CHARLES UNIVERSITY IN PRAGUE

FACULTY OF SOCIAL SCIENCES

Institute of Economic Studies

Matěj Kouřílek

Walras equilibria and emission allowances

Bachelor thesis

Prague 2016

Author: **Matěj Kouřílek**

Supervisor: **RNDr. Michal Červinka, Ph.D.**

Reviewer:

Date of defense: 2016

Grade:

Bibliografický záznam

KOUŘÍLEK, Matěj. *Walras equilibria and emission allowances* Praha 2016. 52s. Bakalářská práce (Bc.) Univerzita Karlova, Fakulta sociálních věd, Institut ekonomických studií. Vedoucí práce RNDr. Michal Červinka, Ph.D.

Abstrakt

Změna klimatu byla motivací pro vznik nových mechanismů, které mají tento jev zmírnit. Jedním z nich bylo vytvoření trhu s takzvanými emisními povolenkami, kde firmy znečišťující ovzduší sdílí celkový počet povolenek. V Evropské unii k tomu slouží Evropský emisní obchodní systém. Práce analyzuje chování firem a vztah mezi cenou povolenek a jejich množstvím na českém trhu. Dále jsou studovány možné dopady politky Evropského emisního systému na český trh s emisemi a trh s elektrickou energií. Využíváme k tomu model, který založen na inovativním konceptu Cournnot-Nash-Walrasovy rovnováhy. Model predikuje 25 a 14 procentní nárůst ceny emisních povolenek mezi lety 2014-2015 a 2014-2020. Dále dle modelu, firma neinvestující do nových produkčních technologií, může ztratit značný podíl na trhu.

Abstract

Global efforts to prevent climate change has been a catalyst for the emergence of many innovative ideas to mitigate this phenomenon. One of them was an introduction of emission markets where polluters share aggregate quantity of so-called pollution permits, e.g., the European Union emission trading system. This work analyses the behaviour of firms and a relation between the European Union Allowances quantity and their price on the Czech market. Furthermore, possible consequences of the EU emission trading system policy on the Czech emission and energy market are analyzed. To do so, we develop equilibrium model which uses an innovative concept of the Cournot-Nash-Walras equilibrium. The model estimates 25 and 14 percent increase in emission allowances price between years 2014-2015, and 2014-2020, respectively. We also find that non-innovating firm can lose significant market share.

Klíčová slova

Cournot-Nash-Walrasova rovnováha, Emisní obchodování, Emisní povolenky, Kjótský Protokol, Matematický program s rovnovážným omezením

Keywords

Cournot-Nash-Walras equilibrium, Emission trading, Emission allowances, Kyoto Protocol, Mathematical Program with Equilibrium Constraints

Declaration of Authorship

I hereby proclaim that I wrote my bachelor thesis on my own under the leadership of my supervisor and that the references include all resources and literature I have used.

I grant a permission to reproduce and to distribute copies of this thesis document in whole or in part.

Prague, May 13, 2016

Signature

Acknowledgment

I would like to express gratitude to RNDr. Michal Červinka, Ph.D. for introducing me topic of Cournot-Nash-Walras equilibria, his patience, and valuable notes.

Contents

Acronyms

AAU Assigned Amount Unit
CDM Clean Development Mechanism
CER Certified Emission Reduction unit
CNW Cournot-Nash-Walras
CO_2 carbon dioxide
COP21 Paris conference of the parties
EEA The European Economic Area
EEX European Energy Exchange
EFTA The European Free Trade Association
ERU Emission Reduction Unit
EUA European Union Allowance
EUAA European Union Aviation Allowance
EU ETS The European Union Emissions Trading System
GHG greenhouse gas
ICE ICE Futures Europe
IET International Emissions Trading
JI Joint Implementation
LDCs Least developed countries
N_2O nitrous oxide
PFC perfluorinated hydrocarbons
RED Renewable Energy Directive
UNFCCC The United Nations Framework Convention on Climate Change

1 Introduction and Preliminaries

Global efforts to prevent climate change has been a catalyst for the emergence of many innovative ideas to mitigate this phenomenon. In 1997, the Kyoto Protocol introduced several economic mechanisms which should motivate polluters to reduce their greenhouse gas (GHG) emissions. One of these mechanisms is a formation of emission markets where polluters share aggregate quantity of so-called pollution permits. The European Union (EU) adopted an European Union emission trading system (EU ETS) in order to jointly reduce emissions of GHGs by companies from the carbon-intensive industries. The pollution permits used within the EU ETS are called the European Union Allowances (EUA). Since 2015 was the second year in a row that global temperatures have broken the record, the development of the emission markets will be crucial for future efforts to stop this trend (NOAA, 2015). Recently, S.D. Flåm investigated markets where the firms behave non-cooperatively and share limited but transferable input. The quantity of this particular input is then controlled by some authority. Flåm described equilibrium conditions in such a market as the Cournot-Nash-Walras (CNW) equilibrium. In Outrata et al. (2015), the authors followed Flåm and present several examples of CNW computation.

The purpose of this thesis is to analyse the behaviour of firms, the connection between the EUAs quantity and their price, and possible consequences of EU ETS policy on Czech emission and energy markets. To do so, we develop equilibrium model which computes CNW equilibria in corresponding markets. Further, we review relevant literature and legal framework to describe development of the EU ETS.

The thesis is planned as follows: Section 2 provides brief introduction to the topic of emission trading. In section 3, we review EU legal framework and regulation and give background to the EU ETS. In section 4, we describe the theory of Walras equilibrium and the concept of CNW equilibrium. In section 5, we present our equilibrium model which reflects Czech emission market and highlights the role of energy companies. In the last section, we summarize and comment on our findings.

Our notation is basically standard. For vectors x and y, $x \geq y$ means $x_l \geq y_l$ for each component l, e.g., $x \geq 0$ means $x_l \geq 0$ for each component l. Further, we use symbol x_{-i} to address strategy profiles chosen by all other agents except agent i, i.e. , $x_{-i} = (x_1, \dots, x_{i-1}, x_{i+1}, \dots, x_k)$.

2 Kyoto Protocol Policy

This section firstly focuses on the legal background of emission trading. Emission trading brings many obligations and costs to the firms obligated to emission reduction. However, those firms which already invested into the "greener" production technologies, may benefit from the emission trading. Thus, emission trading has a large impact on firms decisions in the correspondent market which is important for our further analysis. Next, this section provides a brief introduction to the topic, including development, current legal framework and outlined future goals based on Kyoto Protocol (1997), Directive 2009/29/EC and the Act No. 257/2014 Coll. amending the Act No. 383/2012 Coll.

2.1 Kyoto Protocol

The Kyoto Protocol was adopted in Kyoto, Japan in 1997 in the form of an international treaty, extending the United Nations Framework Convention on Climate Change (UNFCCC) and entered into legal force in 2005 (Kyoto protocol, 1997). In 2012, the Kyoto protocol legal force was extended to 2020 at Doha conference by Doha Amendment. Countries obligated to the Kyoto Protocol must limit their GHG emissions primarily by national measures. However, the Protocol also introduced an original framework of economic mechanisms to fight with growing emissions of anthropogenic meaning, caused or produced by humans GHGs, mainly carbon dioxide (CO_2), on the global scale. Namely, International Emissions Trading (IET), the Clean Development Mechanism (CDM) and Joint Implementation (JI) were established (Kyoto protocol, 1997). Moreover, countries are distinguished with respect to their development level to developed countries and those that are undergoing the process of transition to a market economy. The countries listed in Annex I of the UNFCCC are considered as an industrialized or developed. On the contrary, the countries that are not listed in Annex I of the

UNFCCC are developing countries. Therefore, the developed and developing countries are distinguished to Annex I and non-Annex I countries, respectively. According to the Kyoto Protocol, each Annex I country shall increase energetic efficiency in the particular branch of national industry and support the sustainable form of agriculture. Furthermore, they should support research, development and increased use of new and renewable energy forms in order to achieve its quantified emission limits and reduction commitments. The latter recommendations should be implemented as minimizing the adverse effects of climate change, effects on international trade and economic impacts on other countries, especially developing (Kyoto protocol, 1997).

