Energy Syst
DOI 10.1007/s12667-016-0222-8

ORIGINAL PAPER

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

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Received: 19 May 2015 / Accepted: 16 September 2016

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 prepare for 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.

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Keywords Electricity generation · CO_2 emissions · REDD offsets · Benefit-sharing

1 Introduction

This paper is devoted to the elaboration of financial instruments supporting the reduced emissions from deforestation and degradation (REDD+) mechanisms [24,30]. Over 500 REDD+ pilot projects were initiated worldwide in the decade following the United Nations framework convention on climate change (UNFCCC) negotiations [12]. The total global pledge for REDD+ between 2006 and 2014 was estimated at USD 9.8 billion [11]. Only 10 % of this amount comes from voluntary carbon market with the majority funded by multilateral and bilateral donors (public sector) including the World Bank, the UN REDD initiative, and the Norwegian government [12,29]. The EU and its Member States provided EUR 3 billion in support of REDD+ activities, through a wide range of thematic areas, countries and funding channels [11]. Most of this donor funding is intended for development of governing capacity, which is necessary to properly manage REDD+ funding [12].

REDD is a relatively low-cost mitigation option [6,24], and its integration in the global mitigation strategy has a potential to allow for larger emissions reductions and a lower overall abatement cost [18]. This integration can be done by linking REDD as an emission reduction credit program to major cap-and-trade programs [2]. For example, [34] marks the growing linkages between the world's cap-and-trade systems for GHGs, both directly between systems, and indirectly via connections to credit systems such as the clean development mechanism. However, there is still an ongoing discussion related to uncertainties and risks in REDD implementation. It is difficult to anticipate the combined effects on carbon and other co-benefits owing to the disparity between the activities available under the REDD program [7,22]. Accepting this uncertainty, we explore the relation between REDD supplier and GHG-emitting energy producer in the context of a potentially emerging REDD offsets market.

In the papers [13,39] the price-taking electricity producer's decision-making 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 (see, e.g. [16,17])—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. We, therefore, consider a homogenous product oligopoly model, in which each firm is maximizing its unilateral profits against the residual demand curve constructed using the equilibrium actions chosen by its competitors [42]. In this setting, the residual demand function faced by a single firm gives the difference between the market demand and the amount that firm's competitors are willing to supply at each price. Secondly, the electricity producer in our model is a medium-term decision maker: they do not change their 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. Generally, both investments in power generation capacity and forest management are long-term issues. However, in our analysis we focus specifically on medium-term, where the transition phase to higher CO_2 prices and REDD offsets acceptance might happen. The problem of REDD in the long-term forest management is very complex due to uncertainties in estimating the baseline and sustainable forest management impacts. For example, there are many methodological challenges related to forest definition, additionality, leakage and permanence [35,40]. In our study we do not focus on these technical aspects of REDD implementation. In our model REDD offsets are traded bilaterally between the REDD supplier (forest owner) and consumer (electricity producer) in the "first" period when the future CO_2 prices are uncertain. We assume the acceptance of REDD credits for emission offsetting in the future ("second" period when the CO_2 price reveals), so that the contracted amount of REDD offsets (in tons of CO_2) can be used for emissions offsetting. We assume that in the "first" period the forest owner can supply the amount of REDD offsets sufficient to cover potential emissions of the electricity producer in the "second" period. In this setup the parties choose their fair prices of REDD offsets in the "first" period—before the CO_2 price reveals in the "second" period.

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 this 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. CO_2 prices are exogenous in the proposed partial equilibrium modeling framework. The decision-making process of the electricity producer (under condition of existing or absent CO_2 tax/price) consists of: (1) choosing power plant load factors to minimize the cost given the hourly electricity demand profile and installed capacities of particular power generation technologies; and (2) choosing an electricity price to maximize the profit based on the demand function indicating consumer sensitivity to electricity prices (see, e.g., [25,38]). Here we apply a constant elasticity demand function [4] as a residual demand function in the oligopoly model.

The elevating CO_2 price might impact not only the profits of the electricity producer (which decrease), but also the electricity prices for the consumer (which increase) [20]. Hence, some financial instruments may be implemented today in order to be prepared for uncertain CO_2 prices in the future. 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 decides 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 each parties' indifference to engaging in contracting a given amount of REDD offsets. 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. Where both 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 [37], 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. Forest carbon credits come with inherent risk—carbon storage activities may fail due to leakage, forest fires, and increasing profitability of using the land for alternative activities [35]. Here we do not discuss these risks in detail, assuming that they are either reflected in the offsets price uncertainty or/and are insured.

The general idea of benefit-sharing is important within the REDD context [9,23]. Here we consider specifically a situation where benefits are shared between the REDD supplier and consumer. Technically, a similar mechanism design, including the sharing ratio, is implemented in various studies applied to problems other than REDD and based on different modeling approaches, see e.g. parameter λ in [5] applied to the problem of social control of government expenditures and parameter α in [28] applied to the contracts in nuclear industry. The benefit-sharing scenarios in which certain shares of the project's revenues are earmarked for the local government and injected back into the regional economy are considered in [10]. The benefit-sharing concept is also relevant in the international law context [27].

We propose a benefit-sharing mechanism that is activated 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 in the second period. 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 CO_2 price levels 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. In this framework the optimal response in terms of the emissions reduction and raising electricity price can be constructed for any CO_2 price. Secondly, we introduce a two-period model for REDD offsets contracting. In the first period ("today") there is no CO_2 price and the electricity producer sells the optimal amount of electricity (maximizing their profit). This quantity is generated by an optimal technological mix. A corresponding CO_2 quantity is emitted, and an equilibrium electricity price is charged to consumers. In the second period ("tomorrow"), the uncertain CO_2 price appears. Given the electricity producer's technological capacity and market power, they can solve an optimization problem for potential CO_2 prices. In [20] we show that in response to growing CO_2 price, the profit decreases and electricity price increases. Therefore uncertain CO_2 prices bear risk of profit loss for the electricity producer. Profit losses are higher for higher CO_2 prices. This leads to a consideration of the possibility to contract REDD offsets today in order to offset emissions tomorrow. Assuming a fixed amount of contracted REDD offsets in the first period, and given distribution of uncertain CO_2 price in the second period, the electricity producer solves the optimization problem (choosing technological mix for each CO_2 price realization in the second period) with two options: either (1) to emit more than the available REDD offsets, or (2) to emit less and, hence, sell the excess of offsets on the market, sharing the benefit with the forest owner. The second option is considered under a benefit-sharing ratio given in the first period. Based on the comparison of the second-period expected profits with and without contracting REDD offsets, the electricity producer evaluates their *fair (indifference) price* for each amount of offsets in the first period. Thus, our study deals with the utility indifference pricing similar to [14].

