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on economic growth:
The case of Poland**

J. Gadomski, L. Kruś, Z. Nahorski

**Instytut Badań Systemowych
Polska Akademia Nauk**

**Systems Research Institute
Polish Academy of Sciences**



POLSKA AKADEMIA NAUK

Instytut Badań Systemowych

ul. Newelska 6

01-447 Warszawa

tel.: (+48) (22) 3810100

fax: (+48) (22) 3810105

Kierownik Zakładu zgłaszający pracę:
Dr hab. inż. Lech Kruś, prof. PAN

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

Jan Gadomski, Lech Kruś¹, Zbigniew Nahorski

Systems Research Institute, Polish Academy of Sciences, Newelska 6, 01-447 Warszawa

Abstract The paper aims at answering the following questions: How to proceed with a process of the macroeconomic transformation of a medium-size European country due to adjustment of the national economy to the EU policy limiting emission CO₂? What are the consequences of the enforced emission limits for the economic development and future consumption? To answer these questions at least two competing objectives have to be taken into account: maximization of the development of the national economy, expressed as maximization of the consumption, and minimization of the impact on the climate warming by decreasing the greenhouse gases (GHG) emission. For this, a macroeconomic model has been developed and the multicriteria optimization has been applied. Three sectors are distinguished in the model: the sector *M* produces intermediary inputs, the sector *C* produces consumer goods, and the sector *I* produces investment goods. The sectors interact via markets of the relevant goods. The model is the mid- and long-horizon one, in the sense that only equilibrium trajectories are considered. This is connected with 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 some 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. In assessing the duration of the technology conversion, the obtained results indicate the shortest conversion time assuming that it has been performed optimally.

Keywords: greenhouse gas emissions, cap and trade policy, technological conversion, macromodeling for forecast, CGE models, multicriteria optimization

1. Introduction

Following the growing concern for the role of greenhouse gas (GHG) emissions in the raising earth temperature, global macroeconomic models incorporating GHG emission impacts were constructed, like Global2010 (Manne & Richels, 1992), or DICE (Nordhaus, 1994; Nordhaus & Boyer, 1999). These early modelling focused mainly on discussions of temperature raise extent, the losses induced by it, and costs of abatements, see also Stern (2007). More recently, climate stabilization policies have been subjects of many research projects based on modeling, see presentations, reviews and comparisons published as a results of such projects as 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 there 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 due to 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 on global scenarios, see e.g. Riahi et al. (2007), Krey et al. (2014). 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) consider what they call optimization results for Russia computed with the MERGE model modified by IIASA (Maksimov et al., 2006). However, their paper presents only comparison of results obtained for six scenarios of Russia economic

¹ Corresponding author, email: krus@ibspan.waw.pl

development set by different bodies or assumed by the authors, including a “pessimistic” scenario of 4.5% GDP growth.

In this paper a different approach is applied. An optimization of the pathway for Poland is discussed using a macroeconomic three-sector model of the national economy. The model is constructed to support analysis of the impact of EU limiting policies on growth of a small country economy. 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 CO₂ in a possibly best way? What may be consequences of the enforced emission limits for the economic development and future consumption? The multicriteria optimization is used to harmonize the two conflicting objectives: (i) a possible maximal development of the national economy, (ii) decreasing the GHG emission according to the climate change postulates. Two criteria are formulated: the discounted consumption to be maximized, and the number of emission permits in the preconceived destination year 2050 to be minimized. The number of emission permits in the destination year is treated as a variable in the model. An assumed emission pathway describing the numbers of permits decreasing in consecutive years is a function of this variable. A multicriteria optimization problem is formulated. A representation of the Pareto frontier in the criteria space is obtained by solving the problem for different reference values of the criteria. The decision variables including the investments in the considered technologies in the sectors of the economy, the foreign trade, and the emissions in the sectors and the output quantities of the model, are derived for the long-term period of time. This way the presented multicriteria model can be considered as a tool useful in the stage of preliminary analysis, which can precede the discussion and negotiation of the GHG emission limit, and 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, being the optimal solution under the assumptions taken.

The presented macroeconomic model evolved from the previous versions of the model as presented by Gadomski & Nahorski (2011). The research undertaken was inspired by previous papers dealing with models for analyzing the greenhouse gas (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 use the reference point approach developed by Wierzbicki as well as the multicriteria decision support discussed in the papers by Wierzbicki (1986), Wierzbicki et al. (2000), Kruś & Bronisz (2000), and Kruś (2011).

The paper is organized as follows. The model of economic development, which includes general assumptions, decision variables, output quantities and model relations is presented in Sections 2 and 3. Section 4 presents the general formulation of the multicriteria optimization problem, which is reduced then to a special parametric problem for which the reference point approach is applied. The computational results being representations of the Pareto optimal outcomes are presented in Section 5, where three variants referring to a mild, moderate, and restrictive GHG emission limits, are selected. They results are discussed in Section 6. Section 7 concludes.

2. Macroeconomic model assumptions

Most methodological assumptions of the earlier models by Gadomski & Nahorski (2011) were preserved in the present analysis. The emission limits were used there as constraints in the one-criterion optimization. In the present paper the emissions can be traded, which

introduces additional decision variables to the optimization problem. The assumptions are as follows.

The model is proposed as a tool supporting analysis which focuses on the macroeconomic development of the national economy under the limits imposed on the GHG emission.

The long-term goal of all economic agents is maximization of consumption, which is being pursued as a result of the short-term profit maximization. It is assumed 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 under trade in the emission permits.

The model is the long-term one, which means that only equilibrium trajectories are considered. This is due to the assumption that national and foreign demand for goods and services produced in all sectors equal national and foreign supply of those goods and services in every year. 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 foreign trade. 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 are taken into account.

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 sectors and their products. 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. In each sector considered, the producers can choose from a small number of production technologies. In this paper, only two available production technologies in each sector are assumed: the older one, cheaper but emitting more GHG, and the new one, more expensive but emitting less or none GHG. The reason behind it is the simplification of the problem, but also that pure technologies are often mixed. Then it is assumed that the operating technologies are mixtures of pure ones in certain proportions, with prevailing either old or new ones. Specification of existing technologies in each groups (technology mixt) heavily depends on projections of technological (recently very intensive) development, see e.g. Riahi et al. (2007) or Akashi & Hanaoka (2012), and is left for other studies.

Abundance of the labor is assumed and also that the labor does not substitute fixed assets. 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 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 (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 with emission permits according to the preassigned limits 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. Such separation is slightly artificial, but it considerably simplifies the model.

In each model sector the two available technologies provide identical products, which can be destined for the own sector, other sectors and/or abroad. Whenever the balance of that 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. 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 for its own needs, as well as for the foreign trade. Classification of the production sectors, determination of the fixed assets, and the technology parameters in each sector, have been performed on the basis of the Input–Output Table at Basic Prices in 2005 (Poland), Central Statistical Office (2005). Data from 2005 were chosen because of their completeness. The year 2005 is also important in view of the future emission limits agreed in the European Union.

3. Macroeconomic 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 $t = 1, \dots, T$, to denote the year. The numbering of years starts with the year 2005, so $t = 1$ corresponds to the year 2006.

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 , $t = 1, \dots, T$:

γ_{ijt} - productivity of fixed assets, it is assumed that the technical progress increases the productivity of the fixed assets by a constant ratio 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 year t_0 , and r_γ denotes the growth rate of the productivity of the fixed assets;

δ_{ij} - depreciation rate of fixed assets;

α_{ij} - share of intermediary use of goods produced in sector M in the gross output of i -th sector;

μ_{ij} - unit emission.