The economic mechanisms IET, the CDM, and the JI are closely related to Annex I sorting, as each group is obligated to different regulation. Broadly speaking, Annex I countries have a bigger responsibility to fight climate change. Through the IET or emissions trading system (ETS), so-called Assigned Amount Units (AAUs) are distributed as permits to polluters. Possession of each AAU gives its owner exclusive right to emit one metric tonne of CO_2 or another GHG equivalent. Likewise, by means of the CMD, emitters of GHG are able to obtain saleable certified emission reduction (CERs) credits, equivalent to AAUs. Annex I countries obtain CERs through implementation of an emission-reduction or from afforestation and reforestation projects in non-Annex I countries, which helps with the fulfilment of their reduction commitment (UNFCCC, 2014). The third way of acquiring pollution permits by Annex I countries are investments and technology transfers to another Annex I country. Although the permits earned by this type of investments, called emission reduction units (ERUs), are equivalent to AAUs, ERUs are converted from existing AAUs before being transferred. Thus, JI does not increase the total AAUs of Annex I countries, rather it redistributes AAUs among them (UNFCCC, 2014). CDM and JI are an offset mechanisms offering Annex I countries a flexible and cost-efficient means of fulfilling part of their Kyoto commitments while the host country benefits from foreign investment and technology transfer (Kyoto Protocol, 1997). The strength of such an approach is that climate change mitigation is done at lowest possible costs and with global effort, which is based on the idea that some GHG in the atmosphere are spread uniformly, and is therefore not so important where the reduction takes place, but rather the fact that is happening.

3 The European Union Emissions Trading System

The EU ETS is the biggest international system for trading GHG emission allowances covering more than 11 000 heavy energy-using installations in power generation and manufacturing industry and aircraft operators performing aviation activities within 28 EU states plus Iceland, Liechtenstein and Norway. The latter three countries are the so-called EEA-EFTA member states. The EU ETS works on the same basis as economic mechanisms introduced by Kyoto Protocol. Currently, the EU ETS covers approximately 45 percent of GHG emissions produced within all member states (European Commission, 2016). The System is based on "cap and trade" principle, where cap refers to limit of GHG that can be emitted. Reduction in the cap over time guarantees fall in emissions. Each member state should define rules of penalties applicable to violation of emission limits. Those penalties should be effective and discouraging (European parliament, 2003). The official title of one pollution permit traded in the EU ETS is EUA. Recall, EUA is the right to emit one tonne of CO_2 or an amount of any other GHG with an equivalent global-warming potential[1]. The cap for emissions from power stations and other fixed installations differs from one for aviation operators. Aviation sector receives aviation allowances (EUAA) while other carbon market participants use EUAs. Despite the fact that aviation operators are given

[1] List of such a gases can be found in Annex II of Directive 2003/87/EC

different allowances, they may use both EUAs and EUAAs for compliance purposes. Fixed installations can use only EUAs (European Commission, 2016). According to the Directive 2009/29/EC each stationary installation with annual emissions more than 25 000 tonnes of CO_2 equivalent and thermal input above 35 MW per year, excluding emissions from biomass, is obligated to participate in the EU ETS. The allocation of allowances on national level to firms takes place in February each year. On the other hand, the firms have to surrender used allowances from the previous year, by the end of April (European Commission, 2016).

3.1 Policy Development

The Directive 2003/87/EC is considered to be the first incentive for EU polluters to invest into "greener" technology. Approval and implementation of this directive, undertake the EU to strive to prevent of climate change. It incorporated the targets of the Kyoto Protocol to the European legal system and bound member states to adopt national policy frameworks to meet commitment of 8 percent reduction in GHG with respect to pre-industrial levels during the first compliance period, i.e., the 2008-2012 period. Nowadays, the EU ETS is divided into four phases. Phase one was a three-year pilot period in 2005-2007, followed by the second phase in 2008-2012. The ongoing third phase corresponds to the period between 2013-2020. The last, fourth phase considered by European legal system is planned for the period of years 2021-2030.

During phase one, the penalty for non-compliance was set at 40 EUR per tonne. Allowances distributed in phase one were intended to cover emissions of CO_2 only from power generators and energy-intensive industrial sectors. In this trial period, nearly all EUAs were allocated for free. Annual average freely allocated EUAs was equivalent to approximately 2 152 Mt CO_2, however, the annual amount of verified emissions did not exceed 2 050 Mt CO_2 (European Commission, 2016). Therefore, the price of allowances dur-

Table 1: Description of the EU ETS phases

Key features	**Phase 1 (2005-2007)**	**Phase 2 (2008-2012)**	**Phase 3 (2013-2020)**
Geography	EU27	EU27 + EEA-EFTA states	EU27 + EEA-EFTA states + Croatia from 1.1.2013
Sectors	Power stations, Oil refineries, Coke ovens, Production of: Iron and steel; Cement; Glass; Lime; Bricks; Pulp; Ceramics; Paper and cardboard	Same as phase 1 plus Aviation (from 2012)	Same as phase 2 plus Production of: Aluminium; Petrochemicals; Ammonia; Nitric, adipic, glyoxal and glyoxylic acids
GHGs	CO_2	CO_2,N_2O	CO_2,N_2O,PFC
Cap	2 058 million tCO_2	1 859 million tCO_2	2 084 million tCO_2 in 2013, decreasing in a linear way by 38 million tCO_2 per year
Eligible trading units	EUAs	EUAs, CERs, ERUs Not eligible: Credits from forestry, and large hydro-power projects.	EUAs, CERs, ERUs Not eligible: CERs and ERUs from forestry, N_2O or large hydro-power projects.

Source: European Commission, EU ETS Handbook ing phase one dropped almost to zero in 2007. Banking of unused EUAs to the second phase was not allowed, i.e., if a firm ended up with a surplus of allowances at the end of the first phase, the firm was not allowed to carry forward these allowances for compliance purposes in the next phase.

At the beginning of phase two, all three EEA-EFTA states joined the EU ETS (EU Business, 2016). Both CERs and ERUs were allowed to be used simultaneously with EUAs. Few adjustments were made in order to meet targets set by the Kyoto Protocol. Non-compliance penalty rose to 100 EUR per tonne. Conversely, the proportion of freely allocated EUAs slightly dropped to 90 percent and the total quantity of EUAs in the cap was reduced by 6.5 percent with respect to 2005 levels. On the contrary to the first phase, banking of allowances is permitted from 2008 onwards (European Commission, 2016).

The phase three of the EU ETS coincides with second commitment period set by Doha Amendment to the Kyoto Protocol. Doha Amendment forces member states to reduce emissions by at least 18 percent compared with 1990 levels (UNFCCC, 2014). However, the European Commission adopted even more ambitious targets through the Renewable Energy Directive 2009/28/EC (RED). It defines the so-called "20-20-20" targets which are to be met in 2020. The main objectives are 20 percent improvement in the EU's energy efficiency; 20 percent of EU energy from renewable (wind, solar, biomass, etc.) and the key objective for the EU ETS is 20 percent reduction in GHG from 1990 levels. Further, auctions progressively replace the free allocation of allowances and the quantity of EUAs issued each year starting in 2013 is decreased by a linear factor of 1.74 percent compared to the average annual total quantity of allowances issued by a member state in the first commitment period, i.e., 2008-2012. After 2020, this factor will increase to 2.2 percent (European Commission, 2016). This only applies to cap for fixed installations, not for aviation cap. The aviation cap is set at 210 million allowances for 2013-2020 period and will remain the same each year. On the contrary, cap for fixed installations was set at 2 084 301 856 allowances for 2013 according to the legislation. Thus, the number of general allowances will be reduced annually by 38 264 246 (European Commission, 2016). As in phase two, all types of pollution permits are allowed. However, CERs from projects registered after 2012 must be from least developed countries (LDCs).[2]

In the future, the emission market will be affected mainly by the 2015 Paris climate conference COP21. The agreement resulting from this conference should replace the current Kyoto Protocol. According to the COP21 report, atmosphere temperature may not increase above 1.5°C compared to pre-industrial levels. Nevertheless, the Paris Agreement does not contain any specific actions or mechanisms to achieve this objective. In order to ratify this treaty, it is required to be signed by 55 countries representing 55 percent of global GHG emissions. Only then it will come to effect from 2020. The European Commission in reaction to the COP21 proposed a revision of the EU ETS for period after 2020, i.e., phase four. Under the proposed 2030 climate & energy framework strategy, GHG emissions should be cut at least by 40 percent compared to level in 1990 (European Commission, 2016).

