

Thus, for any fixed amount of $\mathcal{E} \in (0, E^0]$ available in the second period the electricity producer chooses the best response to CO_2 price $p = p_l$ in terms of profit-maximization – between $\hat{\Pi}_3^R$ (24) and $\hat{\Pi}_4^R$ (28):

$$\hat{\Pi}^R(p) = \max\{\hat{\Pi}_3^R, \hat{\Pi}_4^R\}, \tag{29}$$

[1] Even though this would imply excessive risk for both parties.

which is equivalent to (13)-(14). The solution to Problem 2 is chosen according to the rule:

$$\boldsymbol{x_2^*} = \begin{cases} \boldsymbol{x_3^*}, & \text{if } \hat{\Pi}^R = \hat{\Pi}_3^R \\ \boldsymbol{x_4^*}, & \text{if } \hat{\Pi}^R = \hat{\Pi}_4^R \end{cases} \tag{30}$$

The described optimization alternatives as possibilities for the electricity producer in our two-stage model are illustrated in Figure 1.

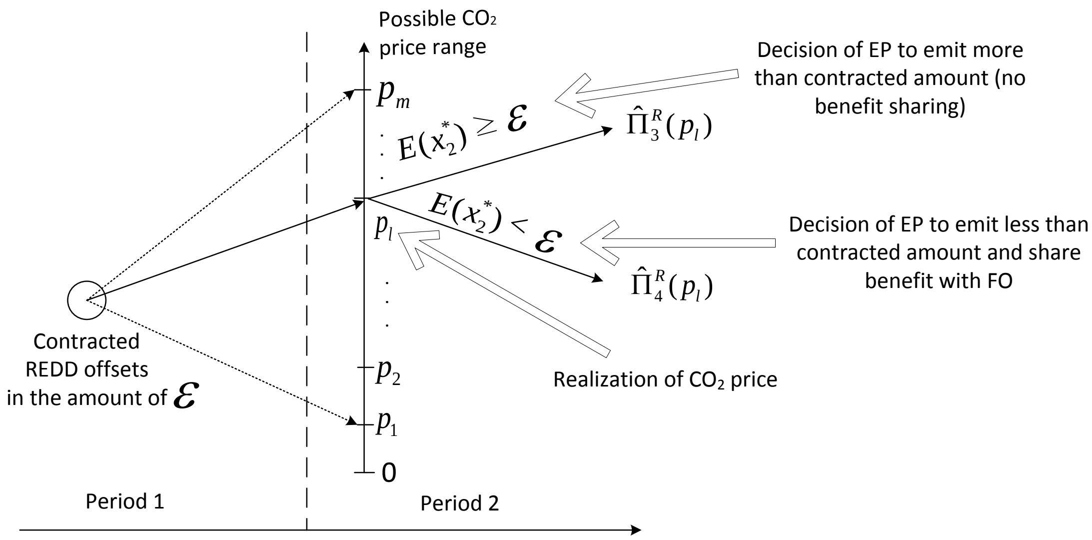

Figure 1: Illustration of the problem setting: initially contracted amount of offsets $\mathcal{E}$ and realization of the uncertain CO_2 price.

3 Analytical results

In this section we analytically find the maximum profit (29) 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 estimate of the amount of REDD offsets that can be contracted.

Lemma 2. *For any CO_2 price p, any benefit sharing ratio $\delta \in [0, 1]$, and any fixed amount $\mathcal{E}$ of contracted offsets in the first period such that $\mathcal{E} \in (0, E(\boldsymbol{x_1^*}(p))]$ the maximum profit with REDD (29) is calculated as follows:*

$$\hat{\Pi}^R(p) = \hat{\Pi}_3^R = \Pi_e(\boldsymbol{x_1^*}(p)) - pE(\boldsymbol{x_1^*}(p)) + p\mathcal{E}. \tag{31}$$

The proof is in the Appendix A.2

Remark 3. *The definition of Lemma 2 is that for any realization of future CO_2 price p the optimal emissions and profits in the case of contracting REDD offsets are equal to those without contracting REDD offsets, provided that the contracted amount does not exceed the optimal quantity of emissions (without contracting REDD) for that CO_2 price p.*

Lemma 3. *For any CO_2 price $p \in [0, \tilde{p}]$, any benefit sharing $\delta \in [0, 1)$, and any amount $\mathcal{E}$ of contracted offsets in the first period such that $\mathcal{E} > E(\boldsymbol{x_1^*}(p))$ the fair price of the forest owner p_F (18) is always higher than the fair price of the electricity producer (19).*

The proof is in the Appendix A.3.

Finally, let us formulate and prove the following theorem.

