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LONG-TERM CONSEQUENCES OF THE CO2 EMISSION CURBING POLICY IN POLAND

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Abstract. This study aims at an analysis of the impact of CO2 limiting policy on the macroeconomic structure and growth. The structure in question encompasses macroeconomic proportions and the sectoral structure of production. This policy is expected to change the used technologies for the cleaner, less emitting ones, thus slowing down the negative impact of the climate change. A long-term optimization macroeconomic dynamic model is proposed as an alternative to CGE modelling. The model concerns a small open economy, which is the price-taker of the system of the world prices, and its functioning has negligible impact on the world prices. The model embraces four production sectors, a consumption sector, and foreign trade. Each production sector chooses between a finite number of available technologies representing respectively the traditional, and new cleaner but more expensive ones. The bicriteria optimization problem is formulated. In this problem, contradictory goals are considered jointly: maximization of consumption, and minimization of CO2 emissions over the considered time-period. A cost of the CO2 emission reduction in terms of the decreased consumption has been assessed.

Keywords: macroeconomic modelling, economic policy, technological change, multicriteria optimization, gaseous emissions, international relations.

JEL codes: C54, C61, C63, E17, E61, F41,F51.

Introduction

This paper aims to present an analysis of the impact of the CO2 limiting policy on the economy of a small country, assumed to be an open one and the world price taker, whose impact on the world economy remains negligible. All analyses have been performed on the example of the Polish economy.

The CO2 limiting policy is conducted by an upper level body (European Commission, EC) and governments of the EU member countries in order to curb emissions of greenhouse gases that cause climate warming, and their negative consequences. This policy consists in allotting free and tradeable allowances to emit to each country: in case of a surplus, a country can sell the excessive number of allowances; in case of a deficit, it has to buy lacking allowances. The number of allowances is the subject of negotiations between the government of a given country and the EC; the numbers of allowances in the beginning period are agreed upon in earlier negotiations and treated as fixed, while the quantities to be allotted for the last considered period are a subject of future negotiations. Distribution of the emission allowances among the individual firms is performed within the country.

As desired and expected, this policy should lead to a replacement of cheaper, but more polluting production technologies used by enterprises by cleaner, but more expensive ones. This forced technology conversion is conducted at a cost. Determination of this cost is one of the most important goals of this analysis. However, an interpretation of this cost is necessary.

From the technical point of view, the main uncertainty is related to the expected negative impact of the climate warming on production technologies. One could expect that if the emission mitigation policy is not introduced, production technologies would be exposed to the negative impact of that phenomenon. We believe therefore that the above-mentioned cost should be treated in relative terms, by comparing different emission mitigation policy scenarios.

Most research on this topic presented in the literature has employed Computable General Equilibrium (CGE) models. In the Polish case, one can mention e.g. the PLACE model, see Antoszewski (2015), Boratyński (2012), Roberts (1994), and others. The development of CGE models involves large teams and a detailed structure of the models. However, not all research is concerned with very detailed questions, and not all assumptions of the research based on CGE models are relevant. For example, the energy sector does not adhere to the model of the perfect competition, on which CGE models are based. A monopoly (or oligopoly) can operate in a range of technical inefficiency. Such a situation is not accounted for in the model of perfect competition. This is why neoclassical production functions such as, for example, Cobb-Douglass or CES, commonly used in CGE modelling, cease to be adequate. Moreover, a significant part of the energy sector consists of integrated networks (electricity, gas), where it is necessary, for strategic reasons, to maintain larger reserves of the unused production capacities than is common in other sectors. This also makes simplifying assumptions applied in CGE models hard to accept. Another far-reaching simplification commonly used in CGE models is micro-rationality of producers, who maximize profits and are not concerned with market shares or other long-term factors affecting the behavior of firms. One more problem concerning CGE models is that they assume there exists a continuum of available technologies. We doubt that, because it is hard to imagine a complex technology combining, for example, the nuclear technology and the renewable one. These technologies coexist, but develop separately and remain so. As for the utilization of production capacities, reserves of unused capacities persist in long periods. This feature is common not only in network monopolies (for example in the motor car manufacturing).

The above discussion of some weaker aspects of CGE modelling does not dismiss this technique but it shows that there is still space for other approaches. In this paper we propose a method based on a model that is simpler and thus much less work-intensive, yet able to generate no-nonsense results. It has evolved from an earlier version; see Gadomski et al. (2016), with the separate energy sector added as the main source of the gaseous pollution. They differ mainly in that in the former version all calculations were performed in real terms; this model takes into consideration changing world prices and their transmission to national markets.

The concept of the proposed model is based on the assumption of macroeconomic rationality and a perfect ability of the macroeconomic policy to pursue its goals by optimal allocation of resources. Such approach provides a benchmark. Similarly to CGE models, all changes preserve sectoral equilibria in real terms at every step. Quantitative equilibria are maintained in such a way that surpluses/deficits of the domestic markets are cleared via the foreign trade. Producers react to changes in demand by changing the utilization of the production capacities, and/or changing the production capacities by purchases of investment goods. In the long run, without the technical progress, the sectoral output structure and the country's GDP would be determined by the amount of the final allotted amount of the emission allowances. This would be equivalent to the zero growth economy. In the presence of advantageous technical changes, such as a beneficial evolution of the technological parameters or the emergence of a new economically more efficient technology, economy would start growing at a rate determined by the improvement of the relevant technology parameters.