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

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

where K_{ijt} stands for stock of the fixed assets in i -th sector and j -th technology at the beginning of year t . 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. Actual gross output X_{ijt} may be smaller due to the fact that production capacity may not be fully used:

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

where λ_{ijt} stands for the 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, $\lambda_{ijt} = 0$ indicates fully idle capital and $\lambda_{ijt} = 1$ represents full utilization of the production capacity. Total actual output of i -th sector is the sum of outputs produced using both technologies:

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

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

$$K_{ijt} = K_{ijt-1} + I_{ijt-1} + \delta_j K_{ijt-1}, \quad i = M, C, I; \quad j = 1, 2; \quad t = 1, \dots, T, \quad (4)$$

where I_{ijt} denotes investment in i -th sector and the term $\delta_j K_{ijt-1}$ denotes depreciation of the capital in i -th sector. 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 i -th sector using j -th technology causes the emissions E_{ijt} of GHG:

$$E_{ijt} = \mu_j X_{ijt}, \quad i = M, C, I; \quad j = 1, 2; \quad t = 1, \dots, T. \quad (5)$$

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

$$E_{it} = E_{i1t} + E_{i2t}, \quad i = M, C, I; \quad j = 1, 2; \quad t = 1, \dots, T, \quad (6)$$

and the total emission is given by the following expression:

$$E_t = E_{Mt} + E_{Ct} + E_{It}, \quad t = 1, \dots, T. \quad (7)$$

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

Balance of the sector M . 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 the domestic supply:

$$\alpha_{M1} X_{M1t} + \alpha_{M2} X_{M2t} + \alpha_{C1} X_{C1t} + \alpha_{C2} X_{C2t} + \alpha_{I1} X_{I1t} + \alpha_{I2} X_{I2t} + B_{Mt} = X_{M1t} + X_{M2t}, \quad t = 1, \dots, T; \quad (8)$$

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

Balance of the 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 I , equals domestic supply of these goods in all sectors:

$$I_{M1t} + I_{M2t} + I_{C1t} + I_{C2t} + I_{I1t} + I_{I2t} + B_{It} = X_{I1t} + X_{I2t}, \quad t = 1, \dots, T; \quad (9)$$

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:

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

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

$$Y_t^d = Y_t - rD_{t-1}, \quad t = 1, \dots, T. \quad (11)$$

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

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

$$C_t = Y_t^d - I_t, \quad t=1, \dots, T. \quad (12)$$

where the total investment in all sectors I_t equals:

$$I_t = I_{M1t} + I_{M2t} + I_{C1t} + I_{C2t} + I_{I1t} + I_{I2t}. \quad (13)$$

Balance of the sector C. 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:

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

Discounted consumption. A country pursues maximization of the consumption in the long run, which in this model is represented by the discounted value of the future flow of consumption (present value at the time point $t=t_0$):

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

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

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

$$N_t = f_N(t, N_{t_d}), \quad t=1, \dots, T. \quad (16)$$

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

$$V_t = p_t(N_t - E_t), \quad (17)$$

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, 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; they are set in an international GHG permit market.

Debt. Debt D_t is defined by the following relationship:

$$D_t = D_{t-1} - (B_{Mt} + B_{Ct} + B_{It}) - p_t(N_t - E_t), \quad t=1, \dots, T. \quad (18)$$

Note that the debt can be positive or negative; net import increases the debt while the trade surplus decreases it. Note also that interest on the 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.

Decision variables. The decision variables are: actual gross output from each technology in every sector, investment in each technology in every sector and balances $B_{M,t}, B_{C,t}, B_{I,t}$ of the foreign trade in each sector:

$$X_{M1}, X_{M2}, X_{C1}, X_{C2}, X_{I1}, X_{I2}, I_{M1}, I_{M2}, I_{C1}, I_{C2}, I_{I1}, I_{I2}, B_{M,t}, B_{C,t}, B_{I,t}, N_{I,t}.$$

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

$$X_{M1}, X_{M2}, X_{C1}, X_{C2}, X_{I1}, X_{I2}, I_{M1}, I_{M2}, I_{C1}, I_{C2}, I_{I1}, I_{I2}, N_{I,t} \geq 0. \quad (19)$$

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

$$EXP_{M,t} = \begin{cases} B_{M,t}, & B_{M,t} \geq 0; \\ 0, & B_{M,t} < 0. \end{cases} \quad i = M, C, I; j=1, 2; t=1, \dots, T, \quad (20)$$

and

$$IMP_{M,t} = \begin{cases} 0, & B_{M,t} \geq 0; \\ -B_{M,t}, & B_{M,t} < 0. \end{cases} \quad (21)$$

On the basis of the above, we have

$$IMP_{M1}, IMP_{M2}, IMP_{C1}, IMP_{C2}, IMP_{I1}, IMP_{I2}, EXP_{M1}, EXP_{M2}, EXP_{C1}, EXP_{C2}, EXP_{I1}, EXP_{I2} \geq 0.$$

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

$$I_t \leq \alpha_{I/Y} Y_t, \quad (22)$$

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

$$-\alpha_{B_j/X_j} \leq \frac{B_{j,t}}{X_{j,t}} \leq \alpha_{B_j/X_j}, \quad j = M, C, I; \quad (23)$$

imposes 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 maximum share of net foreign exchange in given product in its national gross output. Another two sets of constraints:

$$-r_{j,t}^- \leq \frac{I_{j,t} - I_{j,t-1}}{I_{j,t-1}} \leq r_{j,t}^+, \quad j = M, C, I; \quad (24)$$

and

$$-r_{cons,t}^- \leq \frac{C_t - C_{t-1}}{C_{t-1}} \leq r_{cons,t}^+ \quad j = M, C, I; \quad (25)$$

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

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

4. Multicriteria optimization

Decrease of GHG emissions is implemented by allotting to a country a prenegotiated diminishing number of the emission permits that should be met in a given time period. In this study, a linear-wise pathway of emission permit limits is assumed. The pathway trajectories are formed by joining values of 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 GHG emission time trajectory in our study can however differ from the assumed pathway, due to allowed trade of the permits.

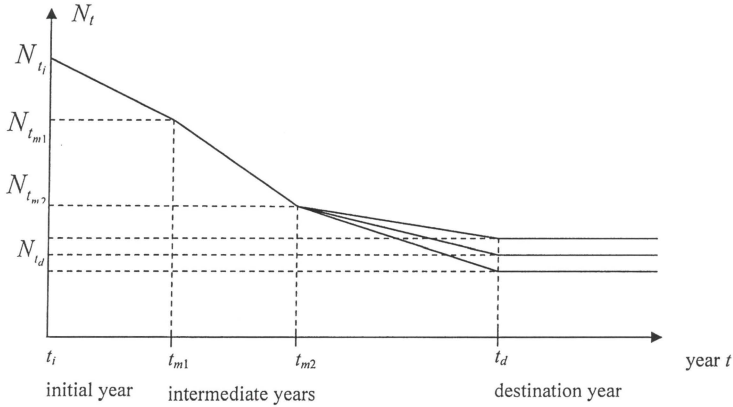


Fig. 1. Assumed emission permit pathway trajectories. $t_i = 2005$, $t_{m1} = 2020$, $t_{m2} = 2030$, $t_d = 2050$.