Theorem 1. *For a given CO_2 price distribution $\{p_l, w_l\}, l = 1, .., m$ (12) 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 (18) and of the electricity producer p_E (19) 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 $\tilde{p} = \max\{p_l\}$:*

$$p_F = p_E = \bar{p} \quad \textit{for any} \quad \mathcal{E} \leq \tilde{\mathcal{E}}, \quad \delta \in [0, 1], \tag{32}$$

where

$$\tilde{\mathcal{E}} = E(\boldsymbol{x}_1^*(\tilde{p})). \tag{33}$$

For any amount of REDD offsets larger than $\tilde{\mathcal{E}}$ (33) the fair price of the forest owner p_F is higher than the fair price of the electricity producer p_E:

$$p_F > p_E \quad \textit{for any} \quad \mathcal{E} > \tilde{\mathcal{E}}, \quad \delta \in [0, 1). \tag{34}$$

The proof is in the Appendix A.4

Remark 4. *Theorem 1 shows that in the case of a bounded CO_2 price distribution of the CO_2 price, 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 main 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 with possibility of a high CO_2 price the contracted amount is non-zero, hinting at possibly implementing the REDD-based offset instrument featuring a benefit sharing approach as considered in this paper.

4 Modeling results

Analytical results obtained in the previous section are valid for a broad range of possible model setups in our modeling framework. In order to provide a numerical example and illustrate the impact of a contracted amount of REDD offsets on the profit distribution of the electricity producer, we calibrate the model for a realistic case-study, and carry out numeric optimization.

4.1 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/IEDIndex3.cfm?tid=2&pid=2&aid=7

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 gasfired 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 the 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. This simplification allows us to link the hourly profile with the aggregate demand. We estimate the hourly profile change assuming that a change in aggregate demand leads to the proportional shifts in every hour of the profile for an average day. Our model is working 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]).

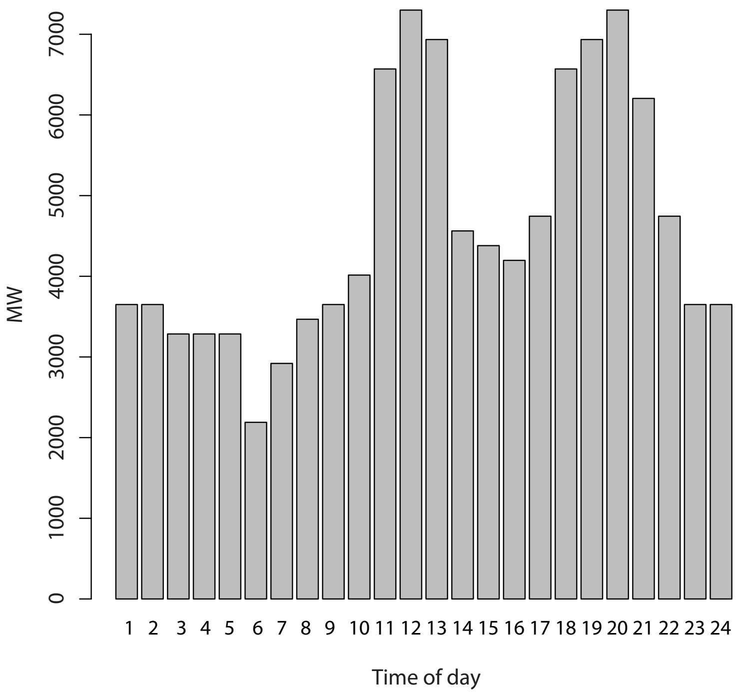

Figure 2: Average hourly electricity demand.

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.:

$$P^e = D^{-1}(Q) = AQ^{\alpha}, \tag{35}$$

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 as a solution to the optimization Problem 1. The estimated parameters of the demand function (35) are $A = 1.05 \times 10^5$, $\alpha = -0.612$. These values are consistent with $P^e = 90.5\,\text{US\$/MWh}$ at profits maximum 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 $Q^0 = 100.47\,\text{GWh}$ (which is approximately equal to the average daily electricity consumption in Belarus[4]), and the corresponding profit is $\hat{\Pi}(Q^0) = 3.56\,\text{mln. US\$}$.

Emissions factors. For presently operating, coal-fired power plants the cummulative emissions range between 950 and 1250 gCO_2 eq/ kWh [15]. In our study we use a value from an indicated interval given in Table 1. Emissions factors for gas powered plants are taken from [16].

4.2 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:

$$p_l = 10(l-1), \quad w_l = \frac{1}{9}, \quad l = 1, .., 9. \tag{36}$$

Sizes of REDD-based offset contracts used in the model are within the range $[0, E^0]$, where E^0 is the optimal emissions without CO_2 price. In Figure 3 the *fair prices* (18)-(19) 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 $\tilde{\mathcal{E}} = E(\boldsymbol{x}^*(p_9)) = 10.93$ $MtCO_2$. 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 analytical results of the paper.