3.2 Trades and Auctions

The following subsection will summarize free allocation of pollution permits, their distribution among carbon market participants, auctioning platforms and essentials of an auction. From now on, term agent refers to any stationary installation or aviation operator who performs trades in one of the auctioning platforms.

Although auction is the default method of the EU ETS, also free EUAs are distributed to each member state. The volumes of free distributed EUAs are calculated based on the average emissions during the 2005-2007 period (Directive 2009/29/EC, 2009). Each member state then assigns those EUAs

[2]List of the LDCs can be found on the United Nations web page.

Table 2: Percentage of free allocated allowances during Phase 3 of trading

Year	Percentage
2013	80%
2014	72.86%
2015	65.71%
2016	58.57%
2017	51.43%
2018	44.29%
2019	37.14%
2020	30%

Source: COMMISSION DECISION of 27 April 2011 determining transitional Union-wide rules for harmonised free allocation of emission allowances pursuant to Article 10a of Directive 2003/87/EC of the European Parliament and of the Council 2011.

to agents in its territory. In 2013, 80 percent of all EUAs were allocated freely among all agents. This proportion will decrease each year to 30 percent of EUAs allocated freely in 2020. In 2016, almost 60 percent of EUAs is to be given for free. Table 2 presents exact data for the third trading phase. Due to the volume of unused allowances and a growing volume of CERs, the European Commission in 2014 adopted amendment reducing the quantity of auctioning allowances by 900 million cumulatively for period 2014-2016 and adding 300 and 600 million in years 2019 and 2020, respectively. This practice known as "back-loading" is a short-term measure dealing with the surplus of allowances accumulated during the economic crisis. Speaking about allowances intended for auction, they are allocated among member state in the following manner as stated in Directive 2009/29/EC.

The major part, 88 percent of the total quantity of allowances to be auctioned, is being distributed likewise free allowances, i.e., with respect to average emissions during the 2005-2007 period. Further 10 percent of allowances are being distributed for the purpose of solidarity and growth within the member states. The remaining 2 percent of allowances are being allocated to member states which emissions of GHG in 2005 were at least 20 percent below their emissions in 1990.

Auctions within the EU ETS have to have the following format defined by Commission Regulation (EU) No 1031/2010. An auction has a single round and sealed bids are used, i.e., agents submit their bids during one bidding window without the possibility of seeing bids submitted by other agents. A base unit and, therefore, the smallest tradable quantity is one lot, which is equal to 500 allowances. Hence, bids have to be in the form of an integer multiple of the lot. Furthermore, each bid has to state the identity of the bidder and the price in euros specified to two decimal points. The auction clearing price is determined upon closure of bidding window as follows. An auction platform sorts submitted bids in price order. Next, the volumes of bids are summed up, starting at the bid with the highest price. The clearing price equals the price of the bid where the sum of bids matches or exceeds the volume of allowances auctioned. Thereby, all agents participating in one bidding window pay the same clearing price.

The emission trading is divided into the primary market and the secondary market. Allowances purchased in the primary market, i.e., at auction, can by applied for covering emissions or they may be freely traded within the secondary market. The secondary market is determined for trading between agents. Thus, a agent may sell its surplus of EUAs or buy additional EUAs. In the secondary market, allowances can be traded either as two-day spots or five-day futures.

There are two trading platforms operating under the EU ETS framework; the European Energy Exchange (EEX) and ICE Futures Europe (ICE). The ICE trading platform is located in London and only Great Britain use the ICE for auctioning EUAs. Conversely, the majority of allowances is traded on the EEX in Leipzig (EEX, 2016). Most of the states which participate in the emission trading system make use of three bidding windows held weekly to auction their EUAs.

4 Theory of General Equilibrium

In this section we study behaviour of the EU ETS participants as well as market structure. Given that emission trading system is still the best mechanism to mitigate climate change, it is vital to know how and under which assumptions is an equilibrium in corresponding market achieved. Following section is based on Arrow and Debreu (1954), Nash (1950), Flåm (2016), Varian (2010), Flåm (2002) and Outrata et al. (2015).

4.1 Walras Equilibrium

Competitive equilibrium is characterized by a large number of consumers and producers maximizing their utilities and profits in competitive markets, i.e., everyone is a price taker. In the competitive market prices convey all necessary information for consumers and producers to determine their consumption and production. Nevertheless, this applies only to the markets where producers have convex technologies and consumers have convex preferences. Discussion about convexity of technologies and preferences will be given later.

Arrow and Debreu (1954) formed and proved two theorems according to which a competitive equilibrium exists. The first theorem claim that if every individual is endowed with some initial amount of every commodity available for sale, then a competitive equilibrium exists. While, according to the second theorem, there have to be certain types of labour which are beneficial for the production of traded commodities and each individual must be able to provide at least one type of such work. Loosely speaking, the assumptions for the first theorem are as follows:

- There are finite number of different saleable commodities .
- At least some commodities are produced in firms, each having its production function with non-increasing returns to scale.

- There are consumption units, i.e., households and individuals also including institutional consumers. Each individual possess some initial endowment and there is no point of saturation for each individual.

More precisely, let $n,\ h,\ k$ denote number of firms, consumers and commodities, respectively. Further, let each firm $j \in \{1, \ldots, n\}$ has a set $Y_j \subset \mathbb{R}^k$ of all possible production quantities and $y_j \in Y_j$ is a vector in $\mathbb{R}^k$. Each Y_j is a closed convex subset of $\mathbb{R}^k$. Assuming every firm can go out of business $0 \in Y_j$. Similarly, a vector $x_i \in X_i$, $i \in \{1, \ldots, h\}$, represents consumption of consumption unit i and X_i is a closed convex subset of $\mathbb{R}^k$ consisting of all consumption vectors, bounded from below. In Arrow and Debreu (1954), supplied labour services are regarded as a negative "consumption" and naturally this amount of labour is limited. For instance, one cannot work more than 24 hour per day. As usual, u_i donates utility function of consumer i. A function u_i is assumed to be continuous on X_i and non-satiated. Non-satiation of consumer preferences is an economic assumption which states that for any bundle of goods there is always another bundle of goods that is preferred to it. Mathematically, for any $x_i \in X_i$ there is a $x_i^, \in X_i$ such that $u_i(x_i^,) > u_i(x_i)$. Also indifference sets are assumed to be convex. Further, initial endowment of consumer i is in the form of vector $e_i \in \mathbb{R}^k$ and α_{ij} denotes share on profit of firm j, $\alpha_{ij} \geq 0$ for all i, j and $\sum_{i=1}^{m} \alpha_{ij} = 1$ for all j. An important assumption for endowments $e_i \in \mathbb{R}^k$ is that for some $x_i \in X_i, x_i < e_i$. In words, every individual, after consuming some of his initial endowment, is still left with some positive amount of each commodity for trading purposes (Arrow and Debreu, 1954). Further, let z be a vector representing excess of demand. Thus, z equals

$$z = \sum_i x_i - \sum_j y_j - \sum_i e_i.$$

Assuming that all of the previously mentioned conditions are met, an equilibrium in a competitive economy is defined by the following expressions:

$$\bar{y_j} \in \text{ arg max } \{\bar{p} \cdot y_j : y_j \in Y_j\} \qquad \forall j, \tag{1}$$

$$\bar{x_i} \in \text{ arg max } \{u_i(x_i) : x_i \in X_i,\, \bar{p} \cdot x_i \leq \bar{p} \cdot e_i + \sum_{j=1}^{n} \alpha_{ij} \bar{p} \cdot \bar{y_j}\}, \tag{2}$$

$$\bar{p} \in P = \{p \in \mathbb{R}^k : p \geq 0\}, \tag{3}$$

$$\bar{z} \leq 0,\, \bar{p} \cdot \bar{z} = 0. \tag{4}$$

The meaning of these expressions is as follows: Term (1) expresses that each firm has to maximize its profit over the set of production plans taking price as a given. Term (2) states that each consumer maximizes his utility over the set of his consumption preferences with respect to constraint given by his initial endowment. Term (3) asserts that commodity prices are non-negative and not all zero. The last expression (4) asserts that in an equilibrium, supply of the particular commodity is lower or equal to the demand or supply exceeds demand and price of such a commodity is zero.

