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A multicriteria model for analyzing the impact of EU GHG limiting policies on economic growth: The case of Poland*

by

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Abstract: In this study, a macroeconomic model and the multicriteria approach are used to analyze the impact of the enforced greenhouse gas (GHG) emission limits on economic development and future consumption in a small open economy country, like Poland. The following questions are considered: how economic transformation, connected with adjustment of the national economy to the policy limiting GHG emission would proceed? what may be the consequences of the enforced emission limits for the economic development and future consumption?

The model answers these questions by presenting time trajectories, describing the evolution of three sectors, which influence GHG emission, namely those producing intermediary inputs, consumer goods, and investment goods. The sectors interact via markets of the relevant goods. The model takes into account the inertial behavior of the large-scale dynamic system, as well as social and political resistance to changes. It also indicates technological changes in the form of time-varying shares of two technologies, namely the GHG emission intensive and the GHG emission avoiding ones.

Two competing objectives are considered in the multicriteria analysis, i.e. maximization of consumption and minimization of GHG emission. The costs of pursuing the GHG limiting policy are assessed in terms of lost consumption. The multicriteria analysis is performed with the use of the derived representation of the Pareto optimal outcomes.

Computational results are presented for the case of Poland. They show three phases in a transition period, early growth on the basis of existing assets in the initial years, a depression phase, where technological changes mainly occur, and a period of renewed growth. They are followed by a steady development under new emission conditions.

Keywords: greenhouse gases, curbing emissions, government policy, multicriteria optimization, technological change, economic growth

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1. Introduction

The main purpose of the analysis presented in this study is to assess how decreasing the amount of national greenhouse gas (GHG) emission permits, assigned to a given economy, influences its economic development. Following the concern about the rising earth temperature, global macroeconomic models incorporating GHG emission impacts on the economy were constructed, like Global2010 (Manne & Richels, 1992), or DICE (Nordhaus, 1994; Nordhaus & Boyer, 1999). These early modelling efforts focused mainly on discussions of temperature rise magnitude, the losses induced by it, and costs of abatement, see also Stern (2007). More recently, climate stabilization policies have been the subject of many research projects, based on modeling, see presentations, reviews and comparisons published as the results of such projects, like, e.g., ADAM (Edenhofer et al., 2010), AMPERE (Kriegler et al., 2015), CLIMSAVEC (Harrison et al., 2015), EMF-27 (Kriegler et al., 2014), or RECIPE (Luderer et al., 2012). The models developed within such projects usually attempt to answer global or regional questions, pertaining to the stabilization issues, taking into account a broad set of components influencing climate change, in particular those arising from human activities and energy mix portfolio, see, e.g., Eom et al. (2015). Little has been published on optimization of national pathways to reach the emission limitation targets, as the main focus was put there on global scenarios, like in Riahi et al. (2007), Krey et al. (2014).

Concerning national studies, Manne & Richards (2004) used MERGE model (Manne et al., 1995) to investigate the impact of US decision to reject the Kyoto Protocol. But their main focus was on assessing how this decision would affect the compliance costs of other Annex B countries. Maksimov & Rozenberg (2015) considered what they called optimization results for Russia, computed with the MERGE model modified by IIASA (Maksimov et al., 2006). However, their paper presents only the comparison of results obtained for six scenarios of Russia's economic development that were set by different bodies or assumed by the authors. No optimization in the continuous set of policies was considered, as is done in our study.

In the discussion of methodological approaches, the agent based modeling, see, e.g., Niamir et al. (2018), is worth to be mentioned. This new and promising paradigm presents a bottom-up approach to assessing the GHG-limitation impact on transition to low carbon economy. It requires many detailed information on individual behaviors and still needs more research to establish its practical usefulness.

An analysis of the impact of the imposed limits of GHG emissions on Polish economy has been attempted by Antoszewski et al. (2015), and Bukowski & Kowal (2010), using models based on the Walrasian general equilibrium theory. In these models, economic development is shaped by taxes, interest rate and subsidies. However, the influence of the decreasing emission allowances on the economic development is not explicitly taken into account there, unlike the active constraint used in our model. In their approach, the firms and other agents at the micro level, maximize profits and operate in the economic environment under the conditions of perfect or monopoly competition. The Cobb-Douglas or CES neoclassical production functions are used to describe production processes. Hence, production technologies in the sectors are not differentiated and there is close to perfect substitution of the capital and labor. Consequently, some basic assumptions of these models are partly inappropriate, as the firms, particularly in the energy sector, quite often operate in the monopoly markets, for which the assumptions of the neoclassical production functions are inadequate.

This study presents a different approach. An optimization of the pathway for Poland is discussed using a macroeconomic three-sector optimization model of the national economy. The model is developed to support the analysis of the impact of the EU GHG emission limiting policies, with decreasing quantities of the free emission allowances, on the economic growth of a small country economy. Both allocation and trading of the emission allowances are considered. The multicriteria optimization is used to harmonize two conflicting objectives: (i) a possibly high rate of development of the national economy, (ii) decrease of the GHG emission according to the climate change postulates. Hence, two criteria are formulated: (i) the discounted consumption, to be maximized, and (ii) the number of emission permits in the predetermined destination year 2050, to be minimized. The decision variables, including investments in technologies in all sectors of the economy, foreign trade, emissions in the sectors, and output quantities of the model, are determined by optimization. Owing to this, the here presented multicriteria model can be considered as a useful tool in the stage of preliminary analysis, which can precede the discussion and negotiation of the GHG emission limits, and the numerical results can serve as a support for better conceiving and planning the real life economic policy.

Modelling always introduces different simplifying assumptions and our work is not free from that. However, notwithstanding these necessary simplifications, we find it worthwhile to propose a complementary approach to that based on the general equilibrium theory in order to shed light on effects difficult to obtain when using other models. Considering the rather skeptical comments on CGE approaches by Stern (2016), one can conclude that different modeling paradigms seem to be worth of investigation.

The here presented macroeconomic model evolved from the previous versions of the model as presented by Gadomski & Nahorski (2011). The research undertaken was inspired by the previous papers, dealing with models for analyzing the GHG emission impacts and climate policy effects, like Pizer (1994) or Keller et al. (2004). As one of several distinctions, in comparison to the cited papers, the model presented in this paper aims at the multicriteria analysis of the problem. The multicriteria optimization approach, applied in this study, uses the reference point methodology, developed by Wierzbicki (1986), as well as the multicriteria decision support, discussed in the papers by Wierzbicki et al. (2000), Kruś & Bronisz (2000), and Kruś (2011).

Our aim is also to investigate the usefulness of optimization models in the analysis of links between the economic and environmental systems. Multicriteria approach enriches this analysis. A conclusion from our analysis is also that the desired technology conversion depends largely on the determination to introduce and maintain the high prices of the emission permits.

The paper is organized as follows. The model of economic development is presented in Sections 2 and 3. Section 4 presents the general formulation of the multicriteria optimization problem. The computational results are presented in Section 5. The results are discussed in Section 6. Section 7 concludes.

2. General macroeconomic assumptions

The proposed model consists of three sectors which produce, respectively, material inputs, consumer goods, and investment goods, as well as one consuming sector that represents both the households and the public consumption. Such a disaggregation has been chosen because of the distinctive differences in technologies used by these sectors and their impact on the GHG emissions. Distinguishing these production sectors also facilitates the analysis of consumption and investment within the process of technological conversion. Such a model has predictable properties.

Without barriers to growth, the economy described by the model would continuously develop with the rate depending on the investment and the long-run productivity increase rates. The GHG emission limiting policy introduces a barrier and forces economic agents to carry out technology conversion.

The model describes the adjustment process of the economy, due to imposed and decreasing in time volume of GHG emission permits. A new equilibrium sectoral structure is induced by the newly employed technologies in the sectors. The growth rate at this stage depends on the rate of the technological change, subject to satisfaction of the GHG emission constraint.