In Figure 4 we show how the contacted amount $\tilde{\mathcal{E}}$ impacts the profit distribution of the electricity producer. The plot shows that although the mean profit determined by the considered CO_2 price distribution stays the same with REDD offsets (compared to the case without them), $\mathbb{E}\hat{\Pi}^R = \mathbb{E}\hat{\Pi}$ (15), entering into REDD offsets contract does impact the profit distribution. Notably, REDD offsets help the electricity producer to hedge against higher CO_2 prices and almost double their profit in this case.

[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/IEDIndex3.cfm?tid=2&pid=2&aid=2

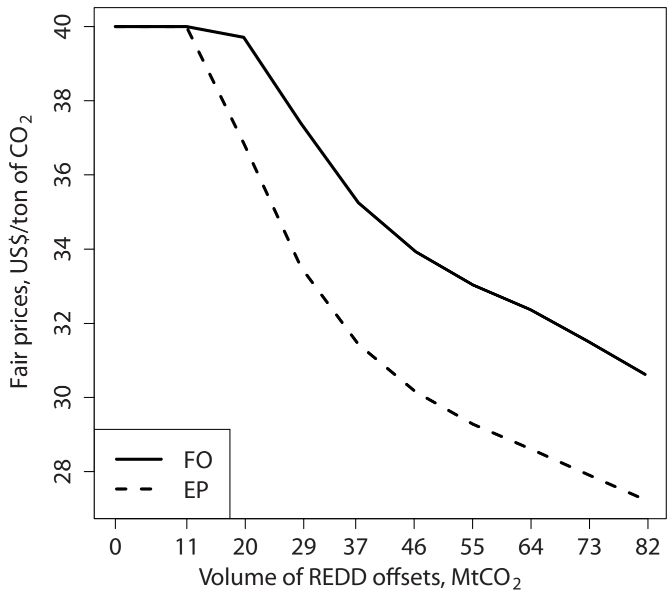

Figure 3: *Fair prices* of the electricity producer (EP) and forest owner (FO) depending on the volume of REDD offsets. *Benefit sharing ratio* is $\delta = 0.5$, and future CO_2 price distribution is uniform within the range 0–80 US$/ton CO_2.

4.3 The role of the benefit sharing mechanism

In this section we provide a numerical illustration of how the benefit sharing mechanism determined by the parameter δ can impact the amount of contracted REDD offsets. Even though the benefit sharing concept is at the core of the suggested construction, it remains inactive if electricity producer and forest owner use one common CO_2 price distribution in their decision-making. Let us explore a situation when the electricity producer and forest owner perceive the CO_2 price distribution asymmetrically. For instance, they could put different weights w_l in (12) for the same values of CO_2 prices p_l. For example, the forest owner may expect the distribution as in (36), while the electricity producer may put more weight on higher prices, i.e. his distribution can be:

$$p_l = 10(l-1), \quad w_l = 0.01(l+6.11), \quad l = 1,..,9. \tag{37}$$

The difference between (36) and (37) can be interpreted as the electricity producer is more sensitive to larger profit loses (risk-averse). In the case of price distribution (37) (risk-averseness) the contracted amount $\tilde{\mathcal{E}}$ of the electricity producer is higher as he is willing to pay a higher *fair price* compared to the case with the distribution (36). The Figure 5 demonstrates how the *benefit sharing ratio* δ impacts the amount of contracted offsets $\tilde{\mathcal{E}}$: for larger parameter δ, the contracted amount $\tilde{\mathcal{E}}(\delta)$ is larger. In this example for $\delta = 0.5$ the contracted amount of REDD offsets has increased considerably compared to no benefit sharing, $\delta = 0$. This preliminary analysis shows that the benefit sharing mechanism has a potential to increase the volume of REDD contracts.

5 Conclusions

In developing a fair mechanism for REDD it is important to understand the decision-making process (optimal behavior) of energy producers – the potential buyers of REDD-based offsets, because of considerable total share of emissions coming from the energy