The initial year t_i chosen in this study is 2005. The number of the emission permits N_{t_i} in this year is known. The numbers of the emission permits N_{t_m} in the intermediate years, $t_{m1}=2020$ and $t_{m2}=2030$, 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 inequality $N_{t_d} \leq N_{t_{m2}}$. The linear-wise decrease of the emission permits going through the points (t_j, N_{t_j}) with constant emissions for $t > t_d$, i.e.:

$$N_t = \begin{cases} N_{t_i} - t \cdot (N_{t_i} - N_{t_{m1}}) / (t_i - t_{m1}), & t \in (t_i, t_{m1}]; \\ N_{t_{m1}} - t \cdot (N_{t_{m1}} - N_{t_{m2}}) / (t_{m1} - t_{m2}), & t \in (t_{m1}, t_{m2}]; \\ N_{t_{m2}} - t \cdot (N_{t_{m2}} - N_{t_d}) / (t_{m2} - t_d), & t \in (t_{m2}, t_d]; \\ N_{t_d}, & t > t_d. \end{cases} \quad (26)$$

The first part of the pathway depends on the value N_{t_d} which is set in the optimization process. The multicriteria analysis is applied. Two criteria are taken into account. The first, which is the discounted consumption that represents 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 emission curbing EC policy, is minimized.

As the model relations include only the affine expressions (1) – (14), they can be described in the form:

$$A \cdot x \leq b, \quad (27)$$

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

$$x^T = (X_{M1t}, X_{M2t}, X_{C1t}, X_{C2t}, X_{I1t}, X_{I2t}, I_{M1t}, I_{M2t}, I_{C1t}, I_{C2t}, I_{I1t}, I_{I2t}, IMP_{M1t}, IMP_{M2t}, IMP_{C1t}, IMP_{C2t}, IMP_{I1t}, IMP_{I2t}, EXP_{M1t}, EXP_{M2t}, EXP_{C1t}, EXP_{C2t}, EXP_{I1t}, EXP_{I2t}, N_{td}). \quad (28)$$

The decision variables are nonnegative i.e $x \geq 0$ according to (19), (20), and (21).

Denote by $y(x) = (y_1(x), y_2(x))$ the vector of the criteria: y_1 is the discounted consumption, y_2 is the number of the emission permits in the destination year t_d . Due to the affine model relations, the criteria $y_i, i=1,2$, can be expressed as:

$$y_i = c_i^T \cdot x + d_i, \quad (29)$$

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

The criteria are conflicting. That is why the multicriteria optimization is applied, in which the decision variables satisfying the constraints, and jointly maximizing y_1 and minimizing y_2 are looked for. The problem is considered in two spaces: that of the decision variables and that of the criteria. The model constraints define the set X_0 of admissible values of the decision variables in the first space. In the second two-dimensional space there exists the set Y_0 of attainable values of the criteria (outcomes). Decision variables leading to the nondominated (Pareto optimal) points in the set Y_0 are looked for.

The following domination relation is introduced in the space 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 $y, v \in R^2$, 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 $y, v \in R^2$, 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 one. So, in this case the traditional optimality concept defined for one criterion is not valid.

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 the case analysed here the set Y_0 is not given explicitly. Particular points of the set can be only found by computer simulations. There exist the decision variables in X_0 which correspond to the set of the Pareto optimal points in Y_0 . This set will be derived and analysed.

The analysis of possible Pareto optimal outcomes is made here by applying the reference point approach developed by Wierzbicki (Wierzbicki, 1986; Wierzbicki et al., 2000) with the use of the order approximation achievement functions. In this approach, some reference points in the criteria space are given by a system analyst and then the computer-based system generates corresponding outcomes which are Pareto optimal in the set of attainable outcomes. This way a representation of the Pareto frontier can be obtained.

Outcomes characterizing the Pareto frontier are derived by:

$$\max_{x \in X_0} [s(y(x), y^*)] \quad (30)$$

where:

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

$y^* = (y_1^*, y_2^*)$ - 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.

The following form of the achievement function that is suitable in this case is applied:

$$s(y, y^*) = \min[\beta_1(y_1 - y_1^*), \beta_2(y_2^* - y_2)] + \varepsilon[\beta_1(y_1 - y_1^*) + \beta_2(y_2^* - y_2)], \quad (31)$$

where $y^* \in \mathbf{R}^2$ is the reference point, $\beta_i, i=1, 2$, are scaling coefficients, and $\varepsilon > 0$ is a small parameter.

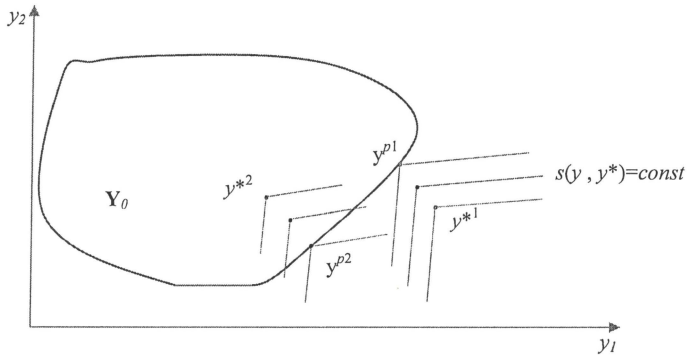


Fig. 2. Derivation of the Pareto optimal point y^p by the reference point method for an assumed reference point y^* .

Now, the optimization problem (30) can be reformulated with the use of auxiliary variables $z, z_1, z_2 \in \mathbf{R}$ as follows:

$$\max [z + \varepsilon \sum_{k=1,2} z_k]. \quad (32)$$

Maximization is with respect to variables and subject to the constraints of the reference point method:

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

as well as subject to the constraints (27) on admissible values of the decision variables x , with $x \geq 0$. The method values y_1^{up} , y_2^{lo} have to dominate the attainable values y_1 and y_2 respectively, and should be chosen in order to scale appropriately the variables z, z_1, z_2 , which are in the result independent of the dimensions of y_1 and y_2 .

The optimization problem (32) 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. A hypothetical set of attainable payoffs Y_0 is presented in the space of the 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 (32). The achievement function $s(y, y^*)$ is illustrated by sets of points, for which the function is constant. The system analyst can assume another reference point, solve again the problem (31) and obtain a successive Pareto optimal point. In such an interactive way a representation of the Pareto frontier of the unknown set Y_0 can be obtained. Two reference points y^{*1}, y^{*2} are given in Fig. 2, for which two respective Pareto optimal outcomes y^{p1}, y^{p2} are defined by maximization of the achievement function $s(y, y^*)$.

5. Optimization results

The computations were performed for the Polish data. As motivated earlier, the year 2005 is chosen as the initial year to start simulation. It is assumed that before the initial year the economy has grown along the equilibrium path with a steady growth rate which determined proportions between sectors. The imposed emission pathway disturbs the growth but, after a turbulent transition period of the technology conversion, the economy resumes to grow along the new equilibrium path. Our analysis is focused on the period where most macroeconomic adjustments is performed.

The emission of GHG in Poland in 2005 was 353.9 mln ton of CO₂eq (Olecka et al., 2014). This value is adopted as initial number of permits allotted to Poland. The emission permit pathway is assumed to have the shape presented in Fig. 1. The intermediate years are 2020 and 2030, and the destination year is 2050. The numbers of permits in the intermediate years are assumed as 79% and 57% of the initial number in 2005, respectively, in accordance with the EC directives, or emission reductions of 21% and 43%, respectively. The number of permits in the destination year is minimized. The discounted consumption in the full period of time is the another criterion that is maximized. For different aspiration points assumed in the space of these two criteria, 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, which form a representation of the set of the nondominated outcomes (Pareto frontier) in Y_0 which is approximated in Fig. 3 by a dashed line. The outcomes located on the right hand side and below the Pareto frontier are unattainable, i.e. they do not belong to the set Y_0 . The numerical computed results are presented in Table 1.

