Large scale, multi-sector DSGE model as a climate policy assessment tool*

- Macroeconomic Mitigation Options (MEMO) model for Poland -

INSTYTUT BADAŃ STRUKTURALNYCH

Institute for Structural Research[†]

Maciej Bukowski[‡], Pawel Kowal

IBS WORKING PAPER #03/2010

July 27, 2010

---

[*] Authors acknowledge that this paper was prepared within the World Bank project: *Country Economic Memorandum: Transition to a Low Carbon Economy in Poland*

[†] Address: Institute for Structural Research, ul. Rejtana 15 lok. 24/25, 02-516 Warsaw, Poland

[‡] contact author, maciej.bukowski@ibs.org.pl, www.ibs.org.pl

Abstract

We assess the macroeconomic impact on Polish economy of the diversified package of about 120 different GHG mitigation levers, which were identified in the bottom-up sectoral analysis. For this purpose, we constructed a large scale, multi-sector dynamic stochastic general equilibrium (DSGE) model of Polish economy. Despite its size (compared to most of the other models in this class) our model has been directly calibrated on the latest statistical data for Poland and the EU. This applies both with respect to the calibration of its steady-state and dynamic properties. In the second stage, we focused on empirical moments and among them on relative standard deviations and inter-variable correlation structure, as those two aspects are of primary importance for model's predictive quality. We managed to adjust our model to dynamic properties of the data with only few macroeconomic shocks. In our opinion, this means an important step forward as compared to the other large scale DSGE models like seminal Smets-Wouters one. Good empirical properties of our model justify its application as a macroeconomic policy assessment tool in medium and long term horizon. In contrast to the traditional CGE approach, DSGE modeling enables us to analyze full dynamic, year-by-year, macroeconomic response to the GHG abatement policies over the entire 2010-2030 period. We present conditional macroeconomic projections of the entire abatement package as well as its decomposition into several major subgroups including: investments in energy capacity (fuel switch), industry or agriculture interventions, and energy and fuel efficiency improvements. We considered alternative government tax and expenditure closures in order to compare the macroeconomic results depending on the fiscal policy measures. This allowed us to construct detailed macroeconomic versions of marginal abatement curves which show the macroeconomic effects related to carbon abatement for Poland's economy for every individual levers and the package as a whole.

Keywords: Muti-sector DSGE models, GHG abatement, CO2 mitigation, climate policy, conditional forecasts, energy efficiency, Energy and the Macroeconomy, Government Policy, Energy forecasting technological change.

JEL Classification Numbers: C61, C67, C68, E37, Q43, Q48, Q51, Q54

1 Introduction

It is argued by many scientists that the observed rise in a global temperatures in the last 200 years should be associated with the anthropogenic emission of large amounts of CO2 and other greenhouse gases (GHG) mainly by industrial economies of the West. It is also believed that without significant shift in the environmental policy and limiting the emissions there is a serious danger of large and permanent rise in the earth temperatures in the next 100 years. Major example is the Intergovernmental Panel on Climate Change fourth Assessment Report (IPCC, 2007) that states that global warming is certain phenomenon despite the fact that projected temperatures rise ranges from 1-6 degrees Celsius in this period. Significant increase in the frequency of natural disasters such as droughts, floods or hurricanes is expected to occur as a consequence of global warming together and systemic changes in the sea level and ice covers can seriously endanger the existence of many very populated coast areas around the world, leading to the non negligible socio-economic losses.

This kind of reasoning encouraged policy makers to undertake actions that aim at significant reductions of CO2/GHG emissions in Europe. It is now openly stated in the "EU 2020" document that European economic policy should be much more "green oriented" than before. Despite the fact that the other major global players (e.g. USA, China, India, Russia) are less proactive with respect to these issues, EC seems to be determined to enforce its strategy. After the relative failure of late 2009 Copenhagen summit the EU plans to run unilateral climate policy while trying, unsuccessfully so far, to convince the rest of the world to undertake emission reduction commitments for the medium and long term.

This policy can be challenging to implement for most of the New Member States, as those countries are much more dependant on traditional heavy industry branches and coal power plants than their west European partners and at the same time their catching-up process with the most developed economies of the World is far from ending. Therefore the European climate action agenda is criticized and debated in those countries and in particular in Poland that belongs to the most coal based economies in Europe. One major question mark can not be ignored in this context is the overall macroeconomic and welfare cost of potential GHG abatement policies for relatively less developed and at the same time more coal oriented economies of Central Europe. This question mark is especially sound if we take into account that Northern Europe in general and Poland in particular could rather benefit from global warming due to higher humidity and longer vegetation period. If this casual claims materialize bearing the social and economic costs of mitigation policy can be unattractive option for Polish society especially if those costs will be too large to be balanced with benefits of non-economic nature like improvement un the international position and/or perception of the country. Having this in mind the quantitative, multidimensional ex-ante impact assessment of macroeconomic costs/benefits from the implementation of climate policies in the NMS in general and in Poland in particular, is crucial for the success of the EU climate policy on the continent scale.

In the literature there is a very wide range of quantitative studies that try to assess a potential costs and/or macroeconomic impact of proposed environmental policy changes and understand what kind of causal chains are present between various GHG abatement options and their consequences. As this kind of policy is an ongoing issue, classical ex-post empirical analysis is not a viable option. Therefore those studies are normally composed of counterfactual ex-ante comparisons, comparing the costs/outcomes of the reforms in place with what would have happened had they not been undertaken. Their primary focus is purely economic as they concentrate either on the careful microeconomic cost-benefit analysis or general equilibrium macroeconomic impact on GDP level and growth. At the same time only very limited rigorous policy impact assessments have been prepared for Poland being the largest and most coal-oriented economy among the New Member States. An example of the microeconomic non-general equilibrium approach could be found in the McKinsey country report published in the early 2010 called "Assessment of Greenhouse Gas Emissions Abatement Potential in Poland by 2030". On the other hand macroeconomic type of ex-ante research performed with the simple CGE type of model was presented in the Energsys report ("Impact of the Proposed EU Energy and Climate Policy on the Polish Energy Security", Synthesis 2008). None of them takes into account welfare and alternative costs analysis significantly reducing our understanding of short, medium and long term impact of these policies on Polish economy. As a result the information basis for wise public decision making is substantially limited.

Research on CO2 mitigation options that is broadly represented in the contemporary literature in the field normally starts with the choice of modeling tool that will be used for counterfactual policy assessment. Three main decisions must be undertaken: (i) sectoral details of the model against its macroeconomic relevance, (ii) degree of direct utilization of statistical data, and (iii) the richness of behavioral assumptions for economic agents. As there is always a trade off between those dimensions, different authors made different choices of their methodology usually focusing only on one of them. Although in general, there is no macroeconomic model type, which perfectly answers to all demands of multidimensional, economy-wide climate policy impact assessment, there is often stated in the literature that only general equilibrium models are capable to provide sound and flexible backbone for such analysis. Throughout the years the computable general equilibrium (CGE) modeling framework became dominant in the literature of the field. Its major weakness is however the limited dynamic structure and perfect foresight approach. In this article we would like to show that fairly good compromise between large sectoral disaggregation, data proximity of the model and detailed, realistic representation of the economic agents behavior can be achieved in the DSGE type of model. Major limitation of DSGE methodology i.e. the model size limit must have been overcome in order to construct the large scale, multi-sector macroeconomic model of this class. Because of this limitation the multi-sectoral structure based on Input-Output flow tables, typical for CGE modeling, have been incorporated in DSGE models only exceptionally and in the limited way. We show that large scale DSGE model can be successfully fitted to both short and long term data, and its perturbation solution utilized to form the conditional forecast of economic policy and shock transmission in the economy. In that way we try to step ahead of contemporary literature by applying the fully dynamic and stochastic type of model to the climate policy issues and simultaneously explaining the interlinks between origin and spending of environmental measures and calculating their impact not only on macroeconomic variables like GDP, employment and unemployment but also on agents' welfare.

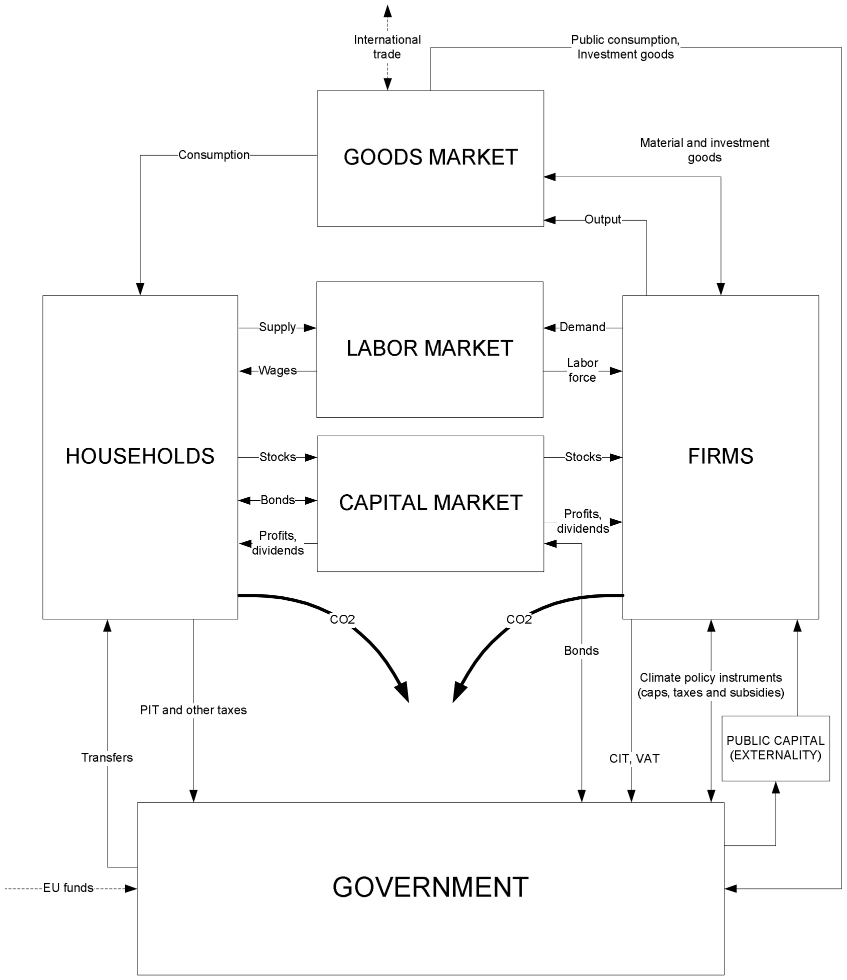
The dynamic structure of the DSGE model let us perform all necessary calculations in the dynamic way e.g. in different time horizons important from the perspective of policy makers. In contrast to the typical research in the field we make conditional macroeconomic projections for the 2010-2030 period focusing our attention not on the purely macroeconomic measures like carbon taxes but rather on the detailed microeconomic package consisted of potential GHG abatement options identified by McKinsey in their report on Poland. In particular we consider seven major types of mitigation levers including: investments in energy capacity (fuel switch), industry or agriculture interventions, and energy and fuel efficiency improvements. We are able to construct the macroeconomic versions of marginal abatement curves which relate the macroeconomic impact of individual policies with their abatement potential. All effects are analyzed in alternative fiscal frameworks as different government tax and expenditure closures are considered. In that way we show that overall assessment of the climate policy packages may, especially in the medium term, strongly depend on the way it is composed and implemented.

2 Model structure

2.1 Main model segments

Model is divided into three main blocks: (i) households, (ii) firms, and (iii) government. Those blocks are interconnected one with another on three separate markets: (i) labor (ii) capital, and (iii) goods market (see Figure 1). Households supply labor, decide on the level of their consumption as well as for government bonds and firm stocks. Households communicate with producers on labor market where wages are negotiated and vacancies filled. This market is operated by a special intermediatory firm that buys labor from households and sells it to firms in eleven production sectors: (1) agriculture with food industry, (2) light industry, (3) heavy industry, (4) mining and fuels, (5) energy, (6) construction, (7) trade, (8) transport, (9) financial services, (10) public services, (11) other services. In each sector there are firms producing basic goods using capital, labor and materials (including energy) as inputs. The structure of the production process is presented in figure 2. In exchange for they work and savings they receive dividends and wages from firms and interest payments from government, paying at the same time taxes directly imposed on them by government. Firms produce final goods that are later consumed by households, re-invested by producers or utilized by government. Both production and consumption evoke green house gases (GHG) emission, that is modeled on sectoral and household level. In the production process, that we describe in detail in section 2.3, firms employ labor, capital, intermediate goods and energy. As they are owners of capital, and have some monopolistic power their profits are positive allowing them to pay dividend for their shareholders. Apart from it they also pay income and value added taxes to government. Government divides its tax income and EU funds subsidy into public investments, public consumption and social transfers to households for unemployed and retired. In the goods market prices

Figure 1: Main blocks of the model and their interrelations



for consumption, investment and intermediate goods are set. Firms purchase materials and investment goods from other companies and utilize them them as inputs in the production process. Furthermore, the latter may be bought by the government to improve economical environment for the firms and households. In the labor market the wages are set to equalize labor market and supply. Labor market is non-Walrasian as a job search mechanism and centralized wage negotiations between employees and employers are implemented. Therefore, unemployment rate is higher than zero. Capital market allows borrowing through the issue of bonds. Furthermore, companies may share their profits with households paying out dividends and rise capital issuing stocks. Thus capital market allows for streaming sources of financing from households to firms and smoothing consumption over time of the former. Formal description of the model is presented in following sections.

2.2 Households

In time $t \geq 0$ our model economy is populated with POP_t consumers that form a representative household consisted of employed and non-employed (either unemployed or non active) members. Household maximizes expected discounted utility from a stream of consumption that can be recursively written as:

$$\begin{aligned} U_t &= u_T + \beta \times E_t \left[U_{t+1} \left(\frac{U_{t+1}}{U_t^L} \right)^{\epsilon_U} \right] \\ U_t^L &= \omega^U \times U_{t-1}^L + (1-\omega^U) \times U_{t-1} \\ u_t &= N_t \times u(C_t^N, L_t^E) + NE_t \times u(C_t^U, L_t^U) \\ u(C_t, L_t) &= \frac{1}{1-\sigma} \left[\left[C_t (L_t)^{\omega} \right]^{1-\sigma} - 1 \right] \end{aligned}$$

where L_t^E and L_t^U denote leisure time of persons employed and unemployed respectively. Similarly N_t is a number of employed and $NE_t = POP_t - N_t$ is a number of not employed household members, that consume respectively, C_t^N, and, C_t^U, in time t. Note that, although in the steady state utility U_t reduces to the standard form, its dynamic properties are modified because of the term $\left(U_{t+1}/U_t^L \right)^{\epsilon_U}$ that incorporates lagged utility U_t^L. Its presence strengthens the intertemporal substitution effect and increases the response of labor supply to shocks. Elasticity parameter ϵ_U controls this effect.