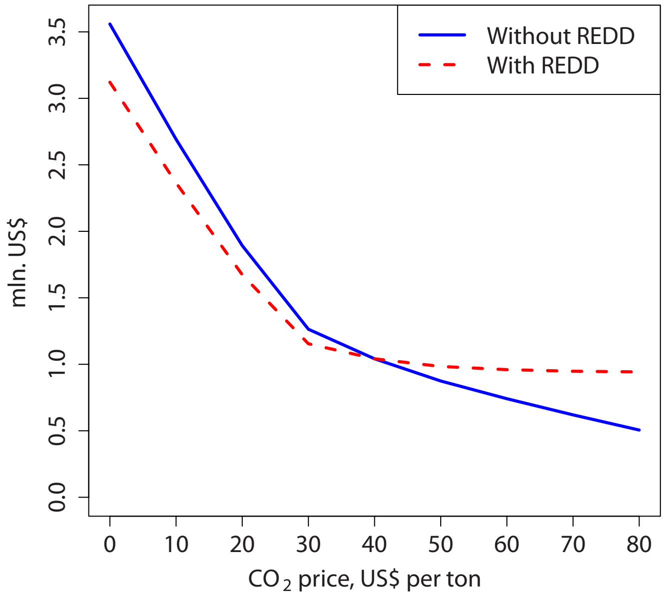

Figure 4: Profit of the electricity producer (distribution) without contracting REDD offsets and with contracting REDD offsets for the optimal volume ($\tilde{\mathcal{E}} = 10.93$ $MtCO_2$) and *benefit sharing ratio* $\delta = 0.5$.

sector (see, e.g., [21]). Our model deals with medium-term planning of the electricity producer who possesses flexibility in his responses to uncertain CO_2 prices. The electricity producer in the model is restricted in exercising market power (charging the electricity price) by the elasticity of demand coming from electricity consumers and is maximizing his profit by optimizing technological mixes in the production. The analytical results provided in the paper are based only on the assumption that with growing CO_2 Price, optimal profit and corresponding emissions are strictly declining functions. The problem of optimal usage of REDD offsets by the electricity producer is formalized in the two-period model with an uncertain CO_2 price.

The valuation of REDD offsets by the forest owner (seller) and electricity producer (buyer) based on their fair (indifference) conditions has several important implications. We show that when there is no profit sharing mechanism and the forest owner can use and resell all the offsets traded at the first stage, then the agreement can be made for any amount of REDD offsets at the mean CO_2 price. This, however, would imply a high level of certainty about the future CO_2 price, so that the risk for the buyer (possible lower price) and risk for the seller (possible higher price) are acceptable. Under the condition of highly uncertain CO_2 prices and consequently higher risks, the benefit sharing mechanism allows to reduce this risk thanks to a greater future flexibility. In the case of benefit sharing coming from selling the unused offsets on the market and sharing the profit between the forest owner and electricity producer, we analytically prove two results. Firstly, there exist amounts of REDD offsets for which the *fair prices* coincide and are equal to the mean CO_2 price. The maximum contracted amount corresponds to the minimum amount of emissions generated by the electricity producer – at the maximum expected CO_2 price. Secondly, for larger amounts the *fair price* of the electricity producer is lower than the *fair price* of the forest owner and, therefore, these amounts are not contracted. This fact is not straightforward in the scenario when the electricity producer can share the profit with the forest owner, and the analytical proof is given in Lemma 3 (see Case 2 in Appendix A.3). This means that if the forest owner agrees to sell a “larger” amount of REDD offsets at

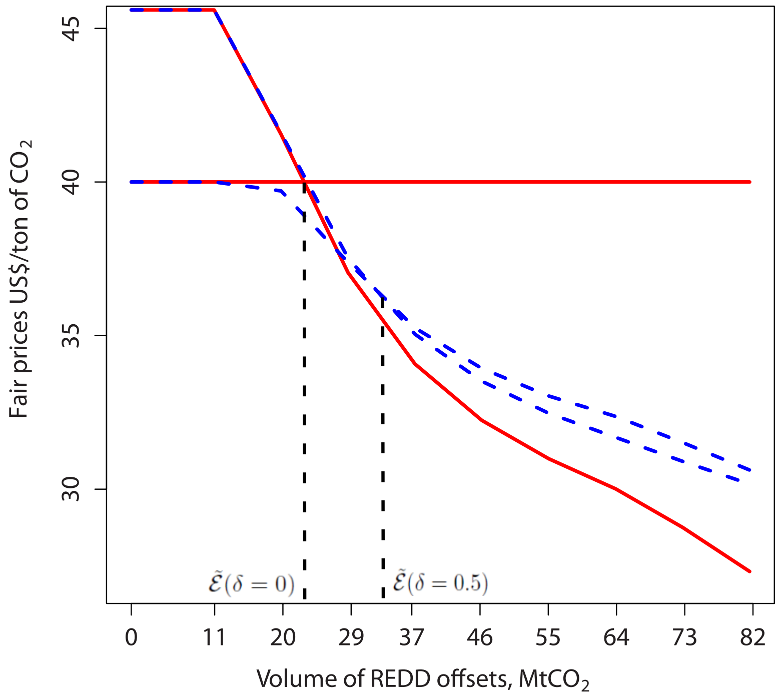

Figure 5: Impacts of benefit sharing on the contracted amounts of REDD-based offsets under asymmetric information on the CO_2 price distribution. Dashed lines are *fair prices* of the forest owner (FO) and electricity producer (EP) for *benefit sharing ratio* $\delta = 0.5$, solid lines – for $\delta = 0$ (no benefit sharing).

the price suggested by the electricity producer someone will lose compared to a situation when not making this deal. In our problem setting two characteristics of the expected CO_2 price distribution are important for contracting REDD offsets – the mean CO_2 price, and the maximum expected CO_2 price. Even with the parties being considered as risk neutral, it is not only the average price they should take into account when making a decision on contracting REDD offsets.