Main novelties in the paper include: a new version of model describing development of economy and CO2 emission, including different variants of technologies applied in considered sectors of economy, also accounting for the impact of the world prices on the structure and growth of the national economy; formulation of the bi-criteria optimization problem to harmonize two conflicting objectives: maximization of the discounted future consumption and minimization of the cumulated CO_2 emissions; calculation of the Pareto-optimal outcomes using the modern interactive reference point approach; analysis of the computation results showing the required changes of technologies in time to fulfill assumed reduction of CO_2 emission and resulting lower GDP and consumption.

Following this introduction, the paper is divided into three sections. The first one describes the method of analysis. The next section describes the simulation results, and the final one contains conclusions. The bi-criteria optimization problem is described in Appendix.

1. Method of analysis

The process of the macroeconomic technological conversion is analyzed with the support of the macroeconomic long-term model embracing four production sectors, each having a limited number of available production technologies. The sectors exchange their products at both the domestic and international markets. The focus is on modelling a small-country economy, a price-taker of international prices. The analysis is simplified by assuming that a change in emission levels does not affect productivities of the production factors. It is an optimization model, and its result indicates a perfect reaction of the national economy to the changes in its conditions/rules. In the variant considered in this investigation, the overall economic goal of the national economy is the maximization of the present value of total consumption over the whole simulation period.

In developing this model we do not point to tools or channels of the economic policy. Instead, this model is to serve as a benchmark showing ideal, but feasible in real terms, long-term behavior.

We assume that up to the introduction of the CO2 limiting policy the economy described by the model developed along the long-term growth path using a single technology in each sector, maintaining in all sectors both domestic and external equilibria. The rate of growth is determined by the propensity to invest. This type of growth is characterized by constant proportions of the sectors' outputs, fixed assets, balances of foreign trade, and a certain rate of the utilization of the production capacities.

At the starting point (2010) the sectors come across the emission limits, which force an adoption of cleaner, previously unconsidered, economically inefficient technologies. Technology conversion influences both amounts, and the output and costs structures. In this paper we consider only simple hypotheses, such as the one of technology parameters gradual improvement, which reflects a long-term technical progress. A similar hypothesis is adopted in studying two possible developments of future energy prices: steady and moderately growing.

The letter t, $t = t_0, \ldots, T$, denotes the year. The numbering of years starts with the year 2010, so that t_0 corresponds to the year 2010. The following convention of indexing the model parameters has been applied in this paper: The letter $i = M, E, C, I$, denotes the sector, the letter $j = 1, 2, 3$, denotes technology. M stands for the sector producing non-energy intermediate inputs used in all producing sectors, E denotes the sector producing energy used in all producing sectors as well as the consuming sector, C stands for the sector producing consumption goods consumed by households and the public sector, and I denotes the sector producing the investment goods supplying the stocks of fixed assets in the production sectors. It is assumed that the number of the available technologies is limited to two in the sectors M, C, I, and three in the energy sector E.

The technology of production in all sectors is described by the following set of parameters in i-th sector, $i= M, E, C, I$; in j-th technology, j=1, 2, 3; in year t, t=1,..,T: γ_{ijt} -

productivity of fixed assets in year t in i-th sector and j-th technology; δ_{ij} - depreciation rate of fixed assets in i-th sector and j-th technology; τ_{ij} - number of years necessary for the investment to become fixed assets; α_{ij} - use of goods produced in sector M in producing the unit of the gross product of the i-th sector and j-th technology; β_{ij} - use of goods produced in sector E in producing the unit of the gross product of the i-th sector and j-th technology; μ_{ijt} - emission per unit in producing the gross product of the i-th sector and j-th technology in year t.

In the production sectors M, C, I two competing technologies are assumed: the old one, cheaper but emitting more CO2, and the more expensive but cleaner one. In the energy sector E three technologies are available: the old (first) one, cheaper but emitting more CO2; the costlier but cleaner one (second); and the preferred one, the cleanest of them all but economically inefficient (of which the second one can be interpreted as modernized conventional technology, and the third one as renewable energy).

Throughout this paper all variables related to the production capacities, output, export and import are expressed in real terms; the variables derived from income are expressed in money terms.

Production capacity defined as the potential gross output Q_{ijt} of the sector i, i=E, M, C, I; using j-th technology, j=1, 2, 3; in the year t , t=1,..,T; is described by the following one factor production function:

$$Q_{ijt} = \gamma_{ijt} K_{ijt-1}, \qquad (1)$$

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

Actual gross output X_{ijt} of the sector *i*, *i*=*E*, *M*, *C*, *I*; using *j*-th technology, *j*=1, 2, 3; in the year *t*, *t*=1,..,*T*; cannot exceed the production capacity

$$0 \le X_{ijt} \le Q_{ijt}, \qquad j=1, 2, 3;\ t=1,..,T. \tag{2}$$

Total actual output of the *i*-th sector, *i*=*E*, *M*, *C*, *I*; is the sum of outputs produced using available technologies:

$$X_{it} = X_{i1t} + X_{i2t} + X_{i3t}, \qquad t=1,..,T. \tag{3}$$

Stock of the fixed assets K_{ijt} using *j*-th technology, *j*=1, 2, 3; in the *i*-th sector, *i*=*E*, *M*, *C*, *I*; at the end of year *t*; *t*=1,..,*T*; is given by the following equation:

