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# Analysis of the impact of EU GHG limiting policies on economic growth: The case of Poland

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**Abstract** The paper aims at analyzing the following questions. How to best 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 $CO_2$? What may be the consequences of the enforced emission limits for the economic development and future consumption? To answer these questions a macroeconomic model has been developed and the multicriteria optimization has been applied. Two competing objectives are considered: maximization of the consumption and minimization of the greenhouse gases (GHG) emission. The model includes three sectors: producing intermediary inputs, consumer goods, and investment goods. The sectors interact via markets of the relevant goods. The model is the long-horizon one and describes equilibrium trajectories. This is due to the assumption that every year the national and foreign demand for goods produced in all sectors equal national and foreign supply of those goods and services. The model takes into account the inertial behavior of the large-scale dynamic system, as well as social and political resistance to changes. Computational results are presented for the case of Poland. The welfare costs of the pursuing GHG limiting policy are assessed.

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JEL: Q580, O33, C61

## 1. Introduction

Main purpose of our analysis is to determine the impact of decreasing amount of emission permits endowed to given economy on its economic development. 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 (Nordhous, 1994; Nordhous & 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 at al., 2010), AMPERE (Kriegler at al., 2015), CLIMSAVEC (Harrison at al., 2015), EMF-27 (Kriegler at al., 2014), or RECIPE (Luderer at 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 at 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 at al. (2007), Krey at 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 development set by different bodies or assumed by the authors.

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 developed to support analysis of the impact of EU limiting policies on growth of a small country economy. The following questions are considered. How to plan a process of the economic transformation due to adjustment of the national economy to the EU policy limiting emission of $CO_2$ in a possibly best way? What may be consequences of the enforced emission limits for the economic development and future consumption? 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 at 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 at 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. The results are discussed in Section 6. Section 7 concludes.

## 2. Macroeconomic model assumptions

In order to analyze the process of adjustment to the GHG limiting policy, a simple growth model is used. This model consists of three production sectors producing material inputs, consumer goods, and investment goods, as well as one consuming sector (including both households and the public sector). Distinguishing these production sectors facilitates 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 be continuously developing with the rate depending on the investment and the long-run productivity increase rates. GHG emission limiting policy introduces a barrier and forces economic agents to carry out technology conversion.

The model describes the economy adjustment process due to changed amount of GHG emission permits. The new equilibrium sectoral structure is induced by the newly employed technology in sectors. The growth rate at this stage depends on the rate of the technological change enabling to satisfy the GHG emission constraint under economy growth.

The largest technological changes occur during the intermediary stage of the adjustment process; when the sectors intensively exchange the old technologies to the cleaner ones. The new production capacities based on the new technologies are created and the old ones are being decommissioned.

Important role in the technology conversion is played by the foreign trade, which enables both solving surpluses and deficits of goods produced by sectors, and selling/buying emission permits.

Duration of the technology conversion is affected by the system's properties (the inertial behavior of the large-scale systems, social resistance to economic policy, etc.), but also by the policy measures.

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

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 enables 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. 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. The available technologies in sectors provide identical products, which can be designed for the own sector, other sectors, 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.

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 the producers choose from only two available production technologies: the older one that is cheaper but emitting more GHG, and the new one that is more expensive but emitting less or none GHG. These two production technologies can be conceived as mixtures of pure technologies in certain proportions, with prevailing either the old or the new ones. The reason behind it is simplification of the problem. Specification of existing technologies in each group (technology mixt) heavily depends on projections of 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 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 and/or new ones), as well as the structure and rates of the utilization of the production capacities of two technologies at the disposal. In order to simplify the analysis, the full availability of the labor is assumed. It is also assumed that the labor does not substitute fixed assets.

Classification of the production sectors, determination of the fixed assets, and the technology parameters in each sector have been set 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 as the base year for comparison of the future emission limits agreed in the climate conferences.