An important role in the technology conversion is played by the foreign trade, which enables both solving of surpluses/deficits of goods produced by sectors, and selling/buying of the emission allowances. Hence, the prices in the national economy are affected by the world prices and it is assumed that they are determined on the world markets.

The model is the long-term one. This is due to the assumption that the national and foreign demands for goods and services produced in all sectors equal the national and foreign supplies of these goods and services in every year. Such an approach enables the production sectors to follow the long term evolution path with persisting sectorial surpluses and deficits exchanged via the balancing mechanism of foreign trade.

3. Macroeconomic model formulation

As mentioned earlier, three production sectors are distinguished in the model, which are denoted by letters M, C, and I, used to represent both the relevant sectors and their products. Sector M produces intermediary inputs (raw materials, energy, communication and transport services, etc.). Sector C produces consumer goods and services. Sector I produces investment goods and services. The technologies available in the sectors provide identical products, which can be destined for the own sector, other sectors, or abroad. Whenever the balance of such exchange is positive, it means that there is a net export from that sector; if the balance is negative, then there occurs a net import.

The production technology in the model is defined by the set of the following parameters: the productivity of capital, the depreciation rate, the intermediate usage rate, and the unit emission. In each sector the producers choose among only two available production technologies: the older one that is cheaper, but emits more GHG, and the new one that is more expensive, but emits less or no GHG. These two production technologies, in general, can be conceived as mixtures of pure technologies in certain proportions, with prevailing either the old or the new ones. The reason behind this kind of assumption is to simplify the problem. Specification of the existing technologies in each group (technology mix) heavily depends on projections of the technological development, see, e.g., Riahi et al. (2007) or Akashi & Hanaoka (2012), and is left for other studies.

Production capacity in each technology in a given sector is determined by the amount of the fixed assets, associated with that technology. Those fixed assets are decreased by the depreciation and increased by the investments, attributed to that technology. The decision-maker considers the choice of the technology structure of investments (the old and/or the new ones), as well as the structure and rates of the utilization of production capacities of the two technologies that are at the disposal. In order to simplify the analysis, full availability of labor is assumed. It is also assumed that labor does not substitute for the fixed assets.

Classification of the production sectors, determination of the fixed assets, and of the technology parameters in each sector have been performed on the basis of the Input–Output Table at Basic Prices in 2005 for Poland (Central Statistical Office, 2005). Data from 2005 were chosen because of their completeness. The year 2005 is also important as the base year for the comparison of future emission limits, agreed at the climate conferences.

In this section the following notation of numbering the model parameters is adopted. The letter $i = M$, C, I, is used to denote the production sector, the letter $j = 1, 2$, to denote technology, and the letter $t = 1, \ldots, T$, to denote the year; $t = 1$ corresponding to year 2006. All computations are performed in constant 2005 prices.

Technology of production. Each technology of production in any sector is described by the following set of parameters in i-th sector, $i = M, C, I$; in j-th technology, $j = 1, 2$; in year t, $t = 1, .., T$:

γ_{ijt}– is the productivity of fixed assets, defined in the simulation scenario; it is assumed that the technical progress increases the productivity of the fixed assets by a constant ratio r_γ in each year:

$$\gamma_{ijt} = \gamma_{ijt_0}(1 + r_\gamma)^{t-t_0};$$

where γ_{ijt_0} denotes productivity of the fixed assets in the initial year t_0;

δ_{ij} – is the depreciation rate of fixed assets;

$\alpha_{i\,j}$ – is the share of intermediary use of goods, produced in sector M, in the gross output of the i-th sector;

$\mu_{i\,j}$ – is the unit emission.

Potential gross output. Potential gross output $Q_{i\,jt}$ produced by the i-th sector using j-th technology in the year t is described by the Harrods production function:

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

where $K_{i\,jt}$ stands for the stock of the fixed assets in the i-th sector and j-th technology at the beginning of year t. In this paper, the potential gross output (1) will be also called the production capacity of j-th technology in i-th sector in year t. Note that this specification assumes abundant labor as well as no explicit substitution of capital and labor.

Actual gross output. Actual gross output X_{ijt} may be smaller than Q_{ijt} due to the fact that production capacity may not be fully used:

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

where $\lambda_{ij\,t}$ stands for the coefficient of production capacity utilization in the i-th sector, $i = M, C, I$; in j-th technology, $j = 1, 2$; in year t, assuming values from the range of [0;1]. In particular, $\lambda_{ij\,t} = 0$ indicates fully idle capital and $\lambda_{ij\,t} = 1$ represents full utilization of the production capacity. Total actual output of the i-th sector is the sum of outputs produced using both technologies:

$$X_{i\,t} = X_{i\,1t} + X_{i\,2t},\ i = M, C, I; t = 1, .., T. \tag{3}$$

Stock of the fixed assets. Stock of the fixed assets K_{ijt} in the i-th sector is given by the standard relationship:

$$K_{ijt} = K_{it-1} + I_{i1t-1} - \delta_{ij} K_{ij\ t-1},\ i = M, C, I;\ j = 1, 2;\ t = 1, .., T, \tag{4}$$

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

Emission. Production of the i-th sector using j-th technology causes the emissions $E_{i\,j\,t}$ of GHG:

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

The emission $E_{i\ t}$ of the i-th sector equals:

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

and the total emission is given by the following expression:

$$E_t = E_{M\,t} + E_{C\,t} + E_{I\,t},\ t = 1, .., T. \tag{7}$$

It is also assumed that there exist market equilibria in all three markets.

Balance of sector *M*. The demand for the intermediary goods and services produced by sector M is assumed to be fully satisfied, i.e. their total consumption in all sectors, with added balance of the foreign trade, equals the domestic supply:

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

where $\alpha_{i\,j}\,X_{ij\,t}$, $i = MCI$, denotes consumption of the intermediary goods and services produced in sector M, and consumed in the i-th sector, using j-th technology, in the year t, and $B_{M\,t}$ denotes the balance in foreign trade (export – import) in sector M in year t.

Balance of sector *I*. 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 in sector I, equals domestic supply of these goods in all sectors:

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

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

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

$$\begin{aligned} Y_t = {} & (1-\alpha_{M\,1})\,X_{M\,1\,t} + (1-\alpha_{M\,2})\,X_{M\,2\,t} + \\ & + (1-\alpha_{C\,1})\,X_{C\,1\,t} + (1-\alpha_{C\,2})\,X_{C\,2\,t} + \qquad t = 1,..,T. \\ & + (1-\alpha_{I\,1})\,X_{I\,1\,t} + (1-\alpha_{I\,2})\,X_{I\,2\,t}. \end{aligned} \tag{10}$$

Disposable income. Disposable income Y_t^d is given as:

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

where r denotes the interest rate, D_{t-1} stands for the debt at the beginning of the year t (or the end of the year *t-1*), rD_{t-1} is the payment of interest on the debt, if D_{t-1} is positive, or an income from foreign assets, if D_{t-1} is negative.

Consumption demand. National consumption demand C_t is given by the following expression:

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

where the total investment in all sectors, I_t, equals:

$$I_t = \sum_{i=1}^{4}\sum_{j=1}^{3} I_{ij\,t},\ t = 1,\ldots,T. \tag{13}$$

Note that consumption is the residual value, remaining after subtraction of the total investment from the disposable income. Further on, we take the investments in each technology and sector as the decision variables, while the consumption is a part of the criterion, which is maximized.

Balance of sector *C*. Total demand for products of sector C, namely the sum of the national consumption demand and the balance in the foreign trade in C satisfies the following balance equation:

$$C_t + B_{C\,t} = X_{C\,1\,t} + X_{C\,2\,t},\ t = 1,..,T. \tag{14}$$

Discounted consumption. A country pursues maximization of the consumption volume in the long run, which is represented in this model by the discounted value of the future flow of consumption, related to the time point $t = t_0$, i.e.:

$$PVC = \sum_{i=0}^{\infty} \frac{C_{t_0+i}}{(1 + r_d)^i}, \tag{15}$$

where r_d denotes the discounting rate and C_{t_0+i}, i =0, 1, 2, ... , denote future consumption rates.

