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A MULTICRITERIA MODEL FOR ANALYSIS OF THE IMPACT OF EU GHG LIMITING POLICIES ON ECONOMIC GROWTH. THE CASE OF POLAND.

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ABSTRACT

The aim of the paper is an attempt to answer the following questions: how to proceed with a process of the economic transformation due to adjustment of the national economy to the EU policy limiting emission CO_2, what are the consequences of the enforced emission limits for the economic development and future consumption. To answer these questions the macroeconomic model has been developed and the multicriteria optimization has been applied. The multicriteria approach is an answer to the decision making problem with the two competing objectives taken into account in the EU policies: on the one hand maximum development of the national economy and on the other hand minimization of the impact on the climate warming by decreasing the greenhouse gases (GHG) emission. The analysis focuses on the macroeconomic development of the national economy under the limits imposed on the GHG emission. The long-term goal of the all economic agents is maximization of consumption. The economic sectors interact via markets of the relevant goods. The model is the mid- and long-horizon one, meaning that we consider only equilibrium trajectories due to the assumption that every year national and foreign demand for goods and services produced in all sectors equal national and foreign supply of those goods and services. The model accounts for phenomena having an impact on the economic development, such as the inertial behavior of the large-scale dynamic system, as well as social and political resistance to changes. The numerical results can serve as a reference for the real life economic policy. In assessing the duration of the technology conversion, the obtained results indicate the shortest conversion time assuming that it has been performed optimally. Three production sectors are distinguished: the sector *M* produces intermediary inputs, the sector *C* produces consumer goods, and the sector *I* produces investment goods. The simulation experiments are presented.

A MULTICRITERIA MODEL FOR ANALYSIS OF THE IMPACT OF EU GHG LIMITING POLICIES ON ECONOMIC GROWTH. THE CASE OF POLAND.

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1. Introduction

The aim of the paper is to analyze the problem of harmonization of two competing goals: supporting the long-term economic growth and decreasing the GHG emission.

The following questions are considered: How to pass a process of the economic transformation due to adjustment of the national economy to the EU policy limiting emission of CO_2 in a possibly best way? What may be consequences of the enforced emission limits for the economic development and future consumption? To find solutions to these questions a computer-based modeling of the macroeconomic development of the national economy and the multicriteria optimization approach are applied. The multicriteria optimization is used because of the above mentioned two conflicting objectives which have to be taken into account in making decision: (i) a possible maximal development of the national economy, (ii) decreasing the GHG emission according to the climate change postulates.

The model is constructed as a tool supporting analysis of the impact of EU limiting policies on economic growth of a small country. The multicriteria optimization approach is applied. Two criteria are formulated: the discounted consumption which should be maximized, and the number of emission permits in the destination year which should be minimized. The number of emission permits in the destination year is treated as a variable in the model. A scenario describing the numbers of permits decreasing in consecutive years is a function of this variable. A multicriteria optimization problem is formulated. Analysis of possible Pareto optimal outcomes is made using the reference point approach developed by Wierzbicki (Wierzbicki, 1986), (Wierzbicki at al., 2000). According to this approach, a special unicriterial parametric optimization problem is formulated. Parameters in the problem are defined as the reference – aspiration values for the criteria. The solution of the problem for given reference values of the criteria gives the Pareto optimal outcome with respect to the defined criteria. The corresponding values of decision variables, including the investments in the considered technologies in the sectors of the economy, the foreign trade, as well as the emissions in the sectors and the output quantities of the model are derived. The decision variables and the output quantities are derived for the long-term period of time. Therefore the impact of the limiting GHG emissions on the economic growth after the destination year can be also analysed. Solving the problem for different reference values of the criteria enables us to obtain a representation of the Pareto frontier in the criteria space. The relations between the economic development of the country and discussed limits imposed on the GHG emission can be analysed comparing different points of the Pareto frontier.

The presented multicriteria model can be considered as a tool useful in the stage of preliminary analysis preceding the discussion and negotiation of the GHG emission limits in European Commission.

The paper is organized as follows. The model of economic development is presented in Section 2. General assumptions, decision variables, output quantities and model relations are presented.

A scenario describing the number of emission permits allocated to the country in consecutive years as a function of the number of the permits allotted to the country in the destination year is described in Section 3.

Section 4 presents the general formulation of the multicriteria optimization problem and then formulation of a special parametric problem in the reference point approach.

Results of computational experiments are presented in Section 5. The experiments have been made for Poland, starting from the year 2005. They include results of the multicriteria optimization. A representation of the Pareto optimal outcomes has been obtained. Results including a sequence of the decision variables and the output quantities are presented in the long time period – till the year 2085. They are shown, compared, and discussed in the case of two selected variants referring to the moderate and restrictive policies of the GHG emission limits.

The bibliography attached includes descriptions of the previous versions of the model (Gadomski, 2008; Gadomski & Nahorski, 2010, 2011). The research undertaken was inspired by the previous papers dealing with models for analyzing the greenhouse gas (GHG) emission impacts and climate policy effects, like Global2010 (Manne & Richels, 1992) or DICE (Nordhouse, 1994). DICE model enjoys broader attention and many of its revisions has been proposed (e. g. Nordhouse & Boyer, 1999; Pizer, 1999; Keller at al., 2004). The DICE model is a dynamic growth model that relates economic activity and climate change in the global scale. The papers by Roberts (1964); Goulder & Schneider (1999); Nahorski & Ravn (2000);

Hart (2004); Grimaud & Rouge (2008), Goulder & Schneider (1999); Hart (2004) present an approach to modeling the technology change including the research and development (R&D) sector. Effects of the knowledge dissemination and spillover are analyzed by Allen (1977), Jaffe at al .(2002). Paretto (2008) studied effects of taxes on firms' allocation of resources to cost- and emission-reduction R&D. In comparison to the cited papers, the model presented in this paper is aimed at the multicriteria analysis of the adjustment of a small country economy to the introduction of the rules that could be agreed according to the EU Directives.

The multicriteria optimization approach used in this study, as well as the multicriteria decision support are discussed in the papers by Kruś (2008, 2011), Kruś & Bronisz (2000), Wierzbicki (1986), and Wierzbicki at al. (2000).

2. Model description

The model presented in this paper evolved from older models, (Gadomski, 2008; Gadomski & Nahorski, 2010, 2011), aimed at an analysis of the impact of limiting the greenhouse gases emission on the technological conversion, economic structure and the speed of economic adjustment. In the present paper a different approach to the emission limits is taken; formerly these limits were used as constraints, while in the model discussed they are traded.

In the present analysis we preserve most methodological assumptions of the earlier models, which are as follows.

Our analysis focuses on the macroeconomic development of the national economy under the limits imposed on the GHG emission. The long-term goal of the all economic agents is maximization of consumption, which is being pursued as a result of the short-term profit maximization. We assume that economic sectors interact with each other via markets of the relevant goods and services. The model solution is optimized. It determines adjustment of the national economy to the imposition of the GHG emission limits and trade in the emission permits.

The model is the long-term one, which means that we consider only equilibrium trajectories due to the assumption that every year national and foreign demand for goods and services produced in all sectors equal national and foreign supply of those goods and services. Such an approach makes it possible for the production sectors to follow the long term equilibrium path with persisting sectorial surpluses and deficits exchanged via balancing the foreign trade.

The model does not use macroeconomic tools for achieving optimum path. However, we account for phenomena having an impact on the economic development, such as the inertial behavior of the large-scale dynamic system, as well as social and political resistance to changes. The numerical results can serve as a reference for the real life economic policy. For example, in assessing the duration of the technology conversion, the obtained results indicate the shortest conversion time assuming that it has been performed optimally.

Three production sectors are distinguished in the model: the sector M produces intermediary inputs (raw materials, energy, communication and transport services, etc.), the sector C produces consumer goods and services, and the sector I produces investment goods and services. Letters M, C and I will be used to denote both the relevant sector as well as its product. A sector which is worth of including into the consideration, although not included yet, is the household sector, which receives incomes from the production sectors and divides them between the consumption and investment.