What is the difference between the classical concept of supply and demand rule and the fourth expression? If the demand for certain commodity rises and demand exceeds supply, the price of commodity will rise too. On the contrary, an excess of supply in any market reduce the price of the corresponding commodity. The difference is that the concept of Walras equilibrium assigns zero price to the commodity with the excess of supply.

All previously mentioned assumptions are rather common in classical economic theory. To apply this theory on the EU ETS and relevant production units, we first need to describe basics of this market. In Flåm (2016) and Outrata et al. (2015) the authors describe Cournot-Nash equilibrium for firms that are obligated to use the so-called rare resource in their production process. The model of oligopoly assumes that firms maximize their profit by setting the quantity of output simultaneously. Another assumption for the oligopolistic market is that firms produce homogeneous product. Indeed, this description fits the EU ETS quite well. Despite the fact, the trading system covers large variety of firms including ironworks, production of construction materials, *etc.*, so far the largest economic sector covered by the EU ETS is energy industry (European Commission, 2016). Thus, the majority of the market is linked to production of electricity. Is fairly common to assume production functions with non-increasing return to scale for these firms. In most cases we talk about already large power plants, so effect of diminishing returns to scale is likely to be present as substantial investment are needed to either increase efficiency or reduce emissions. Hence, rare resource is in form of emission allowance as a tradable commodity distributed by international authority (EU) and firms use this compulsory permit to produce electricity. All firms obligated to emission reduction within the EU ETS are given with some positive initial endowment. However, market participants face joint constraint, since the amount of allowances is limited.

4.2 Cournot-Nash-Walras Equilibrium

Despite the EU ETS is subject to regulation arising from European directives as was mentioned in previous sections, we can consider emission market as a non-cooperative game in the sense of Nash (1950) with a finite set I of agents. In such a game, the pay-off of each agent is conditional to strategies chosen by others agents. Therefore, a generalization of the market as a game make sense, since the action of one individual effects pay-offs and the set of actions of others.

Assume, each agent $i \in \mathbf{I}$ maximizes corresponding pay-off function π_i, by selecting a certain strategy profile $x_i \in X_i$. If agent i selects strategy profile x_i, he gets pay-off $\pi(x_i, x_{-i}) \in \mathbb{R}$. Then strategy profile $\bar{x} \in \mathbb{X}$ is a Cournot-Nash equilibrium if

$$\forall i, x_i \in X_i : \pi_i(\bar{x}_i, \bar{x}_{-i}) \geq \pi_i(x_i, \bar{x}_{-i}) \tag{5}$$

where $\mathbb{X} = \prod_{i \in I} X_i$.

If we think of a strategy profile x_i as a quantity chosen by agent i, then term (5) constitutes to Cournot-Nash equilibrium (Varian, 2010). Recall, Y_i is a set of choices of production quantities for agent i. In our model, which will be presented in section 5, we assume only production of electricity. Thus, we use $Y_i \subset \mathbb{R}$. Nevertheless, each agent $i \in I$ faces decision about quantity y_i of electricity energy which is to be produced and the amount of allowances which will be used. Let z_i denotes agent i additionally bought or sold allowances. Further, let $Z_i \subset \mathbb{R}$ be a set of choices about z_i. Let a vector $x \equiv (x_i, x_{-i})$. In Flåm (2016) a set of decisions about x is defined as

$$X := \{x = (x_i, x_{-i}) : x_i = (y_i, z_i) \in Y_i \times Z_i : \sum_{i \in I} z_i \leq \sum_{i \in I} e_i\}.$$

Let $c_i(y_i, z_i), P(Q)$ and m denote cost function of agent i, inverse demand function for aggregate output $Q = \sum_{i \in I} y_i$ and m stands for allowance price, respectively. The precise form of $P(Q)$ will be given later. Given strategy profiles from set X, firm i maximizes its profit function

$$\pi_i(y_i, y_{-i}, z_i) = P(Q) \cdot y_i - c_i(y_i, z_i) + m \cdot (e_i - z_i), \tag{6}$$

In (6), the first term represents firm earnings, followed by costs and last term stands for revenues (possibly negative) from purchases and sales of allowances. Given the set X and profit functions in (6), the definition of the CNW equilibrium is as follows.

Definition 1. (Flåm) A profile $x = (x_i, x_{-i}) \in X$, alongside a price m, constitutes a *Cournot-Nash-Walras* equilibrium whenever

$$x_i = (y_i, z_i) \in \arg\max\{\pi_i(\bar{y}_i, y_{-i}, \bar{z}_i) - m \cdot \bar{z}_i : \bar{y}_i \in Y_i, \bar{z}_i \in Z_i\} \qquad \forall i, \tag{7}$$

and the allowance market clears in that

$$m \geq 0, \qquad \sum_{i \in I} z_i \leq \sum_{i \in I} e_i, \qquad \text{and} \qquad m \cdot (\sum_{i \in I} z_i - \sum_{i \in I} e_i) = 0. \tag{8}$$

One of the assumptions for equilibrium existence is a concave pay-off function. As we mentioned above, production functions of considered firms are likely to show diminishing return to scale, i.e., cost function $c_i(y_i, z_i)$ are jointly convex. Concavity of inverse demand function $P(Q)$ is a regular assumption in microeconomic theory (Varian, 2010).

The proof of the existence of CNW equilibrium is based on the Brouwer Fixed Point Theorem (Flåm 2016), (Outrata et al., 2015).

Proposition 1. (Brouwer Fixed Point Theorem) Let $D^n = \{x \in \mathbb{R}^n : |x| \leq 1\}$. Every continuous function $f : D^n \to D^n$ has a fixed point.

Loosely speaking, the theorem states that every continuous function from convex compact set to itself has a fixed point, i.e., there is a point $x \in D^n$ such that $f(x) = x$ (Brouwer, 1911). The proof of this statement is beyond the scope of this text. One may see (Flåm 2016) and Outrata et al. (2015).

The question then arises, "Is there a unique Walras equilibrium?". In most cases, the answer is not. Under assumptions stated in subsection Walras equilibrium, there may be multiple locally unique equilibria, i.e., there is no other Walras equilibrium within in sufficiently small neighbourhood around the original equilibrium price. To ensure unicity of Walras equilibrium, it suffices for consumers to have continuous, strictly convex and strongly monotone preferences (Mas-Colell, 1995).

5 CNW Equilibria and Czech Emission Market

In this section we focus on computation of CNW equilibria in the emission market, to be more specific, the model is based on the Czech allowance market and highlights the role of energy companies. The model computes CNW equilibria in two corresponding markets; in the primary market and secondary one. The primary market refers to the market with electricity. The secondary market stands for emission market. We consider several possible scenarios based on the current EU ETS framework. Given that firms receive very large number of allowances, we will assume that allowances are infinitely divisible. The goal is to describe possible impact of the European legal system on Czech energy market. The following section is based on Flåm (2016), Bhatt (2014), Outrata et al. (2015), Mas-Colell (1995), Murphy et al. (1982) and Varian (2010).