Number of committed emission permits. The number of the committed emission permits is modeled by a time trajectory of an assumed form, dependent on the number of permits N_{t_d} in the destination year t_d (see Fig 1):

$$N_t = f_N\left(t, N_{t_d}\right),\ t = 1,..,T. \tag{16}$$

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

$$V_t = p_t\left(N_t - E_t\right), \tag{17}$$

where p_t stands for the permission price in year t and N_t is the number of the committed emission permits. In the case of an excess in the emission permits, that 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 a deficit a country has to buy the lacking amount of emission permits at price p_t. Prices p_t are determined exogenously; they are set in an international GHG permit market.

Debt. Debt D_t is defined by the following relationship:

$$D_t = D_{t-1} - \left(B_{M\,t} + B_{C\,t} + B_{I\,t}\right) - p_t\left(N_t - E_t\right),\ t = 1,..,T. \tag{18}$$

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

The balances of the foreign trade in products M, C and I can take any value, but the net exports, $EXP_{i\,t}$ and the net imports $IMP_{i\,t}$, are non-negative as a consequence of the relationship:

$$EXP_{it} = \begin{cases} B_{it}, & B_{it} \geq 0; \\ 0, & B_{it} < 0. \end{cases} \quad i = M, C, I;\ t = 1, .., T, \tag{19}$$

and

$$IMP_{it} = \begin{cases} 0, & B_{it} \geq 0; \\ -B_{it}, & B_{it} < 0. \end{cases} \quad i = M, C, I;\ t = 1, .., T, \tag{20}$$

Decision variables. The decision variables that include actual gross outputs from each technology in every sector, investments in each technology in every sector, and balances $B_{M\,t}, B_{C\,t}, B_{I\,t}$ of the foreign trade in each sector, form altogether the following vector x:

$$\begin{aligned} x = (&X_{M1\,t}, X_{M2\,t}, X_{C1\,t}, X_{C2\,t}, X_{I1\,t}, X_{I2\,t}, \\ &I_{M1\,t}, I_{M2\,t}, I_{C1\,t}, B_{M\,t}, B_{Ct}, B_{I\,t},\ N_{t_d}) \,. \end{aligned} \tag{21}$$

Constraints. The model contains also the following inequality constraints. First, the outputs and the investments are all non-negative:

$$\begin{aligned} &X_{M\,1\,t}, X_{M\,2\,t}, X_{C\,1\,t}, X_{C\,2\,t}, X_{I\,1\,t}, X_{I\,2\,t}, I_{M\,1\,t}, \\ &\qquad I_{M\,2\,t}, I_{C\,1\,t}, I_{C\,2\,t}, I_{I\,1\,t}, I_{I\,2\,t},\ N_{t_d} \geq 0. \end{aligned} \tag{22}$$

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

$$I_t \leq \alpha_{I/Y} Y_t, \tag{23}$$

prevents too high investment rates; coefficient $\alpha_{I/Y}$ denotes the highest acceptable investment rate. The constraints in each sector:

$$-\alpha_{B_j/X_j} \leq \frac{B_{j,t}}{X_{j,t}} \leq \alpha_{B_j/X_j},\ j = M, C, I; \tag{24}$$

impose the maximum share of foreign trade in the national supply of the given product, where coefficients α_{B_j/X_j}, $j = M$, C, I; denote the maximum share of the net foreign exchange in this product in its national gross output. Further two sets of constraints:

$$-r^-_{I\,j} \leq \frac{I_{j,t} - I_{j,t-1}}{I_{j,t-1}} \leq r^+_{I\,j},\ \ j = M, C, I; \tag{25}$$

and

$$-r^-_{cons} \leq \frac{C_t - C_{t-1}}{C_{t-1}} \leq r^+_{cons},\ j = M, C, I; \tag{26}$$

limit relative increases and decreases of the investments in the sectors and total consumption, respectively, where parameters $r^-_{I\,j}$ and $r^+_{I\,j}$ stand for the lowest and highest admissible rates of increase of investment in technology j, $j = M$, C, I; while r^-_{cons} and r^+_{cons} denote the lowest and highest admissible rates of the consumption change.

The end-point constraint included in the model requires that the debt from the year 2080 onwards should be equal to zero, $D_t = 0$, $t = 2080, 2081, \ldots,$ 2085; thereby enforcing the completion of the process of adjustment till the year 2080. Note that actually, the computations are made till the year 2100, and only variable values in the figures are presented till the year 2085. This is because the model quickly achieves the long run equilibrium after the year 2050 and showing the whole trajectory does not add significant information.

In order to perform computations, the available data were transformed into the form suitable for the model. The main source of the data was a report by the Central Statistical Office (2005). The method of disaggregation of the original input-output table was as follows. Products of all sectors were classified respectively as: M – the intermediary inputs in other production sectors, C – consumer goods used in the consuming sector (consisting of the households and the public sector), and I - investment goods serving for creation of the fixed assets, exploited in the production sectors. The structure of the end utilizations of goods served also as a structure for decomposition of the exports and imports of the original sectors. The model-defined sectors were obtained by summing up all similarly classified parts of the original sectors; the same procedure was used in determining the exports and imports of the model-defined sectors. The initial values of the variables were taken from the original input-output table and the data concerning the fixed assets. In particular, the productivities of the fixed assets were estimated on the basis of the input-output data and the additional assumption on the utilization rates in sectors as equal 90%. Table 1 presents the initial values and coefficients of the model.

4. Multicriteria optimization

To force the decrease of GHG emissions, a country is allotted a prenegotiated and diminishing in time number of the emission permits. In this study, a piecewise linear pathway of emission permit limits is assumed. The pathway trajectories are formed by joining the values of the emission permit limits in the initial year, in the intermediate years, and in the destination year. The form of these trajectories is shown in Fig. 1. The actual time trajectory of GHG emissions in our study can, however, differ from the assumed pathway, due to the allowed trading of the permits.

The number of the emission permits N_{t_0} in the initial year $t_0 = 2005$ is known. The numbers of the emission permits N_{t_m} in the intermediate years, $t_{m_1} = 2020$ and $t_{m_2} = 2030$, are fixed as they have been already set in negotiations. The number of the permits in the destination year $t_d = 2050$ is a free variable, satisfying the inequality $N_{t_d} \leq N_{t_{m2}}$. The piecewise linear pathway of

Table 1: Initial values and coefficients of the model

1 - old technology			2 - new technology		
initial values of the productivity of capital			initial values of the productivity of capital		
$\gamma M1$	$\gamma C1$	$\gamma I1$	$\gamma M2$	$\gamma C2$	$\gamma I2$
1	0.9	0.9	0.95	0.9	0.9
initial values of unit emission			initial values of unit emission		
$\mu M1$	$\mu C1$	$\mu I1$	$\mu M2$	$\mu C2$	$\mu I2$
241.7	118.8	180.2	180.2	98.3	143.4
depreciation rate			depreciation rate		
$\delta M1$	$\delta C1$	$\delta I1$	$\delta M2$	$\delta C2$	$\delta I2$
0.075	0.075	0.075	0.075	0.075	0.075
intermediary inputs per unit			intermediary inputs per unit		
$\alpha M1$	$\alpha C1$	$\alpha I1$	$\alpha M2$	$\alpha C2$	$\alpha I2$
0.596	0.5	0.5	0.55	0.495	0.485
initial capital assets in 10^{12} PLN			initial capital assets in 10^{12} PLN		
K_{M1}	K_{C1}	K_{I1}	K_{M2}	K_{C2}	K_{I2}
1.0385	0.708633	0.16618	0.0	0.0	0.0
gross output in 2005 in 10^{12} PLN			gross output in 2005 in 10^{12} PLN		
X_{M1}	X_{C1}	X_{I1}	X_{M2}	X_{C2}	X_{I2}
1.03852	0.6378	0.1496	0.0	0.0	0,0

the emission permits goes through the points $(t_k,\, N_{t_k})$, $k = 0, m1, m2, d$, and then is constant for $t{>}t_d$. The final value N_{t_d} is set in the optimization process.