The forest owner—the seller of REDD offsets—calculates their fair price in the first period by comparing their expected profits with and without selling REDD offsets to the electricity producer in the first period. In the latter case the forest owner sells the offsets only in the second period at the realized market price. The forest owner knows the electricity producer's best response in the second period in terms of their utilization of REDD offsets for actual offsetting versus the option of partly reselling them on the market. This best response is expressed in the offsets amounts shared in the second period under a given amount of REDD offsets contracted in the first period and benefit-sharing ratio fixed in the first period. The focus of the study is on construction of the fair prices for a range of REDD-based offsets in order to find the quantities which can be contracted (i.e. those quantities for which the seller's price does not exceed the buyer's price). We also look at how the benefit-sharing ratio can impact contracted amounts.

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:

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

v_i are variable costs (US$/MWh);

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

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

$\boldsymbol{q}(\boldsymbol{x}) = (q_1, \dots, q_{24}) = \{\sum_{i=1}^{n} a_i x_{ij}\}$ 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 Sect. 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 do 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 [20] and Sect. 4.1 for details) and introduce the feasibility domain $\boldsymbol{X}$, which contains all technological mixes (controls) satisfying the hourly demand:

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

where $\boldsymbol{d}^{\boldsymbol{0}} = (d_1^0, \dots, d_{24}^0)$ 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), the electricity producer chooses technological mix $\boldsymbol{x}$ maximizing their profit (5) at a CO_2 price p:

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

Let us denote a solution to 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 First period: no carbon price

We assume, that in the first period ("today") there is no CO$_2$ price. Hence, Problem 1 is solved for $p = 0$. The electricity producer chooses an optimal technological mix $\boldsymbol{x}_1^*(0)$, and gets the corresponding profit $\hat{\Pi}(0)$, by charging electricity price $P^e = D(Q^0)$ (see (6)). Simultaneously, they emit the amount $E^0 = E(\boldsymbol{x}_1^*(0))$ of CO$_2$. The electricity producer envisions uncertain CO$_2$ prices in the second period ("tomorrow").

2.3 Second period without REDD offsets: assumptions for modeling

In the second period the electricity producer can solve Problem 1 for any potential CO$_2$ price. In our study we assume the following properties of optimal profit $\hat{\Pi}(p)$ (9) and emissions $\hat{E}(p) = E(\boldsymbol{x}_1^*(p))$ 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 [20]. It is also consistent with results of larger scale modeling [31].

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 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 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.

2.3.1 Modeling CO_2 price uncertainty

Let the future CO_2 price be an uncertain variable [33] following a discrete probability distribution:

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

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

In our model we assume that the electricity producer and forest owner are both risk neutral and, therefore, we deal with expected values. Given the distribution (12), the electricity producer calculates their expected utility in the second period (without REDD):

$$\mathbb{E}[\hat{\Pi}] = \sum_{l=1}^{m} \hat{\Pi}(p_l) w_l. \tag{13}$$

High CO_2 price decreases the profit of the electricity producer. The emitter can prepare for possibly high future CO_2 price by contracting REDD offsets before the information about CO_2 price is revealed; contracted REDD offsets would allow offsetting CO_2 emissions in the future with forest owners 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.

A problem is divided into two stages: at the first stage forest owner and electricity producer assign their prices for an amount $\mathcal{E} \in (0, E^0]$ of REDD offsets. Here E^0 is the maximum amount of emissions—generated by the electricity producer at zero CO_2 price, i.e. $E^0 = \hat{E}(0)$. If the forest owner does not make contracts with the electricity producer in the first period, for any amount $\mathcal{E}$ their expected utility in the second period is calculated as follows:

$$\mathbb{E}[\Pi_F^0] = \sum_{l=1}^{m} \mathcal{E} p_l w_l = \mathcal{E} \sum_{l=1}^{m} p_l w_l = \bar{p}\mathcal{E}, \tag{14}$$

where $\Pi_F^0 = \Pi_F^0(p_l)$ is their profit in the second without contracting the electricity producer in the first period, and $\bar{p}$ is the mean of distribution (12). Expression (14) means keeping all the offsets in the first period, and selling them in the second period at a market price.

2.4 Second period with REDD offsets

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 their 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 evaluation process of offsets amount $\mathcal{E}$ by the REDD offsets supplier (forest owner) and consumer (electricity producer) in the first period. Namely, for a given δ and $\mathcal{E}$ in the first period, the forest owner and electricity producer choose their fair prices, based on the electricity producer's decision-making in the second period with REDD. This is illustrated in Fig. 1.

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), 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 chooses technological mix $\boldsymbol{x}$ maximizing their profit at a CO_2 price realization p_l in the second time period:

$$\underset{\boldsymbol{x}\in\boldsymbol{X}}{\text{maximize}}\, \Pi^R(\boldsymbol{x}, p_l), \tag{15}$$

where

$$\Pi^R(\boldsymbol{x}, p_l) = \Pi_e(\boldsymbol{x}) - p_l\big[E(\boldsymbol{x}) - \mathcal{E}\big]_+ + \delta p_l\big[\mathcal{E} - E(\boldsymbol{x})\big]_+. \tag{16}$$