The production technology in the model is defined by a set of the following parameters: the productivity of capital, the depreciation rate, the intermediate usage rate, and the unit emission. We assume that in each sector considered the producers choose from a small number of production technologies. In this paper, only two available production technologies in each sector: the older one, cheaper but emitting more GHG and the new one, more expensive but emitting less GHG, are assumed. The reason behind it is that pure technologies hardly ever exist. Then we assume that the technologies in operation are mixtures of pure ones in certain proportions, with prevailing either old or new ones. More precisely, we consider "old" as those emitting a large amount of GHG, and "new" as those emitting much less or none.

We assume abundance of the labor and that the labor does not substitute fixed assets. Production capacity in each technology used in a given sector is determined by the amount of the fixed assets associated with that technology. Those fixed assets are being decreased by the depreciation and increased by the investments attributed to that technology. The decision-makers consider the choice of the technology structure of investment (in the old or/and new ones), as well as the rates and structure of the utilization of the production capacities of two technologies at the disposal.

The cap and trade policy of curbing GHG emissions is considered. It consists in endowing the countries participating in the agreements permits with the preassigned amounts of the GHG emissions and then allowing a trade in the permits. Countries having surplus of permits sell them to the countries which have deficits. Charging for the excessive GHG emissions forces the producers to convert from the cheaper but dirtier technologies to the more expensive but cleaner ones.

The foreign trade module in the model does not reflect the total Polish foreign trade, but only the trade associated with technology conversion and the trade in the emission permits. We admit though that such a separation is artificial, but it considerably simplifies the model.

In each model sector the two available technologies provide identical products, which can be destined for itself, other sectors and/or abroad. Whenever the balance of that exchange is positive, it means that there is a net export of that sector; if the balance is negative then there occurs a net import. Sector *M* produces intermediary inputs for all internal sectors, as well as for exchange on the international market. Sector *C* produces consumer goods for the consumption demand coming from both the internal consumption expenditures and the balance of the foreign exchange in consumer goods and services. Sector *I* produces investment goods and services for the other production sectors and itself, as well as for the foreign trade. Classification of the production sectors, determination of the fixed assets, and the technology parameters in each sector, has been performed on the basis of the Input–Output Table at Basic Prices in 2005 (Poland), Central Statistical Office (2005). (The input- output tables for Poland are also available for year 2010. We base our computation on those from 2005 because the use of these data requires considerable amount of processing, which includes division of capital assets between three sectors and estimation of the values of parameters. The mentioned processing has been performed for the data from 2005, while we plan updating after the feedback from the reviewers).

3. Model formulation

In this section the following notation of numbering the model parameters is used. The letter $i = M, C, I$, is used to denote the sector, the letter $j = 1, 2$, to denote technology, and the letter $t = 1, \ldots, T$, to denote the year. The numbering of years starts with the year 2005, so $t = 1$ corresponds to the year 2006.

Each technology of production in any sector is described by the following set of parameters:

γ_{ijt} - productivity of fixed assets in *i*-th sector, $i= M, C, I$; in *j*-th technology, $j=1, 2$; in year t, $t=1,..,T$;

δ_{ij} - depreciation rate of fixed assets in i-th sector, $i= M, C, I$; in j-th technology, j=1, 2; in year t, t=1,..,T;

α_{ijt} - share of intermediary use of goods produced in sector M in the gross output of i-th sector, $i= M, C, I$; in j-th technology, j=1, 2; in year t, t=1,..,T;

μ_{ij} - unit emission in i-th sector, $i= M, C, I$; in j-th technology, j=1, 2; in year t, t=1,..,T.

Potential gross output Q_{ijt} produced in i-th sector using j-th technology in year t equals:

$$Q_{ijt} = \gamma_{ijt} K_{ijt}, \quad i= M, C, I; j=1, 2; t=1,..,T, \tag{1}$$

where K_{ijt} stands for stock of the fixed assets in i-th sector and j-th technology at the beginning of year t. (Harrods production function). In this paper, the potential gross output (1) will be also called the production capacity of the j-th technology in i-th sector in year t.

Actual gross output X_{ijt} in i-th sector, $i= M, C, I$; in j-th technology, j=1, 2; in year t, t=1,..,T; accounts for the fact that production capacity may not be fully used:

$$X_{ijt} = \lambda_{ijt} Q_{ijt}, \quad i= M, C, I; j=1, 2; t=1,..,T, \tag{2}$$

where λ_{ijt} stands for coefficient of the production capacity utilization in i-th sector, $i= M, C, I$; in j-th technology, j=1, 2; in year t, assuming values from the range [0;1], in particular 0 indicates fully idle capital and 1 represents full utilization of the production capacity.

Total actual output of i-th sector is the sum of outputs produced using both technologies:

$$X_{it} = X_{i1t} + X_{i2t}, \quad i= M, C, I; t=1,..,T. \tag{3}$$

Stock of the fixed assets K_{ijt} in i-th sector, $i= M, C, I$; in j-th technology, j=1, 2; in year t, t=1,..,T; is given by the standard relationship:

$$K_{ijt} = K_{ijt-1} + I_{ijt-1} - \delta_{ijt} K_{ijt}, \quad i= M, C, I; j=1, 2; t=1,..,T, \tag{4}$$

where I_{ijt} denotes investment in i-th sector, $i= M, C, I$; in j-th technology, j=1, 2; in year t, t=1,..,T; and term $\delta_{ijt} K_{ijt}$ denotes depreciation of capital in i-th sector, $i= M, C, I$; in j-th technology, j=1, 2; in year t, t=1,..,T. One year lag between the investment and its contribution to the stock of fixed assets determining production capacity has been assumed for simplicity.

Production of i-th sector using j-th technology causes emission E_{ijt} of GHG:

$$E_{ijt} = \mu_{ijt} X_{ijt}, \quad i= M, C, I; j=1, 2; t=1,..,T, \tag{5}$$

We assume that the technical progress decreases the value of the emission coefficients with a constant ratio in each year.

Emission E_{it} of the i-th sector equals:

$$E_{it} = E_{i1t} + E_{i2t},\ i = M, C, I;\ j=1,\ 2;\ t=1,..,T, \tag{6}$$

and the total emission is given by the following expression:

$$E_t = E_{Mt} + E_{Ct} + E_{It},\ t=1,..,T, \tag{7}$$

We assume that there exist market equilibria in all three markets. So the demand for goods and services produced by sector M, i.e. their consumption in all sectors with added balance of the foreign trade equals domestic supply:

$$\alpha_{M1}X_{M1t} + \alpha_{M2}X_{M2t} + \alpha_{C1}X_{C1t} + \alpha_{C2}X_{C2t} + \alpha_{I1}X_{I1t} + \alpha_{I2}X_{I2t} + B_{Mt} = X_{M1t} + X_{M2t},\ t=1,..,T. \tag{8}$$

where $\alpha_{ijt} X_{ijt}$ denotes consumption of goods and services M in i-th sector, $i= M, C, I$; using j-th technology, j=1, 2; in year t, t=1,..,T; and B_{Mt} denotes the balance in foreign trade (export – import) in sector M in year t.

Demand for the goods and services supplied by sector I, being the sum of domestic demand and the balance of the foreign trade in goods and services I, equals domestic supply of these goods in all sectors:

$$I_{M1t} + I_{M2t} + I_{C1t} + I_{C2t} + I_{I1t} + I_{I2t} + B_{It} = X_{I1t} + X_{I2t},\qquad t=1,..,T; \tag{9}$$

where B_{It} denotes the balance in foreign trade (export-import) in sector I in year t.