5.1 Theoretical Framework

The EU ETS is largely affected by regulations, e.g., annually decreasing cap, lump-sum reduction or increase in an overall quantity of EUAs in the system for a particular year (European Commission, 2016). These regulations affect the behaviour of the firms subjected to emission reductions. In Flåm (2016), the author compares the market with pollution permits to a Cournot oligopoly with a price setter whose priority is to minimize the excess supply by setting the price. This description fits the EU ETS perfectly. The European Commission and the member states can set the price of EUAs through some particular market factors. For instance, the member states control the already mentioned EUAs volume or number of companies, which are obligated to participate in the system. These interventions can affect not only EUAs prices but also prices of commodities which have EUAs as the "production factor", in our case electricity energy. To summarize, the allowance price is largely determined by the legislative framework.

Outrata et al. (2015) suggests method and gives an example of CNW equilibria computation on markets with rare resources. One of the assumptions for these markets is that aggregate quantity of the rare resource is always greater or equal to endowment distributed among market participants. More precisely, $\Xi \geq \sum_{i \in I} e_i$, wherein Ξ is the aggregate quantity of the rare resource. In our case, the rare resource is assumed to be emission allowances. Using this notation, the terms (3) and (4) or term (8) can be rewritten as

$$\bar{m} \geq 0,\ \Xi - \sum_{i \in I}(e_i + \bar{z}_i) \geq 0, \qquad \text{and} \qquad \bar{m} \cdot (\Xi - \sum_{i \in I}(e_i + \bar{z}_i)) = 0. \quad (9)$$

Again, the expression states condition for clearing the market with allowances. Then the maximization problem for the firm i is formulated as follows.

$$\begin{aligned} &\text{maximize} \quad p(Q)y_i - c_i(y_i) - m(q_i(y_i) - e_i) \\ &\text{subject to} \quad y_i \in A_i \end{aligned} \qquad (10)$$

The firm minimizes its costs with respect to set A_i. The A_i defines the interval for i-th firm production. For simplicity, the inequality $q_i(y_i) \leq z_i + e_i$ is replaced by the equality $q_i(y_i) = z_i + e_i$, which implies that $z_i = q_i(y_i) - e_i$. The equality corresponds to the assumption that produced quantity of electricity energy y_i with technology q_i should by equal to the quantity of the allowances initially endowed e_i plus additional purchased quantity z_i. In words, all allowances are used, that is, firms use the necessary amount of allowances and sell the rest of allowances on the secondary market. Obviously, z_i can be negative since each firm can either buy or sell allowances.

5.2 Model

In contrast to Flam (2016) and Outrata et al. (2015), we apply CNW equilibrium to the real market. Our model considers nine market participants. One auctioneer (i.e., state) who does not produce any output but is endowned with some initial endowment and eight oligopolistic firms which maximize their profit; each with the classical Cobb-Douglas production function with capital and labour as the production factors. One may see, e.g., Mas-Colell (1995), Bhatt (2014). Further, trades are computed as a classical exchange, i.e., the model does not consider any bids from the firms to the auctioneer. The output of firm i is given by

$$y_i = f_i(K, L) = A_i K_i^{\alpha_{1i}} L_i^{\alpha_{2i}}, \qquad \forall i \in 1, 2, \ldots, 8$$

where parameters A_i represent the scale of production of firm i and y_i is output of electricity. The parameters α_{1i}, α_{2i} measure how the amount of output responds to some changes in the production factors. To ensure that each production function has a non-increasing return to scale, we set $\alpha_{1i} + \alpha_{2i} < 1$ and hence the f_i function is jointly convex in K, L. Such a production function corresponds to a cost function

$$c_i(y_i) = \alpha_i b_i y_i^{\frac{1}{\alpha_i}} w_i^{\beta_{1i}} r^{\beta_{2i}},$$

where w_i, r, y_i denotes the wage in firm i, the interest rate and the quantity of output, respectively. Interested reader may see Mas-Colell (1995) for complete derivation of cost function c_i. In our model, the price of capital equals its opportunity costs, i.e., rental rate (Varian, 2010). We use interest rate as a price of capital, since we do not know the exact cost of capital for each firm. Constants α_i, β_{ji} and b_i are simplifications of following expressions:

$$\alpha_i = \alpha_{1i} + \alpha_{2i}\,, \qquad \beta_{ji} = \tfrac{\alpha_{ji}}{\alpha_{1i}+\alpha_{2i}}, \qquad j \in 1, 2,$$

and

$$b_i = A_i^{\frac{-1}{\alpha_i}} \prod_{j=1}^{2} \alpha_{ji}^{-\beta_{ji}}.$$

Each cost function c_i is convex with respect to y_i. Further, as in Murphy et al. (1982) we consider inverse demand function

$$P(Q) = K^{\frac{1}{\eta}} Q^{\frac{-1}{\eta}}$$

for output y_i, where $Q = \sum_{i=1}^{8} y_i$ is the total electricity produced and K is a constant. The demand function was scaled in order to fit our model, i.e. $K = 11\ 000$ insted of original $K = 5\ 000$. The difference is that our model allows for a much larger amount of output. Provided that $\eta > 0$, it it easy to see that the inverse demand function is concave in y_i.

Unlike Outrata et al. (2015), where the authors suppose various types of technological functions, including non-convex case, our model assumes only linear technological functions for all firms, i.e., $q_i(y_i) = t_i y_i$, $i \in \{1, \ldots, 8\}$ Thus, we get $t_i y_i = z_i + e_i$ for $i = 1, \ldots, 8$. Assuming firm i maximizes its profit, the optimization problem can be formulated in the following manner.

$$\begin{aligned} &\text{maximize} \quad P(Q)y_i - c_i(y_i) - m \cdot (t_i y_i - e_i) \\ &\text{such that} \quad \bar{m} \geq 0,\ \Xi - \sum_{i=1}^{8}(\bar{z}_i + e_i) \geq 0,\ \bar{m} \cdot (\Xi - \sum_{i=1}^{8}(\bar{z}_i + e_i)) = 0. \end{aligned} \tag{11}$$

Profit maximizing function of firm i is concave with respect to y_i. Constraints then represents the Walras equilibrium in the allowance market.

Remark In the model, we assume the market as a non-cooperative game, where firms set quantities simultaneously. In theory, the Cournot oligopoly is usually connected to a small number of producers. Nevertheless, even the Cournot equilibrium could be applied to a relatively larger number of producers. In Varian (2010), the author uses the firm shares s_i of total output in market to describe a Cournot equilibrium with many firms. If firm i share is $s_i = 1$ then the firm is a monopolist and faces market demand curve. Conversely, a firm with a small market share faces flatter demand. In other words, some firms may have a bigger impact on a price than the others. Nevertheless, the results of our model are valid.

5.3 Market Description

Our model is the simplification of the Czech market with EUAs. Recall, we selected eight firms listed in Table 3 which perform business in electricity production in the Czech Republic. On the basis of OTE, a.s. compliance 2014 report for fixed installations, these eight firms are the largest emitters of carbon dioxide in the sector of energy production. All of these firms have the production of electricity included in their portfolios. Nevertheless, some of these firms produce also different types of outputs. For instance, the Alpig Generation (CZ) a.s., the ČEZ a.s., the Elektrárny Opatovice a.s. and Energetika Třinec a.s. also produce heat energy. The vast majority of the

Table 3: Largest emitters of CO_2 in Czech Republic during year 2014

Firm	Submitted EUAs
TAMEH Czech s.r.o.	5 302 878
ČEZ, a.s.	24 736 229
Elektrárna Chvaletice, a.s.	3 763 084
Elektrárny Opatovice, a.s	2 115 525
Sokolovská uhelná, a.s.	4 098 901
Veolia Energie ČR, a.s.	2 770 687
Alpiq Generation (CZ) s.r.o.	2 108 093
Energetika Třinec, a.s	1 830 527

Source: Authors calculation based on Complience 2014 report, OTE, a.s.