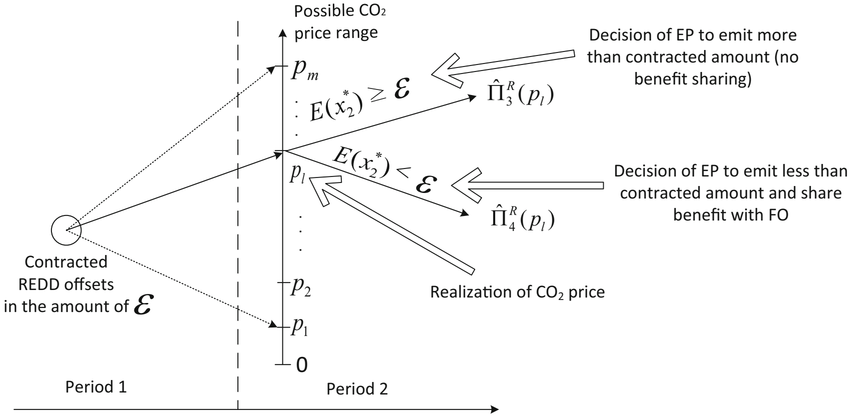

Fig. 1 Illustration of the problem setting: potentially contracted amount of offsets $\mathcal{E}$ and realization of the uncertain CO$_2$ price. Given $\mathcal{E}$ and benefit-sharing ratio δ the electricity producer optimizes their technological mix in order to maximize their profits in the second period. This optimization determines whether they share REDD offsets with the forest owner, and, if yes, the amount of shared offsets. This best response in the second period is used by parties to evaluate the fair prices (23), (24) for the amount $\mathcal{E}$ (under a given δ) in the first period

Here $[y]_+ = \max\{y, 0\}$, meaning that the electricity producer can offset their 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 (15)—generates the maximum profit with REDD: $\hat{\Pi}^R(p_l) = \Pi^R(\boldsymbol{x}_2^*(p_l), p_l)$ at a particular CO$_2$ price p_l. We denote by the symbol $E^R(p_l) = \left[\mathcal{E} - E(\boldsymbol{x}_2^*(p_l))\right]_+$ the corresponding amount of emission offsets, shared with the forest owner in the second period. The corresponding expected values are calculated as follows:

$$\mathbb{E}[\hat{\Pi}^R(\mathcal{E}, \delta)] = \sum_{l=1}^{m} \hat{\Pi}^R(p_l) w_l, \quad \bar{p} = \sum_{l=1}^{m} p_l w_l. \tag{17}$$

Here $E^R(p_l)$ is the best response of the electricity producer in the second period, which is known to the forest owner in the first period. This allows to calculate their expected profit, when contracting REDD:

$$\mathbb{E}[\Pi_F^R(\mathcal{E}, \delta)] = \sum_{l=1}^{m} (1 - \delta) p_l E^R(p_l) w_l. \tag{18}$$

Here Π_F^R denotes the forest owner's profit, when dealing with the electricity producer in the first period. Note that profit of the electricity producer, $\hat{\Pi}^R$, with REDD in the second period does not include the cost of offsets paid to the forest owner in the first period. The profit of the forest owner, Π_F^R, with REDD in the second period also does not include the benefit from selling offsets to the electricity producer in the first period.

We will introduce these costs (benefits) below, when defining the fair prices for REDD offsets.

2.5 Fair prices of REDD offsets

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 their fair price p_F at which they can sell the amount of offsets $\mathcal{E}$ in the first period using the utility indifference condition:

$$\mathbb{E}[\hat{\Pi}_F^R + p_F \mathcal{E}] = \mathbb{E}[\Pi_F^0], \tag{19}$$

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. Substituting (18) and (14) to (19), we obtain the following equation with respect to p_F:

$$(1 - \delta) \times \sum_{l=1}^{m} p_l E^R(p_l) w_l + p_F \mathcal{E} = \bar{p} \mathcal{E}, \tag{20}$$

Similarly, the electricity producer derives the price they are willing to pay for the REDD offsets according to their indifference condition:

$$\mathbb{E}[\hat{\Pi}^R - p_E \mathcal{E}] = \mathbb{E}[\hat{\Pi}]. \tag{21}$$

Susbstituting (17) and (13) to (21), we obtain the following equation with respect to p_E:

$$\mathbb{E}[\hat{\Pi}^R(\mathcal{E}, \delta)] - p_E \mathcal{E} = \mathbb{E}[\hat{\Pi}]. \tag{22}$$

For the given CO_2 price distribution $\{p_l, w_l\}, l = 1, \dots, m$ (12), benefit-sharing ratio $\delta \in [0, 1]$ and amount of offsets $\mathcal{E} \in (0, E^0]$ based on Eqs. (20), (22) we derive the fair prices of the forest owner p_F and the electricity producer p_E:

$$p_F = p_F(\mathcal{E}, \delta) = \bar{p} - (1 - \delta) \frac{\sum_{l=1}^{m} p_l E^R(p_l) w_l}{\mathcal{E}}, \tag{23}$$

$$p_E = p_E(\mathcal{E}, \delta) = \frac{\mathbb{E}\left[\hat{\Pi}^R(\mathcal{E}, \delta)\right] - \mathbb{E}\left[\hat{\Pi}\right]}{\mathcal{E}}. \tag{24}$$

For a fixed parameter $\delta \in [0, 1]$ Eqs. (23), (24) represent supply and demand curves for REDD offsets within the suggested benefit-sharing approach. The following analysis is based on the decision-making of the electricity producer with REDD offsets in the second period. We find their fair price p_E (24) in the first period for a given δ and $\mathcal{E}$. The forest owner knows the best response of the electricity producer in terms of $E^R(p_l)$. Based on this information, they calculate their fair price, p_F, in the first period according to Eq. (23).

2.6 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, Problem 2 can be split into two alternative profit-maximizing tasks. In short, they represent two alternatives: to share, or not to share.

Problem 3 $(E(\boldsymbol{x}) \geq \mathcal{E})$ Given the feasibility domain $\boldsymbol{X}$ (6) and the amount of REDD offsets $\mathcal{E} \in (0, E^0]$, find technological mix $\boldsymbol{x}$ maximizing the profit at a CO$_2$ price realization p:

$$\underset{\boldsymbol{x} \in \boldsymbol{X_3}}{\text{maximize}}\, \Pi_3^R(p, \boldsymbol{x}), \tag{25}$$

where

$$\Pi_3^R(p, \boldsymbol{x}) = \Pi_e(\boldsymbol{x}) - p(E(\boldsymbol{x}) - \mathcal{E}), \tag{26}$$

$$\boldsymbol{X_3} = \boldsymbol{X} \cap \{\boldsymbol{x} : E(\boldsymbol{x}) \geq \mathcal{E}\}. \tag{27}$$