## 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 $t = 1, \ldots, T$, to denote the year. The numbering of years starts with the year 2005, so $t = 1$ corresponds to the 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 $t$, $t=1,..,T$:

$\gamma_{ijt}$ - 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 $\gamma_{ijt_0}$ denotes productivity of the fixed assets in the initial year $t_0$, and $r_\gamma$ denotes the growth rate of the productivity of the fixed assets;

$\delta_{ij}$ - depreciation rate of fixed assets;

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

$\mu_{ij}$ - 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:

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

where $K_{ijt}$ stands for stock of the fixed assets in *i*-th sector and *j*-th technology at the beginning of year *t*. 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:

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

where $\lambda_{ijt}$ 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:

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

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

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

where $I_{ijt}$ denotes investment in *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 *i*-th sector using j-th technology causes the emissions $E_{ijt}$ of GHG:

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

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

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

and the total emission is given by the following expression:

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

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:

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

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:

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

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

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

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

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

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

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:

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

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

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

**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 $C$:

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

**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 $t=t_0$):

$$PVC = \sum_{i=0}^{\infty} \frac{C_{t0+i}}{(1+r_d)^i}, \tag{15}$$

where $r_d$ denotes the discounting rate and $C_{t0+i}$, $i= 0, 1, 2, ...$ ; 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 $t_d$:

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

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

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

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, 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:

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

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 include actual gross outputs from each technology in every sector, investments in each technology in every sector, and balances $B_{M\,t}, B_{Ct}, B_{I\,t}$ of the foreign trade in each sector:

$$X_{M1t}, X_{M2t}, X_{C1t}, X_{C2t}, X_{I1t}, X_{I2t}, I_{M1t}, I_{M2t}, I_{C1t}, I_{C2t}, I_{I1t}, I_{I2t}, B_{M\,t}, B_{Ct}, B_{I\,t}, N_{td}\,.$$

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

$$X_{M1t}, X_{M2t}, X_{C1t}, X_{C2t}, X_{I1t}, X_{I2t}, I_{M1t}, I_{M2t}, I_{C1t}, I_{C2t}, I_{I1t}, I_{I2t}, N_{td} \geq 0. \qquad (19)$$

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 $EXP_{ijt}$ and the net imports $IMP_{ijt}$ are non-negative as a consequence of the relationship:

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

and

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

On the basis of the above, we have

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

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

$$I_t \leq \alpha_{I/Y} Y_t, \tag{22}$$

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

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

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

$$-r_{Ij}^{-} \leq \frac{I_{j,t} - I_{j,t-1}}{I_{j,t-1}} \leq r_{Ij}^{+}, \qquad j = M, C, I; \tag{24}$$

and

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

limit relative increases and decreases of investments in sectors and total consumption, respectively, where parameters $r_{Ij}^{-}$ and $r_{Ij}^{+}$ stand for the lowest and highest admissible rate of increase of the investment in technology *j*, *j*= *M*, *C*, *I*; while $r_{cons}^{-}$ and $r_{cons}^{+}$ 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, ... ; determining completion of the process of adjustment till year 2080.

The following table presents the initial values and coefficients of the model.

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 the unit emission | | | initial values of the 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 in10^12PLN | | | Initial capital assets in10^12PLN | | |
| $K_{M1}$ | $K_{C1}$ | $K_{I1}$ | $K_{M2}$ | $K_{C2}$ | $K_{I2}$ |
| 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 |