$$K_{ijt} = K_{ij\,t-1}(1-\delta_{ij}) + I_{ij(t-\tau_{ij})} / PP_{I(t-\tau_{ij})}, \tag{4}$$

where I_{ijt} denotes investment in the *j*-th technology, *j*=1, 2, 3; in the *i*-th sector, *i*=*E*, *M*, *C*, *I*; in the year *t*. The average purchase price PP_{It} of the fixed assets acquired from the domestic suppliers and import in year *t* is given by the following expression:

$$PP_{It} = \frac{(X_{IT} - EXP_{It})P_{dIt} + IMP_{It} \cdot P_{fIt}}{X_{IT} - EXP_{It} + IMP_{It}};$$

where P_{dIt} denotes price of the investment goods offered by sector *I* at the domestic market, and P_{fIt} denotes world price of the investment goods; relationship between the domestic and world price is described by the following equation:

$$P_{dIt} = W_I(L)P_{fIt},$$

where $W_I(L)$ is a polynomial lag operator, which describes transmission of the world prices on to the country market of the investment goods. Note that the proportion of domestic versus imported investment goods is constant and equal in all production sectors. This assumption has been motivated by unavailability of detailed data. The same assumption applies to the purchase price of goods produced by sector E and the non-energy intermediary goods produced by sector M. Average purchase prices PP_{Mt}, PP_{Ct} PP_{Et} of goods produced respectively by sectors M, C and E are defined in analogous way.

The average sales price SP_{it} of goods sold by sector i, i=E, M, C, I; in year t, t=1,..,T, to the domestic buyers and for export is given by the following expression:

$$SP_{it} = \frac{(X_{it} - EXP_{it})P_{dit} + EXP_{it} \cdot P_{fit}}{X_{it}}.$$

Output of the i-th sector using j-th technology in year t causes the emissions S_{ijt} of CO2:

$$S_{ijt} = \mu_{ijt} S_{ijt}, \; i=E,\ M,\ C,\ I; \quad j=1,\ 2; \; t=1,..,T. \qquad (5)$$

The total country emission of CO_2 in year t equals the sum of emissions from all sectors and technologies used by these sectors:

$$S_t = \sum_{i=M,E,C,I} \sum_{j=1,2,3} S_{ijt}. \qquad (6)$$

Gross income GI_t is defined as the sum of incomes generated in the sectors E, M, C and I:

$$\begin{aligned} GI_t = & [SP_{Et} - (PP_{Mt}\alpha_{E1} + PP_{Et}\beta_{E1})]X_{E1t} + [SP_{E2t} - (PP_{Mt}\alpha_{E2} + PP_{Et}\beta_{E2})]X_{E2t} + \\ & + [SP_{Et} - (PP_{Mt}\alpha_{E3} + PP_{Et}\beta_{E3})]X_{E3t} + \\ & + [SP_{Mt} - (PP_{Mt}\alpha_{M1} + PP_{Et}\beta_{M1})]X_{M1t} + [SP_{Mt} - (PP_{Mt}\alpha_{M2} + PP_{Et}\beta_{M2})]X_{M2t} + \\ & + [SP_{Ct} - (PP_{Mt}\alpha_{C1} + PP_{Et}\beta_{C1})]X_{C1t} + [SP_{Ct} - (PP_{Mt}\alpha_{C2} + PP_{Et}\beta_{C2})]X_{C2t} + \\ & + [SP_{It} - (PP_{Mt}\alpha_{I1} + PP_{Et}\beta_{I1})]X_{I1t} + [SP_{It} - (PP_{Mt}\alpha_{I2} + PP_{Et}\beta_{I2})]X_{I2t}. \end{aligned} \qquad (7)$$

Each year the country is endowed with a certain number N_t of the emission allowances and its trajectory is determined by the following relationship:

$$N_t = f_N(t, N_{t_d}), \qquad t=1,..,T. \qquad (8)$$

where N_{t_d} denotes the yearly number of the emission permits in the last period. Two variants of the function N_t considered in this paper are presented in Fig. 1d. The mild variant assumes decreasing numbers of the emission permits till 2030, after which it attains steady value of 57% of the 2005 emission level, and the restrictive variant with decreasing numbers of the emission permits till 2050, after which it attains a steady value of 45% of the 2005 emission level.

Disposable income DI_t equals the defined above gross income GI_t, decreased/increased by the debt servicing/income from foreign assets and selling/buying allowances:

$$DI_t = GI_t - r \cdot D_{t-1} + P_{St}(N_t - S_t), \tag{9}$$

where parameter r stands for the interest rate, and variable D_t denotes foreign debt (if positive)/ foreign assets (if negative) at the end of the year t:

$$D_t = D_{t-1} - \sum_{i=M,E,C,I} (EXP_{Et} - IMP_{Et}), \tag{10}$$

where P_{St} stands for the price of the emission permit, while N_t denotes the number of the emission allowances in the year t.

Trade balance of all sectors (the sum in (10)) increases debt if it is negative, and decreases debt if positive. Negative debt is interpreted as foreign assets, which in the year t generate an income equal to $-r \cdot D_{t-1}$. Note also that the excessive emission above the number of the emission allowances has to be purchased in the international market at the emission unit price P_{St}, thus decreasing disposable income. In the opposite situation a country's disposable income is supplemented by the sale of the excessive emission allowances in the international market.