Total income Y_t from sectors M, C and I is given in the following expression:

$$\begin{aligned} Y_t &= (1-\alpha_{M1})X_{M1t} + (1-\alpha_{M2})X_{M2t} + \\ &+ (1-\alpha_{C1})X_{C1t} + (1-\alpha_{C2})X_{C2t} + \\ &+ (1-\alpha_{I1})X_{I1t} + (1-\alpha_{I2})X_{I2t} \ . \end{aligned} \qquad t=1,..,T. \tag{10}$$

Disposable income Y_t^d is given in the following expression:

$$Y_t^d = Y_t - rD_t, \qquad t=1,..,T. \tag{11}$$

where rD_t is the payment of debt (if D_t positive, or an income from foreign assets if D_t negative); r denotes interest rate, while D_t stands for the debt at the beginning of year t.

National consumption demand C_t is given by the following expression:

$$C_t = Y_t^d - I_t \qquad t=1,..,T. \tag{12}$$

where total investment in all sectors I_t equals:

$$I_t = I_{M1t} + I_{M2t} + I_{C1t} + I_{C2t} + I_{I1t} + I_{I2t}\,. \tag{13}$$

Total demand for products of the sector C, namely the sum of the national consumption demand and the balance in the foreign trade in C:

$$C_t + B_{Ct} = X_{C1t} + X_{C2t}, \qquad t=1,..,T. \qquad (14)$$

Number of the emission permits being administered to the national economy is described by a trajectory of an assumed form in time, dependent on a number of the permits N_{t_d} in the destination year t_d:

$$N_t = f_N(t, N_{t_d}), \qquad t=1,..,T. \qquad (15)$$

In each year the trade in the emission permits gives the following net result V_t:

$$V_t = p_t(N_t - E_t), \qquad (16)$$

where p_t stands for the permission price in year t and N_t is the number of the emission permits administered to a given country. In the case of an excess in the emission permits, this is when

$$N_t - E_t > 0,$$

a country sells the surplus of the emission permits at price p_t, while in the case of deficit a country has to buy the lacking amount of emission permits at price p_t. Prices p_t are determined exogenously and are subject of the GHG curbing policy.

Debt D_t is defined by the following relationship:

$$D_t = D_{t-1} - (B_{Mt} + B_{Ct} + B_{It}) - p_t(N_t - E_t), \qquad t=1,..,T. \qquad (17)$$

Note that debt can be positive or negative; net import increases debt while the trade surplus decreases it. Note also that interest on debt affects the disposable income, as described by equation (11). Foreign debt is interpreted in this paper as a result of trade in the emission permits as well as products *M*, *C* and *I*. By assuming initial value $D_0 = 0$, we will attribute changed structure of the foreign trade to the process of technology conversion.

The decision variables are as follows: actual gross output from each technology in every sector, investment in each technology in every sector, net export or net import from/into each sector.

The model consists also of the following inequality constraints. The outputs and investment outlays are non-negative:

$$X_{M1t}, X_{M2t}, X_{C1t}, X_{C2t}, X_{I1t}, X_{I2t}, I_{M1t}, I_{M2t}, I_{C1t}, I_{C2t}, I_{I1t}, I_{I2t} \geq 0. \qquad (18)$$

Note that the balances of the foreign trade in products *M*, *C* and *I* can be either non-negative or non-positive, so that net exports $EXP_{i,j,t}$ and net imports $IMP_{i,j,t}$ are non-negative as a consequence of the relationship:

$$EXP_{Mt} = \begin{cases} B_{Mt}, & B_{Mt} \geq 0; \\ 0, & B_{Mt} < 0. \end{cases} \qquad i = M, C, I; j=1, 2; t=1, .. ,T, \qquad (19)$$

and

$$IMP_{Mt} = \begin{cases} 0, & B_{Mt} \geq 0; \\ -B_{Mt}, & B_{Mt} < 0. \end{cases} \tag{20}$$

On the basis of the above, we have

$$IMP_{M1t}, IMP_{M2t}, IMP_{C1t}, IMP_{C2t}, IMP_{I1t}, IMP_{I2t}, EXP_{M1t}, EXP_{M2t}, EXP_{C1t}, EXP_{C2t}, EXP_{I1t}, EXP_{I2t} \geq 0.$$

The following constraints make the technological conversion socially and politically feasible.

The constraint:

$$I_t \leq \alpha_{I/Y} Y_t, \tag{21}$$

prevents too high investment rates; coefficient $\alpha_{I/Y}$ denotes the highest acceptable investment rate.

The constraint in each sector:

$$-\alpha_{B_j/X_j} \leq \frac{B_{j,t}}{X_{j,t}} I_t \leq \alpha_{B_j/X_j},\ j = M, C, I; \tag{22}$$

imposes maximum share of foreign trade in the national supply of the given product, where coefficients α_{B_j/X_j} $i = M, C, I$; denote maximum share of net foreign exchange in given product in its national gross output.

Another two sets of constraints:

$$-r_{Ij}^{-} \leq \frac{I_{j,t} - I_{j,t-1}}{I_{j,t-1}} \leq r_{Ij}^{+}, \qquad j = M, C, I; \tag{23}$$

and

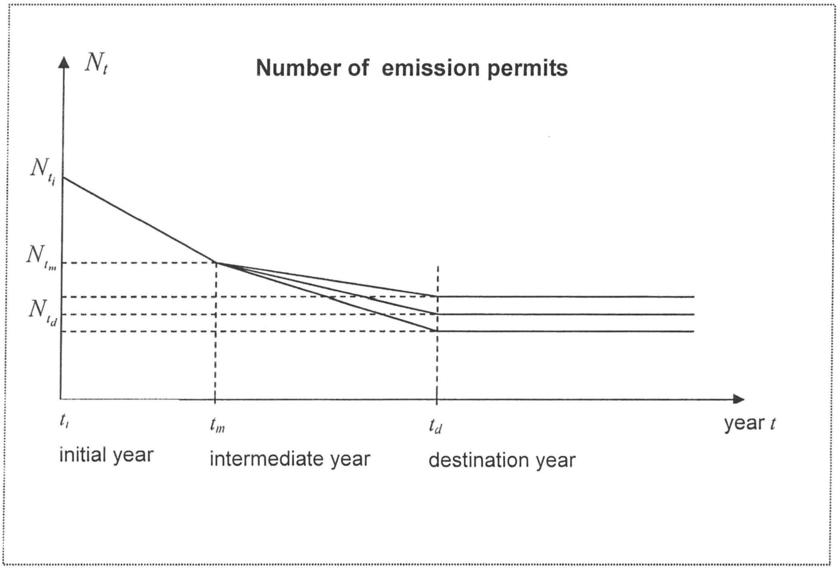
$$-r_{cons\,j}^{-} \leq \frac{C_t - C_{t-1}}{C_{t-1}} \leq r_{cons\,j}^{+},\ j = M, C, I; \tag{24}$$

limit relative increases and decreases of investments in sectors and total consumption, respectively.

The end-point constraint included into the model requires that the debt from year 2080 and beyond should be equal to zero, $D_t = 0$, t=2080, 2081, … ; determining completion of the process of adjustment till year 2080.

4. Assumed scenarios describing decrease of emission permits allotted to a country

The EC tends to decrease emissions of CO_2 by allotting to particular countries a diminishing number of the emission permits. Decrease of the permits in assumed time periods is discussed and negotiated first and then finally written down in EC regulations. We try to analyze an impact of the EC policies on the economic growth of Poland, assuming a given form of scenario describing decreasing emission permits allotted to the country. Let us notice that the model provides for possible trade of the permits. Therefore the GHG emission in particular years can differ from the number of permits defined in the scenario.