We assume that there is no perfect diversification of risk concerning loss of a job between working and not working members of a household that the government provides non-retired, non-employed household members with net transfer T_t^H. Formally it means that:

$$(1+\tau_t^G) \times C_t^N = C_t^B + (1-\tau_t^W) W_t - T_t^N \tag{1}$$

$$(1+\tau_t^G) \times C_t^U = C_t^B - T_t^{NE} + T_t^H \tag{2}$$

where C_t^B denotes the base consumption of an individual given by the following equation:

$$P_t^C C_t^B = \frac{1}{POP_t} \times \left[(1-\tau_t^D) \times \Pi_t + B_{t-1}^{hh} - \frac{B_t^{hh}}{R_t} + B_{t-1}^{hf} \frac{q_t^f}{q_{t-1}^f} - \frac{B_t^{hf}}{\varrho_t R_t^f} \right] \tag{3}$$

where P_t^C is a price of a consumption good, Π_t is a profit of household-owned firms, B_t^{hh} is a number of domestic and B_t^{hf} number of foreign non-risky assets (government bonds) owned by a household at time t. Profit is non-zero because firms are owners of capital. Moreover, , $R_t = 1 + r_t$ and $R_t^f = 1 + r_t^f$ are real interest rates on domestic and foreign bonds respectively, ϱ_t is risk premium on foreign interest rate, W_t^c is a real gross wage per 1 hour of work, τ_t^D is a profit tax rate, τ_t^W denotes total wage tax rate whereas τ_t^G is a general tax rate described in the government section below. Moreover, T_t^N and T_t^{NE}, denote mutual transfers inside the household to people employed and non-employed accordingly, that satisfy the following equation:

$$N_t \times T_t^N + NE_t \times T_t^{NE} = 0 \tag{4}$$

In case of perfect diversification of unemployment risk those transfers would be set in such a way, that marginal utility of consumption of employed and non-employed would be equal. However, an extent of these mutual insurances is reported to be limited. Therefore, it is assumed in the model that $T^N = T^{NE} = 0$ in the steady state which means that only the base consumption is distributed among the members of a household while labor profit and government transfers finance the consumption of, accordingly, employed and non-employed members exclusively. This condition implies that there exists a constant $\bar{\omega}^T$ such that:

$$\frac{\partial u(C_t^U, L_t^U)}{\partial C_t^U} = \bar{\omega}^T \frac{\partial u(C_t^N, L_t^E)}{\partial C_t^N} \tag{5}$$

inducing the steady state values of C^U and C^N to be set in such a way that $T^N = T^{NE} = 0$ (no diversification of risk within household). For the sake of simplicity, it is assumed that representative household may change only an extensive labor supply, N_t, whereas intensive labor supply can fluctuate only with response to shocks $L_t^E = \bar{L}^E + \xi_t^L$, where ξ_t^L is an intensive labor supply shock that we use for calibration purposes of our model dynamics. On the other hand labor search intensity h_t^U of non-employed is not constant and can be adjusted to shocks. It affects leisure time of non-employed in following way

$$L_t^U = 1 - \bar{\omega}^U (h_t^U)^\chi \tag{6}$$

where χ is a leisure elasticity with respect to search effort h_t^U and $\bar{\omega}^U$ is a parameter set in such a way that $h^U = 1$ i steady state i.e. it is equal to long term labor search intensity of non-employed household member measured in hours. Decisions concerning labor supply is affected by labor market frictions implied by inefficiencies of matching between jobs offers posted by firms and unemployed consumers looking for a job. Consequently, when calculating shadow price of labor supply, Γ_t, household takes into account that:

$$N_t = (1 - \delta^N) N_{t-1} + \Phi_t NE_{t-1} \times h_t^U \tag{7}$$

where probability of finding a job, Φ_t, is exogenous from the point of view of the household (but not from the point of view of the economy). Finally, total consumption of household sector, C_t, is defined as

$$C_t = N_t C_t^E + NE_t C_t^U + T_t^R \tag{8}$$

where T_t^R denotes the government transfers to retired household members. Hence, for the sake of simplicity we assume that there is a fixed number of retirees that consume their entire income. Their behavior is not modeled explicitly. Total consumption expenditures $C_t^{EXP} = P_t^C C_t$ let us to define the welfare loss/gain W_t^L

$$W_t^L = \frac{U_t - \overline{U}}{U_t^C} \tag{9}$$

$$U_t^C = \lambda_t^c C_t^{EXP} + E_t U_t^C \tag{10}$$

$$\tag{11}$$

In other words welfare loss is defined as a deviation of the total utility U_t from its steady state $\overline{U}$ equivalent to the permanent change in consumption expenditure U_t^C. Note that a Lagrange multiplier λ_t^c recalculates consumption expenditure to utility units.

2.3 Firms

2.3.1 Production structure

There are eleven sectors in the model: (1) agriculture and manufacture of food products (AGR), (2) light (manufacturing) industry (LIND), (3) heavy industry (HIND), (4) energy and heat production (ENG), (5) coal mining and fuel production (FLS), (6) construction services (CST), (7) transport services (TRN), (8) financial services (FIN), (9) public services (PUB), (10) retail and whole trade services (TRD) and (11) other services (SRV). Production is divided into four stages (see 2). In the first stage basic sectoral good is produced by a perfect competitive firms that employ capital, labor, materials and energy as production factors. This good is thereafter differentiated by price setting firms and sold to the trading firms operating both on domestic and foreign sectoral market. Finally, production of trading firms is bought by basic good producers (in the form of intermediate demand) and three types of final good producers yielding (1) investment (2) government and (3) private consumption good. Final production is traded on the goods market with households, basic producers and government according to the flows established from the input output matrix.

2.3.2 Production firms

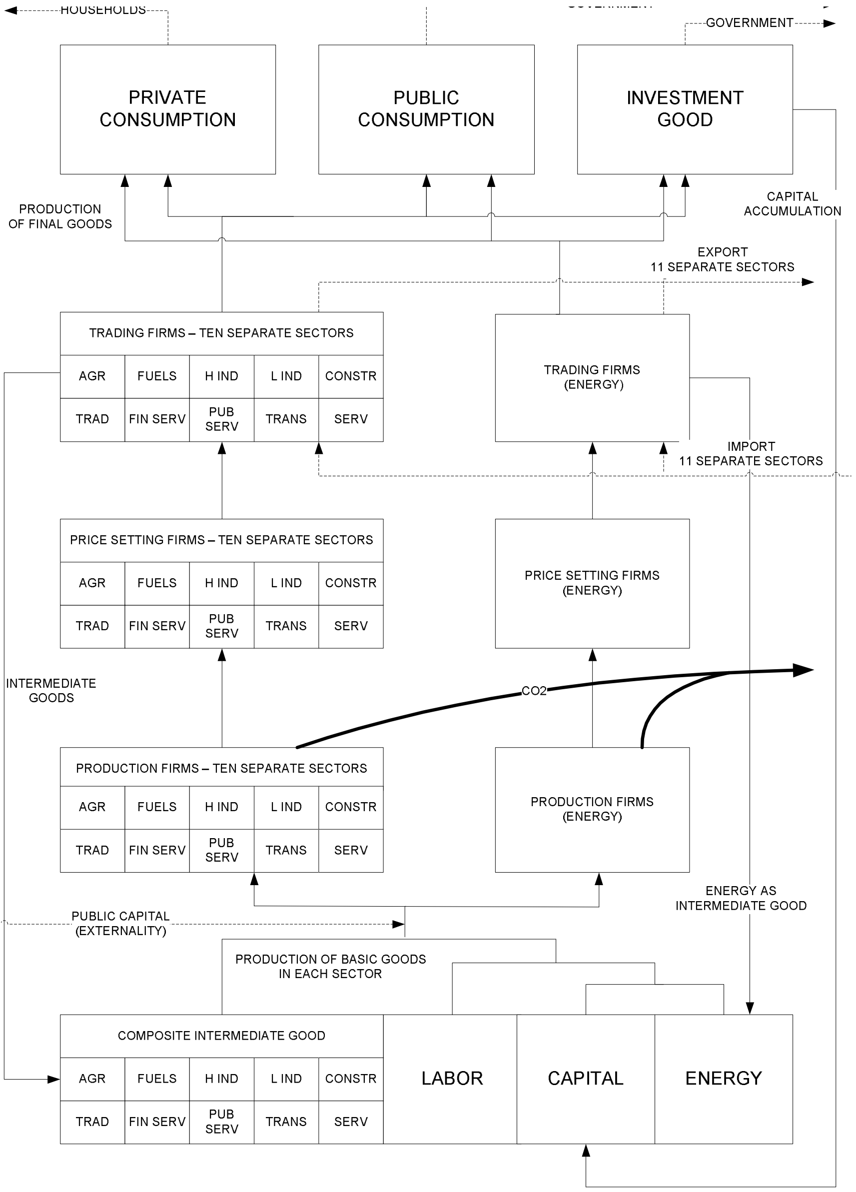
In each sector $s \in \mathcal{S}$ there exists a representative firm producing basic good Y_t^s and selling it for a price P_t^s. Extent of monopolistic power of the firm is denoted as θ_s. During the production process firm uses the capital, $K_t^{s,c}$, labor , N_t^s, materials, M_t^s and energy ENG_t^s, as input factors. Firms are imposed to pay CIT and VAT taxes. Decision process is based on a maximization of expected discounted cash-flow from production:

$$\max E_0 \widetilde{\Pi_0}^s, \qquad \widetilde{\Pi}_0^s = \sum_{t=0}^{\infty} \Lambda_t \Pi_t^s. \tag{12}$$

where Π_t^s denotes temporary cash-flow obtained at time t and $\Lambda_t = \frac{\lambda_t^c}{\lambda_{t-1}^c}$ represents the stochastic discount factor mirroring preferences of the household owning the firm, where Lagrange multipliers, λ_t^c, are related to household budget constraint 3. Therefore, temporary cash-flow of a firm is equal to $P_t^s Y_t^s$ plus government subsidy to production $S_t^{G,s}$ minus investment expenditure, $P_t^I I_t^s$, labor force expenditure, $N_t^s W_t^c$, cost of purchasing intermediate goods and energy, CM_t^s minus imposed taxes EXC_t^s, CIT_t^s and VAT_t^s. Intermediate goods $M_{i,t}^s$ are mainly used to produce materials, M_t^s, which are required input factors to a production technology. Formally:

$$\Pi_t^s = P_t^s Y_t^s - N_t^s W_t^s - P_t^I I_t^s - CM_t^s - CIT_t^s - EXC_t^s - VAT_t^s + S_t^{G,s} \tag{13}$$

Figure 2: Production process



where N_t^s represents labor demand reported by sector s. P_t^I is a price of investment good, I_t^s denotes investment demand of firm s while $M_{i,t}^s$ is an intermediate demand reported by sector s for good (priced $P_t^{OE,s}$) produced in sector i by trading firms. Taxes paid by the firm to government are defined in the following way:

$$VAT_t^s = \frac{\tau_t^{V,s}}{1+\tau_t^{V,s}} \times P_t^s Y_t^s - \sum_{i\in S} \frac{\tau_t^{V,i}}{1+\tau_t^{V,s}} P_t^{OE,i} M_{i,t}^s \tag{14}$$

$$CIT_t^s = \tau_t^C \times \Big(P_t^s Y_t^s - N_t^s W_t^s - CM_t^s - VAT_t^s - (\delta_K^s + \psi^s r_t) \times K_{t-1}^{A,s}\Big) \tag{15}$$

$$EXC_t^s = \tau_t^{E,s} \times P_t^s Y_t^s \tag{16}$$

where $\tau_t^{V,s}$, τ_t^C and $\tau_t^{E,s}$ are efficient value added, corporate income and excise tax rates accordingly. Moreover $K_t^{A,s}$ stands for book value of fixed assets of a firm which may be financed (share of ψ^s) by external capital constituting a tax shield for the firm. Cost of materials bought by firms operating in sector s are given by:

$$CM_t^s = \sum_{i \in \mathcal{S}} P_t^{OE,i} M_{i,t}^s + IM_t^{E,s} \tag{17}$$

where $IM_t^{E,s}$ is a shift of demand towards imported goods and is defined in section 2.3.4. Level of accumulated assets registered in the company books, $K_t^{A,s}$, is implied by the following equation:

$$K_t^{A,s} = (1 - \delta_K^s) K_{t-1}^{A,s} + P_t^I I_t^s \tag{18}$$

where δ_K^s is the rate of depreciation which may differ across sectors due to the specificity of fixed assets involved in the production of each of them. Book capital differs from production capital due to investment frictions. Investment influences the accumulation of the production capital in the following way:

$$K_t^s = (1 - \eta^{-1} \delta_K^s) K_{t-1}^s + \left(\frac{I_t^s}{K_{t-1}^s} \right)^{\eta} K_{t-1}^s \tag{19}$$

where η is elasticity mirroring an extent of investment rigidities. Capital, intermediate goods, energy and labor are involved in the three-stage production process of the basic good Y_t^s (see bottom of Figure 2). In the first stage capital, K_t^s, and energy , ENG_t^s, are used to produce composite good KE_t^s according to the following CES production technology:

$$KE_t^s = \left[(1 - \theta_{ENG}^s)^{\frac{1}{\epsilon_E^s}} (K_t^s)^{\frac{\epsilon_E^s - 1}{\epsilon_E^s}} + (\theta_{ENG}^s)^{\frac{1}{\epsilon_E^s}} (ENG_t^s)^{\frac{\epsilon_E^s - 1}{\epsilon_E^s}} \times e^{\xi_t^{EF}} \times e^{\xi_t^{ENG,s}} \right]^{\frac{\epsilon_E^s}{\epsilon_E^s - 1}} \tag{20}$$

where θ_{ENG}^s denotes intermediate consumption if energy in sector s and ϵ_E^s is the elasticity of substitution between capital and energy. With shocks ξ_t^{EF} and $\xi_t^{ENG,s}$ we implement changes in energy efficiency and shifts in intermediate demand respectively. In the second stage good KE_t^s together with labor N_t^s are used to produce another composite good:

$$KLE_t^s = \left[(1 - \theta_N^s)^{\frac{1}{\epsilon_N^s}} (KE_t^s)^{\frac{\epsilon_N^s - 1}{\epsilon_N^s}} + (\theta_N^s)^{\frac{1}{\epsilon_N^s}} (N_t^s)^{\frac{\epsilon_N^s - 1}{\epsilon_N^s}} \times e^{\xi_t^{Y,s}} \right]^{\frac{\epsilon_N^s}{\epsilon_N^s - 1}} \tag{21}$$

where θ_N^s sets share of labor in the production technology and ϵ_N^s sets the elasticity of substitution between labor and capital-energy composite. Sectoral, technological shock, $\xi_t^{Y,s}$, directly influences labor productivity in sector s. In the final stage aggregate of labor, capital and energy, KLE_t^s, and composite material good M_t^s are used as an input factors in the production of basic good, Y_t^s, according to the following production technology:

$$KLEM_t^s = \left[(1-\theta_M^s)^{\frac{1}{\epsilon_M^s}} (KLE_t^s)^{\frac{\epsilon_M^s-1}{\epsilon_M^s}} + (\theta_M^s)^{\frac{1}{\epsilon_M^s}} (M_t^s)^{\frac{\epsilon_M^s-1}{\epsilon_M^s}} \right]^{\frac{\epsilon_M^s}{\epsilon_M^s-1}} \tag{22}$$

$$Y_t^s = e^{\xi_t^Y} \times KLEM_t^s \times \left(\frac{K_t^P}{K^P} \right)^{\epsilon_{KP}} \tag{23}$$

where analogically θ_M^s represents a share of materials in a production process of basic good and ϵ_M^s is the elasticity of substitution between materials and labor-capita-energy composite good. Note that production of sectoral good benefits from externality from public capital, K_t^P, i.e. capital accumulated in a public sector. Moreover ξ_t^Y is an economy wide productivity shock that we use to calibrate the dynamic properties of our model. Elasticity of product to public infrastructure is ϵ_{KP}. Aggregate intermediate material M_t^s is produced with Leontief technology from materials $M_{i,t}^s$ bought by the producer of basic good in all sectors (apart from energy):

$$M_{i,t}^s = \theta_i^s M_t^s + \xi_{i,t}^{M,i} \tag{24}$$

where α_i^s with $\sum_{i \in S-\{ENG\}} \theta_i^s = 1$ defines the share of intermediate good i in overall material consumption in sector s. Shock $\xi_{i,t}^{M,i}$ enables us to model shifts in the intermediate demand in sector s towards goods of sector i. Let us underline that parameters $\theta_{i,M}^s$ for $i \in S - \{ENG\}$ and θ_E^s allow us to represent fully the inter-sectoral flows exhibited in the I/O matrix.