## 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.

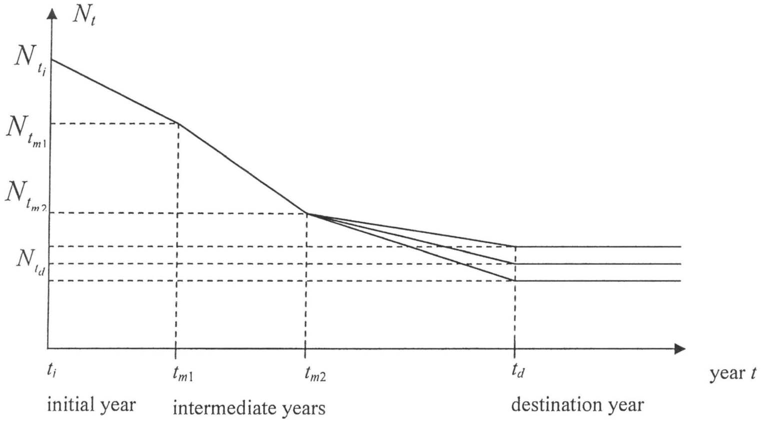


Fig. 1. Assumed emission permit pathway trajectories. $t_i = 2005$, $t_{m1} = 2020$, $t_{m2} = 2030$, $t_d = 2050$.

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 $N_{t_d} \le N_{t_{m2}}$. The linear-wise decrease of the emission permits going through the points $(t_j, N_{t_i})$ with constant emissions for $t > t_d$. The final value $N_{t_d}$ 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:

$$A \cdot x \le b, \tag{26}$$

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 decision variables, that are 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 $t=1,..,T$, as well as the number of emission permits in the destination year $t_d$:

$$x^T = (X_{M1t}, X_{M2t}, X_{C1t}, X_{C2t}, X_{I1t}, X_{I2t}, I_{M1t}, I_{M2t}, I_{C1t}, I_{C2t}, I_{I1t}, I_{I2t}, IMP_{M1t}, IMP_{M2t}, IMP_{C1t}, IMP_{C2t},$$

$$IMP_{I1t}, IMP_{I2t}, EXP_{M1t}, EXP_{M2t}, EXP_{C1t}, EXP_{C2t}, EXP_{I1t}, EXP_{I2t}, N_{t_d}). \tag{27}$$

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

Denote by $y(x) = (y_1(x), y_2(x))$ the vector of the criteria, where $y_1$ is the discounted consumption, and $y_2$ 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:

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

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 are looked for that satisfy the constraints and jointly maximize $y_1$ and minimize $y_2$. 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 attainable values of the criteria (outcomes). Decision variables leading to the nondominated (Pareto optimal) points in the set $\mathbf{Y}_0$ are looked for..

The following domination relation is introduced in the space $\mathbf{R}^2$ of criteria $(y_1, y_2)$. We say that a vector $y = (y_1, y_2)$ *dominates* a vector $v = (v_1, v_2)$, where $y, v \in \mathbf{R}^2$, if $y_1 \geq v_1$ and $y_2 \leq v_2$ and $y \neq v$. A vector $y = (y_1, y_2)$ *strictly dominates* a vector $v = (v_1, v_2)$, where $y, v \in \mathbf{R}^2$, if $y_1 > v_1$ and $y_2 < v_2$. The domination relation defines partial ordering in the criteria space, which is not a linear 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 $\mathbf{Y}_0$, 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 case analysed here the set $\mathbf{Y}_0$ is not given explicitly. Particular points of the set can be only found by computer simulations. The set of decision variables in $\mathbf{X}_0$ which 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 at al., 2000). 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 are derived, compared and analyzed. For this, the order approximation achievement functions is used. 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:

$$\max_{x \in \mathbf{X}_0} [s(y(x), y^*)] \tag{29}$$

where:

$\mathbf{X}_0$ - 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 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, $\beta_i$, $i$=1, 2, are scaling coefficients, and $\varepsilon > 0$ is a small parameter. The reference point can be inside or outside the set.