The case 8 relates to the maximum possible decrease of the number of the emission permits in the destination year, for which the lowest feasible consumption constraint (25) is

active. 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 for the destination year within the assumed constraints, which is around 80% reduction of the Kyoto base emission for Poland. In the case 1, called the mild variant, there is no decrease of the number of emission permits after the second intermediate year 2030. Among the intermediate points, the case 3 is chosen and called the moderate variant. It relates to a moderate decrease of the number of permits in the destination year.

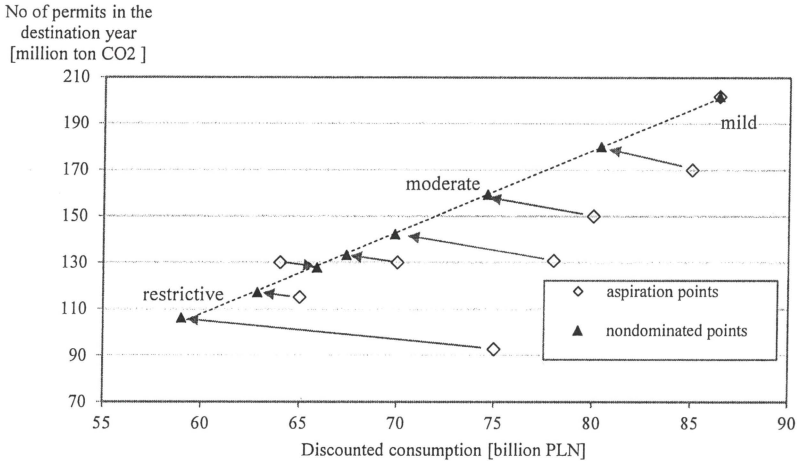


Fig. 3. Results of the interactive multicriteria analysis. The dashed line is an approximation of the Pareto set.

Table 1. Selected results of the multicriteria analysis. In the brackets percent reductions of the discounted consumption with respect to the case 1 (mild variant), and reductions of emissions with respect to 2005 are depicted.

Case 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	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 the decision variables corresponding to the three chosen variants (the cases 1, 3 and 8) are discussed below in detail. The emission permit pathways as well as

emissions obtained from optimization are presented in Fig. 4. The time trajectories of different model variables are presented in Figs. 5 – 10.

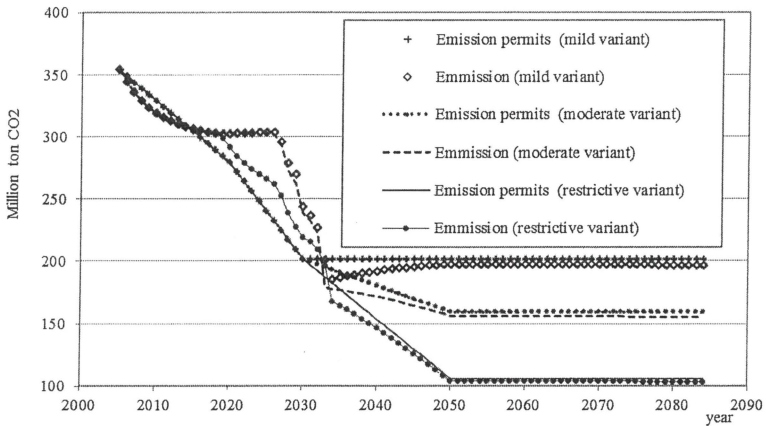


Fig. 4. The assumed emission permit pathways and total computed emission, million ton CO₂.

The common feature of the simulation results of the considered solutions is the immediate technology conversion from the cheaper to the more expensive, but cleaner one (investment in the cleaner technology only), see Fig. 5. However, sufficiently high price of the emission permits is the necessary condition for the prompt technology conversion. Preliminary simulations with assumed low prices of the emission permits (not shown) indicated that in such a case the economic agents were insufficiently stimulated for the technology change. Without the price stimulus, the technology conversion starts later (even up to 20 years) or even may not occur at all within the considered time period.

Technology conversion in sectors can be followed by observing in Fig. 5 the share of the output produced by the capital assets associated with the new technology in total gross output of a sector. When analyzing these curves it should be remembered that due to the assumed properties of the model, the amount of output produced by given technology in a sector depends on the stock of the relevant capital assets and the decision concerning utilization of the production capacity. As no decommissioning of the capital assets is assumed, the stock of the capital assets is being increased by investment and decreased by depreciation, so that without investment the stock gradually shrinks. It seems that the similarity of the technology conversion in sectors indicates the role of the capital depreciation.

Going to analysis of sectors, Fig. 6 shows that the production capacities in sectors and technologies are unevenly utilized. The trajectories in Fig. 6 also suggest that three sub-periods/phases can be distinguished in the simulation period.

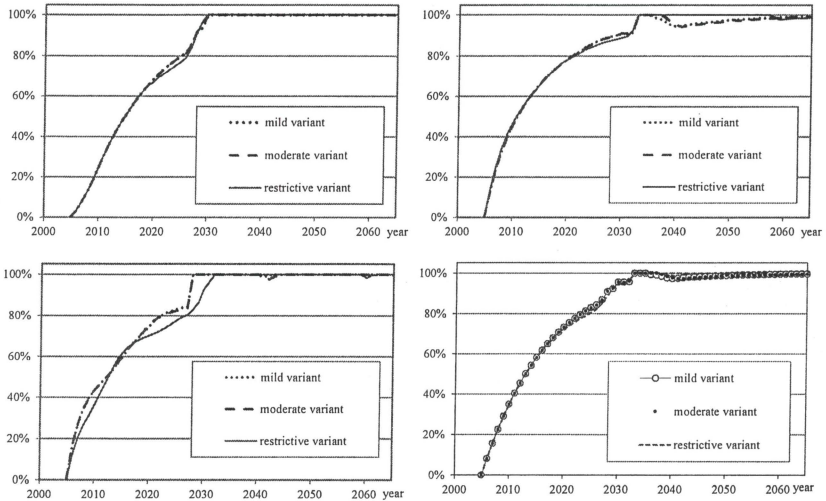


Fig. 5. Share of new technology in gross output of the intermediary inputs sector M (upper left panel), of the consumer goods sector C (upper right panel), of the investment goods sector I (lower left panel), and in the total gross output (lower right panel); for the restrictive, moderate, and mild variants.

In the first sub-period lasting 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 variants, 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 rejection of the old technology in the sectors M and I and temporary decrease of the new technology exploitation. The deepest drop in the utilization of the production capacities of the new technology occurs in the sector I , smaller in the sector M , and the smallest in the sector C . In the sector C the usage of the old technology is resumed and fully employed until its complete decline. In the third phase, the new production capacities are fully used in all sectors, and the old technology is only used in the sector C . Incidental activations of the old technology in the sector I at the beginning of the third phase, when further limitation of GHG emission stops, use the remnants of the old undepreciated yet technology.

Investments in sectors for the restrictive, moderate and mild variants are presented in Fig. 7. They follow similar patterns in the mild and moderate variants. The initial increase of investments is concentrated in the sector M , and the main contraction in the sector I . After initial adjustment, the investment activity rises in all sectors for the duration of few years, to drop next considerably. The investments in the restrictive variant are the most volatile and hardly follow the pattern of the other variants. Turbulences last longer in this variant. In all sectors the investment is volatile during the first and second sub-periods and resumes steady growth during the next phase.