We illustrated the impact of contracted REDD offsets on profit distribution of the electricity producer in the numerical example based on realistic data. The modeling results indicate that contracted REDD offsets might help avoid bankruptcy of CO_2-intensive producers at high levels of CO_2 price and therefore serve as a stabilizing mechanism during the transition of energy systems to greener technologies.

The idea behind the benefit sharing mechanism that we suggested to use, is to reduce the risk of forest owners in selling the offsets for too low a price (as additional market benefits might come later). This could reduce the offsets price in the first period, that consequently reduces the risk of the electricity producer (regret if the CO_2 price stays low).

The modeling of a situation with asymmetric distributions of CO_2 price provides preliminary illustration of the positive role of a benefit sharing mechanism by increasing contracted amounts of REDD offsets. This might be a promising direction for further research.

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A Appendix

A.1 Proof of Lemma 1

Proof. Firstly, by definition of maximum (8) we have:

$$\Pi(\boldsymbol{x}_1^*(p), p) = \Pi_e(\boldsymbol{x}_1^*(p)) - E(\boldsymbol{x}_1^*(p))p \geq \Pi_e(\boldsymbol{x}) - E(\boldsymbol{x})p. \tag{38}$$

Secondly, let us assume on the contrary that for some $\bar{\boldsymbol{x}} \in \boldsymbol{X}$, such that $E(\bar{\boldsymbol{x}}) \neq E(\boldsymbol{x}_1^*(p))$ the relation (38) is equality. Then, we have:

$$\hat{\Pi}(p) = \Pi_e(\boldsymbol{x}_1^*(p)) - E(\boldsymbol{x}_1^*(p))p = \Pi_e(\bar{\boldsymbol{x}}) - E(\bar{\boldsymbol{x}})p. \tag{39}$$

According to Remark 1 to Assumption 1 the equation (39) means that:

$$E(\boldsymbol{x}_1^*(p)) = E(\bar{\boldsymbol{x}}). \tag{40}$$

Thus, we came to a contradiction, meaning that assumption (39) is false, and (11) is true. □

A.2 Proof of Lemma 2

Proof. Firstly, by the condition of the lemma $E(\boldsymbol{x}_{\mathbf{1}}^*(p)) \geq \mathcal{E}$, meaning that $\boldsymbol{x}_{\mathbf{1}}^*(p) \in \boldsymbol{X}_{\mathbf{3}}$ (23). Secondly, (21) is equivalent to (7) and, hence, solution to Problem 3 coincides with the solution to Problem 1: $\boldsymbol{x}_{\mathbf{3}}^* = \boldsymbol{x}_{\mathbf{1}}^*(p)$. To complete the proof we need to show that: $\hat{\Pi}_3^R \geq \hat{\Pi}_4^R$ in (29).

Indeed, using (24), (28) and definition of maximum at price p (8), for $\boldsymbol{x}_{\mathbf{4}}^* \in \boldsymbol{X}_{\mathbf{4}} \subset \boldsymbol{X}$ we come to the following chain of inequalities:

$$\begin{aligned} \hat{\Pi}_3^R(p) &= \Pi_e(\boldsymbol{x}_{\mathbf{3}}^*) - p(E(\boldsymbol{x}_{\mathbf{3}}^*) - \mathcal{E}) = \Pi_e(\boldsymbol{x}_{\mathbf{1}}^*(p)) - pE(\boldsymbol{x}_{\mathbf{1}}^*(p)) + p\mathcal{E} \geq \\ & \Pi_e(\boldsymbol{x}_{\mathbf{4}}^*) - pE(\boldsymbol{x}_{\mathbf{4}}^*) + p\mathcal{E} = \Pi_e(\boldsymbol{x}_{\mathbf{4}}^*) - p(E(\boldsymbol{x}_{\mathbf{4}}^*) - \mathcal{E}) \geq \\ & \Pi_e(\boldsymbol{x}_{\mathbf{4}}^*) - \delta p(E(\boldsymbol{x}_{\mathbf{4}}^*) - \mathcal{E}) = \hat{\Pi}_4^R(p). \end{aligned} \tag{41}$$

This relation means that $\hat{\Pi}_3^R(p) \geq \hat{\Pi}_4^R(p)$ if $\delta = 1$, and $\hat{\Pi}_3^R(p) > \hat{\Pi}_4^R(p)$ if $\delta \in [0, 1)$. Thus,

$$\hat{\Pi}^R(p) = \hat{\Pi}_3^R(p) = \hat{\Pi}(p) + p\mathcal{E}. \tag{42}$$

□

A.3 Proof of Lemma 3

Proof. Let us consider two cases depending on the optimal profit in (29).