In the balance equations presented below the left-hand side denotes supply consisting of domestic output and import, while the right-hand one consists of domestic demand and export. The balance equation of the sector E is expressed by the following equation:

$$\sum_{j=1}^{3} X_{Ejt} + IMP_{Et} = \sum_{i=M,E,C,I} \sum_{j=1}^{3} X_{ijt}\beta_{E1t} + \rho_t \lambda DI_t / P_{dEt} + EXP_{Et}, \tag{11}$$

where the term $\sum_{i=M,E,C,I} \sum_{j=1}^{3} X_{ijt}\beta_{E1t}$ denotes the consumption of energy in year t in the production sectors *M, E, C, I*; using all technologies available in those sectors, the term $\rho_t \lambda DI_t$ stands for the consumption of energy in the consuming sector. The term $\rho_t DI_t$, $0 < \rho_t \leq 1$, denotes part of the disposable income DI_t in the year t designated for the purchases of the consumption goods, of which $\lambda \rho_t DI_t$ stands for the part of the total consumption expenditures directed for the purchases of energy. Note that the part $(1-\rho_t)DI_t$ of the disposable income equals the total investment expenditures. Coefficient ρ_t reflects current propensity to invest. Coefficient λ, $0 < \lambda \leq 1$, assumed to be constant, denotes a share of the energy expenditures in the total consumption expenditures. It is assumed that the consuming sector buys energy from the domestic suppliers only.

Goods produced by the sector *M* are the intermediary non-energy ones and are sold only to the producing sectors and for export. The gross output of the sector *M* is distributed in the way expressed by the following balance equation:

$$\sum_{j=1}^{3} X_{Mjt} + IMP_{Mt} = \sum_{j=1}^{3} \alpha_{Mj} X_{Mjt} + EXP_{Mt}; \quad t=1,..,T; \tag{12}$$

where the term $\sum_{j=1}^{3} \alpha_{Mj} X_{Mjt}$ denotes consumption of goods *M* in the output of all production sectors and technologies.

Goods produced by the sector *I* are supplemented by import, and part of its output can be directed to export. The gross output of the sector *I* is distributed as described by the following balance equation:

$$\sum_{j=1}^{3} X_{Ijt} + IMP_{It} = \sum_{i=M,E,C,I} \sum_{j=1}^{3} I_{ijt} / PP_{It} + EXP_{It}, \qquad t=1,..,T; \tag{13}$$

where the term I_t, $I_t = (1-\rho_t)DI_t = \sum_{i=M,E,C,I} \sum_{j=1}^{3} I_{ijt}$ denotes total investment in the sectors *M, E, C, I*, and all available technologies in year *t*.

Supply of goods produced by the sector *C* is supplemented by import, while some part of its output can be directed to export. The balance equation of the sector *C* is as follows:

$$\sum_{j=1}^{3} X_{Cjt} + IMP_{Ct} = \rho_t \cdot (1-\lambda) \cdot DI_t / PP_{Ct} + EXP_{Ct}, \qquad t=1, .., T; \qquad (14)$$

stating that the domestic supply of the non-energy consumption goods equals the demand generated by the part of the disposable income directed to purchasing non-energy consumption goods.

Households and the public sector belong to the same sector called the consuming sector, where decisions being made concern: utilization of the production capacities in sectors and technologies; distribution of the disposable income between consumption and investment; technology choice; and the role of the foreign trade.

Decision variables of the model include: the actual gross outputs in sectors and technologies; investment in the capital assets in sectors and technologies; and the foreign trade balances of all production sectors:

$$\begin{aligned} &X_{E1t}, X_{E2t}, X_{E3t}, X_{M1t}, X_{M2t}\, X_{C1t}, X_{C2t}\, X_{I1t}, X_{I2t}, I_{E1t}, I_{E2t}, I_{E3t}, I_{M1t}, I_{M2t}\, I_{C1t}, I_{C2t}\, I_{I1t}, I_{I2t}, \\ &EXP_{Et}, EXP_{Mt}, EXP_{Ct}, EXP_{It}, IMP_{Et}, IMP_{Mt}, IMP_{Ct}, IMP_{It}. \end{aligned} \qquad (17)$$

The inequality constraints are as follows.

Non-negative outputs, investments, exports and imports:

$$X_{E1t}, X_{E2t}, X_{E3t}, X_{M1t}, X_{M2t}\, X_{C1t}, X_{C2t}\, X_{I1t}, X_{I2t}, I_{E1t}, I_{E2t}, I_{E3t}, I_{M1t}, I_{M2t}\, I_{C1t}, I_{C2t}\, I_{I1t}, I_{I2t} \geq 0. \quad (18)$$

Investment rate, defined as a ratio I_t / DI_t, cannot exceed the maximum propensity to invest:

$$I_t / DI_t \leq \sigma_{I/DI}, \qquad (19)$$

where $\sigma_{I/DI}$ denotes the maximum value of the investment to income ratio.

The above constraint reflects social resistance to the exceedingly high propensity to invest. The propensity to consume ρ_t is also constrained from beneath:

$$\rho_t \geq \sigma_{cons/DI}, \tag{20}$$

where coefficient $\sigma_{cons/DI}$ denotes the minimum value of the consumption to income ratio.