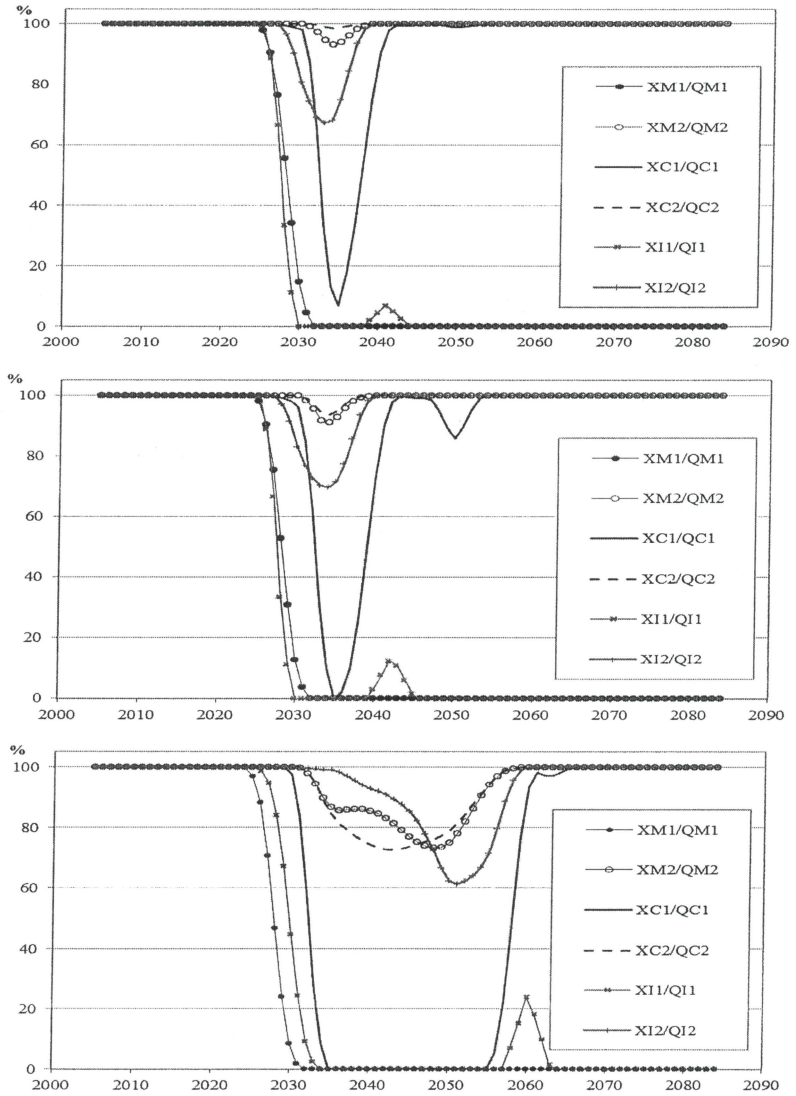


Fig. 6. Use of the production capacity in the sectors, in the mild (upper panel)), moderate (middle panel) and restrictive (lower panel) variants; X denotes actual output, Q stands for the production capacity, M, C and I denote sectors, 1 and 2 denote the old and new technology, respectively.

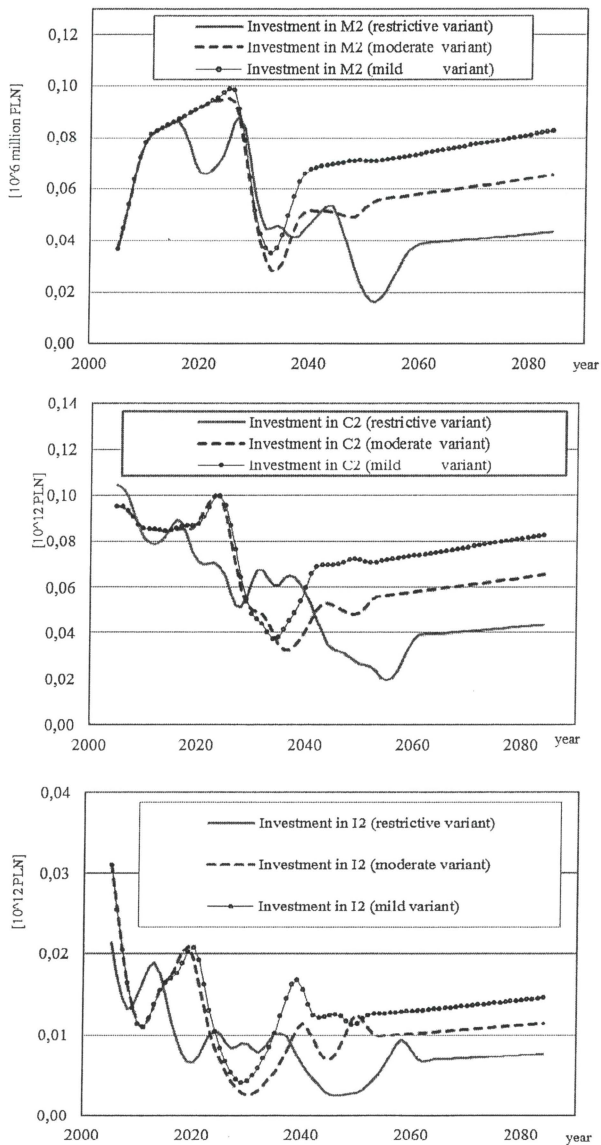


Fig. 7. Investments in the intermediary inputs sector M (upper panel), in the consumer goods sector C (middle panel), and in the investment goods sector I (lower panel) in the mild, moderate and restrictive variants.

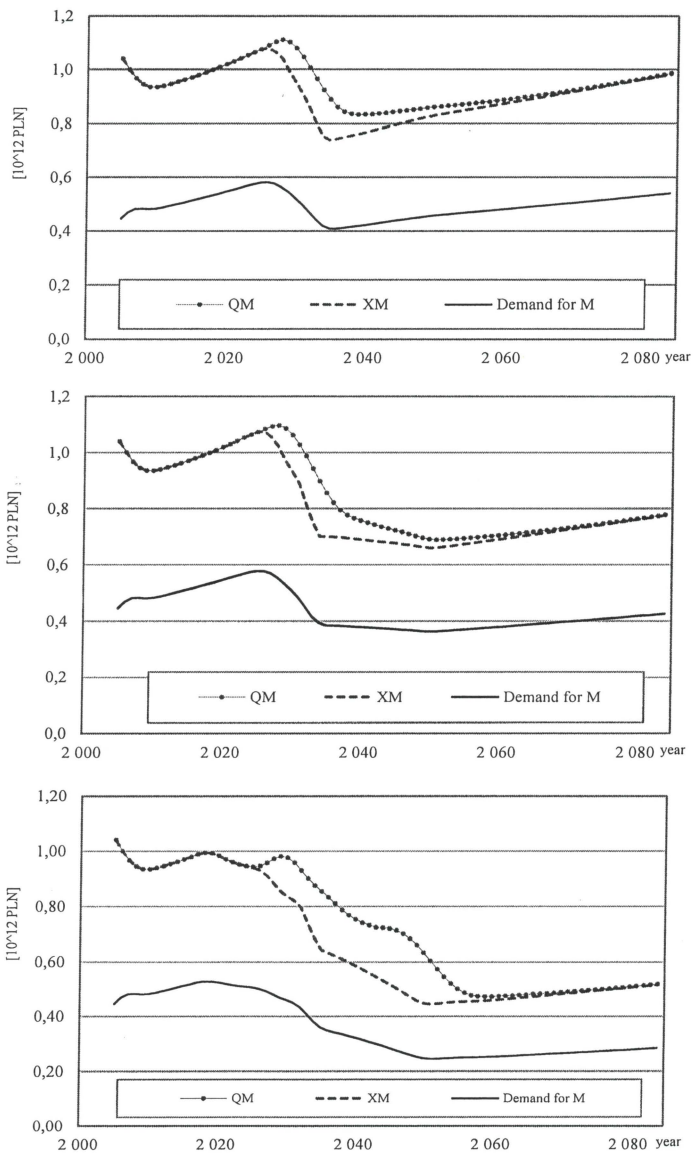


Fig. 8. Production capacity QM , actual gross output XM and domestic demand in the intermediary inputs sector M , the mild variant (upper panel), the moderate variant (middle panel), and the restrictive variant (lower panel).