EUAs submitted by the Veolia Energie ČR a.s., the Elektrárna Chvaletice a.s. (now part of Sev.en EC) and Sokolovská uhelná a.s. cover emissions from the production of electricity. The joint venture called TAMEH holding was established in August 2014 between ArcelorMittal and the Polish Tauron group (All for power, 2015). The ArcelorMittal Energy Ostrava was renamed to TAMEH Czech s.r.o., therefore we sum up its submitted EUAs under TAMEH company. Besides the electricity, TAMEH Czech s.r.o. also produces heat, compressed air, and technological steam. Since it is impossible to distinguish between allowances submitted for different products, we will assume that firms produce electricity through our numerical experiments. In total, these eight firms surrendered 70.5 percent (46 860 704 out of 66 435 325) of the total number of allowances submitted in the Czech Republic for compliance purposes in 2014. Table 3 presents exact amount of submitted EUAs.

Pursuant to the current regulation, 72.86 percent of the overall quantity of EUAs was allocated for free in 2014. Therefore, initial endowments are set to 72.86 percent of the total quantity of EUAs submitted in this year. Table 4 presents the specific parameters for each firm. The endowments are

Table 4: Parameters specification

	w_i	α_{1i}	α_{2i}	A_i	r	e_i	t_i
Firm 1	34	0.5	0.3	4500	1.0164	3.864	3.5
Firm 2	60	0.4	0.4	5500	1.0164	18.023	3.2
Firm 3	25	0.6	0.3	3500	1.0164	2.742	3.3
Firm 4	30	0.3	0.5	3500	1.0164	1.541	3.35
Firm 5	30	0.2	0.6	5000	1.0164	2.986	2.25
Firm 6	33	0.5	0.4	6400	1.0164	2.019	3.3
Firm 7	40	0.4	0.5	3900	1.0164	1.536	3.4
Firm 8	31	0.6	0.3	3500	1.0164	1.334	2.5

Source: Authors calculation

listed in column e_i. The numbers are given in millions of EUAs. Parameters t_i represent firm i technological level of advancement. In the model, we use parameter $t_i \times 10^{-3}$. The wages w_i are based on the information presented on the web pages of firms listed in Table 3. Since it is impossible to obtain precise values of parameters A_i, α_{1i}, α_{2i} and t_i they are set in accordance with the size of the firms. As mentioned above, we use interest rate as a price of capital, since we do not know the cost of capital for each firm. Hence, we set the interest rate to the value of five year Eurobond yield (IND10 Bond yield 5Y - Eurozone) in the beginning of 2014. Such yield serves as a good proxy for rental cost of money in the economy since governmental bonds are considered as almost risk free. Parameters A_i, α_{1i} and α_{2i} are specifications of the production function of firm i. Parameters t_i represent a technological level of advancement of firm i. Essential commodities like energy have inelastic demand (Mankiw, 2012). Therefore, we set $\eta = 0.8$.

5.4 Scenarios

We consider five different scenarios in our numerical experiments. In this subsection, we present motivation for the particular settings. The initial setting, given in the subsection with market description, refers to scenario A.

- **A** All parameters are as in Table 4. The total quantity of EUAs is $\Xi = 46.726$. The sum of endowments is equal to 72.86 percent of Ξ.
- **B** Scenario A is modified by reducing the cap Ξ to 39.163.
- **C** The initial endowments are decreased to 65.71 percent of the original cap. The cap is left the same as in the scenario B, i.e., $\Xi = 39.163$.
- **D** The overall cap is set to $\Xi = 42.055$ the initial endowments are set to 30 percent with respect to the cap in scenario A.
- **E** The last scenario is a modification of scenario B. We leave the cap and endowments as in case B, i.e., $\Xi = 39.163$. Firms 1, 4, 6, 7 and 8 have a "greener" production technologies, i.e, $t(i)$, $i = 1, 4, 5, 7$ are equal to 2.3, 2.35, 2.3, 2.4, 1.5, respectively.

Scenario B examines the effect of reduction in overall cap on the EUAs price. Firstly, the cap is reduced by 1.74 percent with respect to the initial quantity. Secondly, there is a lump-sum reduction of 6.75 million EUAs. Scenario C illuminates the difference between years 2014 and 2015. Recall, the original cap from 2013 is reduced by 1.74 percent annually and there is a lump-sum reduction in the year 2014. Even though it is difficult to predict price changes in a long run, scenario D focuses on simulating the market conditions in 2020 under the assumption that production is the same as in 2014. Thus, the initial endowments are set to 30 percent with respect to 2014 emissions and the cap is reduced annually by 1.74 percent. Since the EUAs that were withdrawn from the market during the years 2014-2016 are to be returned to the circulation in years 2019-2020, there is no lump-sum reduction. Last scenario E simulates the situation when some of the production companies invest into new technologies while the remaining ones are left with status quo.

5.5 Results

The following subsection summarizes achieved numerical results in each outlined scenario A - scenario E. Further, we discuss the possible impact of the results on firms, consumers and state budget.

Corresponding mathematical problem is solved using GAMS distribution of the PATH solver (Dirkse and Ferris, 1995). Initial values of EUA price m and output quantity y_i have been set identical for all scenarios to 200 and 1200, respectively. The computation times for each scenario is less than 0.05 second on a standard laptop thus, can be considered negligible and we do not refer it in our summary Table 5. Initial values of EUA price m and output quantity y_i have been set identical for all scenarios to 200 and 1200, respectively.

Table 5 reports the productions, profits and purchased EUAs of each firm along with price of the EUAs in each of specified scenarios. The production is estimated in the hundreds of watt hours. Thus, we report electricity price per one hundred of watt hours. The weighted average price of EUAs was 156.44 CZK in 2014 (OTE a.s, 2015). The average electricity price was 0.5 CZK in 2014 (Ceny Energie, 2015). According to scenario A, the resulting clearing price of the EUAs is 159.2 CZK. The corresponding electricity price is 0.58 CZK. The difference between actual and estiamted electricity price may be a result of missing production from renewable sources.

Table 5: Productions, profits and EUAs purchases

		Firm 1	Firm 2	Firm 3	Firm 4	Firm 5	Firm 6	Firm 7	Firm 8	Czech Republic
case **A**	$p = 159.20$									
	production	645.48	1745.22	1336.32	1216.38	5238.82	1395.45	1020.39	4214.29	
	profit	633.75	1025.22	780.51	713.50	3076.95	818.16	597.81	2455.36	2018.75
	purchased	-1.605	-12.438	1.668	2.534	8.801	2.586	1.933	9.202	-12.681
case **B**	$p = 198.73$									
	production	540.31	1461.85	1125.70	1014.63	4387.24	1164.74	851.93	3547.47	
	profit	787.19	1072.07	821.00	742.46	3213.53	851.98	622.79	2581.86	1017.09
	purchased	-1.973	-13.345	0.973	1.858	6.885	1.825	1.361	7.535	-5.118
case **C**	$p = 198.73$									
	production	540.31	1461.85	1125.70	1014.63	4387.24	1164.74	851.93	3547.47	
	profit	711.87	1071.72	820.95	742.43	3213.48	851.94	622.76	2581.83	1681.04
	purchased	-1.594	-11.576	1.242	2.009	7.178	2.023	1.512	7.666	-8.459
case **D**	$p = 181.72$									
	production	580.51	1570.18	1206.53	1091.53	4712.68	1252.69	916.15	3803.26	
	profit	307.96	1050.99	804.26	730.39	3157.32	837.85	612.35	2530.34	5095.09
	purchased	0.442	-2.396	2.853	3.022	9.374	3.303	2.483	8.959	-28.038
case **E**	$p = 177.40$									
	production	2541.80	0.00	0.00	2325.85	2925.45	2606.49	2032.23	6931.06	
	profit	893.35	3.20	0.49	1142.22	1440.08	1279.68	996.71	3376.77	907.94
	purchased	1.982	-18.023	-2.742	3.925	3.596	3.976	3.341	9.063	-5.118

Source: Authors calculation

In scenario B, the cap was reduced by 16.2 percent. The EUAs price rose by 24.83 percent which is consistent with expected inverse relationship between supplied quantity and price. Total supplied quantity of output decreased by 16.17 percent. Conversely, the resulting electricity price increased by 24.8 percent. Firm 1 and 2 sell a substantial portion of its initial endowed EUAs in order to maximize their profits. This is caused mostly by their technological function. All other production firms buy certain amount of EUAs. State sells all additional EUAs, i.e., the market with allowances is cleared. Nevertheless, all production firms slightly improved their profits.