The bi-criteria analysis is applied. The first criterion is the discounted consumption that represents the effects of the economic growth of the country. It is maximized. The second is the number of the emission permits in the destination year, representing the emission curbing policy. It is minimized.

The model relations presented above can be described in the form:

$$Ax \leq b, \tag{27}$$

where A is a matrix and b is a vector of the coefficients. The vector x includes the decision variables, which are: production (gross output), investments, imports and exports of all three sectors, and the two technologies (the old and the new), all for the years $t = 1, .., T$, as well as the number of emission permits in the destination year t_d, see (**??**).

We denote by $y(x) = (y_1(x),\, y_2(x))$ the vector of the two criteria, mentioned earlier, respectively. The criteria y_i, i =1,2, can be expressed as:

$$y_i = c_i^T x + d_i, \tag{28}$$

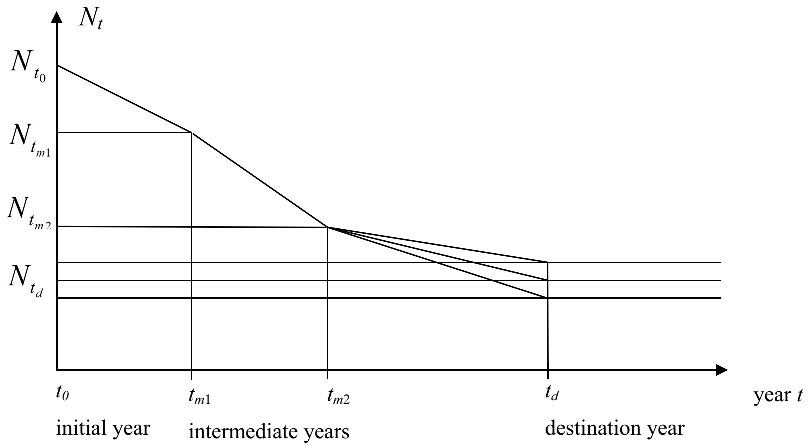

Figure 1: Assumed emission permit pathway trajectories. $t_0 = 2005$, $t_{m_1} = 2020$, $t_{m_2} = 2030$, $t_d = 2050$

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

The criteria are conflicting, hence the multicriteria optimization is applied. The problem is considered in two spaces, that of the decision variables, and that of the criteria. The model constraints define the set $\mathbf{X}_0$ of admissible values of the decision variables in the first space. In the second two-dimensional space, there exists the set $\mathbf{Y}_0$ of the attainable values of the criteria (outcomes).

In the space $\mathbf{R}^2$ of the criteria (y_1, y_2), the domination relation is introduced. 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 $y_1 \geq v_1$, $y_2 \leq v_2$ 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 a partial ordering in the criteria space, which is not a linear one. In this case, the traditional optimality concept, defined for one criterion is not valid.

A vector y is *Pareto optimal* (*nondominated*) in the set $\mathbf{Y}_0$, if $y \in \mathbf{Y}_0$ and there is no $v \in \mathbf{Y}_0$ dominating the vector y. A vector y is *weakly Pareto optimal* (*weakly nondominated*) in the set $\mathbf{Y}_0$, if $y \in \mathbf{Y}_0$ and there is no $v \in \mathbf{Y}_0$ strictly dominating the vector y. In the multicriteria analysis, the set of the nondominated (Pareto optimal) points in the set $\mathbf{Y}_0$ is looked for. In the case analysed here the set $\mathbf{Y}_0$ is not given explicitly. The particular points of the set can be only found through computer simulations, in which the set of decision variables in $\mathbf{X}_0$ that correspond to the set of the Pareto optimal points in $\mathbf{Y}_0$ is derived and analysed.

The multicriteria optimization problem is solved using the reference point approach with an order achievement function, developed by Wierzbicki (Wierzbicki, 1986; Wierzbicki et al., 2000). The computer system, developed at the Systems Research Institute of the Polish Academy of Sciences, generates the Pareto optimal solutions in an interactive way. By assuming and assigning different reference values for the criteria and solving the resulting optimization problems, different Pareto optimal outcomes and decision variable values are computed, compared and analyzed. The reference points in the criteria space are given by a system analyst and then the computer-based system generates the outcomes, which are Pareto optimal in the set of attainable outcomes. In this manner, a representation of the Pareto frontier can be obtained.

The outcomes characterizing the Pareto frontier are derived by:

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

where:
$y* = (y_1*,\, y_2*)$ – a reference (aspiration) point assumed in the space $\mathbf{R}^2$ of the criteria y_1 and y_2, $s(y,\, y*)$ – an order–approximating achievement function, and $\mathbf{X}_0$ as before. The following form of the achievement function is applied:

$$s(y,\, y*) = \min[\beta_1(y_1 - y_1*),\, \beta_2(y_2* - y_2)] + \varepsilon[\beta_1(y_1 - y_1*) + \beta_2(y_2* - y_2)], \tag{30}$$

where $y* \in \mathbf{R}^2$ is the reference point, β_i, $i = 1, 2$, are scaling coefficients, and $\varepsilon > 0$ is a small parameter. The reference point can be either inside or outside of the set $\mathbf{Y}_0$.

Now, the optimization problem (**??**) can be reformulated with the use of the auxiliary variables $z,\, z_1,\, z_2 \in \mathbf{R}$ as follows:

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

with respect to variables $x,\, z, z_1, z_2,$ and subject to the constraints:

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

and the constraints (**??**) on admissible values of the decision variables x, with $x \ge 0$. The variable values y_1^{up}, y_2^{lo} have to dominate the attainable values y_1 and y_2, respectively, and should be chosen so as to normalize the variables and make them dimensionless.

The optimization problem (**??**) has a linear form and can be solved by a linear optimization solver. The optimization process is illustrated in Fig. 2 in the criteria space. As stated earlier, the set of attainable payoffs $\mathbf{Y}_0$ in the criteria space $(y_1,\, y_2)$ is not known explicitly. A system analyst assumes a reference point $y*$ in the space. The corresponding Pareto optimal point y^p is derived by solving the optimization problem (**??**) and then (**??**). The

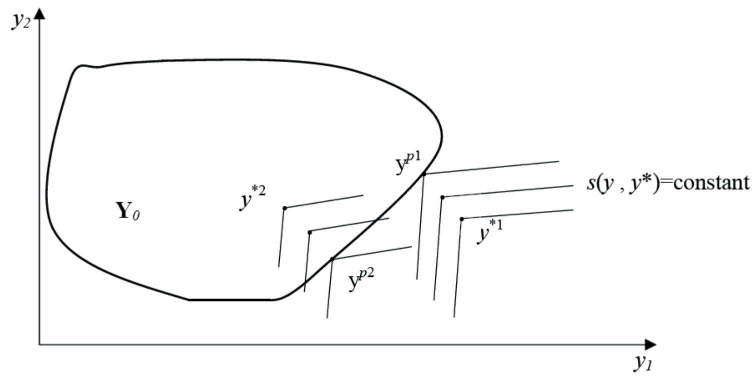

Figure 2: Derivation of the Pareto optimal points y^{p1} and y^{p2} by the reference point method for the assumed reference points y^{*1} and y^{*2}

achievement function $s(y, y*)$ is represented in Fig. 2 by the sets of points, for which the function is constant. By assuming another reference point and by solving again the problem (**??**), a successive Pareto optimal point can be obtained. In such an interactive way a representation of the Pareto frontier of the unknown set $\mathbf{Y}_0$ can be provided. Two reference points $y*^1$, $y*^2$, and two respective Pareto optimal outcomes, y^{p1}, y^{p2} are depicted in Fig. 2.