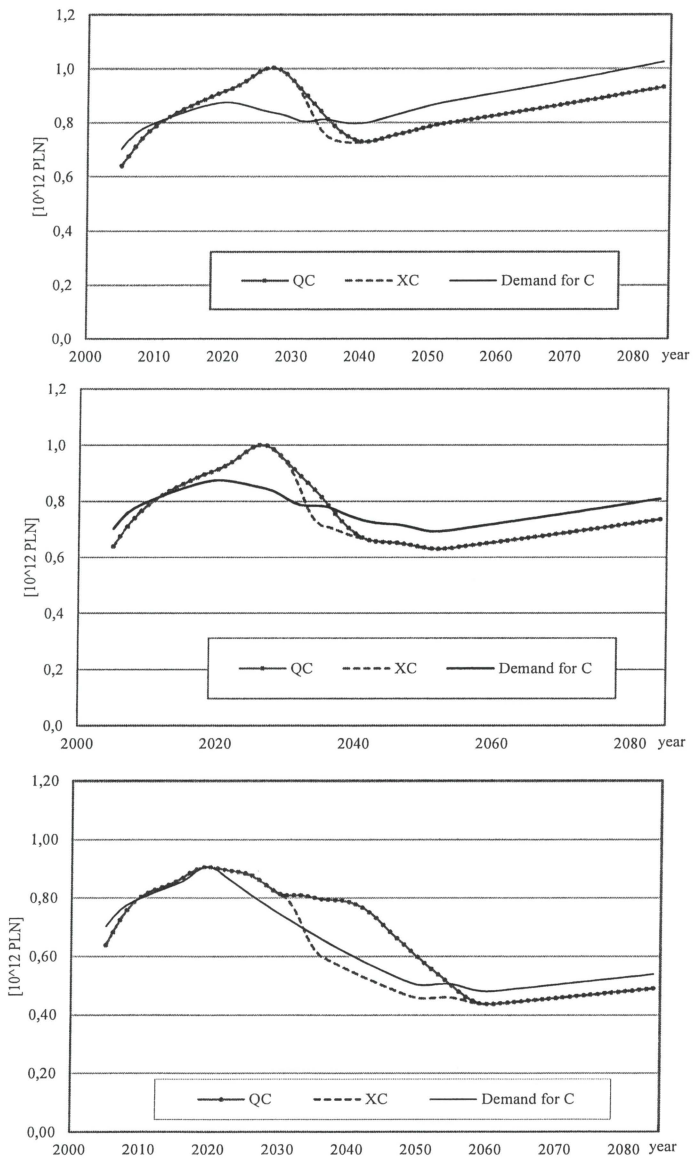


Fig. 9. Production capacity QC , gross output XC and domestic demand in the consumer goods sector C , the mild variant (upper panel), the moderate variant (middle panel), and the restrictive variant (lower panel).

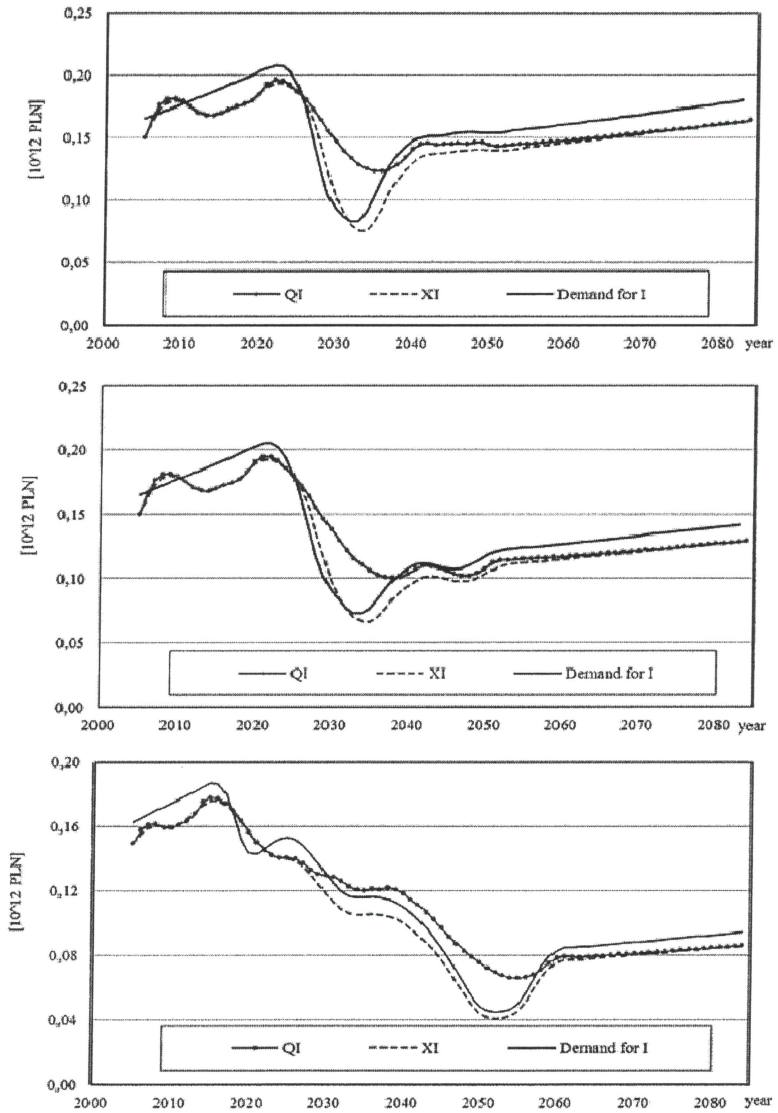


Fig. 10. Production capacity QI , gross output XI and domestic demand in the investment goods sector I , the mild variant (upper panel), the moderate variant (middle panel), and the restrictive variant (lower panel).

Development of the total production capacity Q , total actual gross output X and total domestic demand in the sectors M , C and I in the mild, moderate and restrictive variants, are presented in Figs. 8 - 10, respectively.

Three sub-periods (phases) are evident in all trajectories. In the first phase all variables grow. The end of the grow can be earliest observed in the sector I , in 2015 for the restrictive variant and in 2022 for other variants. In the sectors M and C the end of the growth is shifted to 4-5 years later.

The second sub-period is characterized by drop 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 the sector I , in 2033 for the mild and moderate variants, and in 2053 for the restrictive one. In the sectors M and C the revival starts around 2040 for the mild variant, around 2050 for the moderate variant, and around 2060 for the restrictive variant.

In the third phase all variables grow with the steady rate. The discrepancies between the production capacities and the outputs disappear. In the sectors I and C there is permanent surplus of the demand over the output, which is covered by the import of the investment and consumer goods. The output of the sector M exceeds demand during the whole simulation period, which means that the surplus quantities are exported.

The above distinction of three phases/sub-periods in the economic development revealed in the results concerning sectors is also valid in the macroeconomic analysis. As shown in Fig.11, in each variant there are three distinctive sub-periods: at the beginning of the simulation one can observe continued although slowing down growth till 2022 for the mild and moderate variants, and till 2018 for the restrictive variant. In the second phase GDP decreases till 2033 for the mild variant, and till 2050 for the moderate and restrictive variants. In the following third phase GDP of the modelled economy resumes growth for all three variant and new sector equilibrium is attained.