Source: own design

Fig. 1. Alternative scenarios of emission permits

Exemplary trajectories presenting a decreasing number of the emission permits in time are shown in Fig. 1. The number of the emission permits N_{t_i} in the initial year t_i is given. The initial year t_i corresponds to the year 2005. It is also assumed that the number of the emission permits N_{t_m} in the intermediate year t_m (t_m=2020) is fixed, but the number of the permits $N_{t_d} < N_{t_m}$, in the destination year t_d (t_d=2050) is a free variable. However, we assume that the number of permits in the intermediate year t_m is a parameter. Different values of the parameter can be assumed for different analyzed scenarios. The linear decrease of the emission permits numbers is assumed for the periods $[t_i, t_m]$, $[t_m, t_d]$ and $t > t_d$, i. e.:

$$N_t = \begin{cases} N_{t_i} - t \cdot \left(N_{t_i} - N_{t_m}\right) / \left(t_i - t_m\right), & t \in (t_i, t_m]; \\ N_{t_d} - t \cdot \left(N_{t_m} - N_{t_d}\right) / \left(t_m - t_d\right), & t \in (t_m, t_d]; \\ N_{t_d}, & t > t_d. \end{cases} \quad (25)$$

The multicriteria analysis has been applied. Two criteria are taken into account. The first, which is the discounted consumption (representing effects of the economic growth of the country) is maximized. The second (which is the number of the permits in the destination year representing the EC policy) is minimized. Then, the resulting slope of the emission trajectory in the second period is determined in the optimization process.

5. Multicriteria optimization

As mentioned earlier, the optimization problem is formulated for two conflicting criteria: the discounted consumption is to be maximized and the number of permits in the destination year is to be minimized.

The model relation can be described by a set of linear constraints of the form:

$$A\,x^{\mathrm{T}} \leq b, \quad (26)$$

where x is a vector of decision variables, A is a matrix, and b is a vector of coefficients respectively.

The vector x of decision variables includes production (gross output), investments, imports and exports in the case of the three sectors and the two technologies defined in the model description, all for the years t=1,..,T:

$$x = (X_{M1t}, X_{M2t}, X_{C1t}, X_{C2t}, X_{I1t}, X_{I2t}, I_{M1t}, I_{M2t}, I_{C1t}, I_{C2t}, I_{I1t}, I_{I2t},$$
$$IMP_{M1t}, IMP_{M2t}, IMP_{C1t}, IMP_{C2t}, IMP_{I1t}, IMP_{I2t}, EXP_{M1t}, EXP_{M2t}, EXP_{C1t}, EXP_{C2t}, EXP_{I1t}, EXP_{I2t}). \quad (27)$$

Let $y(x) = (y_1(x),\ y_2(x))$ denote a vector of the criteria, which are dependent on the vector of decision variables x by the model relations, y_1 is the discounted consumption, y_2 is the number of the emission permits in the destination year. The criteria y_i, i=1,2, are calculated according to the linear relations:

$$y_i = c_i\, x, \quad (28)$$

where c_i i=1,2 are vectors of coefficients.

The criteria are conflicting. We deal with the multicriteria optimization problem in which we look for the decision variables satisfying the constraints, maximizing y_1 and minimizing y_2 jointly. The problem is considered in two spaces: in the space of decision variables and in the space of criteria. The model constraints define a set of admissible values of the decision variables in the first space. We denote the set by $\boldsymbol{X}_0$. In the second two-dimensional space there exists a set of attainable values of the criteria (outcomes). We denote it by $\boldsymbol{Y}_0$. According to the theory of multicriteria optimization, we look for decision variables leading to the nondominated (Pareto optimal) points in the set $\boldsymbol{Y}_0$. In this case a point (y_1, y_2) is nondominated in the set $\boldsymbol{Y}_0$ if there is no other point in this set improving jointly the both criteria.

The domination relation is introduced in the space $\mathbf{R}^2$ of criteria (y_1, y_2). We say that a vector $y=(y_1, y_2)$ **dominates** a vector $v=(v_1, v_2)$, where $y, v\in\mathbf{R}^2$, if $y_1 \geq v_1$ and $y_2 \leq v_2$ and $y \neq v$. A vector $y=(y_1, y_2)$ **strictly dominates** a vector $v=(v_1, v_2)$, where $y, v\in\mathbf{R}^2$, if $y_1>v_1$ and $y_2<v_2$. The domination relation defines partial ordering in the criteria space, which is not a linear ordering. Therefore, it is important to emphasize that in this case the traditional optimality concept defined for one criterion are not valid.

We say that a vector y is **Pareto optimal (nondominated)** in the set Y_0, if $y\in Y_0$ and there is no $v\in Y_0$ dominating the vector y. A vector y is **weakly Pareto optimal (weakly nondominated)** in the set Y_0, if $y\in Y_0$ and there is no $v\in Y_0$ strictly dominating the vector y.

In our case the set Y_0 is not given explicitly. Particular points of the set can be found by computer simulations. In general, there is a set of the Pareto optimal points in $\boldsymbol{Y}_0$ and the corresponding decision variables in $\boldsymbol{X}_0$. This set should be derived and analysed.

The analysis of possible Pareto optimal outcomes is made by applying the reference point approach developed by Wierzbicki (Wierzbicki, 1986), (Wierzbicki at al., 2000) with the use of the order approximation achievement functions. According to this approach, reference points in the criteria space are assumed by a system analyst and then the computer-based system generates respective outcomes which are Pareto optimal in the set of attainable outcomes. Assuming some number of the reference points, a representation of the Pareto frontier can be obtained.

Outcomes characterizing the Pareto frontier are derived by:

$$\max_{x\in X_0}[s(y(x), y^*)] \tag{29}$$

where:

x - a vector of decision variables,

X_0 - a set of admissible decisions defined by the model relations,

$y(x)=(y_1(x), y_2(x))$ - vector of the criteria, which are dependent on the vector of decision variables x through the model relations, y_1 is the present value of consumption, y_2 is the number of the emission permits in the destination year t_d,

$y^*=(y_1^*, y_2^*)$ - a reference point assumed in the space $\mathbf{R}^2$ of the criteria y_1 and y_2,

$s(y,y^*)$ - an order approximating achievement function.

The function

$$s(y, y^*)= \min [\alpha_1(y_1-y^*_1), \alpha_2(y^*_2-y_2)]+ \varepsilon [\alpha_1(y_1-y^*_1)+ \alpha_2(y^*_2-y_2)], \tag{30}$$

is an example of an achievement function suitable in this case, where $y^*\in\mathbf{R}^2$ is a reference (aspiration) point, α_i, $i=1, 2$, are scaling coefficients, and $\varepsilon>0$ is a small parameter.

In the considered case, the optimization problem (29) can be reformulated with use of additional variables z, z_1, $z_2\in\mathbf{R}$ as follows:

$$\max z + \varepsilon \sum_{k=1,2} z_k \,, \tag{31}$$

subject to the constraints of the reference point method:

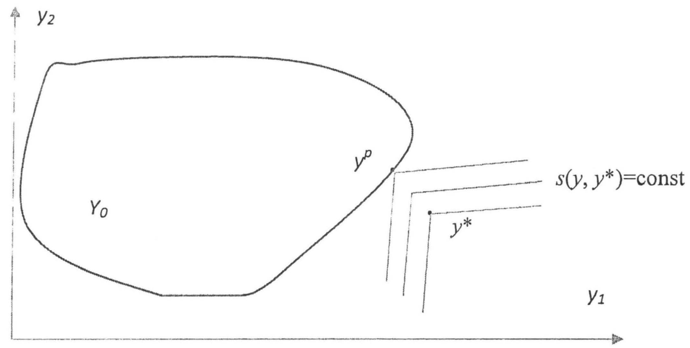
$$\begin{aligned} & z \le z_k, k = 1,2, \\ & z_1 \le (y_1(x) - y_1^*)/(y_1^{up} - y_1^*), \\ & z_2 \le (y_2^* - y_2(x))/(y_2^* - y_2^{lo}), \end{aligned}$$

and the constraints of admissible values of the decision variables x:

$$A\,x \le b,$$

where z, z_1, z_2, x denote variables, y_1^{up}, y_2^{lo} are assumed values dominating attainable values y_1 and y_2, respectively.

The optimization problem (31) has a linear form and can be solved by a linear optimization solver.