5. Optimization results

It is assumed that before the initial year 2005 the economy had been growing along the long-time path with a steady growth rate that determined proportions between sectors. The imposed emission pathway disturbs the growth but, after a turbulent transition period of the technology conversion, the economy resumes its growth along a new equilibrium path. Our analysis is focused on the period, during which most of macroeconomic adjustments are performed.

The following rules were adopted in the construction of the simulation scenarios. We simply assumed constant 0.5% growth rates for the productivity of capital and 1% per year decrease of the unit emission in all of the considered technologies. We also assumed that the proportions of prices of goods M, C and I remain constant during the whole simulation period in all variants. This scenario assumption allows us to avoid forecasting of the future development of the world prices. However, the model can be easily adapted to solving more sophisticated scenarios, including those with changing parameters and world prices.

The emission of GHG in Poland in 2005 was 353.9 million ton of CO_2eq (Olecka et al., 2014). This value is adopted as representing the initial number of permits allotted to Poland. In the emission permit pathway, see Fig. 1, the intermediate years are 2020 and 2030, and the destination year is 2050. The

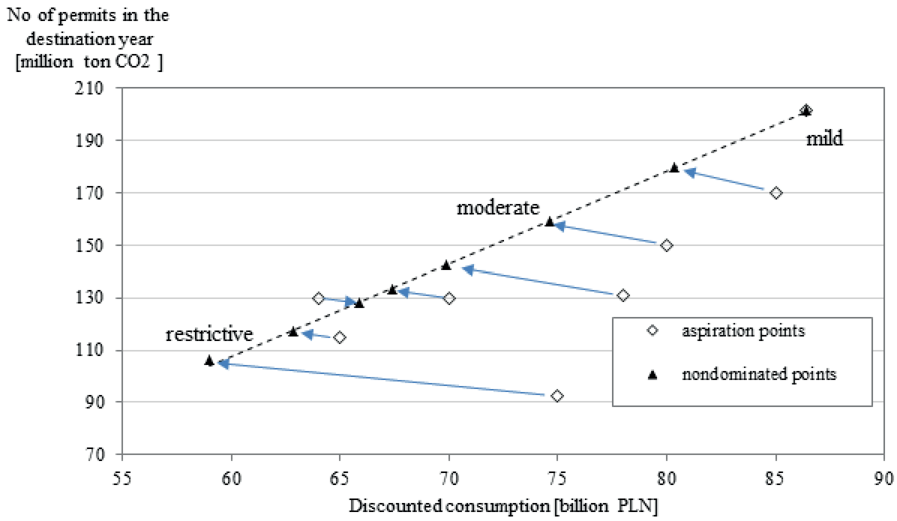

Figure 3: Selected results of the interactive multicriteria analysis. The dashed line is an approximation of the Pareto set

assumed reductions of the emission permits in the intermediate years are 21% and 43%, respectively, as compared to their initial number in 2005, in accordance with the EC directives. The number of the permits in the destination year is minimized, while the discounted consumption in the full period of time is the other criterion that is maximized.

The optimization problem (**??**) was solved using OpenSolver 2.7 linear optimizer for Microsoft Excel, Mason (2012).

Upon choosing different aspiration points, assumed in the criteria space, represented in Fig. 3 by rhombs, the optimized nondominated points, represented by small triangles, were obtained. Arrows indicate correspondence of the nondominated and the aspiration points, the former constituting a representation of the set of nondominated outcomes (Pareto frontier) in $\boldsymbol{Y}_0$. The Pareto frontier is approximated in Fig. 3 by the dashed line. The outcomes located to the right of the Pareto frontier are unattainable, i.e. they do not belong to the set $\boldsymbol{Y}_0$, and those located to the left, are dominated.

The numerical results are presented in Table 2. Eight aspiration points are presented there, and the corresponding solutions are called cases. Case 8 relates to the maximum possible decrease of the emission permit numbers in the destination year, for which the lowest feasible consumption constraint is attained. It is called the restrictive variant. It is the solution of the single criterion optimization problem with minimization of the emission permits number in the destination year. It represents the greatest possible decrease of the emission permits in the destination year within the assumed constraints, equivalent to around 80% reduction with respect to the Kyoto base emission for Poland. In case 1, called the mild variant, there is no decrease of the number of emission permits after the second intermediate year 2030. Among the points situated in between the above two, case 3 is called the moderate variant, as it corresponds to a moderate decrease of the number of permits in the destination year.

Table 2: Selected results of the multicriteria analysis. In the brackets in the third column percent reductions of the discounted consumption with respect to the case 1 (mild variant) are given. The reductions of emissions expressed in percent in the brackets in the last column relate to emissions in year 2005

	Aspiration points		Calculated nondominated points	
Case number	Discounted consumption [10^{12} PLN]	No of permits in the destination year [10^6 tonnes of CO_2]	Discounted consumption [10^{12} PLN]	No of permits in the destination year [10^6 tonnes of CO_2]
1	86.4	201.8	86.4 (-0%)	201.8 (-43%)
2	85.0	170.0	80.3 (-7%)	180.0 (-49%)
3	80.0	150.0	74.6 (-14%)	159.2 (-55%)
4	78.0	130.8	69.9 (-19%)	142.2 (-60%)
5	70.0	130.0	67.4 (-22%)	133.3 (-62%)
6	64.0	130.0	65.9 (-24%)	127.8 (-64%)
7	65.0	115.0	62.9 (-27%)	117.1 (-67%)
8	75.0	92.7	59.0 (-32%)	106.1 (-70%)

The values of all decision variables, corresponding to the three distinguished variants (mild, moderate, and restrictive), are discussed below in detail. The emission permit pathways, as well as emissions obtained from optimization are presented in the upper panel of Fig. 4, together with the real emissions, for the period up to 2015. Panels (b) and (c) in Fig. 4 present the courses of consumption and GDP, respectively, together with the actual values for the period 2005 – 2015.

It can be noticed in Fig. 4, panel (a), that during the adjustment phase, in the period 2015-2035, the emissions exceed the assumed linear trajectory of the emission permits. Then, they cross the path to converge to it from beneath during the last phase. Actual emissions up to 2015 oscillate together with the economic development rate, but approximately follow all paths, which overlap during this period.

Starting from the initial year, the consumption increases in all variants until 2023, when a change of trend occurs. It decreases at that time, and the duration of this phase depends on the availability of the emission permits. A relatively small decrease, observed in the mild variant, lasts ten years. The longer one, which takes place in the moderate variant, and is followed by the stagnation period, lasts till 2050. Around this year ends also the deepest decrease of consumption, observed in the restrictive variant. For this variant, the level of consumption at the end of the simulation period is even lower than in the initial year 2005. In the moderate variant, the level of consumption in the destination year 2050 exceeds that of the initial year, but is still lower than that achieved during the plateau phase. Only in the mild variant the destination year consumption considerably exceeds both the initial and the plateau ones. Finally, these periods are followed in all variants by the period of steady growth.

There are increasing discrepancies between both the actual and simulated consumption and GDP (panels (b) and (c)). An analogous discrepancy can be observed between the total actual and simulated investments in Fig. 5. On the basis of these observations one can suppose that a slow rate of actual introduction of the low emission technologies may be among the reasons of these discrepancies. An additional factor may be constituted by a significant inflow of the foreign direct investments, which would agree with the quick growth of the real total investments, depicted in Fig. 5.

Total investment and investments in sectors M, C and I are presented for the three variants (mild, moderate and restrictive) in Fig. 5. Three sub-periods (phases) are evident in all trajectories, with very similar patterns in the mild and moderate variants. In the first phase all variables grow in the investment sector I after strong initial decrease. The main initial increase of investments is concentrated in sector M of intermediary inputs. The end of the growth can be observed the earliest in sector I, in 2015 for the restrictive variant, and in 2022 for other variants. In sectors M and C the end of the growth is shifted by 4-5 years later. After initial adjustment, the investment activity rises in all sectors for few years, and rapidly drops after that. The second sub-period is characterized by drop of values of all variables. In this phase, discrepancies between the production capacities and the outputs in all sectors appear, the greatest for the restrictive variant. The revival starts again first in sector I, in 2033 for the mild and moderate variants, while being quite volatile for the restrictive variant. In sectors M and C the revival starts around 2040 for the mild variant, around 2050 for the moderate variant, and around 2060, after a volatile earlier evolution, for the restrictive variant. In the third phase, all variables grow with a steady rate. The discrepancies between the production capacities and the outputs disappear.