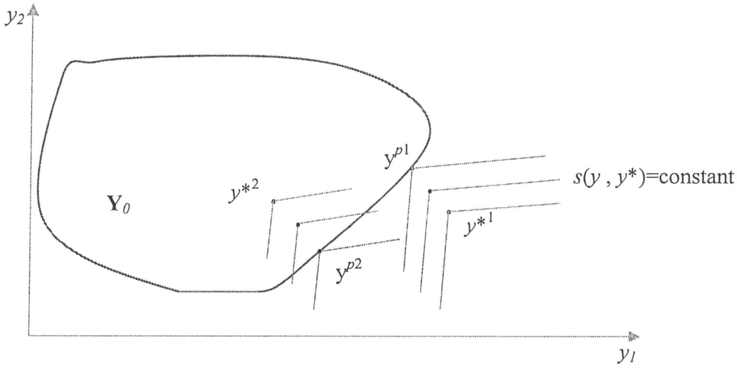


Fig. 2. Derivation of the Pareto optimal point $y^p$ by the reference point method for an assumed reference point $y*$.

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

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

subject to the constraints of the reference point method:

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

and subject to the constraints (26) on admissible values of the decision variables $x$, with $x \ge 0$. Method values $y_1^{up}$, $y_2^{lo}$ have to dominate the attainable values $y_1$ and $y_2$ respectively, and should be chosen to normalize the variable and make them dimensionless.

The optimization problem (31) 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 set of attainable payoffs $\mathbf{Y}_0$ is presented for illustration in the criteria space $(y_1, y_2)$. In fact, it 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 (31). The achievement function $s(y, y^*)$ is represented in Fig. 2 by sets of points, for which the function is constant. Assuming another reference point and solving again the problem (31), 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

The computations were performed for the Polish case. 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 $CO_2$eq (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 assumed reductions of emission permits in the intermediate years are 21% and 43%, respectively, as compared to the their initial number in 2005, in accordance with the EC directives. 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 $\boldsymbol{Y}_0$ which is approximated in Fig. 3 by a dashed line. The outcomes located to the right of the Pareto frontier are unattainable, i.e. they do not belong to the set $\boldsymbol{Y}_0$. The numerical computed results are presented in Table 2.

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.

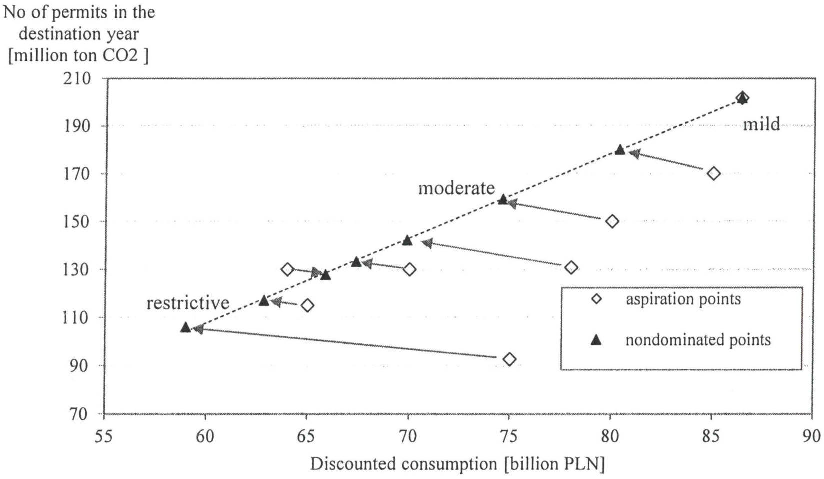


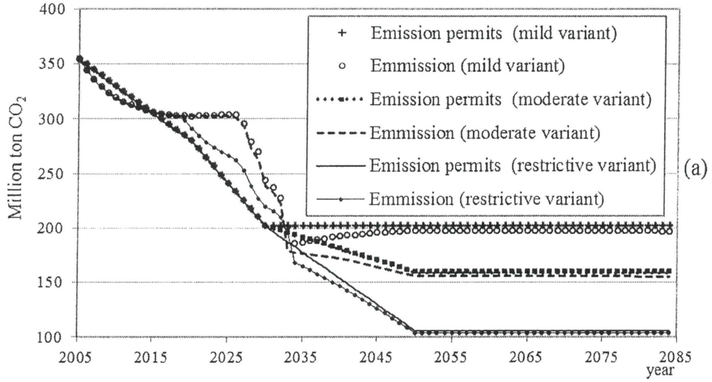
Fig. 3. Results of the interactive multicriteria analysis. The dashed line is an approximation of the Pareto set.