Source: own design

Fig. 2. Derivation of the Pareto optimal point y^p by the reference point method for an assumed reference point y^*.

The reference point method is illustrated in Fig. 2. A hypothetical set of attainable payoffs Y_0 is presented in the space of criteria y_1, y_2. In fact it is not known explicitly. A system analyst assumes a reference point y^* in the space. The point can be inside or outside the set. The corresponding Pareto optimal point y^p is derived by solving the optimization problem (30). Sets of point are presented, for which the achievement function $s(y, y^*)$ are constant. The system analyst can assume another reference point, solve again the problem (30) and obtain next Pareto optimal point. In such an interactive way a representation of the Pareto frontier of the unknown set Y_0 can be obtained.

6. Results of multicriteria analysis

The computer simulations relate to the case of Poland, starting from the initial year 2005. In the simulation experiments we used a property of the model which is, that after initial disturbances caused by the technology conversion, the model attains an equilibrium paths with fixed proportions of the sectors' output and fixed assets, and with the growth rate equal to the growth rate of the productivity of capital, which is assumed to be equal 0.5 percent per year. The further increase of the capital productivity is solely caused by the technical progress accounted for in the model.

The initial number of permits allotted to Poland was 78,5 mln ton of CO_2 in 2005. The emission permit scenario has been assumed to have the shape presented in Fig. 1. The intermediate year and the destination year are 2020 and 2050, respectively. The number of permits in the intermediate year has been assumed as 94% of the initial number. The number of permits in the destination year is not fixed. It is a variable and (at the same time) it is a criterion in the multicriteria optimization which is minimized. The value of the discounted consumption in the full period of time is the another criterion which is maximized. The selected results of multicriteria analysis are presented in Table 1 and in Fig. 2. For different aspiration points assumed in the space of these two criteria, the respective nondominated points have been obtained. The aspiration points are represented in Fig. 2 by small triangles, while the nondominated points by rhombs.

The nondominated points derived for the assumed aspiration points are indicated by arrows. A representation of the set of the nondominated outcomes (Pareto frontier) in Y_0 has been obtained. It means that outcomes located on the right hand side and below in comparison with the outcomes at the Pareto frontier are unattainable, i.e. they do not belong to the set Y_0.

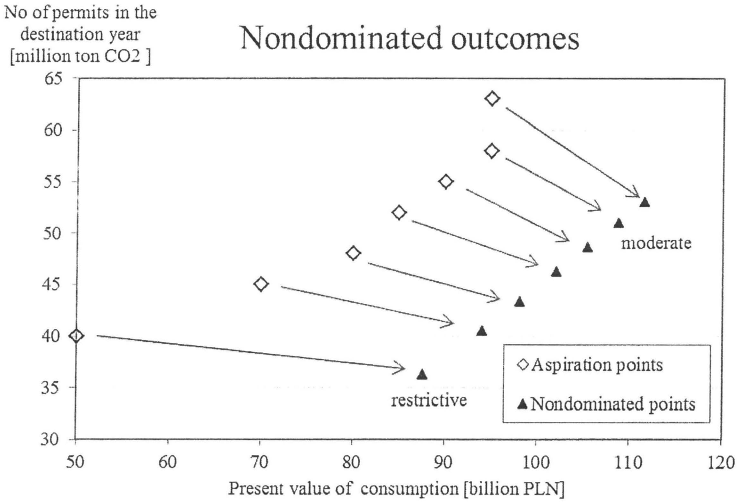
The corresponding values of all the decision variables have been obtained for all the presented outcomes. Two sets of them (variant 2 and 7) are discussed in detail.

The variant 2 relates to the maximum possible decrease of the number of the emission permits in the destination year. In this case the model constraint of the lowest acceptable consumption is active. It is called the restrictive variant. It relates to the solution of the single criterion optimization problem with minimization of the emission permits number in the destination year.

Table 1. Selected results of the multicriteria analysis.

Variant number	Aspiration points		Calculated nondominated points	
	Discounted consumption [10^12 PLN]	No of permits in the destination year [10^6 ton CO_2]	Discounted consumption [10^12 PLN]	No of permits in the destination year [10^6 ton CO_2]
1	95,00	63,00	111,59	53,04
2	50,00	40,00	87,67	36,23
3	70,00	45,00	94,11	40,48
4	80,00	48,00	98,14	43,34
5	85,00	52,00	102,13	46,20
6	90,00	55,00	105,42	48,58
7	95,00	58,00	108,76	50,99

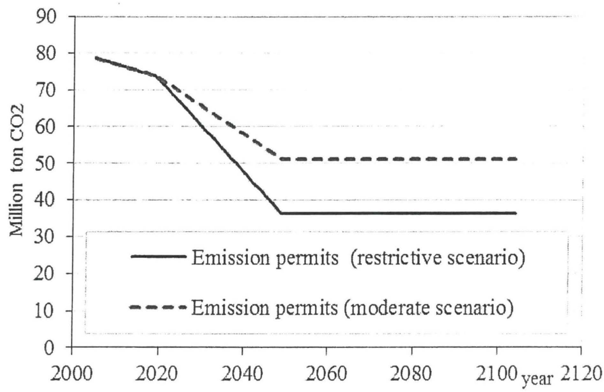
Source: own calculations



Source: own calculations

Fig. 2. Results of the interactive multicriteria analysis

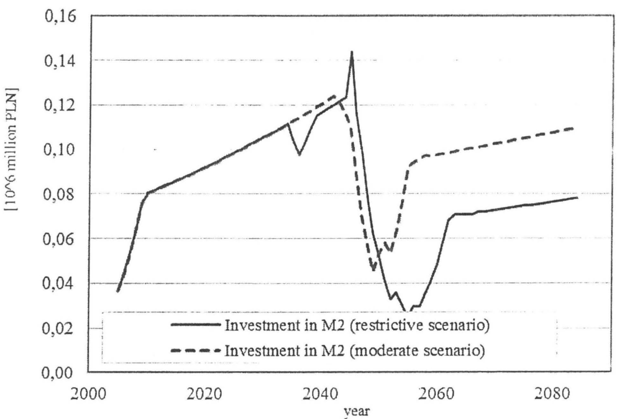
The time profiles of the emission permits for the two scenarios are presented in Fig. 3.



Source: own calculations

Fig. 3. Assigned quantities of the emission permits in the moderate and restrictive scenarios, million ton CO_2.

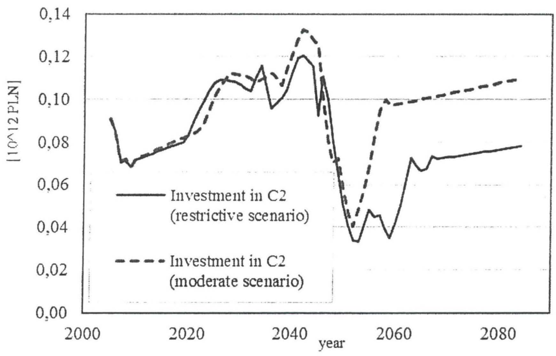
The detailed results are presented in the following figures: Fig. 4 through Fig. 22.



Source: own calculations

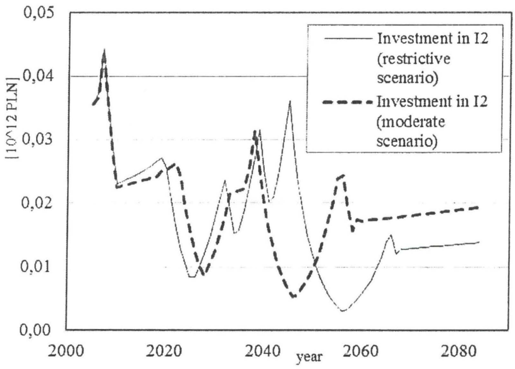
Fig. 4. Investments in sector *M* in the moderate and restrictive scenarios.