2.3.3 Price setting firms

In each sector basic good produced in stage one is blue-marked by the price setter that entertains certain monopolistic power on the sectoral level. In other words, basic good producer is confronted with demand function of the form

$$Y_t^s = \left(\frac{P_t^s}{\widehat{P}_t^s} \right)^{\eta_M^s} \widehat{Y}_t^s \tag{25}$$

where relation $\widehat{P}_t^s = P_t^s$ is taken into account as a market clearing condition in equilibrium, although it is not a part of firm's optimization problem described in the last section. Parameter that measures the monopolistic power (market integration) in sector s i.e. η_M^s is set on the level that guarantees that in the steady state a relation of economic profits Π_E^s to the sectoral value added VA^s reflects the data, where economic profits and value added are defined as follows

$$\Pi_{E,t}^s = \left(\frac{P_t^s}{1+\tau_t^{V,s}} - \frac{\lambda_{Y,t}^s}{1-\tau_t^{C,s}} \right) Y_t^s \tag{26}$$

$$VA_t^s = P_t^s Y_t^s - CM_t^s - VAT_t^s \tag{27}$$

where $\lambda_{Y,t}^s = \frac{\partial \widetilde{\Pi}_t^s}{\partial Y_t^s}$ is a shadow price (marginal cost) of production in sector s.

2.3.4 Trading firms

Firms producing basic goods may sell their products home or abroad. The trade is made by sector trading firms which are maximizing the current one-period profit of the form:

$$\Pi_t^{OE,s} = P_t^{OE,s} Y_t^{OE,s} - P_t^s Y_t^{H,s} - (1 + \tau_t^{V,s}) P_t^{F,s} q_t^F X_t^{F,s} \tag{28}$$

where $\Pi_t^{OE,s}$ is a profit of trading firm operating in sector s, $P_t^{OE,s}$ is a price and $Y_t^{OE,s}$ is a volume of product sold. Moreover, $P_t^s Y_t^{H,s}$ denotes a cost of goods purchased at home and $P_t^{F,s} q_t^F X_t^{F,s}$ denotes cost of goods purchased abroad where q_t^f is a real exchange rate of one unit of foreign good for a good produced at home and $P_t^{F,s}$ is a price of foreign good valuated in a foreign currency. Good produced at home, $Y_t^{H,c}$, and good produced abroad, $X_t^{F,s}$, are used as input factors in a production process of sector aggregate good $Y_t^{OE,s}$ using the following CES technology:

$$Y_t^{OE,s} = \left[(\theta_H^s)^{\frac{1}{\epsilon_H^s}} (Y_t^{H,c})^{\frac{\epsilon_H^s - 1}{\epsilon_H^s}} + (1 - \theta_H^s)^{\frac{1}{\epsilon_H^s}} (X_t^{F,c})^{\frac{\epsilon_H^s - 1}{\epsilon_H^s}} \right]^{\frac{\epsilon_H^s}{\epsilon_H^s - 1}} \tag{29}$$

where similarly θ_H^s sets the share of home production in sector s and ϵ_H^s is the elasticity of substitution between home and foreign goods in sector s.

Foreign economy is represented in the model only through aggregates. Because of that it is assumed that the volume of export is determined by exogenous demand (exogenous from the point of view of the model), $DEM_t^{F,s}$, that one can relate to foreign GDP. Export volume is influenced by the external terms-of-trade and monopolistic power of the home country in sector s determined by the parameter μ_F. Formally speaking:

$$Y_t^{F,s} = \left(\frac{P_t^{OE,s}}{(1 + \tau_t^{V,s}) P_t^{F,s} q_t^F} \right)^{\mu_F} DEM_t^{F,s} \tag{30}$$

We assume that $DEM_t^{F,s} = DEM^{F,s} \times e^{\xi_t^F}$, where steady state level of foreign demand $DEM^{F,s}$ calibrates the volume of export in sector s and ξ_t^F is the foreign demand shock that we use for calibration purposes of our model dynamics. Level of foreign demand can deviate from its steady state value in response to foreign demand shock influencing domestic economy through trade channel. Similarly we assume that the price on a foreign market is fixed and equal to the steady state level of its domestic counterpart $P_t^{F,s} = P^s$. If this price is shocked, external terms-of-trade will change. Introduced notions allow for definition of value of export, EX_t^s, and import, IM_t^s, as well as value added tax paid by importers, $VAT_t^{I,s}$, and refunded to exporters, $VAT_t^{X,s}$, are defined in the following way:

$$IM_t^s = P_t^{F,s} q_t^F (X_t^{F,s} + \xi_t^{I,s}), \qquad EX_t^s = \frac{P_t^{OE,s}}{1 + \tau^{V,s}} Y_t^{F,s} \tag{31}$$

$$VAT_t^{I,s} = \tau_t^{V,s} IM_t^s, \qquad VAT_t^{X,s} = \tau_t^{V,s} EX_t^s \tag{32}$$

Note that shock $\xi_t^{I,s}$ defines the shift in import, $IM_t^{E,s} = P_t^{F,s} q_t^F (\xi_t^{I,s})$ introduced in section 2.3.2. Summing up by all eleven sectors we get aggregated values of import,

IM_t, export, EX_t, and related VAT payments, VAT_t^I and , VAT_t^X. This allows us to calculate gross domestic product in each sector:

$$GDP_t^s = P_t^s Y_t^s - CM_t^s + VAT_t^{I,s} - VAT_t^{X,s} \tag{33}$$

Moreover we can also define current and capital account balances as

$$CA_t = EX_t - IM_t \tag{34}$$

$$KA_t = B_{t-1}^{hf} \frac{q_t^f}{q_{t-1}^f} - q_{t-1}^f B_{t-1}^{fh} + q_t^f \frac{B_t^{fh}}{\varrho_t^f R_t} - \frac{B_t^{hf}}{\varrho_t R_t^f} + EU_t \tag{35}$$

where EU_t denotes level of (net) EU funds absorbed by economy. We assume that foreign interest rate is fixed on the steady state level of its domestic counterpart i.e. $R_t^f = R$. Risk premiums for holding foreign debt are defined as follows

$$\ln \varrho_t^h = -\phi \frac{B_t^{hf} - B^{hf}}{GDP_t} \tag{36}$$

$$\ln \varrho_t^f = -\phi \frac{B_t^{fh} - B^{fh}}{GDP_t^F} \tag{37}$$

where B^{hf} is a steady state level of foreign debt of domestic households and and B^{fh} is a steady state level of domestic debt of foreign households. Similarly $GDP_t = \sum_{s\in\mathcal{S}} GDP_t^s$ is a gross domestic product of the whole domestic economy in equilibrium set to one. And $GDP_t^F = \sum_{s\in\mathcal{S}} Y_t^{F,s}$ is a gross domestic product of the whole foreign economy.

Trading firm operating in sector s sells its product to firms producing final good (final demand), firms producing basic good (intermediate demand) and abroad.

2.3.5 Production of final goods

There are three distinct types of final goods specified in the model: consumption, CNS, investment, INV and government good, GOV. Consumption goods are purchased by households, investment goods take part in a process of accumulation of private and public capital and finally government goods are purchased by government in order to provide public consumption. Let us denote $\mathcal{F} = \{CNS, INV, GOV\}$. For $f \in \mathcal{F}$ the firm producing good f maximizes the following functional at time t:

$$\max \Pi_t^f = P_t^f Y_t^f - \sum_{s\in\mathcal{S}} P_t^{OE,s} Y_t^{f,s} \tag{38}$$

where Π_t^f is a final profit of a firm producing good $f \in \mathcal{F}$, which is equal to an income $P_t^f Y_t^f$ minus cost of sector aggregates $\sum_{s\in\mathcal{S}} P_t^{OE,s} Y_t^{f,s}$, where $Y_t^{f,s}$ is a final demand for sector good $s \in \mathcal{S}$ reported by the final sector $f \in \mathcal{F}$. Like before, technology of production is of CES type:

$$Y_t^f = \left[\sum_{s\in S} (\theta_f^{F,s} + \xi_{tf,}^{F,s})^{\frac{1}{\epsilon_f^F}} (Y_t^{f,s})^{\frac{\epsilon_f^F - 1}{\epsilon_f^F}} \right]^{\frac{\epsilon_f^F}{\epsilon_f^F - 1}} \tag{39}$$

where parameter, $\theta_f^{F,s}$, is a share of sector s good in the production of the final good f, whereas, ϵ_f^F, is the elasticity of substitution between input factors produced by specified sectors. Shock $\xi_{f,t}^{F,s}$ shifts final demand in final sector f towards sectoral good s. In policy simulations we implement this shock solely to shifts in consumption demand e.g. for $f = CNS$.

2.4 Labor market

2.4.1 Matching firm

Households offer aggregated labor supply N_t to a perfectly competitive firm serving as an intermediary in the labor market – the matching firm. The firm maximizes expected discounted profit of the form:

$$\max E_0 \widetilde{\Pi_0}^L, \qquad \widetilde{\Pi}_0^{L,s} = \sum_{t=0}^{\infty} \Lambda_t \Pi_t^L. \tag{40}$$

where Π_t^L is a temporary profit at time t defined in the following way:

$$\Pi_t^L = \sum_{s\in\mathcal{S}} W_t^s N_t^s - W_t N_t. \tag{41}$$

where N_t is a households' labor supply, W_t a wage offered, while N_t^s and W_t^s are realized demand for labor and wage paid in sector s accordingly. Moreover:

$$N_t = \omega_N \times \left(\sum_{s\in\mathcal{S}} \omega_N^s (N_t^s)^{\epsilon_L} \right)^{\frac{1}{\epsilon_L}} + \upsilon_V \times V_t \tag{42}$$

$$N_t = (1 - \delta^N) N_{t-1} + \Psi_t V_t. \tag{43}$$

where parameters ω^s mirror the preferences of workers and impose the structure of labor supply in each sector while ϵ_L is the elasticity of substitution of these preferences. Moreover parameter, υ_V, sets the cost of vacancy measured by a cost of work of recruiting employees who do not create any value added directly. The recruitment cost is equal to $CV_t = W_t \upsilon_V V_t$. In other words only $N_t - \upsilon_V \times V_t$ of employees produce basic goods and employees involved in the recruitment process earn CV_t. Parameter Ψ_t determines the probability of filling open vacancy, and is treated by the matching firm as exogenous. Note that similarly to household problem also labor market intermediator does not take into account employment dynamics in its optimization problem as a constraint, but only calculates first order condition with respect to N_t in order to establish the shadow price of employment for the firm, Σ_t. Parameter ω_N is set in such a way that equilibrium condition $N_t = \sum_{s\in\mathcal{S}} N_t^s$ is satisfied.

2.4.2 Dynamics of employed and non-employed

Search and matching process in the model is based on Mortensen (1989) and Pissarides (1990) results. Firstly, employers post an unfilled vacancy. Unemployed apply for work by sending work offers to firms. Matching process is not perfect hence the number of filled vacancies, J_t^s, is lower than demand of employers and supply of employees. It is assumed that:

$$J_t = \vartheta_t^m V_t^{\lambda_J} (NE_{t-1} h_t^U)^{1-\lambda_J} \tag{44}$$

where V_t is an overall number of unfilled vacancies at time t, ϑ_t^m is a proportionality coefficient determining effectiveness of the matching process and λ_J determines relative weight of supply and demand of labor in the matching process. Consequently, both probability of filling a vacancy, Ψ_t, in sector s and probability of finding a job in this sector, Φ_t, are equal to:

$$J_t = \Psi_t \times V_t, \qquad J_t = \Phi_t \times NE_{t-1} h_t^U \tag{45}$$

At the same time the matching process' is described by the following equation:

$$N_t = (1 - \delta^N) N_{t-1} + J_t. \tag{46}$$

which is taken into account during the wage negotiations.