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:

$$\hat{\Pi}_3^R = \hat{\Pi}_3^R(p) = \Pi_e(\boldsymbol{x_3^*}) - p(E(\boldsymbol{x_3^*}) - \mathcal{E}). \tag{28}$$

Problem 4 $(E(\boldsymbol{x}) \leq \mathcal{E})$ Given the feasibility domain $\boldsymbol{X}$ (6), benefit-sharing ratio $\delta \in [0, 1]$ and the amount of REDD offsets $\mathcal{E} \in (0, E^0]$, find technological mix $\boldsymbol{x}$ maximizing the profit at a CO$_2$ price realization p:

$$\underset{\boldsymbol{x} \in \boldsymbol{X_4}}{\text{maximize}}\, \Pi_4^R(p, \boldsymbol{x}), \tag{29}$$

where

$$\Pi_4^R(p, \boldsymbol{x}) = \Pi_e(\boldsymbol{x}) - \delta p(E(\boldsymbol{x}) - \mathcal{E}), \tag{30}$$

$$\boldsymbol{X_4} = \boldsymbol{X} \cap \{\boldsymbol{x} : E(\boldsymbol{x}) \leq \mathcal{E}\}. \tag{31}$$

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:

$$\hat{\Pi}_4^R = \hat{\Pi}_4^R(p) = \Pi_e(\boldsymbol{x_4^*}) - \delta p(E(\boldsymbol{x_4^*}) - \mathcal{E}). \tag{32}$$

Thus, for any fixed amount $\mathcal{E} \in (0, E^0]$ 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 $\hat{\Pi}_3^R$ (28) and $\hat{\Pi}_4^R$ (32):

$$\hat{\Pi}^R(p) = \max\{\hat{\Pi}_3^R, \hat{\Pi}_4^R\}, \tag{33}$$

which is equivalent to (15), (16). The solution to Problem 2 is chosen according to the rule:

$$\boldsymbol{x}_2^* = \begin{cases} \boldsymbol{x}_3^*, & \text{if } \hat{\Pi}^R = \hat{\Pi}_3^R \\ \boldsymbol{x}_4^*, & \text{if } \hat{\Pi}^R = \hat{\Pi}_4^R \end{cases} \tag{34}$$

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

3 Analytical results

In this section we analytically find the maximum profit (33) 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.

We introduce the following function of CO$_2$ price p:

$$\xi(p) = \frac{\hat{\Pi}^R(p) - \hat{\Pi}(p)}{\mathcal{E}}. \tag{35}$$

Using this function the fair price of the electricity producer (24) can be represented as follows:

$$p_E = p_E(\mathcal{E}, \delta) = \sum_{l=1}^{M} \xi(p_l) w_l. \tag{36}$$

Similarly, we introduce the function:

$$\phi(p) = p - (1 - \delta)\frac{E^R(p)p}{\mathcal{E}}, \tag{37}$$

and represent the forest owner's fair price (23) in the following way:

$$p_F = p_F(\mathcal{E}, \delta) = \sum_{l=1}^{M} \phi(p_l) w_l. \tag{38}$$

Lemma 2 *For any CO$_2$ price realization $p \in [0, \tilde{p}]$ in the second period, any benefit-sharing ratio $\delta \in [0, 1]$, and any fixed amount $\mathcal{E}$ of offsets contracted in the first period such that $\mathcal{E} \in (0, E(\boldsymbol{x}_1^*(p))]$, the maximum profit with REDD (33) in the second period is calculated as follows:*

$$\hat{\Pi}^R(p) = \hat{\Pi}_3^R = \Pi_e(\boldsymbol{x}_1^*(p)) - pE(\boldsymbol{x}_1^*(p)) + p\mathcal{E}. \tag{39}$$

The proof is in Appendix A.2

Remark 3 The definition of Lemma 2 is that for any realization of future CO$_2$ price p in the second period the optimal technological mix, solving Problem 2 with REDD, is the same as in Problem 1 without REDD, i.e. $\boldsymbol{x}_2^*(p) = \boldsymbol{x}_1^*(p)$, provided that the offsets amount (contracted in the first period) does not exceed the optimal quantity of emissions (without REDD) for that CO$_2$ price p (in the second period), $\mathcal{E} \leq E(\boldsymbol{x}_1^*(p))$.

Corollary 1 *If conditions of Lemma 2 are satisfied at a CO$_2$ price realization $p = p_l$ in the distribution (12), then $E^R(p) = 0$ and according to $\hat{\Pi}(p)$ (9), $\hat{\Pi}^R(p)$ (39), $\phi(p)$ (37), $\xi(p)$ (35), the equality takes place:*

$$\phi(p) = \xi(p) = p. \tag{40}$$

Lemma 3 *For any CO$_2$ price realization $p \in [0, \tilde{p}]$ in the second period, any benefit-sharing $\delta \in [0, 1)$, and any amount $\mathcal{E}$ of offsets contracted in the first period such that $\mathcal{E} > E(\boldsymbol{x}_1^*(p))$, the following inequality takes place:*

$$\phi(p) > \xi(p). \tag{41}$$

The proof is in Appendix A.3.

Finally, let us formulate and prove the following theorem.

Theorem 1 *For a given CO$_2$ price distribution $\{p_l, w_l\}, l = 1, \ldots, m$ (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 (23) and of the electricity producer p_E (24) 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 (in the second period without REDD offsets) at the maximum possible CO$_2$ price $\tilde{p} = \max\{p_l\}$:*

$$p_F = p_E = \bar{p} \quad \text{for any } \mathcal{E} \leq \tilde{\mathcal{E}}, \quad \delta \in [0, 1], \tag{42}$$

where

$$\tilde{\mathcal{E}} = E(\boldsymbol{x}_1^*(\tilde{p})). \tag{43}$$

For any amount of REDD offsets larger than $\tilde{\mathcal{E}}$ (43) the fair price of the forest owner p_F is higher than the fair price of the electricity producer p_E:

$$p_F > p_E \quad \text{for any } \mathcal{E} > \tilde{\mathcal{E}}, \quad \delta \in [0, 1). \tag{44}$$

The proof is in Appendix A.4:

Remark 4 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 main result is that—on one hand—the 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 a potentially

Table 1 Technological data for the case-study

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

Sources: [25,36,41]

high CO_2 price, the contracted amount is non-zero, hinting at possible implementation of 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 [25]). 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.[1]

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 Fig. 2. It features the same shape (peaks) as the regional profiles provided in the literature [1,3]. The hourly demand values are scaled to match the installed capacity of the electricity producer (as in Table 1). Similar to [1] 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

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[1] See International Energy Statistics provided by the US Energy Information Administration (EIA) http://www.eia.gov/cfapps/ipdbproject/IEDIndex3.cfm?tid=2&pid=2&aid=7.