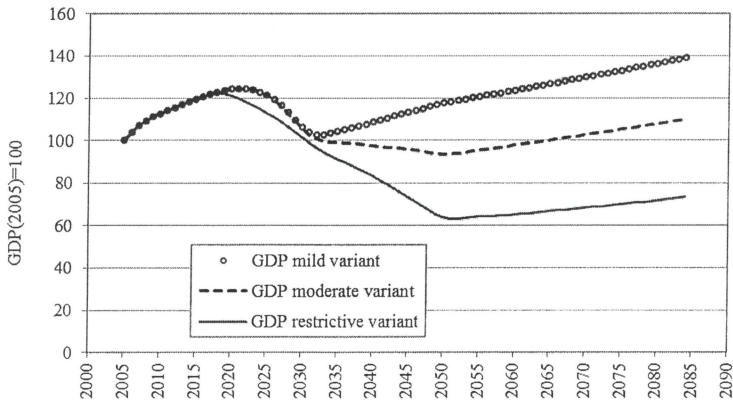


Fig. 11. GDP in the restrictive, moderate and mild variants. GDP in 2005 equals 100.

The components of GDP are depicted in Fig.12. After the period of growth lasting about 15 years in all variants, the consumption achieves climax and starts the second sub-period – the decreasing phase, whose duration depends on the availability of the emission permits, see

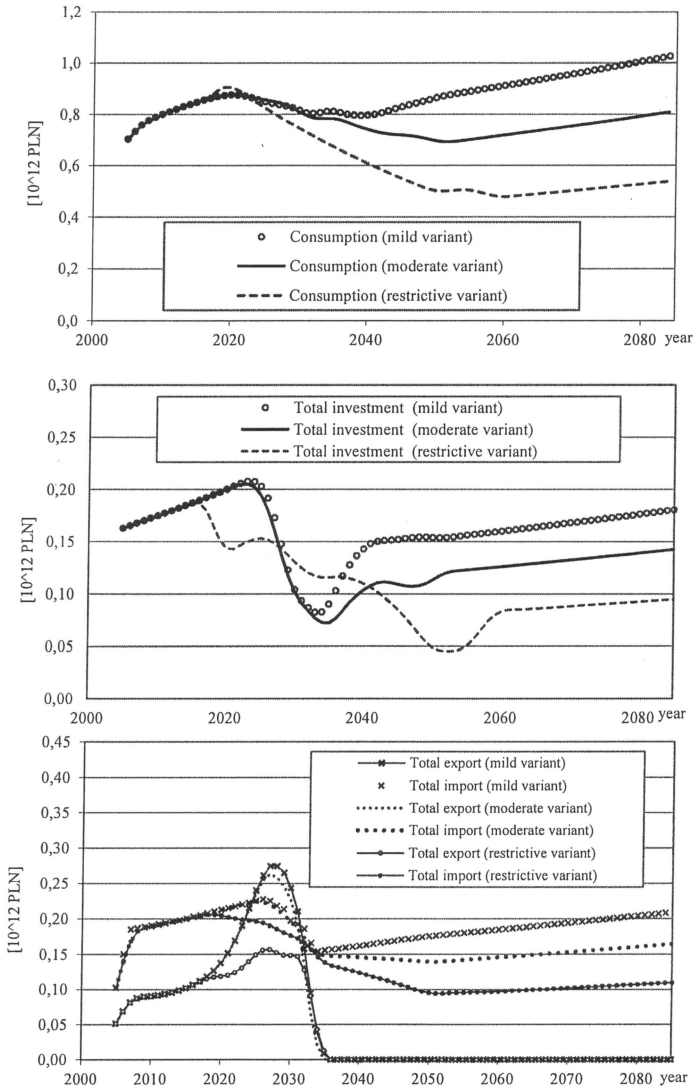


Fig. 12. Consumption (upper panel), total investment (middle panel), the exports and imports (lower panel) for the restrictive, moderate, and mild variants.

upper panel in Fig. 12. In the mild variant this phase lasts about 20 years, in the moderate variant it lasts around 32 years, and in the restrictive variant about 40 years. Note that in the restrictive variant the level of consumption at the end of the simulation period is lower than in the initial year 2005. In the case of the moderate variant the level of consumption at the end of the simulation period exceeds that of the initial year but is still lower than that achieved in its climax. Only in the mild variant the final level of consumption considerably exceeds both the initial and the climax ones.

The final level of total investment is slightly greater from the initial one only in the mild scenario, but in no variant the final level of investment exceeds the level of the climax, see middle panel in Fig. 12. This graph confirms the pattern in the behavior of investment in particular sectors – investment in this model is the most volatile economic category.

Technological conversion is performed with the substantial participation of the foreign exchange, see lower panel in Fig. 12. During the first phase both export and import increase till around year 2028 in all variants, with the exception of import in the restrictive variant, which achieves climax in 2018. During the next phase the export in all variants decreases until reaching zero in 2036. In the third phase import in the moderate and restrictive variants continues to decrease till 2050, and then resumes steady growth. In the mild variant the import increases during the whole third phase. Growing net import is financed by sale of the unused emission permits, as in the last sub-period emission is smaller than the number of the emission permits, see Fig. 4.

6. Discussion of the results

The economy described by the model develops with the long term growth rate, using existing emission intensive technology in all production sectors, until the time of implementation of GHG cap and trade curbing policy. This policy 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 adaptation measures consist of switching technologies, adjustment of the production and/or the fixed assets structure. The trade in emission permits as well as exports and imports of goods and services help in balancing actual emissions with the assumed emission pathways. In this process producers use fixed assets associated with both technologies; full utilization of the production capacities is not assumed.

Applying the multicriteria optimization, a number of solutions was derived, 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 makes it possible to analyze relations between feasible decrease of the emissions and resulting decrease of the consumption. For each solution all model variables have been calculated as well.

The results presented in Fig. 13 show that decrease of emissions can be achieved only at the cost of diminished consumption. The point marked as “unrestricted” has been determined for the business-as-usual (BAU) assumption, that is the economic development is continued at the historical rate of growth without any restrictions concerning GHG emissions. Additional points related to the mild, moderate, and restrictive variants are also depicted.

According to the results, see Fig. 13, 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 et al., 2014), where the decrease of consumption of the order 0.5 – 1.5 were obtained.

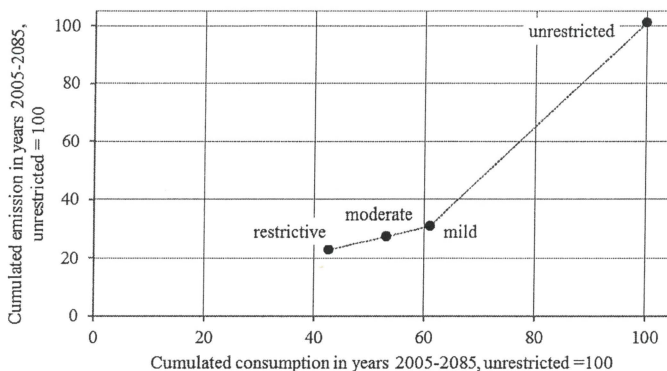


Fig. 13. Cumulated consumption and emission in the years 2006-2085 in three variants of emission curbing policy.