The difference between scenario C and B is in the initial endowment. According to the model, the reduction in endowments has no effect on production and thereby the prices of EUAs and electricity remain the same as in scenario B. Because of the decrease in initial endowments, the profits of all firms slightly dropped. Since firms optimize their production only with respect to the electricity market, this result is in line with our expectation. The change would occur, if one of the firms was pushed out of the market and its profit turn to the deficit. Conversely, the state increased its profit through lower free allocation of the EUAs to the firms. To put the analysis into perspective we compare scenario C with status quo, i.e, years 2014 and 2015. State profit fell by 16.73 percent because of the reduction in the overall cap. As mentioned above, the total supplied quantity of output fell by 16.17 percent, while the profit of every production firm improved. This is caused by inelastic demand function. We can see a decrease in sales of EUAs at Firm 1 and 2. All other firms reduced their purchases. Since 16.17 percent drop in production is noticeable, in real terms it would mean that electricity would have to be imported from neighbouring states or generated from renewable sources. While model predicts 24.83 percent increase in EUAs price, the actual difference between prices in years 2014 and 2015 was 39 percent (Energetický regulační úřad, 2016). The difference may occur due to low control for market share along with some unobserved effects of other markets.

Further, we focus on our numerical experiment which corresponds to the cap and initial endowments proposed by the EU ETS framework for the year 2020, i.e., scenario D. If the cap and the initial endowments are reduced, ceteris paribus, the model predicts an increase in the EUAs price to be 14.15 percent. The estimated increase in the price of the electricity produced by means of fossil fuels is 14.1 percent with respect to 2014. Again, the productions of all firms dropped. However, the decline was smaller than in the case of scenario B and C. Indeed, the total supplied quantity of electricity fell approximately by 10 percent. Since the drop is estimated to happened in a long term, we expect that closing capacity will be replaced by energy from renewable sources. The profit of Firm 1 decreased by one-half compared to scenario A. Conversely, all other firms increased its profits. A significant increase is also in the profit of state, as the majority of allowances has to be sold via auction. Firm 2 is the only producer who still sells at least some EUAs.

The last scenario examines the case where there is a restrictive policy followed by investments into production technologies. Because both effects are expected to have an adverse effect on the price of EUAs, it depends on the setting of parameters which ones prevail. We will compare scenario E with scenario A. Improvement in technological functions of firms 1, 4, 6, 7 and 8 results in a substantial increase in their profits. Even though it is no longer profitable to produce for Firm 2 and 3, still, they can sell their endowments to generate at least some profit. Now, Firm 1 buys additional EUAs instead of selling it. Again, it is caused by the improvement in its technological function. The EUAs price rose approximately by 11.4 percent and the aggregate output increased by 15.2 percent. On the other hand, the price of electricity is estimated to decline by 16.16 percent. To summarize, scenario E shows that the reduction in the overall cap with an improvement of some firms production could push other firms out of business.

6 Conclusion

The idea of GHG reduction through emission trading system was firstly presented in 1997 within the Kyoto Protocol agreement. The EU introduced its own emission trading system in 2006 which has already undergone three phases of development and became the largest emission market in the world. During the first pivotal period of the EU ETS the price of allowances dropped almost to zero. The problem was overallocation of free allowances. The cap was set higher than the actual emissions were, thus, firms were not motivated to buy any allowances. Through amending directives the European Commission successfully managed to transform the EU ETS into functional market. So far, the nearest goal is 20 percent emissions reduction within the member states relatively to emissions in 1990. This target has to be achieved in 2020 with the end of the third trading period of the EU ETS. The future of emission trading will be most likely shaped by the 2015 Paris climate conference agreement which set the upper threshold for temperature increase to 1.5°C compared to pre-industrial level. The European Commission in reaction to the Paris agreement proposed a revision of the EU ETS for period after 2020. The proposal allows for the reduction of GHGs amounting to 40 percent compared to 1990.

The emission market is a mechanism which should motivate market participants to reduce their GHG emissions through economic incentives. An example is a decline in the overall cap of allowances. Companies can respond to such a change in different ways. Investing into production technologies, optimizing the quantity of output or changes in production factors are good examples of such a behaviour.

In the section five, we describe equilibrium model which reflects the Czech emission market and highlights the role of energy companies. The model use innovative concept of CNW equilibrium. According to the theory of CNW equilibrium, the price of EUAs is either zero, in the case when the available amount of EUAs exceeds the interest of the emission market participants, or it is positive under the assumption that EUAs are tradable. With the use of CNW equilibrium concept, we perform various numerical experiments. Some of the experiments reflect changes in Czech emission market while others are rather hypothetical. Our equilibrium model highlights inverse price movements between the EUAs and the electricity. We mainly focus on reduction in the overall cap and the resulting effect on firms profits. According to the results, if the cap is reduced, the price of EUAs and the price of electricity produced by means of fossil fuels increase. We observe higher price increase of EUAs between years 2014 and 2015 than in case of 2014 and 2020. While the price of EUAs increase approximately by 25 percent in the first case, the estimated difference between the EUA price in 2014 and 2020 is 14 percent. The higher increase in 2015 is a result of the lump-sum reduction in the cap during the same year. Further, the model predicts 10 percent drop in the aggregate supplied quantity of electricity in 2020 compared to 2014. Since the drop is estimated to happened in a long term, the closing capacity can be replaced by energy from renewable sources. Last but not least, we find that non-innovating firm can lose significant market share.

Our analyses give some intuition about the linkage between Czech emission market and corresponding electricity production sector. The model uses elements of game theory to predict firms behaviour in primary market while their are subjected to the joint constraint in the secondary market. The theory of general equilibrium and especially the concept of CNW equilibrium is often associated with the markets where it is necessary to buy some permits to run a business. Such permits are usually distributed by state or some other authority. A similar model could be applied in the case of fishing quotas or production allowances.

Bibliography

[1] ARROW, Kenneth J. a Gerard DEBREU. Existence of an Equilibrium for a Competitive Economy. *Econometrica* [online]. 1954, **22**(3), 265- [cit. 2016-05-01]. DOI: 10.2307/1907353. ISSN 00129682. Available at: http://www.jstor.org/stable/1907353?origin=crossref

[2] BHATT, Niharika Joshi. Productivity in Small and Medium Enterprises of India: A Cobb-Douglas Production Function Approach. *IUP Journal of Management Research* [online]. 2014, **13**(1), 29-36 [cit. 2016-05-05]. ISSN 09725342. Available at: http://search.ebscohost.com/login.aspx?direct=true&db=bth&an=95087600&scope=site

[3] BROUWER, L. E. J. Über Abbildung von Mannigfaltigkeiten. *Mathematische Annalen*. 1911, **71**(1), 97-115. DOI: 10.1007/BF01456931. ISSN 0025-5831. Available at: http://link.springer.com/10.1007/BF01456931

[4] FLÅM, Sjur Didrik. Equilibrium, Evolutionary Stability and Gradient Dynamics. *International Game Theory Review* [online]. 2002, **4**(4), 357-370 [cit. 2016-05-05]. ISSN 02191989. Available at: http://search.ebscohost.com/login.aspx?direct=true&db=bth&an=8700719&scope=site

[5] FLÅM, Sjur Didrik. *Noncooperative games, coupling constraints, and partial efficiency*. 2016. DOI: 10.1007/s40505-015-0079-3. ISBN 10.1007/s40505-015-0079-3. Available at: http://link.springer.com/10.1007/s40505-015-0079-3

[6] GEANAKOPLOS, John. Nash and Walras equilibrium via Brouwer. *Economic Theory* [online]. 2003-3-1, **21**(2-3), 585-603. DOI: 10.1007/s001990000076. ISSN 0938-2259. Available at: http://link.springer.com/10.1007/s001990000076

[7] GINTIS, Herbert a Antoine MANDEL. *The Dynamics of Walrasian General Equilibrium* [online]. 2012 [cit. 2015-06-11]. Available at: http://www.umass.edu/preferen/gintis/gestabilityreview.pdf

[8] LEVIN, Jonathan. *General Equilibrium* [online]. 2006 [cit. 2015-06-11]. Available at: http://web.stanford.edu/$~$jdlevin/Econ%20202/General%20Equilibrium.pdf

[9] MANKIW, N. Gregory. *Principles of economics*. 6th ed. Mason, OH: South-Western Cengage Learning, c2012. ISBN 05-384-5305-2.