2.4.3 Negotiation of wage and work time

In each period t employees negotiate their wages with employers in the Nash bargaining procedure. Let us denote households' surplus (shadow price) due to one additional member working (measured in units of lifelong utility) and surplus of the firm in sector s due to one vacancy filled by Γ_t i Σ_t accordingly. It follows that:

$$\Gamma_t = \frac{\partial E_0 \mathcal{U}_0^c}{\partial N_t}, \qquad \Sigma_t = \frac{\partial E_0 \Pi_0^L}{\partial N_t}. \tag{47}$$

Workers and matching firm negotiate the contract which specifies expected wage in the future. Negotiations follow the Nash bargaining scheme in which both sides maximize overall surplus from filled vacancy. The maximization process takes into account first order conditions of the firm being an intermediary in the matching process and household due to individual optimization with respect to level of employment N_t. Influence of wage and work time on consumption and, indirectly, on utility of already employed people is also taken into account. Formally speaking, optimization problem related to negotiations between employees and employers concerns the maximization of the total surplus from the contract measured in utility units of a household. It takes following form:

$$\max_{W_t} (\Gamma_t \lambda_t)^{\eta_N} (\Sigma_t)^{1-\eta_N} \tag{48}$$

when the maximization is performed in the presence of equation 47. As vacancies are not entirely filled we can define unemployment rate in our model as

$$UR_t = \frac{U_t}{N_t + U_t} \tag{49}$$

$$U_t = (1 - e^{-h_t^U}/3) \times NE_t \tag{50}$$

where the U_t denotes the number of unemployed sampled in one month from non-employed pool NE_t.

$$\tag{51}$$

2.5 GHG emission

In our model emission of green house gasses is modeled for firms and households. In the first case GHG is emitted as a byproduct of intermediate goods consumption. Let GHG_t denote total emission of green house gases in the economy. Than

$$GHG_t = \sum_{s \in S} GHG_t^s + GHG_t^{CNS} \tag{52}$$

where GHG_t^s denotes an emission level in sector s and GHG_t^{CNS} emission level in households. We assume that both variables depend solely on the level of fuel consumption. Formally:

$$GHG_t^s = \theta_{GHG}^s M_t^{s,FLS} \times e^{\xi_t^{GHG,s}} \tag{53}$$

$$GHG_t^{CNS} = \theta_{GHG}^{CNS} Y_t^{CNS,FLS} \tag{54}$$

where parameters θ_{GHG}^s and θ_{GHG}^{CNS} calibrate emissions in every sector, whereas shocks $\xi_t^{GHG,s}$ reflect shifts in those levels i.e. changes in emission intensities of production technologies in firms or consumption of households, when energy efficiency measures are introduced.

2.6 Government

The government accrues a tax revenue from consumption, VAT_t, labor, PIT_t, corporate incomes, CIT_t, dividends paid, DIV_t, excise duties EXC_t and other taxes, TAX_t, where:

$$VAT_t = \sum_{s \in \mathcal{S}} VAT_t^s + VAT_t^{I,s} - VAT_t^{X,s} \tag{55}$$

$$TAX_t = \tau_t^G \times \left(N_t \times C_t^E + NE_t \times C_t^U \right) \tag{56}$$

$$PIT_t = \tau_t^W \times W_t \times N_t, \qquad CIT_t = \sum_{s \in \mathcal{S}} CIT_t^s \tag{57}$$

$$DIV_t = \tau_t^D \times \Pi_t, \qquad EXC_t = \sum_{s \in \mathcal{S}} EXC_t^s \tag{58}$$

European Union funds, EU_t, are additional sources of government's income. This income is spent for purchase of public goods, $P_t^{GOV} G_t$, transfers T_t to households, investments in general public capital, $P_t^I I_t^P$, subsidies to energy sector investments $P_t^I I_t^{P,E}$, subsidies to other capital expenditures of firms and households, $S_t^{G,K}$, and finally subsidies to firms, S_t^G. In consequence, the budget constraint of the government takes the form $G_t^{EXP} = G_t^{INC} - G_t^{DEF}$ where

$$G_t^{EXP} = P_t^{GOV} G_t + T_t + P_t^{INV} (I_t^P + I_t^{P,E}) + S_t^G + S_t^{G,K} \tag{59}$$

$$G_t^{INC} = EU_t + VAT_t + EXC_t + PIT_t + CIT_t + DIV_t + TAX_t \tag{60}$$

$$G_t^{DEF} = B_{t-1}^{hh} - \frac{B_t^{hh}}{R_t} + q_{t-1} B_{t-1}^{fh} - q_t \frac{B_t^{fh}}{\rho_t^f R_t} \tag{61}$$

where $T_t = NE_t \times T_t^H + T_t^R$ and $T_t^R = \theta^R \times \overline{T}$ is a transfer to persons who are not active in the labor market (e.g. pensioners), permanently set to its steady state level. Share of pension transfers in total transfers is calibrated according to data. We assume that Public debt $B_t = B_t^{hh} + q_t^f B_t^{fh}$ is constant e.g. $B_t = \overline{B}$. At the same time, equations

$$P_t^{GOV} G_t = \omega^G \times \overline{GDP} \left(\frac{GDP_t}{\overline{GDP}} \right)^{\epsilon_G} \times e^{\xi_t^G} \tag{62}$$

$$EU_t = \omega^{EU} \times \overline{GDP} \left(\frac{GDP_t}{\overline{GDP}} \right)^{\epsilon_{EU}} \times e^{\xi_t^{EU}} \tag{63}$$

relate government consumption and EU incomes to the level of GDP. Variable ξ_t^G is an exogenous stochastic processes describing the discretionary part of governmental expenditure policy that we use to calibrate dynamic behavior of our model. Similarly government subsidies to energy sector investments, $P_t^I I_t^{P,E}$, subsidies to other capital expenditures of firms and households, $S_t^{G,K}$ and subsidies to firms, S_t^G are given by

$$P_t^I I_t^{P,E} = \xi_t^{P,E} \times GDP_t \tag{64}$$

$$S_t^G = \sum_{s \in S} S_t^{G,s} \tag{65}$$

$$S_t^{G,K} = P_t^{LIND} S_t^{G,KL} + P_t^{HIND} S_t^{G,KH} \tag{66}$$

where

$$P_t^{LIND} S_t^{G,KL} = \xi_t^{S,KL} \times GDP_t \tag{67}$$

$$P_t^{HIND} S_t^{G,KH} = \xi_t^{S,KH} \times GDP_t \tag{68}$$

with $\xi_t^{S,KL}$ and $\xi_t^{S,KH}$ being the expenditure shock to public subsidies for private expenditures on light and heavy industry products. We assume that in steady state their value is zero. However, they play important role in modeling of public GHG abatement policy considered in next sections. Public capital is accumulated with accordance with classical equation

$$K_t^P = (1 - \rho_K) K_t^P + I_t^P \tag{69}$$

$$P_t^{INV} I_t^P = \omega^{KP} \times \overline{GDP} \times e^{\xi_t^{IP}} \tag{70}$$

where ω^{KP} determines the steady state share of public investment in GDP and ξ_t^{IP} is an expenditure shock to its value.

On the other hand it is assumed that efficient taxes rates, $\tau_t^{V,s}$, τ_t^W, τ_t^C, τ_t^D, τ_t^E and τ_t^G, are implicitly defined by

$$\tau_t^Z = \omega^{\tau,Z} + \xi_t^{\tau,Z} \tag{71}$$

where parameters $\omega^{\tau,Z}$ determine steady state levels of relevant tax revenues to GDP. Note that those parameters can be shocked by $\xi_t^{Z,\tau}$ in order to analyze economy response to changes in government fiscal policy. Endogenous part of the policy is implicitly determined by the government's objective function, which means that it may respond to macroeconomic shocks by adjusting deficit and transfers level.

2.7 GHG mitigation policies

Shocks that are incorporated in the model can be divided into two categories. To the first category belong four shocks that drive model's cyclical behavior. These are: (1) economy wide ξ_t^Y and sectoral $\xi_t^{Y,s}$ productivity shocks, (2) intensive labor supply shock ξ_t^L, (3) government consumption shock ξ_t^G and (4) foreign demand shock ξ_t^F. In section 4.3 we argue that our model is able to explain major business cycle properties of the data solely with these four shocks.

To the second category we include shocks that let us to implement all types of GHG abatement policies we consider later. These are: (1) shift in material demand $\xi_{i,t}^{M,s}$ (2) import demand shock $\xi_t^{I,s}$, (3) shock to energy efficiency ξ_t^{EF}, (4) shift of energy demand $\xi_{i,t}^{ENG,s}$, (4) shift of consumption demand for good s, $\xi_t^{FC,s}$, (5) shock to emission intensity of production, $\xi_t^{GHG,s}$, (6) shocks to public subsidies for material and consumption expenditures of households and firms for light $\xi_t^{S,KL}$ and heavy $\xi_t^{S,KH}$ industry products, (7) changes in public subsidies for energy investments, $\xi_t^{P,E}$, (8) shocks to tax rates $\xi_t^{\tau,Z}$ for $Z \in \{V, W, C\}$. We assume that individual shocks are represented a autoregressive stochastic processes of order one:

$$\xi_t^X = \rho^X \xi_{t-1} + \varepsilon_t^X \tag{72}$$

where ε_t^ξ represent independent stochastic disturbances drawn from normal distribution $N(0, \sigma^X)$. Those disturbances are filtered in the Kalman filter procedure in policy scenarios described later on.

2.8 Market equilibrium

Market equilibrium conditions impose the clearing of supply and demand in the goods, labor and international exchange markets. Equilibrium in the basic goods market $s \in \mathcal{S}$ means that the demand reported by the trade-firm, which acts as an intermediary in the process of exchange of basic goods home and abroad, must be equal to its volume sold hence $Y_t^{H,s} = Y_t^s$. In turn, the trade-firms offers the basic good to sectors producing the final good (final consumption), sectors producing basic good (intermediary consumption) and foreign sectors (export). As a result the following balance equation is satisfied:

$$Y_t^{OE,s} = \sum_{f \in \mathcal{F}} Y_t^{f,s} + \sum_{i \in \mathcal{S}} Y_{s,t}^i + Y_t^{F,s} + S_t^{G,Ks} \tag{73}$$

where $S_t^{G,Ks} = 0$ for $s \in S \backslash \{HIND, LIND\}$, $S_t^{G,Ks} = S_t^{G,KH}$ for $s = HIND$ and $S_t^{G,Ks} = S_t^{G,KL}$ for $s = LIND$. Market producing final goods must be in equilibrium as well. Therefore demand and supply of investment good must be equal, $Y_t^{INV} = I_t^P + I_t^{P,E} + \sum_{s \in \mathcal{S}} I_t^s$, and public consumption must be equal to supply of government good, $Y_t^{GOV} = G_t$. Note that total expenditures on investment and government goods on the economy are given by $INV_t^E = P_t^{INV} Y_t^{INV}$ and $G_t^E = P_t^{GOV} G_t$. Equilibrium in the consumption good sector is ensured due to the fact that the price of the consumption good is a reference to all the prices in the model (hence the consumption good is so called *numeraire*). Total consumption is equal to:

$$C_t = N_t \times C_t^N + NE_t \times C_t^U + T_t^R \tag{74}$$

Total profit transferred by firms to households is equal to total profit of all firms hence:

$$\Pi_t = \sum_{f \in \mathcal{F}} \Pi_t^f + \sum_{i \in \mathcal{S}} (\Pi_t^s + \Pi_t^{OE,s}) + \Pi_t^L \tag{75}$$

As it was already said, all prices in the model are relative to the price of the consumption good (being a *numeraire*), hence an assumption $P_t^{C,c} = 1$ does not affect the generality of the results of the model. Therefore also total expenditure on private consumption are equal to $C_t^E = C_t$. The last equilibrium condition is the clearing of the exchange market, $CA_t + KA_t = 0$.

3 Numerical algorithm

3.1 Model specification and solving

We solve model in the special modeling environment called FORMA, that we have developed in the Institute for Structural Research. FORMA is a symbolic and numeric computing package specialized in solving optimal steering, deterministic and stochastic problems. It enables efficient solving of DSGE models with number of variables of 10-50 thousands - much more than 2000 needed for the MEMO model described here. CGE models as a special case of DSGE class are therefore also supported by the package. Its particularly useful feature lays in the symbolic language that enables the user to specify dynamic, stochastic optimization problems directly e.g. in the form of dynamically constrained maximization. FORMA automatically computes derivatives of any order of the relevant sets of Langrangeans equations. In particular first order conditions and jacobian matrixes necessary for the perturbation solution algorithm are derived in the FORMA environment automatically. General procedure that we apply is as follows

1. Formulation of the CGE/DSGE model in FORMA symbolic language;
2. Automatic derivation of the relevant FOCs and JACs by FORMA symbolic package;
3. Solving the model for steady state solution by FORMA solver that involves Newton method of solving non-linear equations;
4. Find the linear approximation of the model solution by the perturbation algorithm.

Formally any DSGE (as well as static or dynamic CGE) model can be written as the set of general optimization problems of the form

$$
\begin{aligned}
&\max_{\{y_t,U_t\}_{t=0}^{\infty}} \; E_0\{U_0\} \\
&\text{s.t. } 0 = f(U_{t-k},\dots,U_{t+k},U^*,w_{t-k},\dots,w_{t+k},w^*,\sigma;E_{t-k},\dots,E_{t+k}) \\
&\qquad 0 = g^{\mu}(U_{t-k},\dots,U_{t+k},U^*,w_{t-k},\dots,w_{t+k},w^*,\sigma;E_{t-k},\dots,E_{t+k}) \\
&\qquad w_t = \mathrm{col}(y_t,z_t)
\end{aligned}
\tag{76}
$$

for $\mu = \{0,1,\dots,m\}$ i $t = 0,1,\dots,\infty$, where f, g^{μ} are scalar functions, U_0 is target function, that depends both on current and future levels of modeled variables through f and g^{μ}. We denote steering variables by y and exogenous (also stochastic) variables by z. Steady state values are represented by U^*, $w^* = \mathrm{col}(y^*,z^*)$, y^* and z^*. Scalar functions f and g^{μ} can include conditional expectation operators E_{t+i} for $|i| \leq k$, where k is constant. Expectations are formed conditionally to information sets $I_{t+i} = \{U_s,y_s,z_s\}_{s=0}^{t+i}$. Moreover σ denotes small parameter.

From the problem 76 one can derive relevant Lagrange'a functions and by proper differentiation first order conditions of the form

$$
0 = E_t h(v_{t-k},\dots,v_{t+k},v^*,\sigma;E_{t-k},\dots,E_{t+k}) \tag{77}
$$

where $v_t = \mathrm{col}(U_t,\tilde{y}_t,z_t)$. This equations can be reduced in stepwise procedure to the form

$$
0 = E_t h(x_{t-1},x_t,x_{t+1},x^*,\sigma) + U\epsilon_t + Wz_t + Z\sigma \tag{78}
$$

that sets the basis for establishing the steady state solution together with the linear approximation around it. Endogenous variables we denote by x, exogenous by z and stochastic i.i.d shocks by ϵ. We solve problem (78) utilizing the perturbation method that can be briefly described as finding the exact solution for $\sigma = 0$ and approximate solution for $\sigma = 1$ by expanding the exact (78) into the power series around $\sigma = 0$. Procedure of finding the perturbation solution of the model we utilize is non standard in that sense that it does not need predetermined set of state variables from the user. In consequence both deterministic and stochastic part of the solution is derived automatically. Final, matrix solution of the DSGE model can be written as

$$
x_t = P_t x_{t-1} + Q_t\epsilon_t \tag{79}
$$

$$
y_t = R_t x_{t-1} + S_t\epsilon_t \tag{80}
$$

where x_t is a state variable, y_t, is a control variable and ϵ_t is a stochastic disturbance.