Another similarity of the results of the mild, moderate, and restrictive variants is a comparable speed of conversion, as depicted in Fig. 5. 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 for the restrictive variant, Fig. 13. It can be also noticed that deeper decrease of emissions below the mild variant is occupied by a relatively quicker decrease of consumption. Similar conclusions of relatively higher costs for the deeper reductions are presented in Krey et al. (2014). However, growing limitation of emission permits affects, beside the loss of consumption, also losses due to 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. 11: continuation of the earlier growth, then a recession, and new increase when new emission limitations settle. In the first phase GDP grows with diminishing growth rate achieving climax in year 2022 for the moderate and mild variant, and in year 2018 for the restrictive variant. For all variants considered, the sectors use fully both technologies during this phase, see Fig. 6. Consumption increases at comparable rates, Fig. 12, upper panel. The economy develops along the earlier growing line. The restrictions are too small to change considerably the development, and the technology change is supported by the money coming from the sold permits.

In the second phase GDP decreases from its climax to the nadir achieved in year 2030 for the mild variant and 2050 for the restrictive and moderate variants. The old technology is stopped or significantly limited in all sectors, see Fig. 6. This 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 using the old technology, so that finally in the third phase the production capacities based on the new technologies dominate in all sectors. During this period the emissions exceed quantities of the emission permits in all sectors (the least for the mild variant), therefore the permits have to be purchased. There appear discrepancies between the production capacities and their utilization in all sectors,

Figs. 8 – 10. 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 abandoning of the old technology in all sectors. So, in total, for all variants the sector M sells about half of its output abroad during all three phases of development, Fig. 8.

In the second phase the national supply of the consumption goods is supported by imports. The national demand for the investment goods exceeds the output of the sector I so that the deficit is compensated by imports. During the first and second phases both the total import and total export support the transformation (import exceeding export), see Fig. 12, lower panel. At the end of this phase emissions drop below the amount of 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 deep recession in the second phase; the drop of output in all three sectors is accompanied by a deep decrease of consumption. Growing imbalance in emissions and emission permit pathway pushes the economy into a recession, which is quite acute, particularly for the restrictive variant.

In the third phase, beginning in the year 2030 in the mild variant and in 2050 for the restrictive and moderate variants, the economy develops with the steady growth rate determined by the technical progress. Within this phase the macroeconomic equilibrium is gradually attained. During the third phase the old technology is abandoned in sectors M and I , while it fully uses the capacity in sector C . However, the contribution of the old technology in the output of the sector becomes negligible, see Fig. 5. The national demand for the investment goods exceeds production capacities and the excessive demand is covered by imports, see Fig. 10. The consumption in all variants eventually steadily increases. The economy enters onto a new steady growth path based on the technical progress with new and less emitting technology. However, beginning of growth and the level of consumption differ a lot for the considered variants, see Fig. 11.

General remarks concerning simulation results are as follows. Sharp decrease of the quantity of the emission permits in the restrictive variant deepens and then lasting stagnation. In terms of consumption, see upper panel in Fig. 12, the economy at the end of the analyzed period is not able to reach the highest consumption level achieved in the first phase for the restrictive and moderate variants. Another negative effect is the loss of the resources due to the lowered utilization of the production capacities during the second phase. The third phase of development begins earliest in the mild, and latest in the restrictive variant. The difference is about 20 years.

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

It should be noted that in all analyzed cases the debt remains at the zero level. The emission permits are bought in all cases in the first and second phases, while in the third phase emission converges to the terminal number of permits from below, and the trading surplus of the emission permits is used to compensate for the imports of goods and services in the sectors C and I , Fig. 4.

7. Concluding remarks

The model presented in this study describes a small economy exemplified by the Polish economy. It consists of three production sectors producing the intermediary, consumer, and investment goods. The applied multicriteria optimization focuses on two contradictory

objectives: decreasing GHG emissions and maintaining the highest possible growth rate. This enables an analysis of the trade-off problem between two competing goals: reduction of the GHG emissions 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 done.

The multicriteria optimization problem has been solved using the reference point approach. The elaborated computer system generates 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 were derived, compared and analyzed.

The multicriteria optimization approach proved to be effective in the analysis of consequences of the enforced emission limits for the economic development process and the economic transformation caused by adjustment of the national economy to the emission decreasing policy. The curve of the technological conversion was derived for seven Pareto optimum solutions obtained from the computer simulations. Three Pareto optimum solutions (the mild, moderate, and restrictive variants) have been chosen for presentation and discussion in the paper.

The computer runs based on three significantly different variants imply that during the economic adjustment one can distinguish three phases. The first phase is a continuation of the earlier fast growth using the buildup 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, that is the economy grows along the steady equilibrium path due to the assumed technical progress. The optimization results show that the emission curbing policy slows the growth and causes recession in the country economy. The more restrictive the policy is, the more severe is the recession. In the most restrictive variant (case 8) the recession involves 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 do not reach the previous highest level in the considered period of time, although the difference is not so high. Only for the mild variant (case 1, no decrease of the emission limit after 2030) the consumption 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, which could cause 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 transition.

The obtained results show economic adjustment, which is an effect of the assumed optimal behavior of economic agents, model simplifications, and disregarding the feasibility of implementing the economic policy tools (such as interest rates, taxes etc.). An example of a simplified assumption, which can influence the results, is the constant rate of technological progress. This rate was fixed on the basis of the historical records. However, the technical progress is stimulated by the needs and also by the funds directed to the research and development (R&D) sector, and also depends on some unexpected random important innovations. This has been a subject of many studies. Roberts (1964), Goulder & Schneider (1999), Nahorski & Ravn (2000), Hart (2004), Grimaud & Rouge (2008) present different approaches to modeling the technology change including the R&D sector. Effects of the knowledge dissemination and spillover are analyzed by Allen (1977), Jaffe et al. (2002), and Riahi et al. (2004). Peretto (2008) studied effects of taxes on firms' allocation of resources to cost- and emission-reduction R&D. These or similar approaches could be included into the

model what, however, would necessitate involving much more complicated modelling and optimization tools, including, for example, even stochastic optimization. It may be true that the present trend of R&D development in GHG emission decrease would suggest quicker than a constant technological progress rate, which could mitigate the recession consequences. Changes in this, as also other constant coefficients assumed, depend also on difficult to predict national and international policies. Further development of this subject would perhaps require separate treatment of renewable energy sector, where the technological progress is advancing quicker than for other technologies. More detailed analysis of the problem would then be possible. However, the results obtained seem already to be interesting enough. We are convinced that the developed model and applied method of optimization can be adopted for the analysis of the technological change of other small or medium European countries.

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the 1990s, the number of people in the world who are poor has increased from 1.2 billion to 1.6 billion.

There are a number of reasons why the number of people in the world who are poor has increased. One reason is that the world's population has grown rapidly. Another reason is that the world's economy has not grown fast enough to keep pace with the population growth. A third reason is that the world's resources are being used up too fast.

There are a number of things that we can do to help reduce the number of people in the world who are poor. One thing we can do is to help the world's economy grow faster. Another thing we can do is to help the world's resources last longer. A third thing we can do is to help the world's population grow more slowly.

There are a number of things that we can do to help the world's economy grow faster. One thing we can do is to help the world's countries trade more with each other. Another thing we can do is to help the world's countries invest in each other. A third thing we can do is to help the world's countries improve their infrastructure.

There are a number of things that we can do to help the world's resources last longer. One thing we can do is to help the world's countries conserve their resources. Another thing we can do is to help the world's countries use their resources more efficiently. A third thing we can do is to help the world's countries find new sources of resources.

There are a number of things that we can do to help the world's population grow more slowly. One thing we can do is to help the world's countries improve their health care. Another thing we can do is to help the world's countries improve their education. A third thing we can do is to help the world's countries improve their family planning.

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