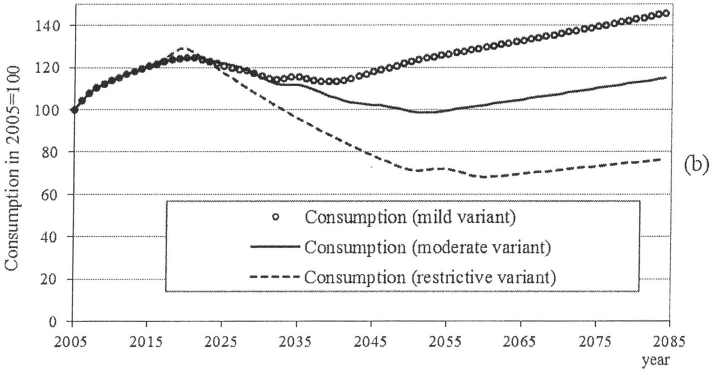
Table 2. Selected results of the multicriteria analysis. In the brackets percent reductions of the discounted consumption with respect to the case 1 (mild variant), and reductions of emissions with respect to 2005 are depicted.

|  | Aspiration points |  | Calculated nondominated points |  |
|---|---|---|---|---|
| Case number | 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 three chosen 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 up to 2013. The middle and lower panel of the Fig. 4 present consumption and GDP, respectively.


400
350
300
250
200
150
100
Million ton CO$_2$
2005
2015
2025
2035
2045
2055
2065
2075
2085
year
Emission permits (mild variant)
Emmission (mild variant)
Emission permits (moderate variant)
Emmission (moderate variant)
Emission permits (restrictive variant)
Emmission (restrictive variant)
(a)


140
120
100
80
60
40
20
0
Consumption in 2005=100
2005
2015
2025
2035
2045
2055
2065
2075
2085
year
Consumption (mild variant)
Consumption (moderate variant)
Consumption (restrictive variant)
(b)

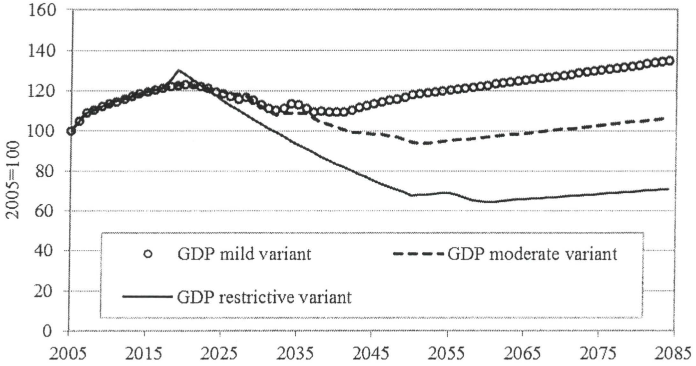

160
140
120
100
80
60
40
20
0
2005=100
2005
2015
2025
2035
2045
2055
2065
2075
2085
GDP mild variant
GDP moderate variant
GDP restrictive variant

Fig. 4. Top panel: emissions and emission permits in three variants. Middle panel: consumption in three variants. The lowest panel: GDP in three variants.

Total investment and investments in sectors M, C and I are presented in three variants (mild, moderate and restrictive) in Fig. 5. 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, and drops considerably in the next ones. The investments in the restrictive variant are the most volatile, last longer and hardly follow the pattern of the other variants. In all sectors the investment is volatile during the first and second sub-periods and resumes steady growth during the final phase. Investments in all sectors are directed mostly to the new technologies.