3.2 Conditional forecasts

In this article we present conditional forecasts of the possible impact of the climate package on the modeled Polish economy. We do this by utilizing the Kalman filtering/smoothing algorithm to the model in the form 79. In other words for the time horizon $T > 0$ and for $k = 1, \dots, T$, we have

$$x_k = P_k x_{k-1} + Q_k \epsilon_k \tag{81}$$

$$y_k = R_k x_{k-1} + S_k \epsilon_k \tag{82}$$

$$z_k = M_k y_k + K_k x_{k-1} + N_k \epsilon_k + V_k \eta_k \tag{83}$$

where equation (81) is called the *state dynamics equation*, equation (82) is a *control equation* and an equation (83) is an *observation equation.* As previously, $x_k \in \mathbb{R}^{n_x}$, $n_x \geq 1$, is a state variable, $y_k \in \mathbb{R}^{n_y}$, $n_y \geq 1$ is a control variable, $z_k \in \mathbb{R}^{n_z}$, $n_z \geq 1$ is a observation variable. Variables $\epsilon_k \in \mathbb{R}^{n_x}$ and $\eta_k \in \mathbb{R}^{n_z}$ represent stochastic measurement components of the variable z. About stochastic variables ϵ_k and η_k we assume that they are independent from their past draws and state variables x_s for $s = 0, \dots, k-1$, and that their distribution is normal:

$$\begin{bmatrix} \epsilon_k \\ \eta_k \end{bmatrix} \sim N\left(0, \begin{bmatrix} \Omega_k & 0 \\ 0 & \Psi_k \end{bmatrix}\right) \tag{84}$$

where information set $I_k = \{z_1, \dots, z_k, \theta\}$, $k = 1, 2, \dots, T$. By θ we understand all model parameters that is matrixes P_k, Q_k, R_k, S_k and Ω_k from equations (81) and (82) (e.g. *matrixes of the unobserved part of the model*) as well as matrixes M_k, K_k, N_k, V_k i Ψ_k present in the equation (83) (e.g. *matrixes of the observed part of the model*).

As a *prediction* of any modeled variable α_k, $k > 1$ we understand the conditional expectation $E[\alpha_{k+1}|I_k]$ and covariation $D[x_{k+1}|I_k]$. As a *filtracji* of variable α_k, $k > 1$ we understand the establishment of $E[\alpha_k|I_k]$ and $D[x_k|I_k]$. Both problems are solved jointly in the same recursive procedure (Kalman filtering algorithm for model 79). When all relevant variables are filtered, the smoothed conditional forecast can be computed e.g. the forecast formed on the full information set, $E[\alpha_k|I_T]$.

4 Model calibration and properties

4.1 Introduction

The model is being parameterized directly on Polish economy data. Following the DSGE modeling methodology, the parameters may be divided into three main classes: (1) parameters determining level of variables in the steady state, (2) parameters controlling elasticities of substitution and relative standard deviation between specified variables, (3) parameters determining the exact form of exogenous stochastic shocks, and lead-lag structure of endogenous variables. The first class is composed mainly of parameters determining shares of input factors in production technologies described above which influence: value of import relative to GDP, (θ^s_H), intermediate consumption relative to value added, (θ^s_M and θ^s_E), and share of labor in final product, (θ^s_N). Additionally, the class includes parameters determining the structure of final demand for sector products ($\theta^f_{i,F}$), and intermediate demand for materials, ($\theta^s_{i,M}$), parameters setting the long run level of employment(δ^N), investment, (δ^s_K), and export, ($DEM^{F,s}$). The first class concludes with the parameters describing the fiscal policy of the government therefore influencing public consumption, transfers, tax revenues in the steady state: tax rates, τ^X for $X \in \{V, C, W\}$ and share of public consumption in DGP, ω^G. Second class includes all elasticities in above mentioned firms' technology of production functions: (ϵ^s_X for $X \in \{E, N, M, P, H\}$ and ϵ^f_F, in utility functions of households: σ, ω and $\bar{\omega}$, and parameters determining adjustment costs, η. The third class is composed by the parameters determining exact form of the exogenous stochastic processes (means, standard deviations and correlation coefficients) which influence the dynamic properties of the model.

4.2 Model long-term, steady state properties

As most of the model parameters determine its steady state, their values are implicitly imposed by the values of directly observable variables. All links between observable variables and parameters are either directly obtained or derived from GUS/EUROSTAT databases (national accounts, labor market indices, and so on) and EU-KLEMS database (I/O matrices disaggregated to 6 sectors specified in the model). Determination of values of the parameters associated with directly observable variables is performed by replacing the initial theoretical model by its calibration-adjusted version. All parameters belonging to the first class mentioned above (i.e. parameters setting the level of variables in the steady state) become special variables that we call *calibrators*, i.e. variables which determine the level of the steady state value of specified observed variable and only that i.e. when the perturbation part of the solution is calculated they are treated as constants. Each calibrator is associated with a variable which is being calibrated. Determination of steady state means to find such a value for a given calibrator (in this case treated as variable) that value of an observed variable associated with this calibrator becomes equal to the value suggested by data (in the steady state). For example, job destruction rate δ^N is set in such a way that the number of employed agents N_t (which is equal to rate of employment due to normalization of the workforce) is equal to the number found in data, in this case 0.58. Values of all calibrators are calculated by numerical solver. Relation of the main non-sector aggregate observed variables with model calibrators is given in a table 1. Determination of some of the parameters

Table 1: Parametrization of steady state values of main macroeconomic variables

variable	interpretation	unit	value	calibrator
N^s	employment	%	58%	δ_N
$P^{GOV}G$	public consumption	% quaterly GDP	18%	ω^{GE}
B	public debt	% quaterly GDP	220%	B_{ss}
VAT	consumption tax	% quaterly GDP	12.6%	τ^V
CIT	capital tax	% quaterly GDP	2.4%	τ^C
PIT	all wage taxes	% quaterly GDP	16%	τ^W
DIV	property gov. income	% quaterly GDP	3.5%	τ^D
EU	EU funds	% quaterly GDP	2.0%	ω^{EU}
TAX	other gov. revenues	% quaterly GDP	2.4%	τ^G

Source: Ministry of Finance

need some additional explanation. Namely, the parameters which are associated with relation of intermediate consumption and value added, θ_i^s, parameters that set the structure of final demand for sector goods, $\theta_{s,F}^f$, as well as parameters determining sectoral structure of value added, θ_M^s, import, θ_H^s, employment, ω_N^s, setting the relation of employees compensation, investment, export and VAT to value added - θ_N^s, δ_K^s, $\tau^{V,s}$ and $DEM^{F,s}$ respectively. All these parameters can be determined straight on Polish data of GUS, EUROSTAT and EU-KLEMS. Details are in the tables 3- 5.

Table 2: Structure of final demand calibrated by $\theta_{s,F}^f$

$f \setminus s$	AGR	HIND	LIND	ENG	TRN	FLS	TRD	CST	FIN	PUB	SRV
CNS	18.6	4.8	9.4	3.2	4.3	1.9	16.2	4.1	23.4	7.3	6.8
GOV	0.8	2.4	0.2	0.4	2.4	0.0	1.0	1.8	4.0	86.6	0.5
INV	1.6	2.8	41.6	0.0	0.3	0.9	9.2	34.7	7.7	1.2	0.0

Source: EU-KLEMS

Table 3: Structure of intermediate demand calibrated by θ_i^s

$i \setminus s$	AGR	HIND	LIND	ENG	TRN	FLS	TRD	CST	FIN	PUB	SRV
AGR	56.9	7.1	4.7	2.8	2.8	2.1	15.6	0.6	5.2	1.5	0.7
HIND	0.7	50.0	8.0	5.9	5.2	8.7	9.7	1.6	7.6	1.1	1.4
LIND	1.7	24.5	41.8	2.2	3.9	0.6	11.6	1.2	10.1	1.1	1.4
ENG	0.1	2.3	7.8	6.9	6.6	39.6	4.7	12.7	15.3	2.7	1.2
TRN	0.6	2.7	11.2	3.2	29.1	17.3	13.1	1.4	11.8	1.8	7.8
FLS	0.1	5.2	6.8	3.8	5.5	65.3	4.6	1.1	5.7	1.3	0.4
TRD	6.9	8.5	10.6	2.3	17.5	2.7	13.5	1.7	28.0	2.8	5.6
CST	0.2	33.7	9.8	1.0	3.5	3.3	10.6	28.9	7.1	0.6	1.2
FIN	0.6	6.0	9.1	13.1	2.0	1.5	4.9	10.1	39.2	7.6	5.8
PUB	2.2	9.3	16.4	8.1	2.6	2.0	10.7	7.2	20.2	15.4	5.8
SRV	13.5	2.2	17.9	3.5	1.2	1.0	11.5	2.8	31.0	2.1	13.3

Source: EU-KLEMS

Table 4: Structure of value added, import, employment and CO2 emission calibrated respectively by θ^s_M, θ^s_H and ω^s_N and ω^s_{CO2} and ω^H

	AGR	HIND	LIND	ENG	TRN	FLS	TRD	CST	FIN	PUB	SRV
VA	7.5	6.2	8.7	3.1	4.7	2.5	18.1	6.3	19.7	19.1	4.1
IM	6.7	28.0	46.2	0.1	2.3	11.2	0.2	0.5	4.1	0.3	0.4
N	22.6	5.2	10.2	1.7	4.1	1.5	15.3	4.6	9.3	22.6	2.9
CO2	13.0	10.2	4.0	43.9	13.1	2.9	1.2	0.7	1.3	1.0	0.3

Source: EU-KLEMS; Note that remaining 8.4% of emission is in households

Table 5: Relation of employees compensation, investment and VAT to sectoral value added, supplemented by the relation of sectoral export to total value added calibrated respectively by θ^s_N, δ^s_K, $\tau^{V,s}$ and $DEM^{F,s}$

	AGR	HIND	LIND	ENG	TRN	FLS	TRD	CST	FIN	PUB	SRV
COMP	32.3	45.0	52.4	35.8	42.0	57.8	25.9	36.4	25.5	67.2	37.0
INV	29.4	24.6	19.5	36.5	21.1	22.5	13.9	11.7	22.8	19.6	21.4
VAT	16.1	11.2	19.3	11.7	23.0	11.8	11.6	16.2	17.1	3.0	22.5
EX	2.9	7.5	17.7	0.2	2.3	1.3	6.2	0.6	1.1	0.1	0.1

Source: EU-KLEMS

4.3 Model cyclical properties

Model cyclical properties are determined by elasticity parameters and properties of stochastic processes built into the model. Elasticities are responsible for relative response of different model variables to economic shocks and in consequence for the relative standard deviations of these variables to the variable of reference (e.g. GDP). On the other hand, the catalogue of stochastic disturbances considered in the model and mutual relations between them (i.e. correlation matrix) determines its dynamic properties i.e. (auto)correlations of variables of interest. Underneath we present our selection of elasticities (that are more important for long-term responses of the model to policy shocks) and eventual parametrization of four stochastic shocks that we use to mimic cyclical behavior of the economy in the model. Resulting dynamic properties of the model together with their empirical counterparts calculated from Polish data are given in a table 6.

Elasticity parameters are considered fundamental in the economics methodology because they describe the universal (i.e. stable in time and across countries) properties of technology of production functions. Unfortunately the estimation of these parameters is difficult and reliable results are available only for a handful of economies. Moreover, errors associated with estimation results are usually considerably big and the results differ across different published papers. Direct estimation of elasticity parameters for Polish economy is virtually impossible. Some of the values are taken from the existing literature. According to common DSGE methodology practice, elasticity of substitution between labor and other production factors is

Table 6: Empirical and model moments of main variables: relative standard deviation to GDP ($\sigma(GDP_t, X_t)$), correlation with GDP ($\rho(GDP_t, X_t)$) and one-period autocorrelation ($\rho(X_t, X_{t-1})$)

	$\sigma(GDP_t, X_t)$		$\rho(GDP_t, X_t)$		$\rho(X_t, X_{t-1})$	
	Model	Data	Model	Data	Model	Data
CA_t	0.24	0.87	-0.74	-0.73	0.92	0.93
C_t^E	0.53	0.65	0.84	0.69	0.90	0.95
G_t^E	0.62	0.62	0.39	0.39	0.92	0.90
INV_t^E	4.76	6.33	0.99	0.94	0.93	0.95
EX_t	0.95	3.22	0.92	0.63	0.91	0.83
IM_t	1.42	4.50	0.99	0.82	0.92	0.91
q_t^f	0.54	5.05	0.71	-0.16	0.91	0.93
N_t	0.97	1.16	0.71	0.72	0.93	0.97
UR_t	6.99	7.94	-0.40	-0.66	0.84	0.95
W_t	0.63	2.39	0.12	0.14	0.91	0.84
DEM_t^f	0.86	0.86	0.70	0.71	0.92	0.92

Source: own calculation on Polish data from EUROSTAT and model simulations; Standard deviation of GDP equals, both in model and data, to 0.01. All numbers where calculated on the HP filtered quarterly time series (1996-2009).

close to 1, $\epsilon^s = 0.9999$. Similarly, risk aversion parameters $\sigma = 2$, time preferences of a consumer $\beta = 0.99$ and investment rigidities $\eta = 10$. Moreover, it is assumed that labor supply in different sectors is perfectly substitutable $\epsilon_L = 1$ and employers have higher negotiation power than employees $\lambda_J = 0.8$ which is recorded in the Polish labor market. Elasticity of substitution between home and foreign goods is set at relatively high level $\epsilon_H = 0.7$, which implies relatively high substitution between imported and home goods. Elasticity of substitution between materials and capital-energy-work aggregate is set at similarly high level $\epsilon_M^s = 0.7$ which allows for mirroring of relatively high volatility of sold production and product in the business cycle. On the other hand elasticity of substitution of intermediate consumption $\epsilon_P^s = 0.3$, which means that materials produced by different sectors are not good substitutes as production input factors which is intuitive. Elasticity between energy and capital is set as a mean of values reported in the literature, $\epsilon_E = 0.51$. Too low value of this parameter would imply too low volatility of energy consumption in the business cycle because energy would be easily substitutable by capital and capital is stable in the business cycle. Elasticities of substitution of final goods production function was set on the same level, $\epsilon_F^f = 0.51$, which means medium substitutability of sector goods in the production of final aggregates.