[10] MAS-COLELL, Andreu, Michael Dennis WHINSTON a Jerry R GREEN. *Microeconomic theory*. New York: Oxford University Press, 1995, xvii, 981 p. ISBN 01-951-0268-1.

[11] MURPHY, Frederic, Hanif SHERALI a Allen SOYSTER. A mathematical programming approach for determining oligopolistic market equilibrium. *Mathematical Programming* [online]. 1982, **24**(1), 92-106 [cit. 2016-05-06]. DOI: 10.1007/BF01585096. ISSN 00255610.

[12] OUTRATA, J. V., M.C. FERRIS, M. ČERVINKA a M. OUTRATA. *On Cournot-Nash-Walras equilibria and their computation*. 2015. Available at: http://www.optimization-online.org/DB_FILE/2015/09/5128.pdf

[13] VARIAN, Hal R. *Intermediate microeconomics: a modern approach*. 8. ed. New York: Norton, 2010, xxiv, 739, 40 s. ISBN 978-0-393-93424-3.

[14] *Sokolovská Uhelná* [online]. c2008-2010 [cit. 2016-05-05]. Available at: http://www.suas.cz/

[15] UNFCCC. *Kyoto Protocol to the United Nations Framework Convention on Climate Change*. 1997. Available at: http://unfccc.int/resource/docs/convkp/kpeng.pdf

[16] Společný energetický podnik TAMEH Holding zahájil svou činnost. Povede jej Kristina Červenková. *All for Power* [online]. c2015 [cit.

2016-05-06]. Available at: http://www.allforpower.cz/clanek/spolecny-energeticky-podnik-tameh-holding-zahajil-svou-cinnost-povede-jej-kristina-cervenkova/

[17] *Předpis č. 257/2014 Sb. Zákon, kterým se mění zákon č. 383/2012 Sb., o podmínkách obchodování s povolenkami na emise skleníkových plynů, a další související zákony.* In: . Sagit, 2014, 257/2014 Sb. Available at: http://www.sagit.cz/info/sb14257

[18] Commission Decision of 27 April 2011 determining transitional Union-wide rules for harmonised free allocation of emission allowances pursuant to Article 10a of Directive 2003/87/EC of the European Parliament and of the Council. In: *EUR-Lex*. Official Journal of the European Union, 2011. Available at: http://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX:32011D0278

[19] *EU ETS Handbook* [online]. European Commission, 2016 [cit. 2016-05-01]. Available at: http://ec.europa.eu/clima/publications/docs/ets_handbook_en.pdf

[20] Veřejné zprávy: *OTE, a.s. povolenky* [online]. c2010 [cit. 2016-05-05]. Available at: https://www.povolenky.cz/uzitecne-informace/verejne-zpravy

[21] *Sev.en EC* [online]. c2013 [cit. 2016-05-05]. Available at: http://www.sev-en.cz/cz/index.html

[22] *UNFCCC* [online]. c2014 [cit. 2016-05-05]. Available at: http://unfccc.int/2860.php

[23] Directive 2009/29/EC of the European Parliament and of the Council of 23 April 2009 amending Directive 2003/87/EC so as to improve and extend the greenhouse gas emission allowance trading scheme of the Community. In: *EUR-Lex*. Official Journal of the European Union,

2009. Available at: http://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX:32009L0029

[24] Directive 2009/29/EC of the Euopean Parliament and of the Council of 23 April 2009 amending Directive 2003/87/EC so as to improve and extend the greenhouse gas emission allowance trading scheme of the Community. In: *EUR-Lex*. Official Journal of the European Union, 2009. Available at: http://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX:32009L0029

[25] Commission Regulation (EU) No 176/2014 of 25 February 2014 amending Regulation (EU) No 1031/2010 in particular to determine the volumes of greenhouse gas emission allowances to be auctioned in 2013-20. In: *EUR-Lex*. Official Journal of the European Union, 2014. Available at: http://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX:32014R0176

[26] *Adoption of the Paris Agreement: Conference of the Parties* [online]. In: . UNFCCC, 2015 [cit. 2016-05-01]. Available at: https://unfccc.int/resource/docs/2015/cop21/eng/l09.pdf

[27] Výroční zprávy. *ArcelorMittal* [online]. 2014 [cit. 2016-05-05]. Available at: http://ostrava.arcelormittal.com/o-spolecnosti/vyrocni-zpravy.aspx

[28] *Elektrárny Opatovice* [online]. c2016 [cit. 2016-05-05]. Available at: http://www.eop.cz/

[29] *Energetika Třinec, a.s.* [online]. [cit. 2016-05-05]. Available at: http://www.etas.trz.cz/

[30] Iceland, Norway, Liechtenstein to join EU emissions trading system. *EU Business* [online]. c2016 [cit. 2016-05-06]. Available at: http://www.eubusiness.com/topics/environ/1193418125.05

[31] Structural reform of the European carbon market. In: *European Commission: Climate Action* [online]. 2016 [cit. 2016-04-25]. Available at: http://ec.europa.eu/clima/policies/ets/reform/index_en.htm

[32] Commission Regulation (EU) No 1031/2010 of 12 November 2010 on the timing, administration and other aspects of auctioning of greenhouse gas emission allowances pursuant to Directive 2003/87/EC of the European Parliament and of the Council establishing a scheme for greenhouse gas emission allowances trading within the Community. In: *EUR-Lex*. Official Journal of the European Union, 2011. Available at: http://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX:02010R1031-20111125

[33] Environmental Markets. *EEX* [online]. 2016 [cit. 2016-05-01]. Available at: https://www.eex.com/en/products/environmental-markets

[34] State of the Climate: Global Analysis for Annual 2015. *NOAA National Centers for Environmental Information* [online]. 2016 [cit. 2016-05-12]. Available at: https://www.ncdc.noaa.gov/sotc/global/201513

[35] *Veolia Energie* [online]. [cit. 2016-05-05]. Available at: http://www.veoliaenergie.cz/cz

[36] *European Commission: Climate Action* [online]. 2016 [cit. 2016-05-01]. Available at: http://ec.europa.eu/clima/index_en.htm

[37] EUA UK Auction Daily Futures. *ICE FUTURES EUROPE* [online]. 2016 [cit. 2016-05-01]. Available at: https://www.theice.com/products/18997864/EUA-UK-Auction-Daily-Futures

[38] Průměrná cena emisní povolenky pro rok 2015. *Energetický regulační úřad* [online]. 2016 [cit. 2016-05-01]. Available at: https://www.eru.cz/-/prumerna-cena-emisni-povolenky-pro-rok-2015

[39] Jaká je aktuální cena kWh a MWh elektřiny? *Ceny Energie* [online]. 2015 [cit. 2016-05-12]. Available at: http://www.cenyenergie.cz/jaka-je-aktualni-cena-kwh-a-mwh-elektriny/#/promo-ele

[40] Kde vás zaplatí nejlépe. *Hospodářské noviny* [online]. Economia, a.s., c1996-2016 [cit. 2016-05-05]. Available at: http://ekonom.ihned.cz/c1-63215580-kde-vas-zaplati-nejlepe

List of Tables