The investments in the restrictive variant are the most volatile, with swings lasting longer. They hardly follow the pattern of the other variants. In all sectors the investments are volatile during the first and second sub-periods and resume the steady growth during the final phase. The final level of the total investment is slightly higher than the initial one only in the mild scenario, but in no variant the final level of investment exceeds the previous peak level. Investments in all sectors are directed mostly to the new technologies. The weakest growth of investment is observed in sector I during the final steady period. This is due to smaller investment demand in this period, because the process of technology conversion has been already terminated.

Technological conversion is performed with the substantial participation of the foreign exchange, see Fig. 6, panels (b), (c), and (d). The net export appears there when the actual output of a sector exceeds the domestic demand, while the net import prevails when the domestic demand exceeds the output of a sector. During the first phase the export and import increase till around the year 2028 in all variants, except for the import in the restrictive variant, which achieves a plateau level in 2018. During the next phase, the export in all variants decreases. In the third phase, import in the moderate and restrictive variants continues to decrease till 2050, and then recovers to resume a steady growth. In the mild variant, the import increases during the whole third phase. Growing net import is financed by the sale of the unused emission permits, because in the last sub-period the emissions are smaller than the number of the emission permits, see Fig. 4, panel (a).

Turning to the analysis of individual sectors, Fig. 6 shows that the production capacities in sectors and technologies are unevenly utilized. The trajectories in Fig. 6 again suggest, as in the earlier figures, that three sub-periods/phases exist during the simulation period. During the first sub-period, which lasts approximately until 2030, both technologies are fully used in all sectors and variants. As there are no investments in old technologies throughout whole simulation period in any variant, the capital assets, associated with the old technologies, gradually shrink. During the second phase, starting around 2030 and terminating around 2040, for the mild and moderate variant, and around 2060 for the restrictive variant, utilization of the production capacities in all sectors and technologies drops due to the rejection of old technology in sectors M and I, and temporary decrease in the exploitation of the new technology. The deepest drop in the utilization of the production capacities of the new technology occurs in sector I, a smaller one in sector M, and the smallest in sector C. In the third phase, the new production capacities are fully used in all sectors, and the old technology is only used in sector C, where it is resumed and fully employed until its complete decline. Incidental activations of the old technology in sector I at the beginning of the third phase, when further limitation of GHG emission stops, use the remnants of the yet non-decommissioned old technology.

The common feature of the optimization results is that all investments are directed towards the development of the new, cleaner, but more expensive technologies, see panel (a) in Fig. 6, where the resulting substitution of the old technologies by the new ones is presented. However, Fig. 5 panel (a) shows that actual investments are much higher than those calculated in the model, due to direct foreign investments and EU funds, which are not considered in the model. These investments do not, at least until now, cause additional reduction of the GHG emissions in comparison to our model projection, see Fig. 4, panel (a). They cause, however, much quicker development of the economy, Fig. 4 panel (b), and consumption, Fig. 4 panel (c), than projected by our model.

It is worth adding that an adequately high price of the emission permits

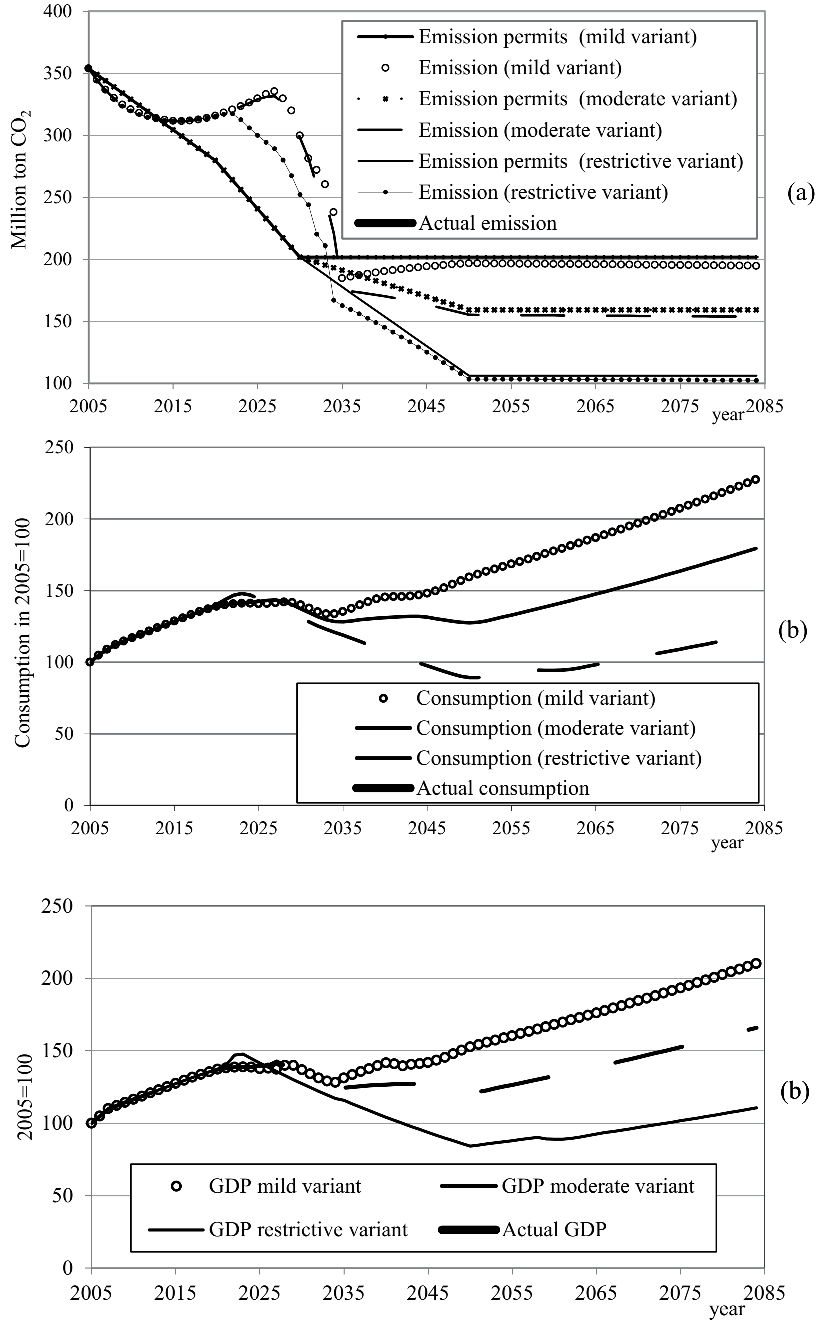

Figure 4: Panel (a): emissions and emission permits in three variants. Panel (b): consumption in three variants. Panel (c): GDP in three variants