Another set of constraints deals with the feasible shares of foreign trade in the output of sectors. The following constraints:

$$\sigma_{IMP/X} \leq \frac{IMP_t}{X_t} \leq \sigma_{IMP/X}, \qquad j= M, E, C, I; \tag{21}$$

$$\sigma_{EXP/X} \leq \frac{EXP_t}{X_t} \leq \sigma_{EXP/X}, \qquad j= M, E, C, I; \tag{22}$$

impose maximum proportion of import and export respectively, in the national supply of the given product, where coefficients $\sigma_{IMP/X}$ and $\sigma_{EXP/X}$, j = *M*, *E*, *C*, *I*; denote respectively the maximum ratio of import and export of a given product to its national gross output.

The following two constraints:

$$-r^{(-)}_{INV\,i\,j} \leq \frac{I_{i\,j\,t} - I_{i\,j\,t-1}}{I_{i\,j\,t-1}} \leq r^{(+)}_{INV\,i\,j}, j=1, 2, 3; \qquad j= M, E, C, I; \tag{23}$$

$$-r^{(-)}_{cons} \leq \frac{\rho_t DI_t - \rho_{t-1} DI_{t-1}}{\rho_{t-1} DI_{t-1}} \leq r^{(+)}_{cons}, \tag{24}$$

limit relative increases and decreases of investments in sectors and total consumption, respectively, where parameters $r^{(-)}_{INV\,i\,j}$ and $r^{(+)}_{INV\,i\,j}$ stand for the lowest and highest admissible rate of increase of the investment in technology *j*, *j*=1, 2, 3; *i*= *M*, *E*, *C*, *I*; while $r^{(-)}_{cons}$ and $r^{(+)}_{cons}$ denote the lowest and highest admissible rate of the consumption change respectively. In particular, the constraint (24) reflects social sensitivity to the changes in consumption and a possible resistance to them.

The following constraint reflects policy decisions concerning the desired share of a certain technology in the total output of a certain sector. In the current version of the model this constraint is the consequence of the requirement that in the energy sector the share of the renewable technology should be at least equal to 20 % from the year 2030:

$$\frac{X_{E3t}}{X_{E1t} + X_{E2t} + X_{E3t}} \geq 20\% \; ; \; t \geq 2030 \, . \qquad (25)$$

The last constraint limits the possibility of the excessive debt/credit relative to gross income (the so called Maastricht parameter)

$$-0.60 \cdot GI_t \leq D_t \leq 0.60 \cdot GI_t \, . \qquad (26)$$

The economic development's overall goal is maximization of the discounted future consumption given by the following expression:

$$PVC = \sum_{t=t_0}^{T} \rho_t DI_t (1 + r_d)^{-(t-t_0)} \qquad (27)$$

subject to the constraints (1)- (26), where r_d denotes the discounting rate and $\rho_t DI_t$, $t = t_0$, t_0+1, t_0+2, ... , T, denote future consumption rates.

The minimization of emissions was another considered goal. Here multicriteria optimization aims at the harmonization of two conflicting objectives: maximization of the discounted future consumption and minimization of the cumulated CO2 emissions (see Appendix). Such an approach was applied in Gadomski, Kruś, Nahorski (2016), and is suitable in the negotiations or training.

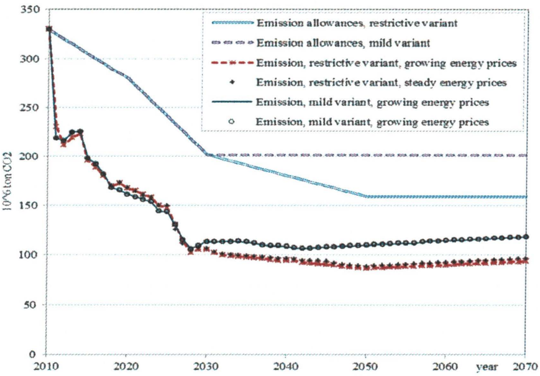
The data were sourced mainly from the Head Statistical Office (2011). It was necessary to transform the available data into a relevant form. The reaggregation method of the original input-output table was performed as follows. The energy sector E was created by aggregating the following products: (i) Coal and lignite; (ii) Crude petroleum and natural gas; (iii) Coke, refined petroleum products; (iv) Electricity, gas, steam and air conditioning. The product of the sector E is interpreted further as the energy produced for the needs of the sector E and all other sectors, as well as tradeable goods in the foreign trade. Products of other sectors were classified respectively as: M – the non-energy intermediary inputs in other production sectors, C – non-energy goods used in the consuming sector (consisting of households and the public sector), and I - investment goods serving for creation of fixed assets exploited in the production sectors. The structure of the end uses of goods served also as a structure for decomposition of exports and imports of the original sectors. The new sectors were created by summing up all similarly classified parts of the original sectors; the same procedure was used in determining the exports and imports of the new sectors. The initial values of variables were taken from the reaggregated input-output table and data concerning fixed assets. In particular, the productivities of the fixed assets were estimated on the basis of the reaggregated input-output table of the Polish economy, see: Central Statistical Office, Republic of Poland (2011). All calculations have been performed using OpenSolver optimizer for Microsoft Excel.