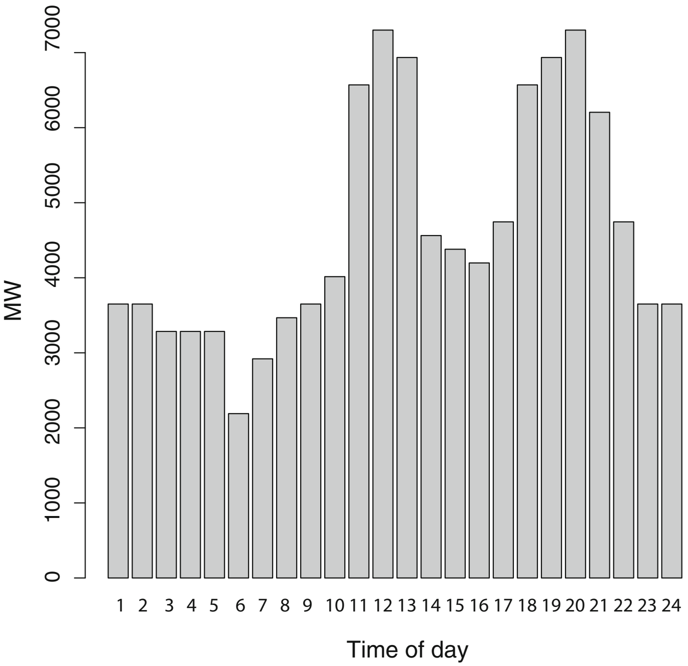

Fig. 2 Average hourly electricity demand

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. [32]).

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 [4,21]. 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.:

$$P^e = D^{-1}(Q) = AQ^{\alpha}, \tag{45}$$

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[2] electricity price) is achieved as a solution to Problem 1. The estimated parameters of the demand function (45) are $A = 1.05 \times 10^5, \alpha = -0.612$. These values are consistent with $P^e = 90.5$ US\$/MWh at profit's 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 $-2.3, \ldots, -0.1$, see, e.g.

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[2] See Quarterly Reports On European Electricity Markets http://ec.europa.eu/energy/en/statistics/market-analysis.

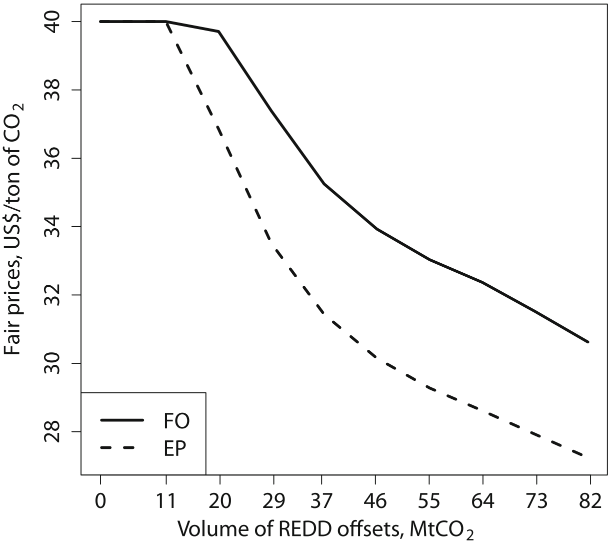

Fig. 3 Fair prices of the electricity producer (EP) and forest owner (FO) depending on the volume of REDD offsets. Benefit-sharing ratio is $\delta = 0.5$, and future CO_2 price distribution is uniform within the range 0–80 US$/ton CO_2

[21]). 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[3]), 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 [41]. In our study we use a value from an indicated interval given in Table 1. Emissions factors for gas powered plants are taken from [36].

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:

$$p_l = 10(l-1), \quad w_l = \frac{1}{9}, \quad l = 1, \ldots, 9. \tag{46}$$

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 Fig. 3 the fair prices (23), (24) with respect to the contracted amount of offsets $\mathcal{E} \le E^0$ 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

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[3] See the EIA website http://www.eia.gov/cfapps/ipdbproject/IEDIndex3.cfm?tid=2&pid=2&aid=2.

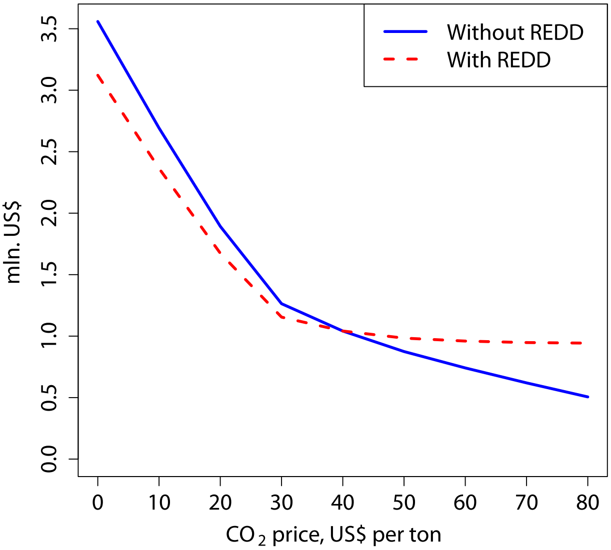

Fig. 4 Profit of the electricity producer (distribution) without contracting REDD offsets and with contracting REDD offsets for the optimal volume ($\tilde{\mathcal{E}} = 10.93$ MtCO$_2$) and benefit-sharing ratio $\delta = 0.5$