Case 1. $\hat{\Pi}^R(p) = \hat{\Pi}_3^R$, meaning that the electricity producer does not share emission offsets with the forest owner and emits $E(\boldsymbol{x}_{\mathbf{3}}^*) \geq \mathcal{E}$. In this case the indifference equation for the forest owner (16) reads as follows:

$$p_F\mathcal{E} = p\mathcal{E} \quad \Rightarrow \quad p_F = p. \tag{43}$$

The indifference equation for the electricity producer (17) is the following:

$$\hat{\Pi}^R(p) - p_E\mathcal{E} = \hat{\Pi}(p), \tag{44}$$

and substitution of (9) and (24) to (44) gives the *fair price*:

$$p_E = p + \frac{\Pi_e(\boldsymbol{x}_{\mathbf{3}}^*) - E(\boldsymbol{x}_{\mathbf{3}}^*)p}{\mathcal{E}} - \frac{\Pi_e(\boldsymbol{x}_{\mathbf{1}}^*(p)) - E(\boldsymbol{x}_{\mathbf{1}}^*(p))p}{\mathcal{E}} \tag{45}$$

For $\boldsymbol{x}_{\mathbf{3}}^* \in \boldsymbol{X}$ such that $E(\boldsymbol{x}_{\mathbf{3}}^*) = \mathcal{E} > E(\boldsymbol{x}_{\mathbf{1}}^*(p))$ we can apply Lemma 1. Hence, (45) leads to the required inequality:

$$\frac{\Pi_e(\boldsymbol{x}_{\mathbf{3}}^*) - E(\boldsymbol{x}_{\mathbf{3}}^*)p}{\mathcal{E}} - \frac{\Pi_e(\boldsymbol{x}_{\mathbf{1}}^*(p)) - E(\boldsymbol{x}_{\mathbf{1}}^*(p))p}{\mathcal{E}} < 0 \quad \Rightarrow \quad p_E < p = p_F, \tag{46}$$

which proves Case 1.

Case 2. $\hat{\Pi}^R(p) = \hat{\Pi}_4^R$, meaning that the electricity producer can share emission offsets. Let us find the optimal technological mix $\boldsymbol{x}_{\mathbf{4}}^*$ – solution to Problem 4. Problem (25)-(27) is equivalent to the following problem (see (5), (7)):

$$\max_{\boldsymbol{x} \in \boldsymbol{X}_{\mathbf{4}}} \Pi(\boldsymbol{x}, \delta p) = \Pi_e(\boldsymbol{x}) - \delta pE(\boldsymbol{x}). \tag{47}$$

Thus, two alternatives are possible in the Case 2.

Case 2a. $\mathcal{E} \geq E(\boldsymbol{x}_1^*(\delta p))$, meaning that the contracted amount of offsets is larger than optimal emissions at the CO_2 price δp. In this case $\boldsymbol{x}_1^*(\delta p) \in \boldsymbol{X}_4$ (27), and as it is the solution to (47), we have:

$$\boldsymbol{x}_4^*(p) = \boldsymbol{x}_1^*(\delta p). \tag{48}$$

Hence, according to Assumption 1 for all $\delta \in [0, 1)$ one has:

$$E(\boldsymbol{x}_4^*) = E(\boldsymbol{x}_1^*(\delta p)) > E(\boldsymbol{x}_1^*(p)). \tag{49}$$

In this case the indifference condition (16) for the forest owner reads as follows:

$$p(1-\delta)\big(\mathcal{E} - E(\boldsymbol{x}_4^*)\big) + p_F \mathcal{E} = p\mathcal{E}, \tag{50}$$

leading to the following *fair price*:

$$p_F = \frac{(1-\delta)pE(\boldsymbol{x}_4^*)}{\mathcal{E}} + \delta p. \tag{51}$$

The indifference equation for the electricity producer takes the form:

$$\Pi_e(\boldsymbol{x}_4^*) - \delta p(E(\boldsymbol{x}_4^*) - \mathcal{E}) - p_E\mathcal{E} = \Pi_e(\boldsymbol{x}_1^*(p)) - E(\boldsymbol{x}_1^*(p))p. \tag{52}$$