Although in principle each parameter of the model can be associated with relevant stochastic disturbance, it would be unwise to do so, as properties of those shocks would have then dominated model's structure. Therefore we limit ourselves to only four shocks: (1) economy wide productivity shock ξ_t^Y, (2) intensive labor supply shock ξ_t^L, (3) government consumption shock ξ_t^G and (4) foreign demand shock ξ_t^F. All those shocks are represented by AR(1) processes of the general form

$$\xi_t^Z = \rho_Z \xi_{t-1}^Z + \varepsilon_t^Z \tag{85}$$

where ε_t^Z are cross-correlated stochastic variables drawn from normal distribution $N(0, \sigma_Z)$. We assume following correlation structure between them As one can see

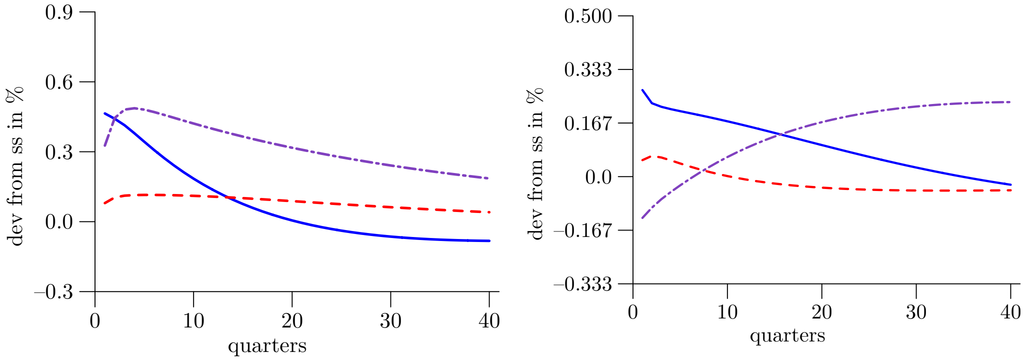
Table 7: Correlation matrix of main stochastic variables in the model

	ϵ_t^Y	ϵ_t^L	ϵ_t^G	ϵ_t^F
ϵ_t^Y	2.36	-0.84	-0.80	0.40
ϵ_t^L	-0.84	0.10	0.99	0.00
ϵ_t^G	-0.80	0.99	0.72	0.00
ϵ_t^F	0.40	0.00	0.00	0.93

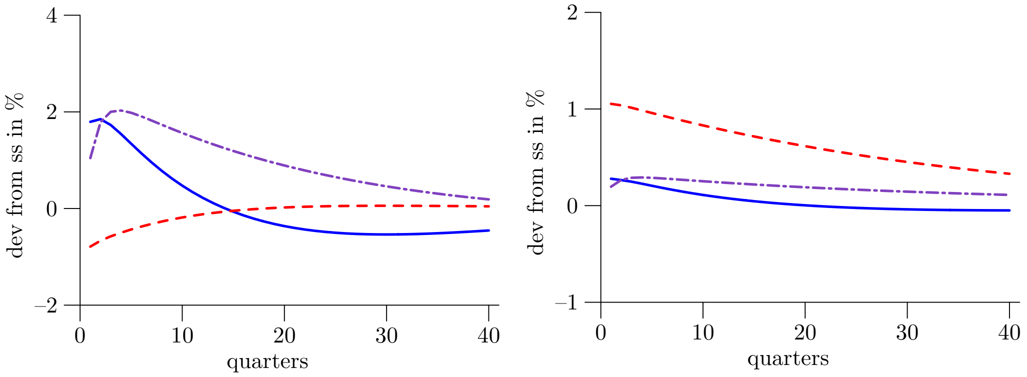
Note: On the diagonal standard deviation of relevant shock σ_Z, out of diagonal cross correlations between shocks ϵ^Z.

in the table 6 chosen levels of elasticity parameters, together with the selected four shocks and their correlation structure enable us to fit our model to Polish data fairly well. We conclude however that abnormally high relative standard deviation of investment to GDP observed in Poland is probably due to short span of available time series and recent economic crises. Therefore we did not try to mimic it through proper adjustment of relevant elasticity parameters accepting lower value typically registered for developed economies over longer periods of time than 13 year of data available for Poland. Only the dynamic properties of open economy variables deviate substantially from data, because of the relatively simple representation of this issue in the model. However as the purpose of our model is to analyze long term response of Polish economy to various climate policy packages we do not consider this as an important drawback.

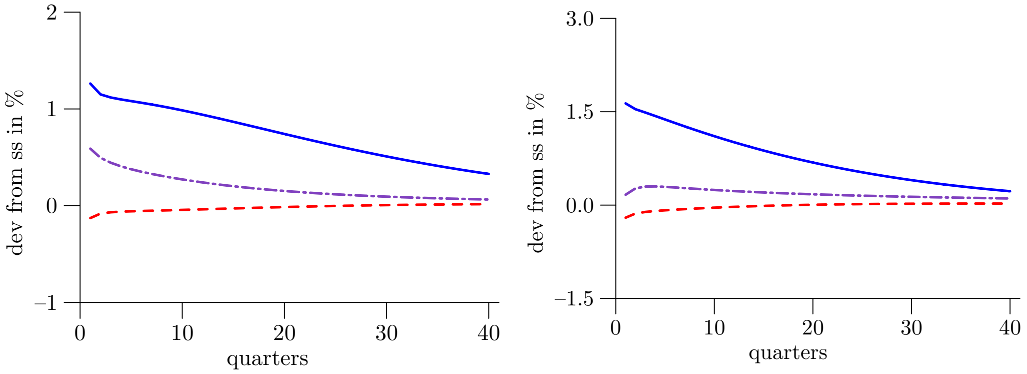
Figure 3: Impulse response functions of major variables (A)



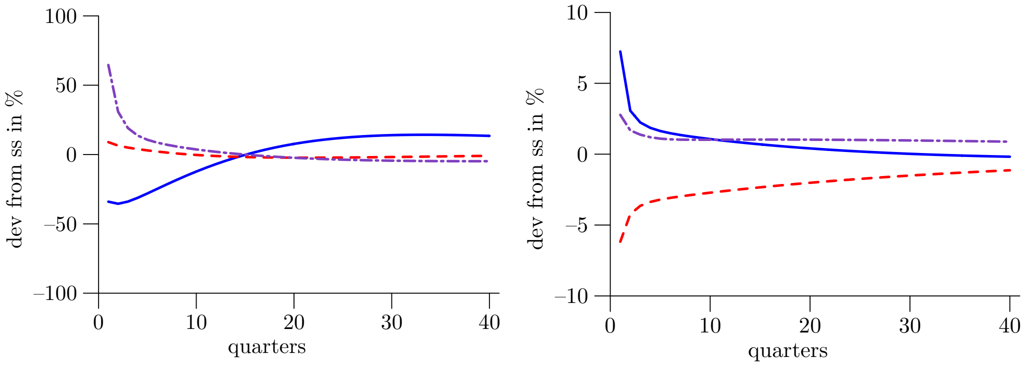
GDP **Private consumption**



Investment **Government consumption**

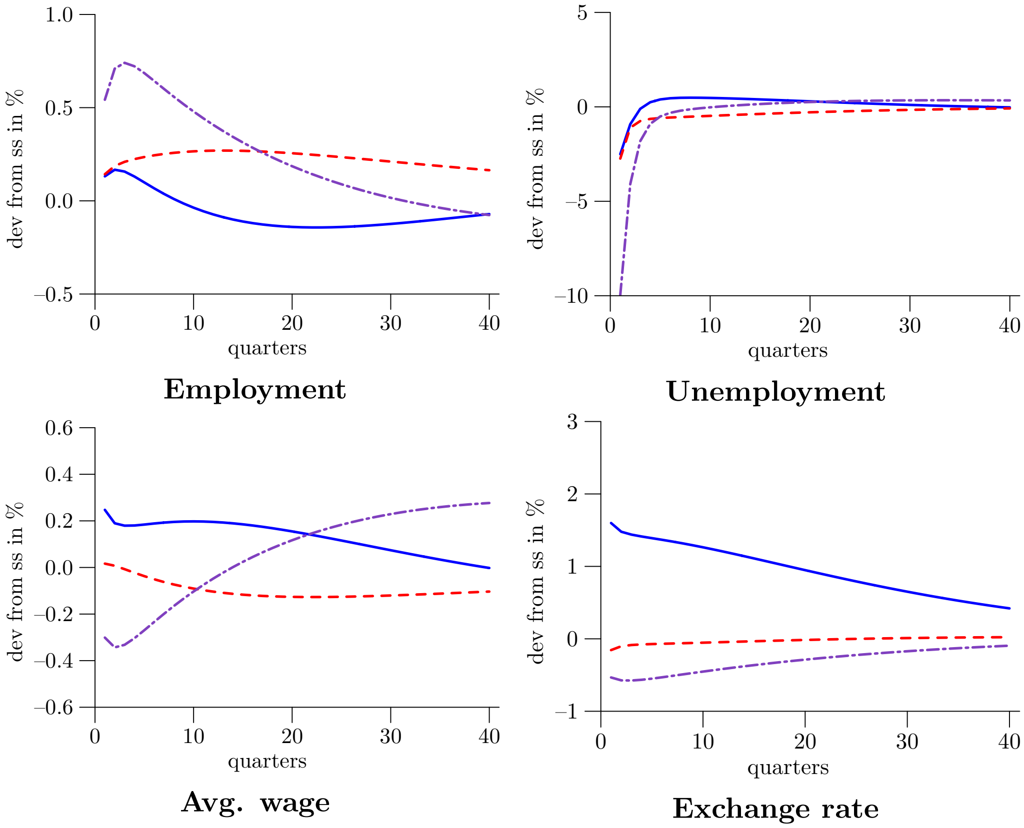


Export **Import**



Current Account **Transfers**

Figure 4: Impulse response functions of major variables (B)



Employment

Unemployment

Avg. wage

Exchange rate

Note: Blue solid line: technological shock, violet dash-dot line: foreign demand shock, red dashed line: public consumption shock

5 Results

5.1 Business as usual scenario

In order to assess the macroeconomic impact of GHG abatement policies we perform simulations in three stage procedure. In the first stage we construct econometricaly the reference, business as usual (BAU), scenario. We simulate what will happen till the year 2030 if the trends and convergence processes observed in Europe and Poland in the past, continue and no significant new abatement policies are introduced. We are particularly interested in projecting the future level of GHG emissions and energy consumption, as those two variables form the key constraints for the ability of the mitigation package to fulfill the EU emission targets in the 2020 and 2030 perspective. Other variables constituting the BAU scenario include value added and emission and energy consumption intensities. All of them were calculated for Poland and the EU for aggregated level, 11 sectors of economy and (if relevant) households and cover 35 year period (1996-2030) with 10 years of historical data and 25 years of projections.

The Business As Usual (BAU) is a reference scenario in which we assume a continuation of recent convergence processes observed in the European Union with respect to all variables under consideration e.g. value added and its structure, Greenhouse Gases (GHG) emission and intensity, energy and its intensity. BAU scenario is aimed at depicting what would happen if past convergence patterns observed within the EU will continue. In other words we assume that relatively less developed member states (including Poland) will catch up to the EU average following the convergence trends observed in the past.

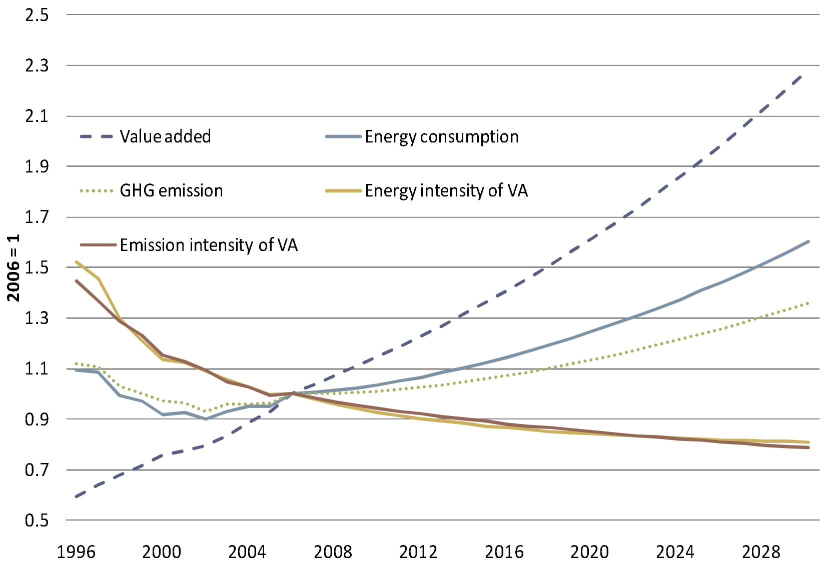
The annual panel data was collected from EUROSTAT database for a period 1996-2006. There are 21 EU countries included in our dataset namely: Poland, Austria, Belgium, Czech Republic, Denmark, Estonia, Finland, France, Germany, Hungary, Ireland, Italy, Lithuania, Latvia, the Netherlands, Portugal, Slovakia, Slovenia, Spain, Sweden, United Kingdom. The constructed database incorporates such variables as: value added expressed both in Purchasing Power Standard and volumes, energy consumption [in tones of oil equivalent], energy intensity [toe/PPS], GHG emission [tones of CO2 equivalent] and emission intensity [tCO2e/PPS].

Each variable in the database is presented for 11 sectors of the economy: agriculture, heavy industry, light industry, energy, transportation, fuels, trade, construction, finance, public services and other services. In order to estimate the relative growth rates for all variables in our database we apply standard growth regression technique determining the beta convergence rates on on sectoral level. For example we look at the difference between the country and average EU shares of all sectors in the total value added in years 1996 and 2006 for all 21 countries from our sample.

Next, for every sector we regress the shares from 2006 on shares from 1996 receiving the measure of the observed convergence rates in the sectoral structure between these two periods. Having this calculated we can compute the average annual rate of growth of the every sector share. We use similar approach to analyze convergence rates of energy and emission intensities. Instead of shares we take logarithms of both measures and their counterparts for EU average. Furthermore, we compute annual rates of growth of energy and emission intensities for all sectors.

Poland AD2010 is responsible for about 1 percent of global GHG emissions in 2010 and about 2 percent historically. That is about 40 percent of the total NMS emissions and 6 percent of the EU overall emissions. Over 82 percent of the country's total GHG emissions is due to the carbon dioxide production mainly in power generation, heavy industry and transport sectors. The rest can be attributed to methane (CH4) and nitrous oxide (N2O) and fluorinated gases. This structure is very similar to the EU average, however Polish economy emits much more CO2 in electricity and heat generation (46 percent vs 32 percent average in the EU27) and much less in transport (almost 10 percent vs almost 20 percent in the EU27). This is partially due to the smaller transport intensity of the economy and partially due to the dominance of hard and lignite coal plants in the power generation sector. In fact, unprecedented 95 percent of electricity is generated from carbon fuels (91.5 percent from coal, 3.3 from gas and oil) making Poland not only European but also global outlier. As Polish electricity mix is dominated by coal, total energy consumption is even more dependant on renewables that constitute less than 5 percent of the domestic energy consumption. At the same time, over last 20 years Poland has achieved significant gains with respect to energy and emission intensity of production. The convergence towards EU15 with this respect is far from ending as the Polish economy uses about twice as much energy to produce one unit of GDP as its Western counterparts. Therefore, further convergence with respect to energy and emission can be expected in the future, although most of the "easy savings" have already been achieved.