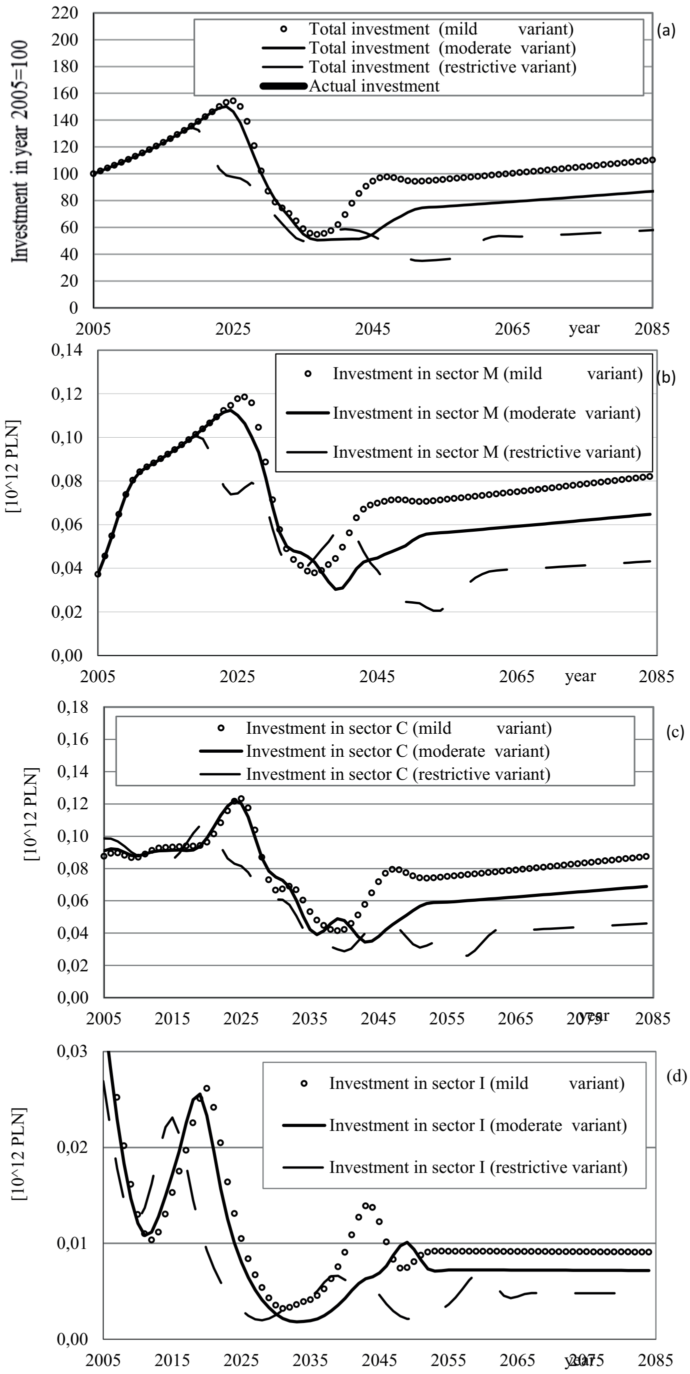

Figure 5: Total investment in three variants and the actual total investment in the period 2005-2015, panel (a); investment in sector M in three variants, panel (b); investment in sector C in three variants, panel (c); investment in sector I in three variants, panel (d)

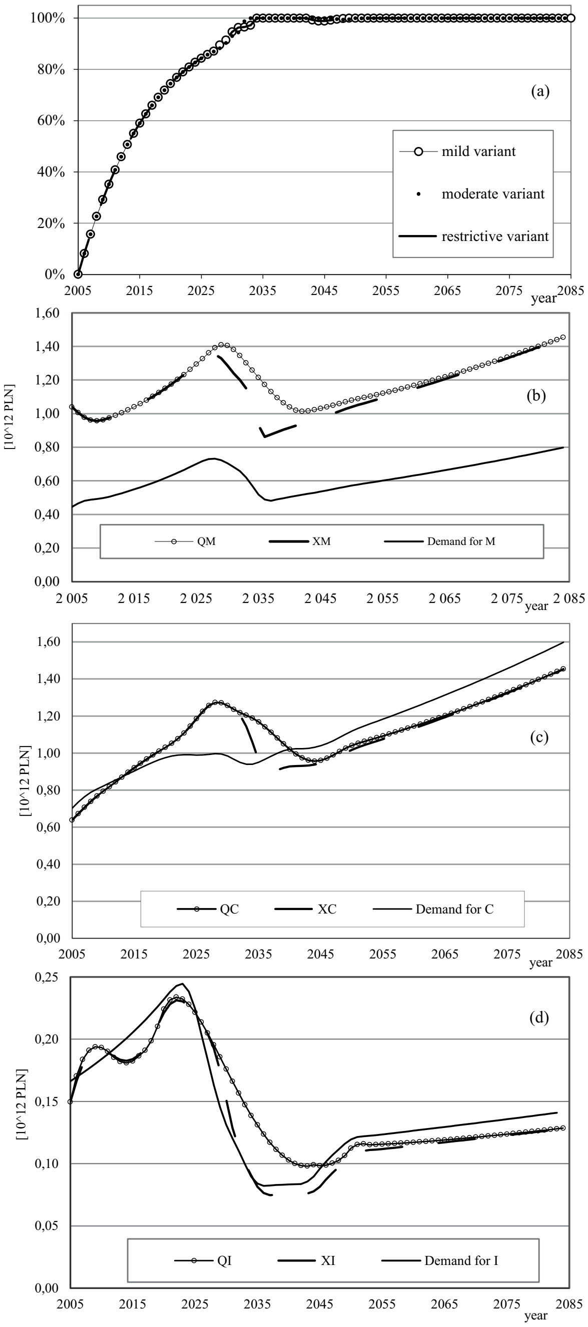

Figure 6: Participation of new technology in the gross output in three variants, panel (a). Rest of the panels depict the results for the moderate variant in three sectors. Production capacity QM, actual gross output XM and domestic demand in sector M, panel (b); production capacity QC, actual gross output XC and domestic demand in sector C, panel (c); production capacity QI actual gross output XI and domestic demand in sector I, panel (d)

is the necessary condition for the prompt technology conversion. Preliminary simulations with assumed low prices of the emission permits (not shown here) caused that the economic agents were insufficiently stimulated to change the technology. Without the price stimulus, the technology conversion starts later (by even up to 20 years) or may ultimately not occur at all within the considered time period.

6. Discussion of the results

Implementation of the GHG cap and trade curbing policy, forces producers either to exchange the old emission intensive technologies for the cleaner, but more expensive ones, or to buy more permits on the market. Available adaptation measures consist of switching the technologies and adjusting the production and/or the fixed assets structure. The trade in emission permits, as well as exports and imports of goods and services help to balance the actual emissions with the assumed emission pathways. In this process, the producers use fixed assets, associated with both old and new technologies; full utilization of the production capacities is not assumed.

By applying the multicriteria optimization, a number of Pareto optimal solutions were derived. Their comparison makes it possible to analyze relations between the feasible decrease of the emissions and the resulting decrease of consumption.

The results presented in Fig. 7 show that decrease of emissions can be achieved only at the cost of lower consumption, which has to be interpreted rather as "lost consumption", as the exact figures would be higher if the direct foreign investments and EU funds were considered. The point marked as "unrestricted" has been obtained for the business-as-usual (BAU) assumption, i.e. when the economic development is continued at the historical rate of growth, without any restrictions concerning GHG emissions and no losses caused by unlimited emissions. Additional points related to the mild, moderate, and restrictive variants, are also depicted.

The results, presented in Fig. 7, indicate that after 80 years (in 2085), one per cent of the GHG emission reduction causes 0.56% decrease of consumption in the mild variant, 0.65% decrease of consumption in the moderate variant, and 0.74% decrease of consumption in the restrictive variant, all in relation to the unrestricted (BAU) case. This is in a good agreement with the EMF 27 modeling results (Kriegler at al., 2014), where the decreases of consumption of the order of 0.5 – 1.5 % were obtained. However, these cumulated numbers hide much more acute yearly decreases within the recession phase.