The variant 7 is called the moderate one. It relates to a moderate decrease of the number of permits in the destination year, which corresponds to the scenario assuming decrease of allotted emission permits with a moderately slow rate. The variant 2, called the restrictive, represents the greatest decrease of the emission permits for the destination year.



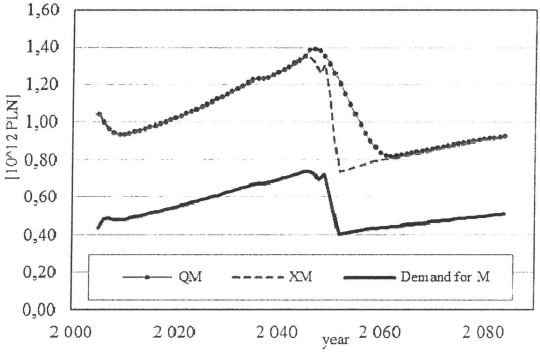
Source: own calculations

Fig. 5. Investments in sector *C* in the moderate and restrictive scenarios.



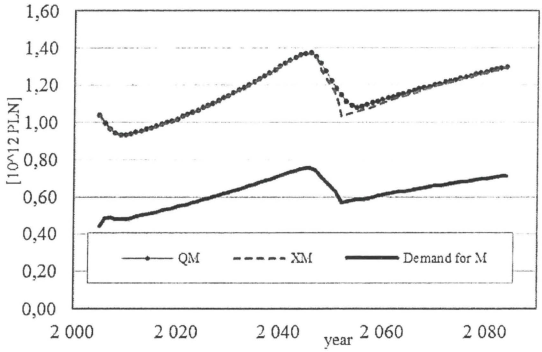
Source: own calculations

Fig. 6. Investment in sector *I* in the moderate and restrictive scenarios.



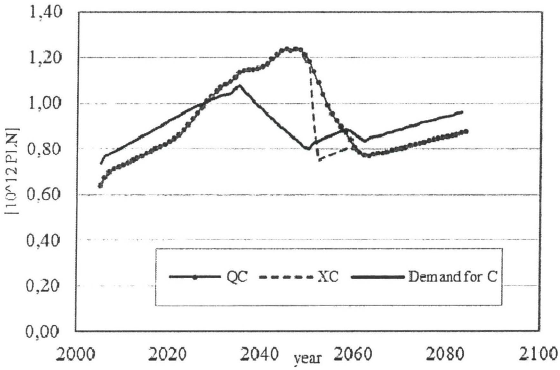
Source: own calculations

Fig. 7a. Production capacity *QM*, actual gross output *XM* and domestic demand in sector *M*, restrictive scenario.



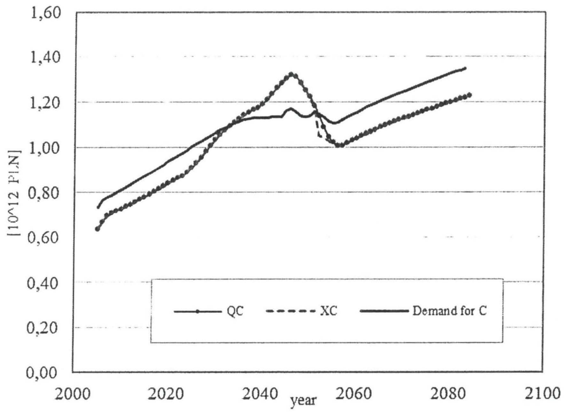
Source: own calculations

Fig. 7b. Production capacity *QM*, gross output *XM* and domestic demand in sector *M*, moderate scenario.



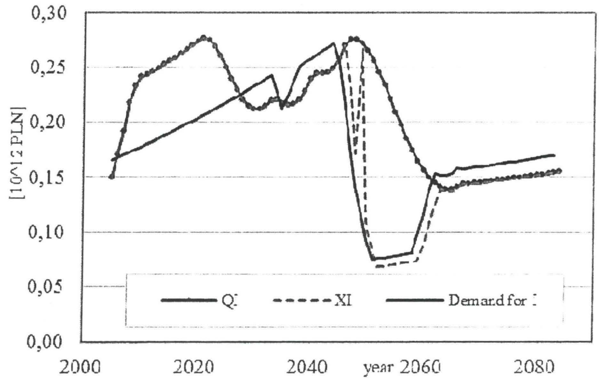
Source: own calculations

Fig. 8a. Production capacity *QC*, gross output *XC* and domestic demand in sector *C*, restrictive scenario.



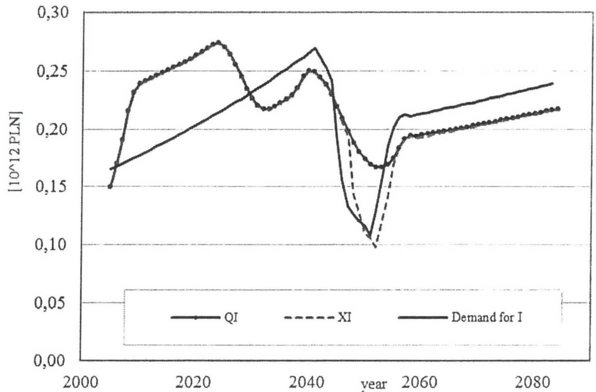
Source: own calculations

Fig. 8b. Production capacity *QC*, gross output *XC* and domestic demand in sector *C*, moderate scenario.



Source: own calculations

Fig. 9a. Production capacity *QI*, gross output *XI* and domestic demand in sector *I*, restrictive scenario.



Source: own calculations

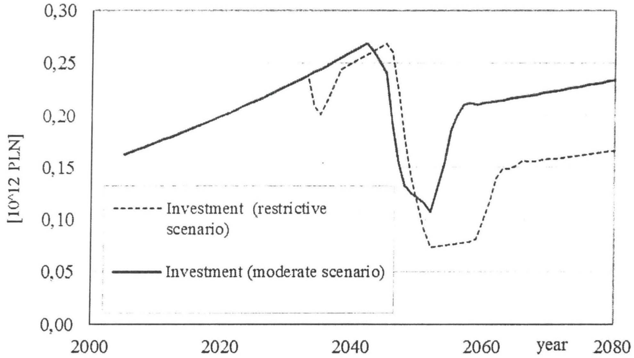
Fig. 9b. Production capacity *QI*, gross output *XI* and domestic demand in sector *I*, moderate scenario.

Investment is used here as the significant indicator of the economic activity. Investment in the three sectors in both scenarios are presented in figures Fig. 4, Fig. 5 and Fig. 6. It can be noticed in these figures that in both scenarios investment follow similar pattern. The initial increase od investment in sectors *M* and *I* is accompanied by the drop in the investment in sector *C*. After that initial adjustment the investment activity is high in all sectors in relation to that, which is achieved in the last period. An important feature of the investment development is that under given assumptions the new technology is being chosen immediately in all three sectors (with only incidental occurrences). It will be shown later that the share of output from the old technology monotonically decreases in all sectors.

Figures Fig. 7a – Fig. 9b present the production capacity *QM*, actual gross output *XM* and domestic demand in sectors *M*, *C* and *I* in the restrictive and moderate scenarios.

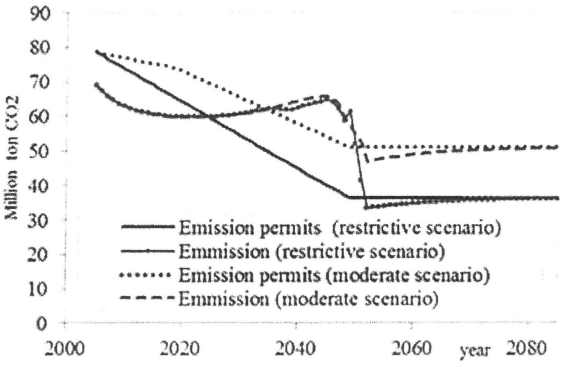
It can be noticed in figures Fig. 7a trough Fig. 9b that the recession during the second phase is much deeper in the recessive scenario with remarkable deterioration of the production capacity utilization.