CO$_2$, while maximizing their 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 Fig. 4 we show how the contracted amount $\tilde{\mathcal{E}}$ impacts the profit distribution of the electricity producer. The plot shows that the mean profit determined by the considered CO$_2$ price distribution stays the same with REDD offsets (compared to the case without them), according to indifference condition (22). However, entering into a REDD offsets contract does impact the profit distribution. Firstly, according to Theorem 1, the fair price of the amount $\tilde{\mathcal{E}}$ is $p_E = \bar{p}$. Secondly, at each price realization, Lemma 2 is valid, meaning that, profits with REDD and without REDD are calculated according to Eq. (39). Including the cost of offsets, $p_E\tilde{\mathcal{E}}$, in the first period, we get the net profit with REDD at each price realization in the second period:

$$\hat{\Pi}^R(p) = \hat{\Pi}(p) + (p - p_E)\tilde{\mathcal{E}} = \hat{\Pi}(p) + (p - \bar{p})\tilde{\mathcal{E}}. \tag{47}$$

This analytical expression is reflected in Fig. 4. The profits coincide at the mean price, which is $\bar{p} = 40$ US$/ton CO$_2$; the profit with REDD is lower than the profit without REDD for price realizations $p < \bar{p}$, and higher—for price realizations $p > \bar{p}$. Notably, REDD offsets help the electricity producer to be better off for higher CO$_2$ prices and almost double their profit in this case.

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

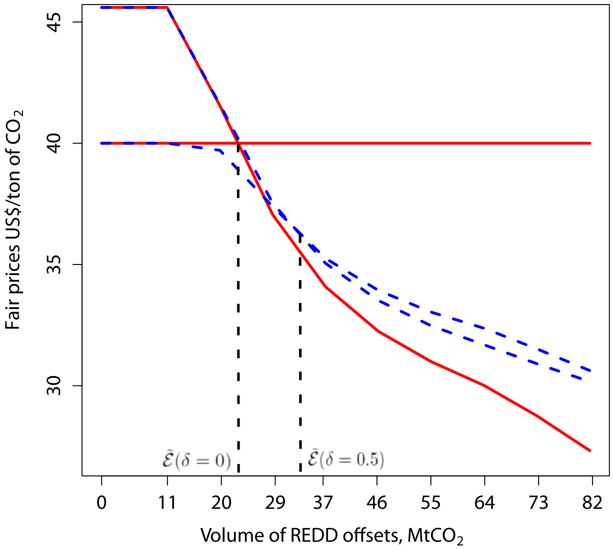

Fig. 5 Impacts of benefit-sharing on the contracted amounts of REDD-based offsets under asymmetric information on the CO$_2$ price distribution. *Dashed lines* are fair prices of the forest owner (FO) and electricity producer (EP) for benefit-sharing ratio $\delta = 0.5$, *solid lines*—for $\delta = 0$ (no benefit-sharing)

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 (46), while the electricity producer may put more weight on higher prices, i.e. their distribution can be:

$$p_l = 10(l - 1), \quad w_l = 0.01(l + 6.11), \quad l = 1, \ldots, 9. \tag{48}$$

The difference between (46) and (48) can be interpreted as the electricity producer is more sensitive to larger profit losses (risk-averse). In the case of price distribution (48) (risk-averseness), the contracted amount $\tilde{\mathcal{E}}$ of the electricity producer is higher as they are willing to pay a higher fair price compared to the case with the distribution (46). 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. Note that in Fig. 5 the total sum of the deal is growing despite the lower price, i.e. about 30 % increase in REDD financing can be achieved.

5 Discussion and conclusions

A considerable total share of emissions is derived from the energy sector (see, e.g., [8]). Therefore in developing a fair mechanism for REDD it is important to understand the decision-making process (optimal behavior) of energy producers. Our model deals with medium-term planning of the electricity producer who possesses flexibility in their 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 residual demand and maximizes their 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 in the sense that the risk-neutral approach is applicable. 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 someone will lose if the forest owner agrees to sell a "larger" amount of REDD offsets at the price suggested by the electricity producer 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.

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 offsets price in the first period providing more favorable conditions for the electricity producer and keeping the flexibility for additional income for the forest owner (as additional benefits might come later in the second period). As we basically explore a contract between two parties, from the legal perspective, we could imagine a trustee keeping the offsets and making sure the benefits are shared. There are also other challenges related to institutional options, e.g. monitoring, reporting and verification for REDD+ programs [15]. However these aspects are clearly beyond the scope of our study.

The current partial equilibrium model connecting CO_2-intensive energy sector with REDD creates the necessary prerequisites for modeling REDD in a wider context. A possible model expansion could be connected with merging the current framework with the detailed analysis of the supply side for REDD, i.e. a sustainable forest management model, where risks associated with ecological hazards, e.g. forest fires [19,26], could be adequately implemented. Finally, institutional grounds could be defined in connection with these research studies.

In the presented modeling exercise, we would like to highlight a situation of asymmetric CO_2 price distributions. It provides a preliminary illustration of the positive role of a benefit-sharing mechanism by increasing contracted amounts of REDD offsets, as well as the volume of a deal. This mechanism has a potential for initiating the direct contracting of REDD offsets, as it provides more flexibility to both parties: energy sector and forestry (lowering initial price for the former and keeping the option for additional benefits for the latter). Let us note, that there is an actual possibility for small-scale implementation of such mechanism, e.g. through the currently active Verified Carbon Standard (VCS) system,[4] which is a known developer of standards for REDD projects.

Acknowledgments Open access funding provided by International Institute for Applied Systems Analysis (IIASA). This research has received financial support from the project “Options Market and Risk-Reduction Tools for REDD+” funded by the Norwegian Agency for Development Cooperation under agreement number QZA-0464 QZA-13/0074, by the project “Delivering Incentives to End Deforestation: Global Ambition, Private/Public Finance, and Zero-Deforestation Supply Chains” funded by the Norwegian Agency for Development Cooperation under agreement number QZA-0464 QZA-16/0218, and was also supported by the EU’s Seventh Framework Programme (FP7) under Grant Agreement No. 603906 (ECONADAPT). We thank anonymous reviewers for their useful comments and suggestions as well as Ruben Lubowski, Alexander Golub, Matthew Cantele, Cynthia Festin, Johannes Pirker, and Hugo Valin for discussions, reviews, and helpful comments.

Compliance with ethical standards

Conflict of interest The authors declare that they have no conflict of interest.

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[4] See REDD+ Methodology Framework (REDD-MF) http://database.v-c-s.org/methodologies/redd-methodology-framework-redd-mf-v15.