One can observe a comparable speed of conversion, particularly for the mild and moderate variants, see Fig. 5. And the most distinguishing feature is the final level of consumption. Deeper decrease of emissions below the mild variant requires a respective decrease of consumption, Fig. 7. Similar conclusions, regarding the relatively higher costs for the deeper reductions are presented in Krey et al. (2014). However, the decrease in the number of emission permits

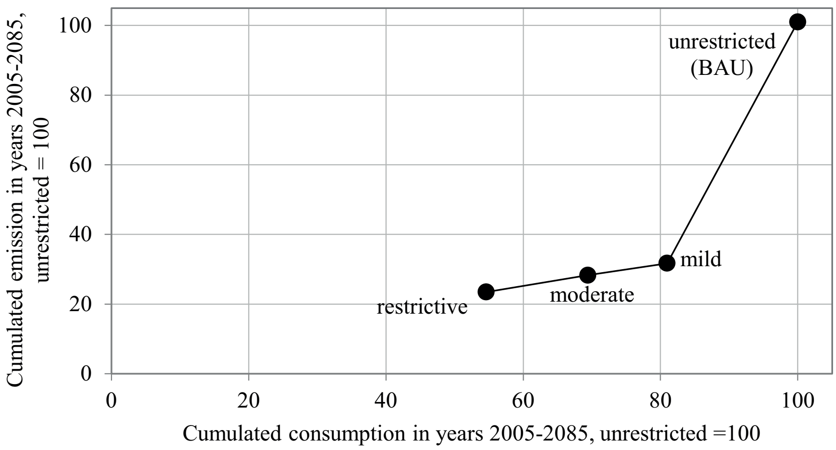

Figure 7: Cumulated consumption and emission in the years 2005-2085 in three variants of emission curbing policy

is reflected, besides the loss of consumption, also in the losses due to the lower usage of the capital assets.

Three phases of the macroeconomic adjustment to the cap and trade policy can be distinguished in GDP trajectories for all three variants, depicted in Fig. 4, panel (c). These are: (i) continuation of the earlier growth, then (ii) a recession, and (iii) a new growth, when new emission limitations settle. During the first phase GDP grows, the sectors behave similarly using fully both technologies in all variants. This is, for example, visible for the moderate variant, presented in Fig. 6. Consumption increases at comparable rates, Fig. 4, panel (b). The economy develops along the earlier growing line. The restrictions start to decelerate the development, while the technology change is supported by the money coming from the selling of the emission permits.

In the second phase GDP decreases. The old technology is stopped or significantly reduced in all sectors, see Fig. 6. An intensive technology conversion causes recession. The depth of the recession is obviously the biggest for the restrictive variant. The main adjustment occurs there; sectors cease to use the old technology, so that, finally, in the third phase, the new technologies are almost solely used in all sectors. During this period the emissions exceed the permits in all sectors (the least for the mild variant), and therefore, the permits have to be purchased. Discrepancies appear between the production capacities and their utilization in all sectors, as this is shown in Fig. 6. These divergences are much bigger for the restrictive variant and are accompanied by their larger volatility. The demand for the intermediary inputs decreases, due to the abandonment of the old technology in all sectors. Hence, for all variants, sector M exports abroad, in total – about half of its output during all three phases of development, see Fig. 6.

In this phase, the national supply of the consumption goods is supported by imports. The national demand for the investment goods exceeds the output of sector I, so that the deficit is compensated by imports. At the end of this phase, emissions drop below the amount, given by the emission permit path and then start to converge towards it from below. This process continues also in the next phase. For all variants, the economy suffers recession in the second phase; the drop of the output in all three sectors is accompanied by a decrease of consumption. Growing imbalance in emissions and emission permit pathways pushes the economy into a recession, which is quite acute, particularly for the restrictive variant.

In the third phase, the economy develops with the steady growth rate, determined by the technical progress. Within this phase, the macroeconomic equilibrium is gradually attained. The old technology is abandoned in sectors M and I, while its available remnants are again fully used in sector C. However, the contribution of the old technology in the output of sector C becomes more and more negligible, see Fig. 5. The national demand for the investment goods exceeds production capacities and the excessive demand is covered by imports, see Fig. 6. The consumption in all variants eventually steadily increases. The economy enters into a new steady growth path, based on the technical progress with the new and less emitting technology. However, the years where the growth begins and the level of consumption starts to increase, differ a lot between the considered variants, see Fig. 4, panel (b).

General conclusions from the simulations are as follows. Sharp decrease of the quantity of the emission permits in the restrictive variant deepens and lengthens the stagnation period. In terms of consumption, see panel (b) in Fig. 4, for the restrictive and moderate variants, the economy at the end of the analyzed period is not able to return to the highest consumption level achieved in the first phase. Another negative effect is the loss of resources due to the lowered utilization of the production capacities during the second phase. The third phase of development begins by about 20 years earlier in the mild than in the restrictive variant.

Comparison of the actual and optimal paths of GDP, consumption and investment in the period 2005-2015, see Figs. 4 and 5, indicates that the Polish economy has been developing significantly faster than this is determined by the optimal solution, supposedly due to the foreign direct investments and EU funds. One can, however, note that the actual total emissions during that period are comparable to those determined by the assumed path of the decreasing number of emission permits. There is also a similar tendency in those variables.

The rate of adjustment of the sectorial structure is depicted in Fig. 5, which presents the advancement of the new technologies in different sectors for the restrictive, moderate, and mild variants. It can be noticed that at the very beginning the fastest progress in technology change occurs in sector I, then in sectors C and M, but in the last phase of transformation this process visibly slows down in sector I.

It should be noted that according to the assumptions taken, the debt remains at the zero level in all of the analyzed cases, although the real Polish debt increases, which is probably another reason for the discrepancies between the real and simulated variables in Figs. 4 and 5. The emission permits are bought in all cases in the first and second phases, while in the third phase emissions converge to the terminal number of permits from below, see Fig. 4, panel (a).

7. Concluding remarks

The model, presented in this study, describes a small economy, exemplified by the Polish economy. It consists of three sectors producing, respectively, the intermediary, consumer, and investment goods. The goal is to analyze economic development subject to increasingly restrictive constraints, concerning emissions of the greenhouse gases, and its consequences for a general structure of the technologies used in production.

The applied multicriteria optimization focuses on two contradictory objectives: decreasing the GHG emissions and maintaining the highest possible growth rate. This enables an analysis of the trade-off problem between two competing goals, meaning reduction of the GHG emissions along with the sustainable economic growth, as well as changes of the sectorial structure of investment and output. Also, assessment of the cost of the GHG emission reduction in terms of the consumption lost is provided.

The multicriteria optimization approach proved to be effective in the analysis of impacts from enforcing the emission limits on the economic development process, and on the economic transformation caused by the adjustment of the national economy to the emission decreasing policy. The technological conversion trajectory was derived for a number of Pareto optimal solutions. Three solutions (referred to as mild, moderate, and restrictive) are presented and discussed in the paper.

Three phases of adjustment can be distinguished in all three variants. The largest technological changes occur during the intermediary stage of the adjustment process; when the sectors intensively exchange the old technologies for the cleaner ones. The new production capacities, based on new technologies, are created and the old ones are being decommissioned. The first phase is a continuation of the earlier growth using the existing production capacities in all sectors. During the second phase all sectors reduce production capacities of the older technology. During the third phase, the economy achieves again the steady structure, but now determined by the new technology, and then grows along a new steady equilibrium path. The optimization results show that the emission curbing policy slows the growth and causes recession in the national economy. The more restrictive the policy is, the more severe is the recession. In the most restrictive variant (case 8), the recession involves a large decrease of consumption, which is far below the previous highest value until the end of the simulation period. This holds even though the consumption is maximized in the optimization. Also for the moderate variant (case 3) consumption drops and does not reach the previous highest level in the destination year 2050, although the difference is not so high. Only for the mild variant (case 1, no decrease of the emission limit after 2030), consumption level practically stagnates in the recession period and then grows above the earlier highest level. In the recession phase, large changes in the economy take place, causing, potentially, social and political strains. The effective desired change of the production technology to the cleaner one strongly depends on the price level of the emission permits. Higher prices force quicker technology conversion.

Although the exact optimization solutions are presented in this study, the results should be rather treated as qualitative, not quantitative. They show tendencies, and years or variable values ought to be considered more as approximate than accurate. Models are only a better or worse approximation of our perception of the real world behavior, and we are aware that our model, like many other, displays definite deficiencies, and that the future technology development is extremely hard to predict. However, the results obtained seem to us to be quite well interpretable, sufficiently interesting, and shedding new light on the transitory effects, connected with limitation of GHG emissions.

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