Comparison of total investment in both scenarios is presented in Fig. 10.



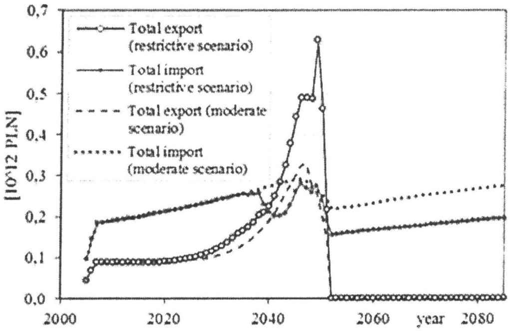
Source: own calculations

Fig. 10. Total investment in the restrictive and moderate scenarios.



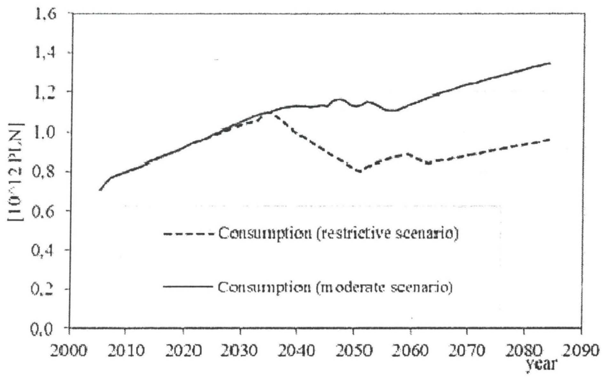
Source: own calculations

Fig. 11. Emission and emission permits in the restrictive and moderate scenarios.



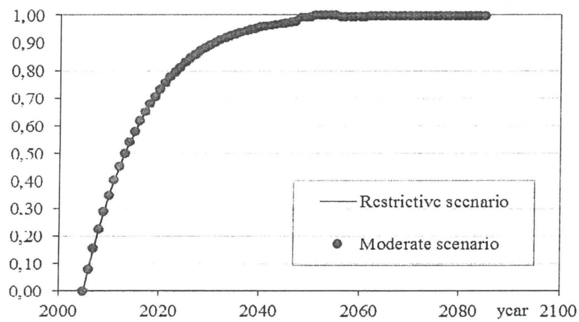
Source: own calculations

Fig. 12. Exports and imports in the moderate and restrictive scenarios.



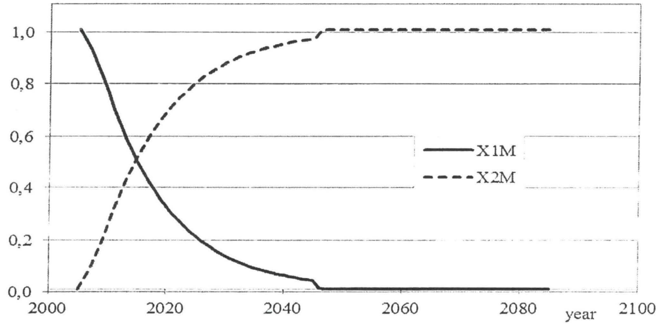
Source: own calculations

Fig. 13. Consumption in the moderate and restrictive scenarios.



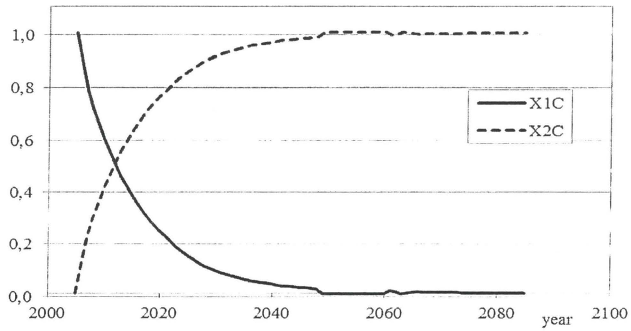
Source: own calculations

Fig. 14. Shares of new technologies in gross output, restrictive and moderate scenarios



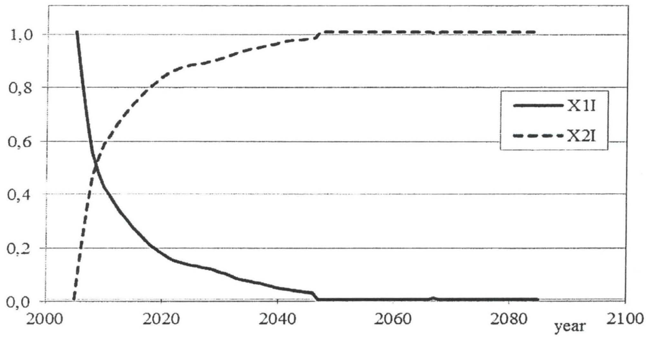
Source: own calculations

Fig. 15. Share of new technology in the gross output in the sector *M*, restrictive scenario.



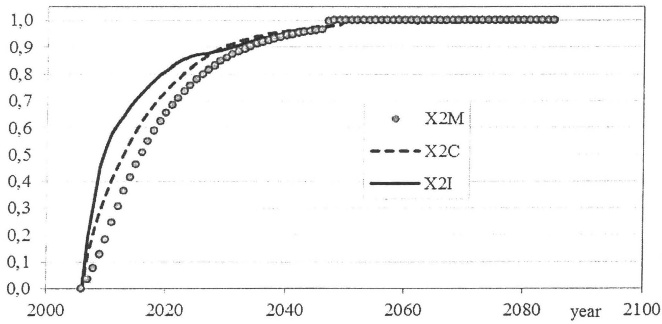
Source: own calculations

Fig. 16. Share of new technology in the gross output in the sector *C*, restrictive scenario.



Source: own calculations

Fig. 17. Share of new technology in the gross output in the sector *I*, restrictive scenario.



Source: own calculations

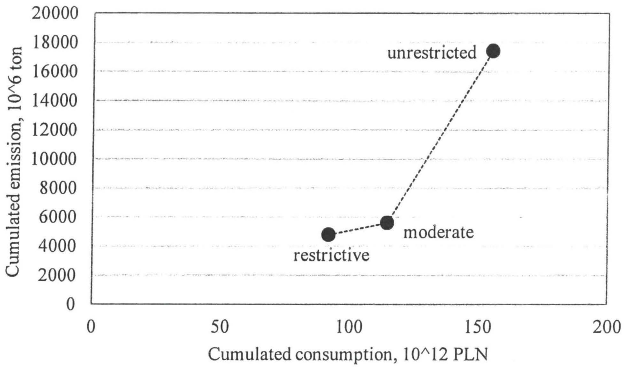
Fig. 18. Shares of the sectorial gross output from the new technology in the gross outputs of the sectors, restrictive scenario.

5. Discussion of the results

Without restrictions concerning GHG emissions the economy described by the model develops using existing emission intensive technology along the equilibrium path determined by certain historically established growth rate, with fixed proportions between sectors determined by the technology parameters and the growth rate. Conditions for development change with the imposition of the emission limits and trade in emission permits.

The reference point method of the multicriteria optimization enabled to derive certain number of solutions, which are Pareto optimal with respect to the discounted consumption being maximized and the number of the emission permits being minimized in the destination year. Comparison of these solutions make it possible to analyze relations between feasible decrease of the emissions and resulting decrease of the consumption. The whole set of the model variables has been determined for each solution.

The results presented in Fig. 19 show that decrease of emission can be achieved only at the cost of diminished consumption. The point marked as "unrestricted" has been determined on the assumption that the economic development would be continued at the historical rate of growth without any restrictions concerning GHG emissions. The further presentation will be focused on two scenarios: the restrictive and moderate one. They were selected from the set of the Pareto optimal solutions.



Source: own calculations

Fig. 19. Cumulated consumption and emission in the years 2006-2085 in three variants of emission curbing policy.