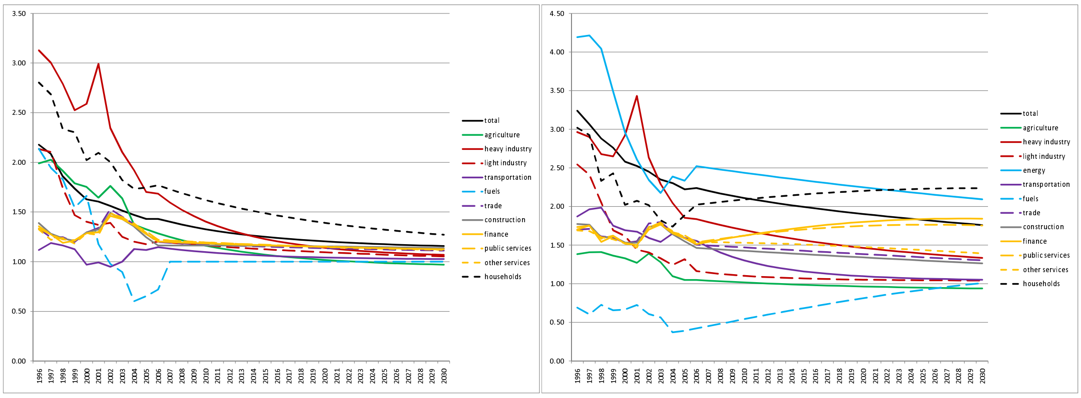
Figure 5: BAU projections of total economy aggregates (2006 = 1)



Using estimated convergence rates we can construct the BAU scenario for Poland and the EU. It is assumed that long term growth rates will be maintained with the correction for convergence pace. If the convergence process is accomplished i.e. country reaches average EU level it continues to develop at the average, trend rate.

Agriculture is the sector whose value added share converged at the fastest rate in our dataset. Furthermore, significant pace of convergence characterized the transport, fuels and construction sectors. As far as energy intensities are concerned almost all of them converge at similar rates. The only exceptions are light industry and fuel sectors. In their case EU-21 countries did not converge to each other in 1996-2006 time period, in the letter case perhaps due to rising diversity in their energy-mix composition in the EU (fuels include hard coal, lignite, oil, gas etc.). The last category - emission intensity - is characterized by much higher dispersion of convergence rate values between sectors. The fastest convergence process could have been observed in the light industry and transport and the slowest in case of households, financial and public services. The challenge of projected GHG abatement can be deduced indirectly from the BAU and EU 2020 targets. As a member of the EU Poland is committed to fulfill EU energy and climate change objectives by 2020 (so called 20-20-20 package) approved in late 2008. This package requires significant emissions reduction across all sectors in the economy and member states. In particular it envisages 20 percent reduction in GHG emissions compared to 1990 levels, achieve 20 percent share of renewables in the final energy consumption (including a 10 percent share of biofuels in transport), and indicatively reduce by 20 percent the primary energy use compared to projected BAU levels thanks to the improved energy efficiency. More detailed EU regulations demand that energy-intensive installations in certain sectors of economy should be covered by so called Emissions Trading Scheme (ETS). Detailed brake-down between ETS and non-ETS sectors depends on the country and in case of Poland it is estimated that about 60 percent of the total GHG emissions can be attributed to the first group (compared to 40 percent in the EU27). EU wide reduction targets in the ETS sectors aim at limiting the GHG emissions by the year 2020 by 21 percent compared to 2005. At the same time non-ETS emissions should drop by 10 percent, with Poland allowed to face a small increase by 14 percent. Although the collapse of the energy inefficient centrally planned economy in 1989 and significant improvements thereafter enabled Poland to already reduce the GHG emission level by 12 percent compared to 1990 (e.g. to 399 million tons of CO2eq in 2007 from 454 MtoCO2eq in 1990) further reductions

Figure 6: BAU projections of energy and emission intensities (EU21 = 1)



(a) Energy intensity (b) Emission intensity are needed to meet the 2020 -20percent target (363 MtoCO2eq). The ultimate scale of these reductions will depend on the rate of economic growth in the next 10 years as well as on the further advancement with respect to energy and emission intensity of value added. Basing on the presented BAU projections we conclude that in 2020 GHG emissions in Poland will be more or less on the level observed in 1990. In consequence the policy package that will be able to successfully achieve EU 2020 targets should deliver a 20 percent emission reduction with respect to BAU. In the following sections we analyze such a package in detail.

5.2 GHG abatement micro-package composition

In the second stage, we consider a package of about 120 mitigation levers which were identified in the bottom-up sectoral analysis and presented in the McKinsey &Company 2009 report for Poland (McKinsey 2009). We analyze the macroeconomic impact of every lever in the package individually and the package as a whole. For presentation purposes each lever from the package was attributed to one of seven categories: (1) agriculture interventions (AGRI), (2) industry CCS and distribution maintenance (CCS), (3) chemical process optimization (CPO), (4) energy sector investments (ESI), (5) energy efficiency (E-EFF), (6) fuel efficiency (F-EFF), and (7) mixed energy/fuel efficiency (EF-EFF). In the original database each lever was described by time series reflecting the expected capital (CAPEX) and operating (OPEX) expenditures from the given measure. Those numbers take into account technological assumptions presented in their report e.g. the scope of investments in the GHG abatement technologies and the resulting operating expenditures or savings to be achieved in the 2010-2030 period. As the source database include 5year aggregates (e.g. there are 4 OPEX and 4 CAPEX values per every lever) and our model is calibrated to quarterly frequency. the Boot-Feibes-Lisman (BFL) interpolation procedure was applied for disaggregation purposes. Moreover, for each lever the "target", "CAPEX" and "OPEX" sectors were identified (see table 8). The "target sector" is a sector that is directly affected by a given measure i.e. the sector that bears the costs and ultimately gains benefits from the introduction of specific GHG abatement technology. Likewise, the increased material demand in the target sector is spent in the "CAPEX sector". Finally, the "OPEX sector" is affected by changes in the operating expenditures of the target sector induced by the implementation of a given measure - in other words. Each lever is implemented by a combination of shocks. For the lever introduced in a target sector $s \in S$ with CAPEX sector $i \in S \in S \setminus \{ENG\}$ and OPEX sector $j \in S \setminus \{ENG\}$ relevant shifts in material demand are implemented by $\xi_{i,t}^{M,s}$ and $\xi_{j,t}^{M,s}$ shocks. Similarly in case of energy efficiency levers, sectoral energy demand, $\xi_t^{ENG,s}$, or economy wide energy efficiency shocks, ξ_t^{EF}, are being used. Those shocks implement direct or indirect improvements in the energy, fuel or mixed efficiency in production and economically are equivalent to the sectoral technology shocks. In case of consumer oriented measures that involve changes in the structure of final consumption of good $j \in S$ (e.g. switch to LED in households) where j denotes the lever's OPEX sector, we utilize the final demand shocks, $\xi_t^{FC,j}$. On the other hand levers belonging to the ESI category are implemented by the set of shocks involving emission intensity shock $\xi_t^{GHG,s}$ (improvement

Table 8: Example of individual levers description

Name	Category	Target Sector	CAPEX sector	OPEX sector
Switch to LEDs, resid.	E-EFF	CNS	LIND	ENG
Retrofit HVAC contr., comm.	EF-EFF	ALL	LIND	ENG/FLS
Ethylene Cracking, new build	CPO	HIND	HIND	HIND
Distribution Maintenance	CCS	FLS	HIND	CST
Transport EF HDV-D1	F-EFF	TRN	LIND	FLS
Recycling new waste	F-EFF	SRV	HIND	FLS
Antimethanogen vaccine	AGRI	AGR	LIND	AGR
Nuclear power plant	ESI	ENG	INV	FLS

in the emission intensity of energy production), public investment subsidy shocks, $\xi_t^{P,E}$, and external demand shock $\xi_t^{I,ENG}$ (in case of nuclear power plants that are associated with the shift from domestic (coal) to imported (uranium) fuel). Similarly in case of other levers the government subsidy shocks in light, $\xi_t^{S,KL}$ and heavy, $\xi_t^{S,KH}$, industry are capable to capture necessary subsidies to CAPEX expenditures if such subsidies are considered as a pre-condition to have certain lever implemented (e.g. to promote house insulation among the householders). Last but not least the fiscal tax closures are associated with relevant tax shocks $\xi_t^{\tau,Z}$ for $Z \in \{V, W, C\}$. Those shocks together are filtered for each lever in the Kalman smoother procedure described shortly above, in order to form the conditional forecasts of its impact on the economy. Information for this forecast is provided by the CAPEX and OPEX numbers, together with government subsidy and GHG abatement gains expected from the implementation of relevant energy sector investments that have a special place in the overall package

This special position of ESI is due to the fact, that current technology in Poland is almost entirely coal based. In result, any shift in energy mix towards non-coal power plants can deliver substantial reductions in total GHG emissions on the country level. As the cheapest available option should be optimal we determined the composition of levers belonging to the energy sector investment category endogenously. In order to do that, basing on the micro data, we computed the NPV of new investment projects in the energy sector (new power plants) of each type (17 options were considered). Secondly, taking into account the ultimate GHG reduction target and projected emission in the business as usual scenario, we calculated the cost of individual energy levers and desired government subsidy necessary to equalize its NPV with the NPV of traditional coal plant. Finally, the cheapest feasible energy-mix package was determined taking into account the technological constraint (maximum availability of a given technology), energy production constraint (projected BAU level of the energy consumption) and GHG reduction constraint (desired abatement).

Our algorithm is based on the assumption that a government intervenes on the market in order to achieve certain reduction target. This intervention can take a form of a new/higher tax on firms producing coal energy, or the cap on prices of emissions of CO2 rights and transfers. The subsidies basically come from the addition tax and emission rights revenues. The target is set in compliance with the government targets and equals to 50% reduction of CO2 emissions comparing to BAU in 2030. Considered scenario is optimal in the sense that the government minimizes its loss function which includes: (1)the upward deviation of the reduction from the target value. As it is costly for government to finance reduction it does not want to achieve higher reduction than it is necessary, (2) the increase in costs relatively to the BAU scenario. The loss function takes a following form:

$$L = W_{GHG} \times \left(\frac{GHG}{GHG_{target} - 1} \right)^2 + \left(\frac{Cost}{Cost_{BAU}} \right)^2 \tag{1}$$

where relative weight W_{GHG} is large enough to guarantee the fullfilment of the GHG abatement target GHG_{target}. The optimal energy package was incorporated into the overall mitigation policy-options package described above. There are only two types of energy plants that have positive NPV: geothermal and coal conventional. The disadvantage of the first is the low capacity, of the second - high CO2 emissions. Therefore, all plants which can effectively help to mitigate CO2 emission in the energy sector have negative NPV. Among them the cheapest are "on shore wind" and "nuclear" plants and the most expensive - biomass dedicated and biomass CCS new built. One can expect that the former two should show up in the optimal scenario - the latter are likely to be avoided and their setting up should be connected with substantial growth of costs. The optimal electricity generation mix in this scenario is presented above. There is a profound decrease in the utilization of energy produced

Table 9: Basic economic features of individual energy investment levers

	NPV	CO2 per GWh	2030 Cap. in GW	ENG price s.t. NPV=0	CO2 price s.t. NPV=0
Coal CCS new	-0.45	103.3	3.5	0.53	202
Coal CCS-EOR new	-0.45	145.7	0.5	0.53	205
Coal IGCC	-0.46	69.8	5.8	0.52	181
Gas CCS new	-0.93	47.2	0.7	0.58	253
Gas CCS/EOR new	-0.09	134.6	0.5	0.43	61
Biomass dedicated	-1.64	558.1	0.9	0.63	921
Biomass.co-firing	-0.28	714.8	0.5	0.45	401
Biomass CCS new built	-1.41	80.2	5.8	0.92	740
Nuclear	-0.3	0	6	0.52	167
On shore wind	-0.12	0	10	0.45	78
Off shore wind	-0.49	0	6	0.6	270
Solar PV	-0.63	0	1.7	1.14	946
Solar conc.	-0.93	0	1.4	1.15	962
geothermal	0.38	0	0.7	0.35	-44
Small hydro	-0.07	0	1.7	0.43	56
Coal conventional	0.01	796.8	38	0.42	N/A
Gas conventional	-0.69	386.1	3.6	0.47	161

Table 10: Optimal electricity generation mix

	2015	2020	2025	2030
Coal IGCC	0.00	0.01	0.05	0.06
Nuclear	0.00	0.10	0.15	0.19
On shore wind	0.06	0.08	0.12	0.14
geothermal	0.00	0.00	0.00	0.02
Small hydro	0.05	0.04	0.03	0.03
Coal conventional	0.81	0.67	0.54	0.44
Gas conventional	0.07	0.07	0.09	0.11

in a conventional coal plants. This is the natural consequence of the GHG reduction target. The same reason stands for profound increase in share of nuclear and wind plants which do not emit CO2 at all as well as Coal IGCC which emits much less than conventional coal. Substantial increase in share of gas plants can be attributed to relatively low gas prices. Thus, in the optimal scenario coal remains the main source of energy in Poland but there is a tendency to increase share of alternative sources. In this scenario the government undertakes the most appropriate decision from the point of view of its socio-political goals (reduction) and efficiency (minimizing costs). This scenario serves as an energy input to the micro-package analyzed in the next section.

5.3 Macroeconomic impact of the GHG abatement micro-package

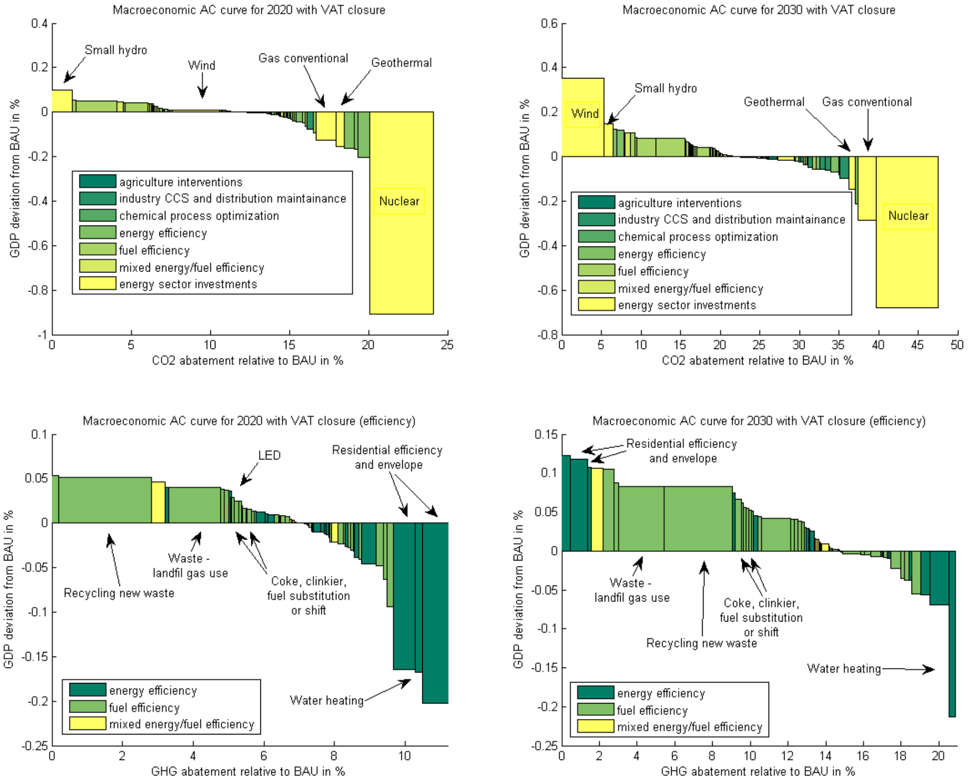
In this section we analyze macroeconomic and fiscal impact of the multi-lever GHG abatement package borrowed from the 2010 McKinsey study on Poland. Common feature of measures constituting this package is their technological aspect - each of them can be strictly associated with particular change in the quality of capital and all of them lead to smaller GHG emissions either through the direct shifts in production technology or through the improvements in the efficiency of factor utilizations. This features are either represented by the relevant shifts in emission intensities or by shifts in the energy of fuel demand toward less emitting resources. Total macroeconomic effect of the considered levers is presented in tables 11-12.