2. Results of the analysis

The analysis has been performed using two development scenarios in two variants. The scenarios differ in the severity of the final emission constraint and the timing of imposing them. All simulations shared an assumption that the productivity of capital of the old technologies in sector M, E, C and I would rise by 0.1% per year, in second (cleaner) technologies in all sectors by 1% per year, and in the third (renewable) technology in the sector E by 2% per year. Emission intensity of output would be constant in all first technologies, would decrease by 0.5% per year in all second technologies, and would be zero and constant in the third technology of the sector *E*. Both material and energy intensities of output would remain constant over the whole simulation period. Two variants differ in the assumption concerning the future development of the energy prices; we consider steady world energy prices at the 2010 level in the first variant, and 0.5% yearly rise of the world energy prices in the second. The above assumptions were intended for an analysis of the impact of the assumed technical progress on the level and structure of output and consumption, as well as foreign trade.

In both scenarios and variants the technologies used in all sectors are instantly changed to the less polluting ones; in the case of the sector *E* both the second and third (renewable) ones are employed in effect of the adopted constraint. This change is caused by high prices of emission allowances.

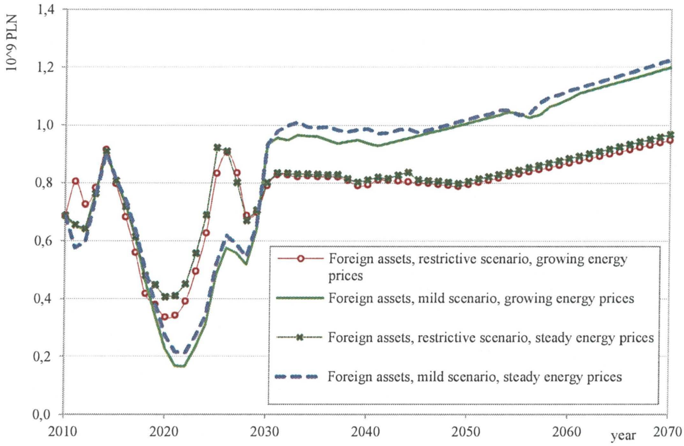
Two stylized trajectories of the emission allowances allotted to Poland and corresponding to two scenarios, the restrictive and mild respectively, are presented in fig. 1. The restrictive scenario assumes reduction of the amount of the emission allowances to 45% of the 2005 level in 2050 and then levelling off, while the mild scenario assumes 57% of the 2005 level in 2030 and then levelling off.



Source: own computations

Fig. 1. Trajectories of decreasing numbers of the emission allowances in the restrictive and mild scenarios and adjusted emissions in variants with and without rising energy prices.

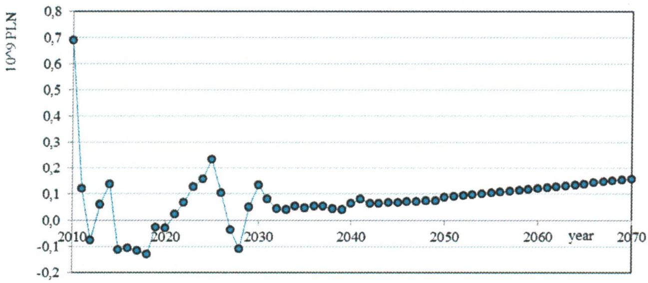
The above figure indicates that in both scenarios and variants emitting below emission allowances and selling surpluses is the optimum behavior. This thesis is supported by fig. 2, which shows that foreign assets are positive in all scenarios and variants; this indicates that the sold surpluses are used for building foreign assets, which generate income. One can notice that there is no qualitative difference between the scenarios and variants; there is a tendency to shift production abroad as a result of growing energy prices.



Source: own computations

Fig. 2. Foreign assets generating income in both scenarios and variants.

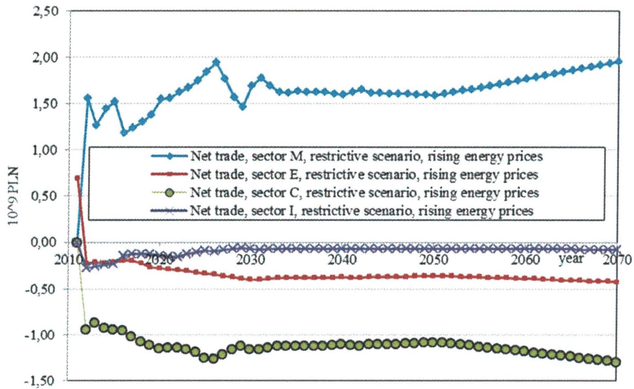
Foreign trade plays an important role as it facilitates technology conversion. Fig. 3 shows that after initial turmoil the net trade stabilizes and grows like production sectors.



Source: own computations

Fig. 3. Macroeconomic net foreign trade in the restrictive variant.

Sectoral net foreign trades in the restrictive variant (other variants behave likewise) are presented in fig. 4, which shows that positive net trade occurs in sector *M*, while the net trades of the sectors *E*, *C* and *I* remain negative. Together with the conclusions from Fig.3, this indicates that the net export from sector *M* is larger than net import of sectors the *E*, *C* and *I*.



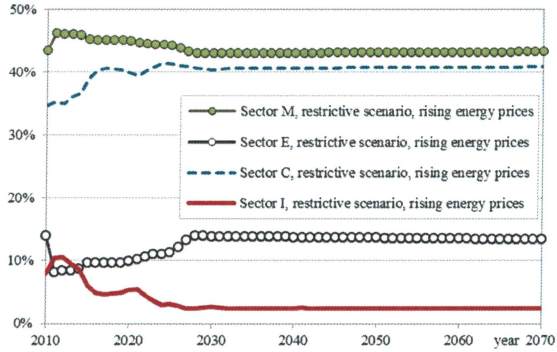
Source: own computations

Fig. 4. Sectoral net foreign trades in the restrictive variant.