His *fair price* in this case is calculated as follows:

$$p_E = \delta p + \frac{\Pi_e(\boldsymbol{x}_4^*) - E(\boldsymbol{x}_4^*)\delta p}{\mathcal{E}} - \frac{\Pi_e(\boldsymbol{x}_1^*(p)) - E(\boldsymbol{x}_1^*(p))p}{\mathcal{E}}. \tag{53}$$

For the optimal mix $\boldsymbol{x}_4^* \in \boldsymbol{X}$ such that (49) is true one can apply Lemma 1:

$$\Pi_e(\boldsymbol{x}_1^*(p)) - E(\boldsymbol{x}_1^*(p))p > \Pi_e(\boldsymbol{x}_4^*) - E(\boldsymbol{x}_4^*)p. \tag{54}$$

Substitution of (54) to (53) gives the required inequality:

$$\begin{aligned} p_E \;=\; & \delta p + \frac{\Pi_e(\boldsymbol{x}_4^*) - E(\boldsymbol{x}_4^*)\delta p - \big(\Pi_e(\boldsymbol{x}_1^*(p)) - E(\boldsymbol{x}_1^*(p))p\big)}{\mathcal{E}} < \\ & \delta p + \frac{\Pi_e(\boldsymbol{x}_4^*) - E(\boldsymbol{x}_4^*)\delta p - \big(\Pi_e(\boldsymbol{x}_4^*) - E(\boldsymbol{x}_4^*)p\big)}{\mathcal{E}} = \\ & \delta p + \frac{(1-\delta)pE(\boldsymbol{x}_4^*)}{\mathcal{E}} = p_F. \end{aligned} \tag{55}$$

Case 2b. $\mathcal{E} < E(\boldsymbol{x}_1^*(\delta p))$, meaning that the contracted amount is less than optimal emissions at price δp. In this case $\boldsymbol{x}_1^*(\delta p) \notin \boldsymbol{X}_4$ (27). According to Assumption 1 there exist price $\hat{p}$, $\delta p < \hat{p} < p$, and technological mix $\boldsymbol{x}_1^*(\hat{p})$ (see Figure 6), such that:

$$\boldsymbol{x}_1^*(\hat{p}) \in \boldsymbol{X}_4 : \quad E(\boldsymbol{x}_1^*(\hat{p})) = \mathcal{E}. \tag{56}$$

Below we show that technological mix $\boldsymbol{x}_4^* = \boldsymbol{x}_1^*(\hat{p})$ is the solution to Problem 4 in this case. Let us take a technological mix $\tilde{\boldsymbol{x}}_4 \in \boldsymbol{X}_4$ (27) different from $\boldsymbol{x}_1^*(\hat{p})$ (56). As $E(\tilde{\boldsymbol{x}}_4) \leq E(\boldsymbol{x}_1^*(\hat{p}))$, the following inequality holds:

$$E(\boldsymbol{x}_1^*(\hat{p}))(\hat{p} - \delta p) \geq E(\tilde{\boldsymbol{x}}_4)(\hat{p} - \delta p). \tag{57}$$

At the same time, by definition of maximum (8) at the price $\hat{p}$ we have:

$$\Pi_e(\boldsymbol{x}_1^*(\hat{p})) - E(\boldsymbol{x}_1^*(\hat{p}))\hat{p} \geq \Pi_e(\tilde{\boldsymbol{x}}_4) - E(\tilde{\boldsymbol{x}}_4)\hat{p}. \tag{58}$$