The common feature of the simulation results of the two considered scenarios is the immediate technology conversion from the cheaper to the more expensive, but cleaner one, see Figures 4 – 6. However, high prices of the emission permits are the necessary condition for the prompt technology conversion. Preliminary simulations assuming constant and low prices of the emission permits showed that the economic agents were insufficiently stimulated for the technology change. Without the price stimulus, the technology conversion starts later (about 20 years) or even may not occur.

Another similarity of the results of both the restrictive and moderate scenarios is a comparable speed of conversion, Fig. 18 and Fig. 19, Fig. 20, Fig. 21, presenting advancement of the technology substitution at the macro as well as the sectorial levels. As shown in Fig. 18, the speed of the above mentioned substitution is similar in both scenarios. This is why Fig. 19, Fig. 20 and Fig. 21 relate to the restrictive scenario only. On the other hand, the most distinguishing feature is the final level of consumption. Much lower level of emission has been achieved at the cost of stagnant and considerably lower consumption in the restrictive scenario.

Simulation results show that in both cases three phases of the economic development can be distinguished. In the first phase which lasts till year 2040, the economy keeps growing, using the surplus of the emission permits for creating production capacities based on the new technology in all sectors. The surplus of the emission permits is consumed at the second part of the first phase and the deficit of the emission permits occurs. In this phase all three sectors use both production technologies. In both scenarios sector M sells about half of its output abroad during all three phases of development. In the first phase national demand for products C exceeds production capacities of sector C, so that the deficit is covered by imports. During this phase production capacities of the sector I exceed the national demand for products I and the deficit is imported. In both scenarios consumption in the first phase increases at comparable rates.

In the second phase, approximately between year 2040 and 2060, the main adjustment occurs; sectors cease using the old technology, so that in the third phase only capacities based on the new technologies are used in all sectors. There appear discrepancies between the production capacities and their utilization in all sectors. Theses divergences are much bigger in the restrictive scenario and are accompanied by volatility of investment. The demand for products M decreases due to abandoning of the new technology in all sectors. In the second phase the national demand for products C is lower than the production capacities in sector C and the surplus is directed for export. In this phase the national demand for products I exceeds the production capacity of sector I so that the deficit is being compensated by imports, however, sector *I* reduces overall production capacities and output; the latter proceeding faster. During the first and second phases both total import and total export occur supporting the transformation (import exceeding export). During this phase emission drops below the amount of the emission permits and starts converging to the latter; this process continues also in the next phase. In the second phase trajectories of consumption in two scenarios start diverging; while in the moderate one consumption stagnates, in the restrictive scenario consumption slightly decreases. In both scenarios during the second phase the economy suffers deep recession; the drop of output in all three sectors is accompanied by the deep decrease of consumption, while in the moderate scenario one can observe stagnation followed by steady growth in the third phase.

During the third phase the national demand for products *I* exceeds production capacities and the excessive demand is met by respective imports. In the third phase the economy grows along the steady equilibrium path. The equilibrium growth in this period is based on the technical progress, which by assumption causes decrease of the unit emission coefficients by half percent per year. In the third phase total net export drops to zero, while the net import persist being compensated by excess of the emission permits over the actual emission. During the third phase consumption in both scenarios increases at steady growth rate, however at significantly different levels; that from the moderate scenario is considerably greater.

General remarks concerning simulation results are as follows. Too restrictive decrease of the quantity of the emission permits causes recession and then lasting stagnation. In terms of consumption, Fig. 16, the economy at the end of the analyzed period is not able to arrive at the highest consumption level achieved in the first phase. Another negative effect is the loss of the resources due to the lowered utilization of the production capacities during the second phase. In the moderate scenario the third phase of development begins earlier.

The rate of adjustment of the sectorial structure is depicted in Fig. 21 presenting advancement of the new technologies in particular sectors in the restrictive scenario (results for two scenarios are similar). It can be noticed that at the very beginning the fastest progress in introducing new technology occurs in the sector *I*, then in sectors *C* and *M*, but in the last phase of transformation this process slows down in the sector *I*.

It should be noted that in both scenarios the debt remains at the zero level. As to the constraints related to emission, the emission permits are bought in both scenarios in the first and second phases, while in the third phase emission converges to the terminal number of permits from beneath, and the trading surplus of the emission permits is used to compensate for the imports of goods and services *C* and *I*.

The economy of a country develops with the long term growth rate using existing emission intensive technology in all production sectors until the time of implementing greenhouse gases curbing policy when producers are allotted tradable emission permits, which can be sold when they are in excess or purchased when they are in shortage. This forces producers to exchange the old emission intensive technologies for the cleaner but more expensive ones, or to buy more permits on the market. Available measures consist of switching technologies, adjustment of the production and/or the fixed assets structure, and in the meantime using the foreign trade as means of balancing trade in emission permits as well as exports and imports of goods and services. In this process producers use fixed assets associated with both technologies; full utilization of the production capacities is not assumed.

6. Final remarks

Presented results are a part of the research aimed at the development of a tool for the computer aided decision making concerning reduction of the gaseous pollution and supporting economic growth. This tool is planned to serve for preparations for or during the negotiations concerning amounts of the emission permits allotted to Poland. This research includes: construction of a macroeconomic model with criteria related to the policies of CO_2 emission reduction on the one hand and economic growth of a country on the other hand; implementation of the model in the form of a computational algorithm; implementation of an interactive mechanism of multicriteria optimization; computer experiments. In this stage an experimental, testing version of the tool has been realized. The initial version of the model of Polish economy has been constructed, implemented in the form of the algorithm, the mechanism of multicriteria optimization has been introduced based on the reference point method, some number of simulation experiments have been done.

The model describes the small economy exemplified by the Polish economy and focuses on presenting two different points of view: that of the EU Commission tending to limit GHG emissions and that of the small country trying to maintain the highest possible growth rate. It consists of three production sectors producing the intermediary, consumer and investment goods. It enables the analysis of the trade-off problem between two competing goals: the sustainable economic growth and reduction of the gaseous pollution, as well as changes of the sectorial structure of investment and output. It also makes it possible to assess the cost of the reduction of the gaseous emissions in terms of the consumption lost.

The multicriteria optimization problem has been solved using the reference point approach. The elaborated computer system enables generation of the Pareto optimal solutions in an interactive way. Assuming and assigning different reference values for the criteria and solving the resulting optimization problems, different Pareto optimal outcomes and decision variables have been derived, compared and analyzed.

The multicriteria optimization approach has proved to be effective in the analysis concerning: consequences of the enforced emission limits for the economic development process of the economic transformation due to adjustment of the national economy to the EU policy limiting emission CO_2. The trajectories presenting the technological conversion are derived for all seven Pareto optimum solutions obtained from the computer simulations. The comparison of different trajectories generated with different Pareto optimal solutions enables an analysis of the impact of various emission limits on the economic development. Two Pareto optimum solutions have been chosen for presentation and discussion.

The results of the simulation experiments show idealized technological conversion and economic adjustment. This idealization is an effect of two elements: assumed simplifications as well as assumed optimal behavior disregarding the feasibility of implementing the economic policy tools.

The simulation experiments based on two significantly different scenarios imply that during the economic adjustment one can distinguish three phases. The first phase is the one continuing fast growth with the buildup of the production capacities in all sectors. During the second phase all sectors reduce production capacities based on the older technology, while during the third phase economy achieves the steady structure determined by the new technology and the technical progress, that means that the economy grows along the steady equilibrium path, due to the assumed technical progress. It should be indicated that during the second phase the largest changes take place, which could cause social and political strains. Another important conclusion from the simulation experiments is that the effective desired change of the production technology to the cleaner one strongly depends on the price level of the emission permits.

In further research it seems reasonable to extend the analysis by adding third technology in each sector; the cleanest, however the most volatile, unpredictable and expensive (for example based on the renewable resources). We also consider application of the multicriteria game approaches developed by Kruś (2011, 2008), Kruś, Bronisz (2000) in supporting negotiations concerning allotment of the GHG emission permits.

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