A Proof of analytical results

A.1 Proof of Lemma 1

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

$$\Pi(\boldsymbol{x}_1^*(p), p) = \Pi_e(\boldsymbol{x}_1^*(p)) - E(\boldsymbol{x}_1^*(p))p \geq \Pi_e(\boldsymbol{x}) - E(\boldsymbol{x})p. \tag{49}$$

Secondly, let us assume on the contrary that for some $\bar{\boldsymbol{x}} \in \boldsymbol{X}$, such that $E(\bar{\boldsymbol{x}}) \neq E(\boldsymbol{x}_1^*(p))$, relation (49) is equality. Then we have:

$$\hat{\Pi}(p) = \Pi_e(\boldsymbol{x}_1^*(p)) - E(\boldsymbol{x}_1^*(p))p = \Pi_e(\bar{\boldsymbol{x}}) - E(\bar{\boldsymbol{x}})p. \tag{50}$$

According to Remark 1 to Assumption 1 Eq. (50) means that:

$$\hat{E}(p) = E(\boldsymbol{x}_1^*(p)) = E(\bar{\boldsymbol{x}}). \tag{51}$$

Thus, we came to a contradiction, meaning that assumption (50) is false, and (11) is true. □

A.2 Proof of Lemma 2

Proof Firstly, by the condition of the lemma $E(\boldsymbol{x}_1^*(p)) \geq \mathcal{E}$, meaning that $\boldsymbol{x}_1^*(p) \in \boldsymbol{X}_3$ (27). Secondly, (25) is equivalent to (7) and, hence, solution to Problem 3 coincides with the solution to Problem 1: $\boldsymbol{x}_3^* = \boldsymbol{x}_1^*(p)$. To complete the proof we need to show that: $\hat{\Pi}_3^R \geq \hat{\Pi}_4^R$ in (33).

Indeed, using (28), (32) and definition of maximum at price p (8), for $\boldsymbol{x}_4^* \in \boldsymbol{X}_4 \subset \boldsymbol{X}$ we come to the following chain of inequalities:

$$\begin{aligned} \hat{\Pi}_3^R(p) &= \Pi_e(\boldsymbol{x}_3^*) - p(E(\boldsymbol{x}_3^*) - \mathcal{E}) = \Pi_e(\boldsymbol{x}_1^*(p)) - pE(\boldsymbol{x}_1^*(p)) + p\mathcal{E} \\ &\geq \Pi_e(\boldsymbol{x}_4^*) - pE(\boldsymbol{x}_4^*) + p\mathcal{E} = \Pi_e(\boldsymbol{x}_4^*) - p(E(\boldsymbol{x}_4^*) - \mathcal{E}) \\ &\geq \Pi_e(\boldsymbol{x}_4^*) - \delta p(E(\boldsymbol{x}_4^*) - \mathcal{E}) = \hat{\Pi}_4^R(p). \end{aligned} \tag{52}$$

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,

$$\hat{\Pi}^R(p) = \hat{\Pi}_3^R(p) = \hat{\Pi}(p) + p\mathcal{E}. \tag{53}$$

□

A.3 Proof of Lemma 3

Proof Let us consider two cases depending on the optimal profit in (33).

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 $E(\boldsymbol{x}_3^*) \geq \mathcal{E}$. In this case $E^R(p) = 0$, meaning that:

$$\phi(p) = p. \tag{54}$$

Substitution of (9) and (28) to (35) leads to:

$$\xi(p) = p + \frac{\Pi_e(\boldsymbol{x}_3^*) - E(\boldsymbol{x}_3^*)p}{\mathcal{E}} - \frac{\Pi_e(\boldsymbol{x}_1^*(p)) - E(\boldsymbol{x}_1^*(p))p}{\mathcal{E}} \tag{55}$$

For $\boldsymbol{x}_3^* \in \boldsymbol{X}$ such that $E(\boldsymbol{x}_3^*) = \mathcal{E} > E(\boldsymbol{x}_1^*(p))$ we can apply Lemma 1. Hence, (55) leads to the required inequality:

$$\frac{\Pi_e(\boldsymbol{x}_3^*) - E(\boldsymbol{x}_3^*)p}{\mathcal{E}} - \frac{\Pi_e(\boldsymbol{x}_1^*(p)) - E(\boldsymbol{x}_1^*(p))p}{\mathcal{E}} < 0 \Rightarrow \xi(p) < p = \phi(p), \tag{56}$$

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 $\boldsymbol{x}_4^*$—solution to Problem 4. Problem (29)–(31) is equivalent to the following problem (see (5), (7)):

$$\underset{\boldsymbol{x} \in \boldsymbol{X}_4}{\text{maximize}}\, \Pi(\boldsymbol{x}, \delta p) = \Pi_e(\boldsymbol{x}) - \delta p E(\boldsymbol{x}). \tag{57}$$

Thus, two alternatives are possible in 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 $\boldsymbol{x}_1^*(\delta p) \in \boldsymbol{X}_4$ (31), and as it is the solution to (57), we have:

$$\boldsymbol{x}_4^*(p) = \boldsymbol{x}_1^*(\delta p). \tag{58}$$

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

$$E(\boldsymbol{x}_4^*) = E(\boldsymbol{x}_1^*(\delta p)) > E(\boldsymbol{x}_1^*(p)). \tag{59}$$

Substituting $E^R(p) = \mathcal{E} - E(\boldsymbol{x}_4^*)$ to (37), leads to:

$$\phi(p) = \frac{(1-\delta)pE(\boldsymbol{x}_4^*)}{\mathcal{E}} + \delta p. \tag{60}$$

Function $\xi(p)$ (35) is calculated as follows:

$$\xi(p) = \delta p + \frac{\Pi_e(\boldsymbol{x}_4^*) - E(\boldsymbol{x}_4^*)\delta p}{\mathcal{E}} - \frac{\Pi_e(\boldsymbol{x}_1^*(p)) - E(\boldsymbol{x}_1^*(p))p}{\mathcal{E}}. \tag{61}$$

For the optimal mix $\boldsymbol{x}_4^* \in \boldsymbol{X}$ such that (59) is true one can apply Lemma 1:

$$\Pi_e(\boldsymbol{x}_1^*(p)) - E(\boldsymbol{x}_1^*(p))p > \Pi_e(\boldsymbol{x}_4^*) - E(\boldsymbol{x}_4^*)p. \tag{62}$$