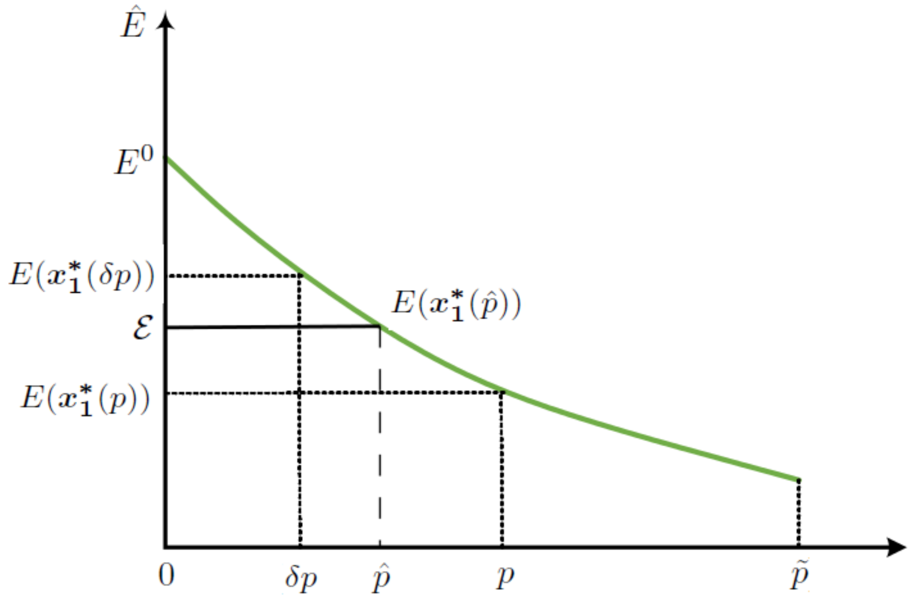

Figure 6: Optimal emissions of the electricity producer with respect to CO_2 price (horizontal axis) without REDD offsets. A conceptual graph of $\hat{E}(p)$, satisfying Assumption 1.

Combining (57) and (58) one gets:

$$\begin{aligned}\Pi_e(\boldsymbol{x_1^*}(\hat{p})) - E(\boldsymbol{x_1^*}(\hat{p}))\hat{p} + E(\boldsymbol{x_1^*}(\hat{p}))(\hat{p} - \delta p) \geq \\ \Pi_e(\tilde{\boldsymbol{x}}_{\boldsymbol{4}}) - E(\tilde{\boldsymbol{x}}_{\boldsymbol{4}})\hat{p} + E(\tilde{\boldsymbol{x}}_{\boldsymbol{4}})(\hat{p} - \delta p),\end{aligned} \tag{59}$$

that leads to:

$$\Pi_e(\boldsymbol{x_1^*}(\hat{p})) - E(\boldsymbol{x_1^*}(\hat{p}))\delta p \geq \Pi_e(\tilde{\boldsymbol{x}}_{\boldsymbol{4}}) - E(\tilde{\boldsymbol{x}}_{\boldsymbol{4}})\delta p \quad \text{for all} \quad \tilde{\boldsymbol{x}}_{\boldsymbol{4}} \in \boldsymbol{X_4}, \tag{60}$$

meaning that $\hat{\Pi}_4^R = \Pi(\boldsymbol{x_1^*}(\hat{p})), \delta p)$, and:

$$E(\boldsymbol{x_4^*}) = E(\boldsymbol{x_1^*}(\hat{p})) = \mathcal{E} > E(\boldsymbol{x_1^*}(p)). \tag{61}$$

We have proved that in the Case 2b the electricity producer does not return any offsets to the forest owner and uses the whole amount $\mathcal{E}$. Thus, in this case $\hat{\Pi}^R(p) = \hat{\Pi}_3^R = \hat{\Pi}_4^R$ and this situation is the same as in Case 1. Thus, we proved that in all cases:

$$p_E < p_F. \tag{62}$$

□

A.4 Proof of Theorem 1

Proof. According to Assumption 1 the amount $\tilde{\mathcal{E}}$ (33) is emitted by the electricity producer at any price p_l in the distribution (12). Hence, for every $p = p_l$ in the distribution the conditions of Lemma 2 are true, meaning that the maximum profit with REDD $\hat{\Pi}^R(p_l)$ (31) differs from the maximum profit without REDD $\hat{\Pi}(p_l)$ (9) by the term $p_l\tilde{\mathcal{E}}$:

$$\hat{\Pi}^R(p_l) = \hat{\Pi}(p_l) + p_l\tilde{\mathcal{E}}. \tag{63}$$

Substituting (63) to the definition of *fair price* of the electricity producer (19) we get:

$$p_E = \frac{\mathbb{E}\hat{\Pi}^R - \mathbb{E}\hat{\Pi}}{\tilde{\mathcal{E}}} = \frac{\mathbb{E}\hat{\Pi} + \mathbb{E}p_l\tilde{\mathcal{E}} - \mathbb{E}\hat{\Pi}}{\tilde{\mathcal{E}}} = \mathbb{E}p_l = \bar{p}. \tag{64}$$

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 (18) one gets:

$$p_F = \bar{p}. \tag{65}$$

The same reasoning is valid for any $\mathcal{E} \in (0, \tilde{\mathcal{E}}]$, and, hence, (32) is true.

For the amount of REDD offsets $\mathcal{E} \in (\tilde{\mathcal{E}}, E^0]$ for some CO_2 price realizations $p = p_l$ in the distribution (12) the conditions of Lemma 2 are satisfied and, hence, the fair prices coincide. At the same time, there are price realizations in the distribution (12), for which conditions of Lemma 3 are satisfied (at least for the price $\tilde{p} = \max\{p_l\}$), meaning that $p_F > p_E$. Therefore in this case $p_F > p_E$, which proves (34). □