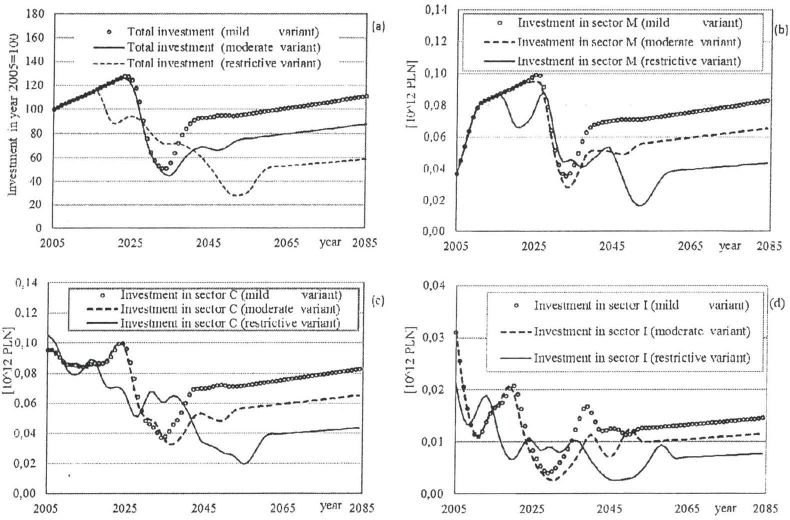


Fig. 5. From top left clockwise: Total investment in three variants, investment in sector M in three variants, investment in sector C in three variants, investment in sector I in three variants.

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.

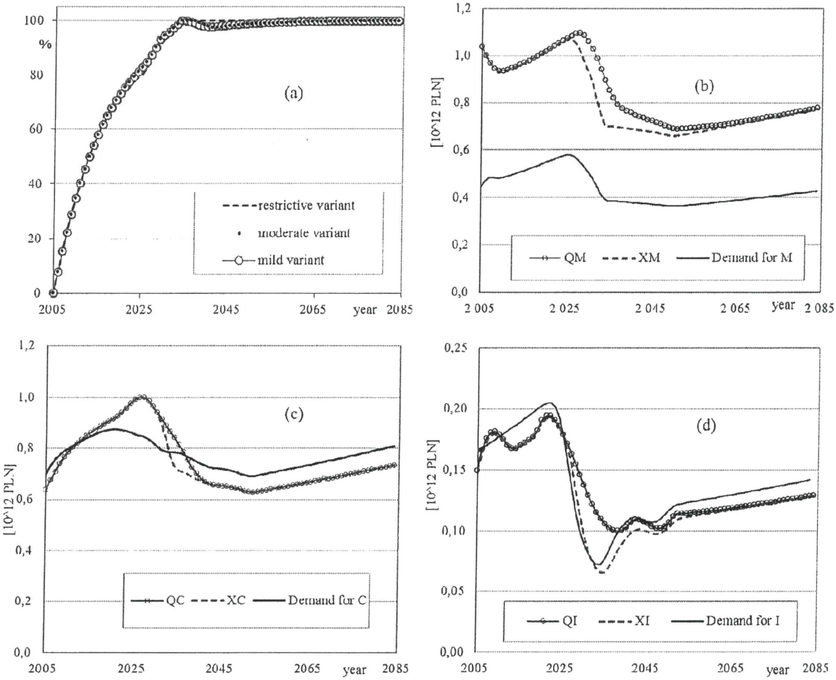


Fig. 6. Participation of new technology in the gross output in three variants, upper left panel. Rest of the panels depict results for the moderate variant in three sectors. Production capacity *QM*, actual gross output *XM* and domestic demand in sector *M* upper right panel; production capacity *QC*, actual gross output *XC* and domestic demand in sector *C* (lower right panel);

production capacity *QI* actual gross output *XI* and domestic demand in sector *I* (lower left panel).

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. 4, 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 inter-sector equilibrium is attained.