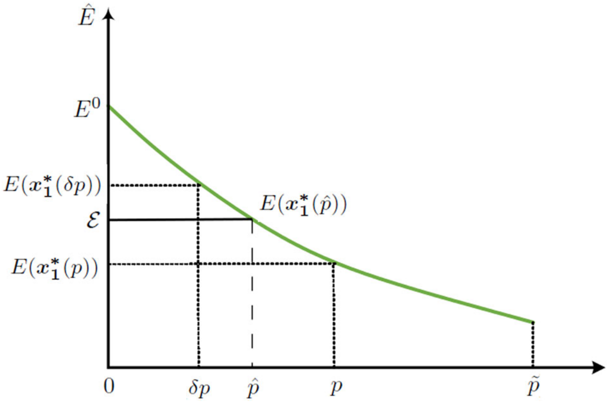

Fig. 6 Optimal emissions of the electricity producer with respect to CO_2 price (*horizontal axis*) without REDD offsets. A conceptual graph of $\hat{E}(p)$, satisfying Assumption 1

Substitution of (62) to (61) gives the required inequality:

$$\begin{aligned}\xi(p) &= \delta p + \frac{\Pi_e(\boldsymbol{x}_4^*) - E(\boldsymbol{x}_4^*)\delta p - \big(\Pi_e(\boldsymbol{x}_1^*(p)) - E(\boldsymbol{x}_1^*(p))p\big)}{\mathcal{E}} \\ &< \delta p + \frac{\Pi_e(\boldsymbol{x}_4^*) - E(\boldsymbol{x}_4^*)\delta p - \big(\Pi_e(\boldsymbol{x}_4^*) - E(\boldsymbol{x}_4^*)p\big)}{\mathcal{E}} \\ &= \delta p + \frac{(1-\delta)pE(\boldsymbol{x}_4^*)}{\mathcal{E}} = \phi(p). \end{aligned} \tag{63}$$

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 $\boldsymbol{x}_1^*(\delta p) \notin \boldsymbol{X}_4$ (31). According to Assumption 1 there exist price $\hat{p}$, $\delta p < \hat{p} < p$, and technological mix $\boldsymbol{x}_1^*(\hat{p})$ (see Fig. 6), such that:

$$\boldsymbol{x}_1^*(\hat{p}) \in \boldsymbol{X}_4 : \quad E(\boldsymbol{x}_1^*(\hat{p})) = \mathcal{E}. \tag{64}$$

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 $\tilde{\boldsymbol{x}}_4 \in \boldsymbol{X}_4$ (31) different from $\boldsymbol{x}_1^*(\hat{p})$ (64). As $E(\tilde{\boldsymbol{x}}_4) \leq E(\boldsymbol{x}_1^*(\hat{p}))$, the following inequality holds:

$$E(\boldsymbol{x}_1^*(\hat{p}))(\hat{p} - \delta p) \geq E(\tilde{\boldsymbol{x}}_4)(\hat{p} - \delta p). \tag{65}$$

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

$$\Pi_e(\boldsymbol{x}_1^*(\hat{p})) - E(\boldsymbol{x}_1^*(\hat{p}))\hat{p} \geq \Pi_e(\tilde{\boldsymbol{x}}_4) - E(\tilde{\boldsymbol{x}}_4)\hat{p}. \tag{66}$$

Combining (65) and (66) one gets:

$$\begin{aligned}&\Pi_e(\boldsymbol{x}_1^*(\hat{p})) - E(\boldsymbol{x}_1^*(\hat{p}))\hat{p} + E(\boldsymbol{x}_1^*(\hat{p}))(\hat{p} - \delta p) \\ &\geq \Pi_e(\tilde{\boldsymbol{x}}_4) - E(\tilde{\boldsymbol{x}}_4)\hat{p} + E(\tilde{\boldsymbol{x}}_4)(\hat{p} - \delta p),\end{aligned} \tag{67}$$

that leads to:

$$\Pi_e(\boldsymbol{x}_1^*(\hat{p})) - E(\boldsymbol{x}_1^*(\hat{p}))\delta p \geq \Pi_e(\tilde{\boldsymbol{x}}_4) - E(\tilde{\boldsymbol{x}}_4)\delta p \quad \text{for all } \tilde{\boldsymbol{x}}_4 \in \boldsymbol{X}_4, \tag{68}$$

meaning that $\hat{\Pi}_4^R = \Pi(\boldsymbol{x}_1^*(\hat{p})), \delta p)$, and:

$$E(\boldsymbol{x}_4^*) = E(\boldsymbol{x}_1^*(\hat{p})) = \mathcal{E} > E(\boldsymbol{x}_1^*(p)). \tag{69}$$

We have proved that in 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 have proved that in all cases:

$$\xi(p) < \phi(p). \tag{70}$$

□

A.4 Proof of Theorem 1

Proof According to Assumption 1 the amount $\tilde{\mathcal{E}}$ (43) 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 according to Corollary 1:

$$\phi(p) = \xi(p) = p. \tag{71}$$

Substituting (71) to definitions of fair prices (36), (38) we get:

$$p_E = \sum_{l=1}^{M} \xi(p_l)w_l = \sum_{l=1}^{M} \phi(p_l)w_l = \sum_{l=1}^{M} p_l w_l = \bar{p}. \tag{72}$$

The same reasoning is valid for any $\mathcal{E} \in (0, \tilde{\mathcal{E}}]$, and, hence, (42) 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 distribution (12) the conditions of Lemma 2 are satisfied and, hence, $\phi(p_l) = \xi(p_l)$. At the same time, there are price realizations in distribution (12), at which conditions of Lemma 3 are satisfied (at least for the price $\tilde{p} = \max\{p_l\}$), meaning that $\phi(p_l = \tilde{p}) > \xi(p_l = \tilde{p})$, and hence:

$$\sum_{l=1}^{M} \phi(p_l)w_l > \sum_{l=1}^{M} \xi(p_l)w_l. \tag{73}$$

Sustitution of (73) to definitions of fair prices (36), (38) provides the required inequality:

$$p_F = \sum_{l=1}^{M} \phi(p_l)w_l > \sum_{l=1}^{M} \xi(p_l)w_l = p_E. \tag{74}$$

□

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