Evolution of the sectoral structure of output is presented in Fig. 5. The share of the sector *E* output in total output increases and stabilizes at the level significantly higher that the share of sector *I*. Shares of sectors *M* and *I* decrease and then level off. As to the quantitative decrease of the share of the sector *I* in total output it is necessary to realize that it is one of the main bearers of the technical progress.

The development of GDP in two version and scenarios is presented in Fig. 6, where one can notice that in the initial period, when the conversion is being performed, GDP stagnates (in the case of the restrictive variant enters a period of recession) only to resume steady growth after the economy as the whole has achieved new structural equilibrium. On the basis of Fig. 6 one can conclude that rising world energy prices have a limited impact on the GDP.

Real consumption follows the development of GDP, see Fig. 7, but the consumption reveals greater sensitivity to rising world energy prices.



Source: own computations

Fig. 5. Shares of sectors in total output, restrictive variant (other variants and scenarios are similar).

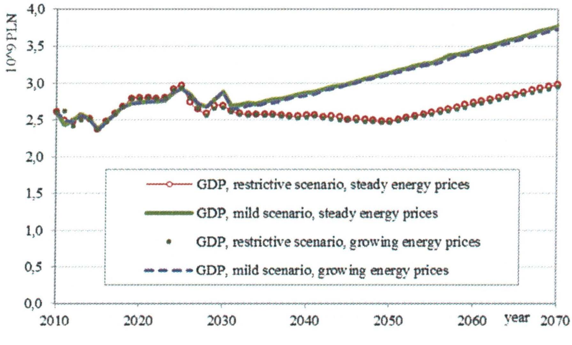


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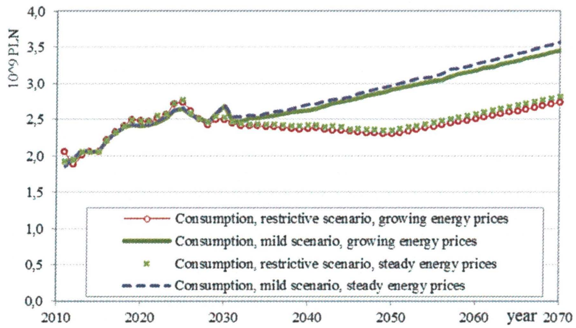
Fig. 6. GDP in constant prices in the restrictive and mild variants and two scenarios of the development of the energy prices.



Source: own computations

Fig. 7. Consumption in constant prices in the restrictive and mild variants and two scenarios of the development of the energy prices.

3. Conclusions

The desired technology conversion consisting in changing the old polluting technologies to the cleaner but more expensive ones depends, as the simulations confirmed, on the relevantly high prices of the emission allowances allotted to the countries being subjects of the emission mitigation policy. Without relevantly high prices the process of technological conversion does not occur in all sectors or lasts much longer. The change of the production technologies causes stagnation or recession (depending on the scenario and variant considered) followed by a period of steady growth with the rate determined by the improved parameters describing productivities of capital in sectors, as well as the emission, material and energy intensities.

Two variants were considered: mild and restrictive. The mild one assumes that the stylized trajectory of the emission allowances would decrease till 2030, and from then on would stabilize at 57% of the reference 2005 emission level. The restrictive variant is based on the assumption that the numbers of the emission allowances would decrease till 2050 and then stabilize at 45% of the reference 2005 emission level.

Two scenarios concerning future development of the world energy prices (the world prices of the products of sectors *M*, *C* and *I* were assumed to be unchanged): a steady one with constant world energy prices, and the rising one with world energy prices growing steadily at a rate of 0.5% per year. The cost of the reduction of the emission from the mild to restrictive level is presented in Fig. 8.

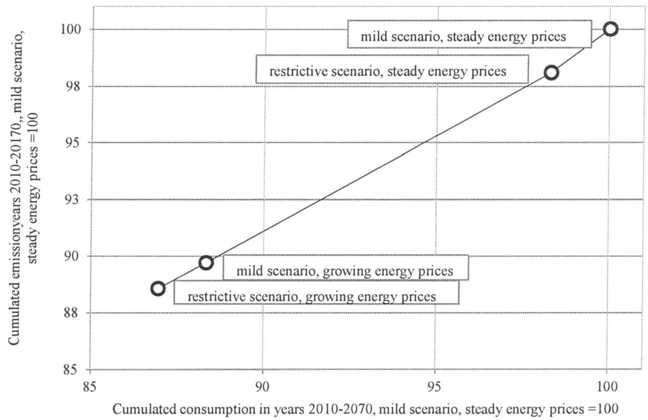


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Fig. 8. Cost of the emission reduction from the mild version and scenario with steady energy prices.

Amounts of allowances allotted to the country have stronger impact on the consumption than the prices of energy.

Adopted assumptions seem to petrify structure of Polish economy; positive net export of intermediary materials is exchanged for the imports mainly of the consumption goods and energy, and to the lesser extent for the investment goods, but also increases assets abroad. The latter suggest increasing inequalities as the ownership of the assets kept abroad is not egalitarian.