The consumption is depicted in Fig. 4, middle panel. After the period of growth lasting about 15 years in all variants, the consumption achieves a plateau and then the second sub-period begins – the decreasing phase, whose duration depends on the availability of the emission permits. In the mild variant this phase lasts about 20 years, in the moderate variant 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 during the plateau. Only in the mild variant the final level of the consumption considerably exceeds both the initial and the plateau ones.

The final level of the 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 plateau level, see top left panel in Fig. 5. 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 Fig. 6. The net export appears when the actual output of a sector exceeds the domestic demand, while the net import prevails when the domestic demand exceeds output of a sector. 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 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 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, top panel.

Going to the analysis of sectors, Fig. 6 shows that the production capacities in sectors and technologies are unevenly utilized. The trajectories in Fig. 6 suggest as well that three sub-periods/phases can be distinguished in the simulation period. During 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 non-decommissioned yet old technology.

The common feature of the simulation results is that all investments are directed into developing the new cleaner but more expensive technologies, see the left upper panel in Fig. 6 where the resulting substitution of the old technologies by the new ones are presented.

It is necessary to emphasize that 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) caused that the economic agents were insufficiently stimulated to change the technology. 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.

## 6. Discussion of the results

Implementation of GHG cap ant 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 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 helps to balance the 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.

The results presented in Fig. 7 show that decrease of emissions can be achieved only at the cost of diminished consumption. The point marked as "unrestricted" has been obtained for the business-as-usual (BAU) assumption, that is when 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.

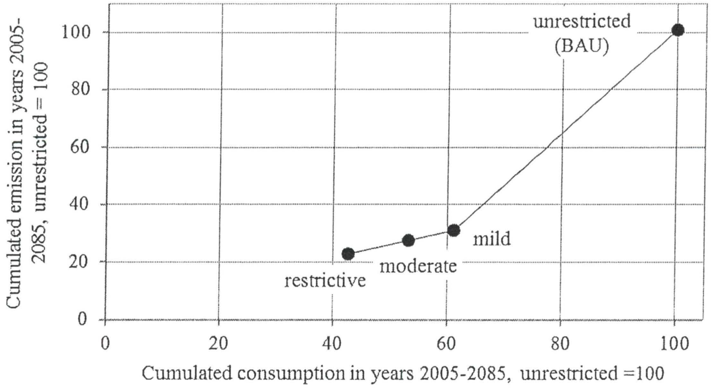


Fig. 7. Cumulated consumption and emission in the years 2006-2085 in three variants of emission curbing policy.

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 decrease of consumption of the order 0.5 – 1.5 were obtained.

Another similarity in the results is a comparable speed of conversion, particularly for the mild and moderate variants, see 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. 7. 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 at 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. 4, lower panel. These are: (i) continuation of the earlier growth, then (ii) a recession, and (iii) a new increase when new emission limitations settle. In the first phase GDP grows with diminishing growth rate achieving a plateau in year 2022 for the moderate and mild variant, and in year 2018 for the restrictive variant. During this phase, 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, middle panel. 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 selling the emission permits.

In the second phase GDP decreases to reach the nadir in year 2030 for the mild variant and 2050 for the restrictive and moderate variants. The old technology is stopped or significantly eliminated 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 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), therefore the permits have to be purchased. There appear discrepancies between the production capacities and their utilization in all sectors, 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 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. 6.

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. 6, lower panel. At the end of this phase emission drops 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 emission 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 its available remnants are again fully used in sector C. However, the contribution of the old technology in the output of the 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 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. 4, middle panel.

General remarks concerning simulation results 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 middle panel in Fig. 4, 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 technology change 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 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 approach proved to be effective in analysis of the impacts of enforcing emission limits on the economic development process, and on the economic transformation caused by adjustment of the national economy to the emission decreasing policy. The technological conversion trajectory was derived for seven Pareto optimum solutions. Three solutions (mild, moderate, and restrictive) are presented and discussed in the paper.