In assessing the above presented results one should have in mind limitations of the model. In the real economy the general assumptions of the model are not satisfied. Neither there is perfect allocation of the resources, nor the general interests of the state matches that of the individual firms and persons. Also, one important factor has been omitted, namely the impact of the climate warming, which, as is widely believed, deteriorates technology parameters. However, results of this model can be used as a reference: in the real world the adjustment processes would last longer, and in particular achievement of the new structural equilibrium would also last longer.

We are convinced that the presented model can be easily adapted to other small country economies having similar economic data based on SNA.

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Appendix

Bi-criteria optimization problem

An analysis of the impact of the CO2 limiting policies on economic growth has been conducted, taking into account the harmonization of two objectives. The first refers to maximization of the discounted consumption. The second relates to the necessary decrease of CO2 emissions. Decrease of CO2 emissions is implemented by allotting to a country a prenegotiated diminishing amount of the emission allowances for a given time period. In this study, a linear-wise pathway of emission allowance limits is assumed. The pathway trajectories are formed by joining values of emission allowance limits in the initial year, in the intermediate years, and in the destination year, which is the first year of the last considered period (see Fig. 1). The numbers of emission allowance limits in the intermediate years are assumed according to the emission curbing EU policy. The amount of allowances in the final period is a subject of the negotiations and is treated as the second criterion to be minimized. The actual CO2 emission time trajectory in our study can of course differ from the assumed pathway, due to allowed trade of the allowances.

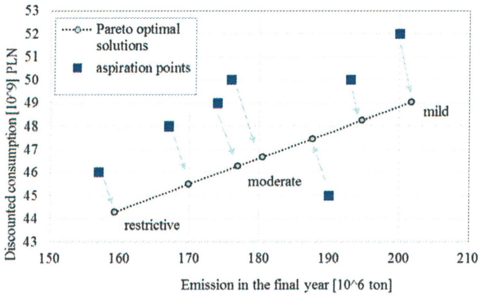
The following bi-criteria optimization problem is formulated and analyzed. Let $y(x)=[y_1(x), y_2(x)]$ denote the vector of the criteria, where y_1 is the discounted consumption (27) to be maximized, and y_2 is the number of the emission allowances to be minimized in the destination year t_d, x is a vector of decision variables (17). The model relations can be described in the form $\boldsymbol{A}x\leq b$, where $\boldsymbol{A}$ is the matrix and b is the vector of the coefficients. The problem is considered in two spaces, that of the decision variables, and that of the criteria. The model constraints define the set $\boldsymbol{X}_0$ of admissible values of the decision variables in the first space. In the second two-dimensional space there exists the set $\boldsymbol{Y}$ of attainable values of the criteria (outcomes). Decision variables leading to the nondominated (Pareto optimal) points in the set ***Y*** are looked for. The set ***Y*** is not given explicitly.

The above multicriteria optimization problem is solved using the reference point approach (Wierzbicki et al. 2000). A respective computer-based system has been elaborated which generates the Pareto optimal solutions in an interactive way similarly as in (Gadomski et al. 2016). Assuming and assigning different reference values for the criteria and solving the resulting optimization problems, different Pareto optimal outcomes and decision Results of the interactive multicriteria analysis are presented in Tab. A1 and Fig. A.1. Table A.1 presents assumed aspiration points and obtained Pareto-optimal outcomes. The case 1 called the restrictive variant relates to the maximum possible decrease of the number of the emission allowances in the destination year, for which the lowest feasible consumption constraint is active. It is the solution of the single criterion optimization problem with minimization of the emission allowances number in the destination year. It represents the greatest possible decrease of the emission allowances for the destination year within the assumed constraints. In the case 7, called the mild variant, there is no decrease of the number of emission allowances 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 allowances in the destination year. For different aspiration points assumed in the space of these two criteria, represented in Fig. A.1 by small squares, the optimized nondominated points, represented by small circles, 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 which is approximated in Fig. 1 by the dotted line. The outcomes located to the left of the Pareto frontier are unattainable, i.e. they do not belong to the set Y.

Table 1. Selected results of the multicriteria analysis

	Aspiration points		Pareto optimal solutions					
Variant	Emission in the final year	Discounted consumption [10^9] PLN	Decrease of emission compared to the initial	Emission in the final year [10^6 ton]	Discounted consumption [10^9] PLN	Decrease of consumption compared to the mild scenario in %	Cumulated consumption [10^9] PLN	Cumulated emission [10^6] ton
1 restrictive	157	46	45%	159,3	44,3	9,69%	143,3	22 047
2	167	48	48%	169,9	45,5	7,26%	150,4	23 008
3	174	49	50%	177,0	46,3	5,65%	155,0	23 649
4 moderate	176	50	51%	180,5	46,7	4,84%	157,4	23 969
5	190	45	53%	187,6	47,5	3,22%	162,1	24 609
6	193	50	55%	194,7	48,3	1,61%	166,7	25 250
7 mild	200	52	57%	201,7	49,0	0,00%	171,4	25 891

Source: own computations



Source: own computations

Fig. A.1. Results of the interactive multicriteria analysis. The dotted line approximates the Pareto set.

Two variants of the trajectory of numbers of the emission allowances were chosen for more detailed presentation: the mild and restrictive one. The former assumes that from year 2030 on the final yearly amount of allowances is equal to 57% of 2005 emission level and the latter assumes that from year 2050 on the final yearly amount of allowances is equal to 45% of 2005 emission level, see Fig.1). Main macroeconomic indicators that are $CO2$ emissions, GDP and consumption, are presented in Fig. 1, Fig. 6 and Fig. 7.