The economic adjustment is an effect of the assumed optimal behavior of economic agents. Three phases of adjustment can be distinguished in all three variants. The first phase is a continuation of the earlier 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, 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 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 model is subject to simplifications. The feasibility of implementation of the economic policy tools (such as interest rates, taxes etc.) is disregarded. An approximation that may seem to 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 at 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. This, however, would necessitate involving much more complicated modelling and optimization tools. 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 approach 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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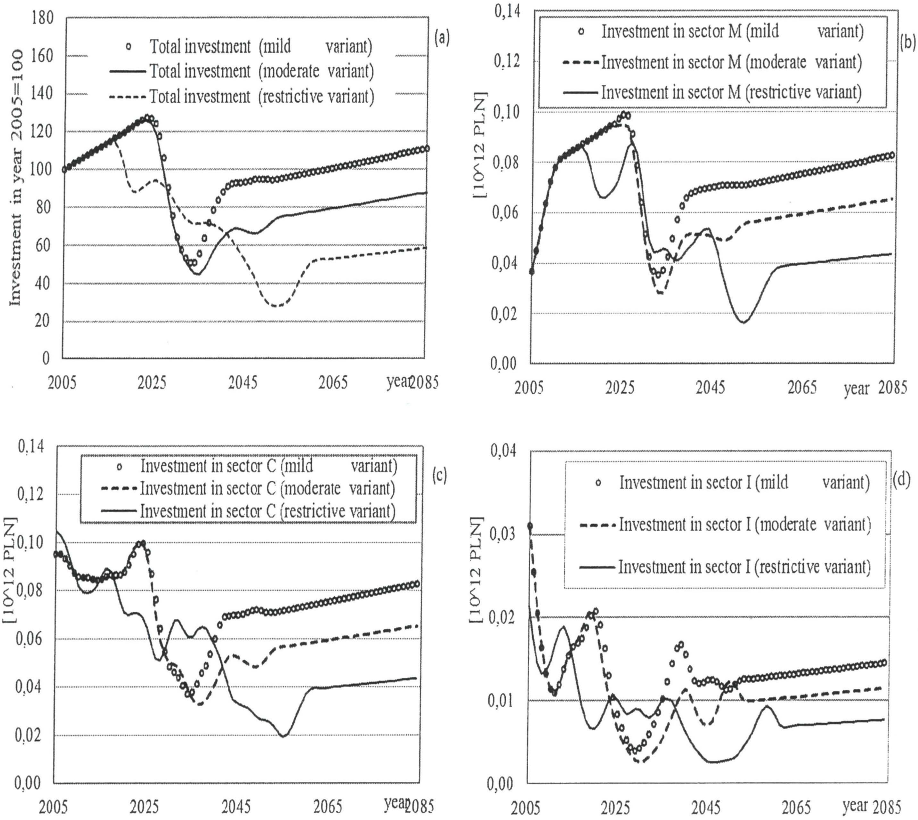
(a)
Total investment (mild variant)
Total investment (moderate variant)
Total investment (restrictive variant)
Investment in year 2005=100
0
20
40
60
80
100
120
140
160
180
2005
2025
2045
2065
year 2085
(b)
Investment in sector M (mild variant)
Investment in sector M (moderate variant)
Investment in sector M (restrictive variant)
[10^12 PLN]
0,00
0,02
0,04
0,06
0,08
0,10
0,12
0,14
2005
2025
2045
2065
year 2085
(c)
Investment in sector C (mild variant)
Investment in sector C (moderate variant)
Investment in sector C (restrictive variant)
[10^12 PLN]
0,00
0,02
0,04
0,06
0,08
0,10
0,12
0,14
2005
2025
2045
2065
year 2085
(d)
Investment in sector I (mild variant)
Investment in sector I (moderate variant)
Investment in sector I (restrictive variant)
[10^12 PLN]
0,00
0,01
0,02
0,03
0,04
2005
2025
2045
2065
year 2085