First of all, it is worth noting, that the package as a whole is capable to reduce GHG up to the year 2020 and 2030 by respectively 24 and 47 percent (relative to BAU). In consequence, emissions would fall from about 455mln ton of CO2e in 2020 and 543mln of CO2e in 2030 to respectively 346mln ton and 286mln ton. Almost half of this potential lays however in the energy sector (see table 12). Moreover, the rest is dominated by fuel efficiency measures that concentrate mostly in the transport and waste management sectors. Consequently, if either the shift of the energy mix towards zero-carbon technologies will occur significantly later than it was assumed, or the levers increasing fuel efficiency will be implemented only partially, the 2020 abatement goal will not be met without additional macroeconomic measures (like carbon tax). On the other hand, even the partial fulfillment of the huge GHG abatement potential of the micro-package up to the year 2030 may increase the likelihood that EU goals up to that date will be met.

Even substantial loses in GHG abatement caused by the significant drop-out of individual levers from the package could be replaced with the rest of them if they are implemented. Moreover, the relative role of energy sector measures in CO2 reduction gradually falls after the year 2020. Symmetrically the relative importance of the efficiency and industrial abatement levers grows in time. This phenomenon may undermine the credibility of the whole package as a policy tool. It can assure that the EU2020 abatement goals will be met only if the households' and firms' approach toward energy and fuel efficiency measures changes significantly - investment in less emitting technologies in the heat and power generation sector are not enough.

Well known barriers like high initial costs and liquidity constraints, agency issues between the owner, operator and bill payer, as well as lack of information can mitigate actual GHG mitigation potential of the energy and fuel efficiency measures. If so, demand steering instruments like carbon taxation, investment subsidies or publicly financed education can be viable solutions to these problems, however their introduction to the package would increase the cost side and mitigate the positive medium and long term effects of efficiency measures.

Figure 7: Macroeconomic abatement cost (MacroAC) curves



Secondly, it is worth noting that the impact of the package on GDP and value added is generally negative over the entire 20 year period with an exception of the social transfer variant, that becomes positive at the very end of the deliberated time horizon. In other words only if we assume that the government finances its climate actions by relevant reduction in social transfers one can guarantee that its policy will not be growth hampering in the long term. This is due to the expected rise in the labor supply in response to the shrinking transfers. However, in this variant the drop in a welfare level, that measures the discounted present value of future utility drown not only from consumption but also from welfare is the most substantial. This is caused by the fact that the reduction in the leisure time, imposed by shrinking transfers, diminishes the well being of households more than the it is gained from larger consumption. Thirdly, one must underline that the negative influence of the package on a GDP level peaks in the year 2017 (in tables below we present only the 2020 number) reaching the level of about 5 per cent below the trend. As this number is fully comparable to the long term annual growth rate of Polish economy we can state that the implementation of the considered package . This drop should be mainly associated with the recession in the ETS sector that bears the heaviest burden of the entire abatement cost (compare table 12), although the Non-ETS sector is also negatively affected in most of the variants. Difference between ETS and non-ETS part of the economy is especially visible on the labor market. Package generates significant employment flows from the first towards the second sector. In the public consumption and social transfer closure variants we can expect that government expenditures will have to be adjusted to the falling GDP level and followed by the relevant collapse of public incomes. On the other hand, growing revenues of the government in the variants with VAT and PIT taxation, should lead to the parallel rise in tax income.

Table 11: Macroeconomic and fiscal impact of micro GHG abatement package (deviation from BAU in %)

Closure	Variable	2015	2020	2025	2030
Public consumption	GHG emissions	-10.33	-24.01	-39.31	-47.34
	GDP	-2.13	-3.08	-2.42	-0.66
	Value Added	-2.20	-3.19	-2.53	-0.74
	Employment	-2.73	-2.09	-2.76	-2.33
	Welfare	-1.03	-1.64	0.01	0.52
	Government expenditures	-2.64	-3.05	-2.15	-1.06
	Government revenues	-2.20	-3.15	-2.76	-1.13
Closure	Variable	2015	2020	2025	2030
Social transfers	GHG emissions	-10.38	-23.86	-39.03	-47.01
	GDP	-1.52	-1.89	-0.28	0.68
	Value Added	-1.51	-1.93	-0.35	0.69
	Employment	-0.67	3.16	6.34	3.34
	Welfare	-2.88	-4.49	-3.27	-1.63
	Government expenditures	-2.86	-1.83	0.94	0.76
	Government revenues	-1.55	-1.86	-0.49	0.30
Closure	Variable	2015	2020	2025	2030
VAT	GHG emissions	-10.56	-24.14	-39.48	-47.50
	GDP	-1.53	-1.79	-0.83	0.16
	Value Added	-2.88	-3.42	-2.81	-1.63
	Employment	-2.59	-0.52	-0.20	-0.85
	Welfare	-1.85	-2.88	-1.54	-0.66
	Government expenditures	1.75	3.23	6.06	5.58
	Government revenues	2.19	2.59	4.30	4.77
Closure	Variable	2015	2020	2025	2030
PIT	GHG emissions	-11.16	-24.63	-40.15	-47.92
	GDP	-2.18	-2.37	-2.07	-0.63
	Value Added	-2.17	-2.41	-2.03	-0.56
	Employment	-6.13	-4.84	-7.35	-6.79
	Welfare	-1.82	-2.49	-0.88	-0.09
	Government expenditures	1.38	2.90	5.44	5.16
	Government revenues	1.74	2.41	3.93	4.38

Table 12: Decomposition of the macroeconomic impact of GHG abatement package (deviation from BAU in %)

Closure	Variable	2015	2020	2025	2030
Public consumption	VA in ETS	-2.06	-3.69	-5.35	-7.07
	VA in Non-ETS	-2.22	-3.12	-2.15	0.14
	Employment in ETS	-1.66	-0.14	-2.36	-4.63
	Employment in Non-ETS	-2.15	-1.56	-1.68	-0.60
	GHG emission in ETS	-11.41	-27.27	-44.06	-52.32
	GHG emission in Non-ETS	-10.73	-22.95	-37.92	-46.49
	GHG emission in households	-0.89	-3.26	-3.97	-3.25
	Emission intensity of VA	-8.32	-21.50	-37.74	-46.95
	Energy intensity of VA	-1.17	-8.02	-11.09	-12.12
	Transport intensity of VA	1.15	1.66	2.25	2.08
Closure	Variable	2015	2020	2025	2030
Social transfers	VA in ETS	-2.73	-3.91	-4.64	-5.85
	VA in Non-ETS	-1.35	-1.67	0.24	1.60
	Employment in ETS	-1.45	3.00	4.52	0.09
	Employment in Non-ETS	-0.35	3.15	6.63	4.59
	GHG emission in ETS	-11.48	-27.04	-43.67	-51.91
	GHG emission in Non-ETS	-10.78	-22.67	-37.29	-45.98
	GHG emission in households	-0.83	-4.61	-7.02	-5.37
	Emission intensity of VA	-9.01	-22.36	-38.81	-47.37
	Energy intensity of VA	-1.83	-9.21	-13.05	-12.90
	Transport intensity of VA	0.41	1.02	1.82	2.45
Closure	Variable	2015	2020	2025	2030
VAT	VA in ETS	-4.06	-5.76	-7.51	-9.06
	VA in Non-ETS	-2.72	-3.10	-2.16	-0.60
	Employment in ETS	-3.38	-1.19	-2.73	-5.15
	Employment in Non-ETS	-2.29	-0.52	0.17	0.39
	GHG emission in ETS	-11.60	-27.38	-44.20	-52.46
	GHG emission in Non-ETS	-11.14	-23.15	-38.05	-46.60
	GHG emission in households	-0.54	-3.22	-4.56	-4.00
	Emission intensity of VA	-7.91	-21.45	-37.73	-46.63
	Energy intensity of VA	-0.53	-7.86	-11.02	-11.57
	Transport intensity of VA	1.20	1.36	2.09	2.58
Closure	Variable	2015	2020	2025	2030
PIT	VA in ETS	-3.53	-4.72	-6.14	-7.92
	VA in Non-ETS	-1.99	-2.10	-1.47	0.46
	Employment in ETS	-7.10	-5.58	-9.49	-10.91
	Employment in Non-ETS	-6.04	-5.19	-7.46	-5.94
	GHG emission in ETS	-11.82	-27.52	-44.55	-52.69
	GHG emission in Non-ETS	-12.24	-24.06	-39.14	-47.27
	GHG emission in households	-1.65	-4.65	-6.04	-4.93
	Emission intensity of VA	-9.18	-22.76	-38.90	-47.62
	Energy intensity of VA	-1.28	-8.80	-11.77	-12.51
	Transport intensity of VA	-0.92	-1.15	-0.94	-0.44

Investigating the package decomposition into the seven "technological clusters" (see tables 13-14) shows that the group of levers with a highest abatement potential e.g. energy sector investments is also the one with the most negative impact on the GDP growth. This is mainly caused by the large investments in nuclear energy capacity that stretch over the entire period and that do not reach the "asset sweating" phase up to the year 2030. In fact, the wind energy plants that can be finished much sooner, and demand much smaller capital expenditure start rather, between the year 2020 and 2030, to enhance than diminish economic growth. One should expect that this will also be the case of nuclear plants in following decades, although in their case fuel import will make the possible positive effect smaller.

Last but not least, one should notice that among efficiency measures the waste management levers are at the same time the most promising with respect to abatement potential and their impact on economic growth. Similarly to the energy investment projects, the energy efficiency measures will switch from growth hampering to growth enhancing group as soon as the investment phase is finished.

Figure 8: Macroeconomic marginal abatement cost (MacroMAC) curves

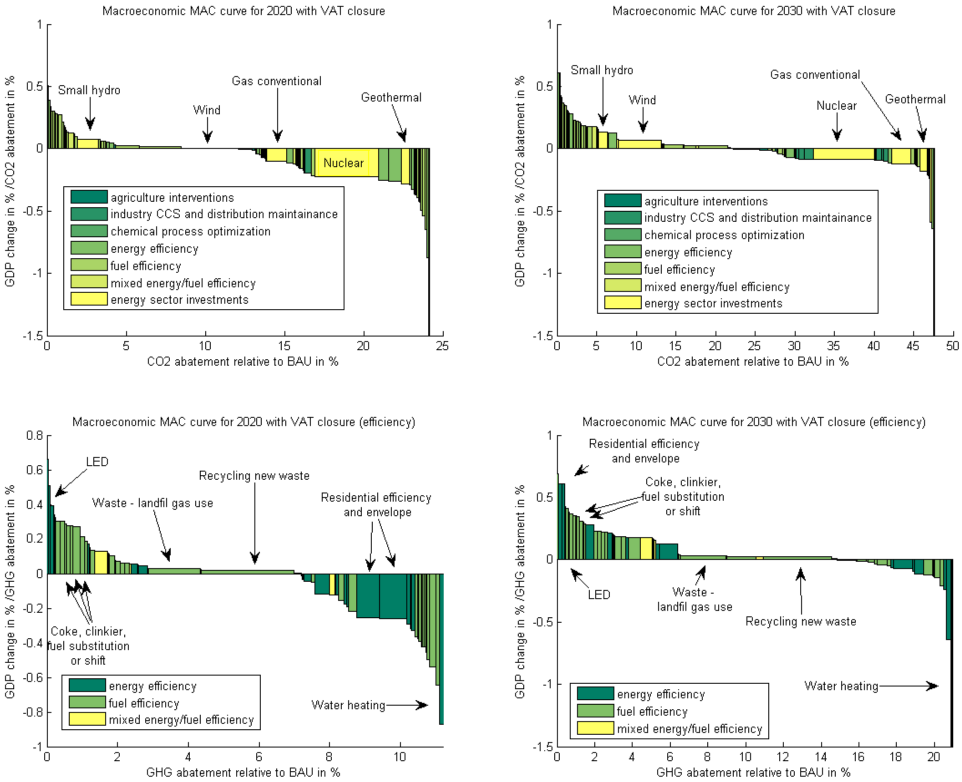


Table 13: Decomposition of the GHG abatement potential of the package (reduction of GHG emissions in %)

Closure		2015	2020	2025	2030
Public consumption	agriculture interventions	0.77	1.27	1.69	1.89
	industry CCS and distr. main.	0.01	0.40	3.49	3.78
	chemical process optimization	0.44	0.70	0.89	0.99
	energy efficiency	2.04	3.45	4.31	4.79
	fuel efficiency	3.40	7.15	11.93	14.83
	mixed energy/fuel efficiency	0.28	0.64	0.98	1.16
	energy sector investments	3.39	10.40	16.03	19.91
Total public consumption scenario		10.33	24.01	39.31	47.34
Social transfers	agriculture interventions	0.77	1.27	1.69	1.89
	industry CCS and distr. main.	0.01	0.40	3.42	3.56
	chemical process optimization	0.44	0.69	0.88	0.98
	energy efficiency	2.08	3.32	4.13	4.65
	fuel efficiency	3.39	7.14	11.94	14.86
	mixed energy/fuel efficiency	0.27	0.64	0.99	1.17
	energy sector investments	3.41	10.40	15.98	19.90
Total social transfers scenario		10.38	23.86	39.03	47.01
VAT	agriculture interventions	0.77	1.27	1.69	1.89
	industry CCS and distr. main.	0.01	0.41	3.65	3.79
	chemical process optimization	0.45	0.71	0.90	1.00
	energy efficiency	2.20	3.49	4.32	4.87
	fuel efficiency	3.39	7.14	11.90	14.84
	mixed energy/fuel efficiency	0.27	0.64	0.98	1.17
	energy sector investments	3.46	10.48	16.03	19.95
Total VAT scenario		10.56	24.14	39.48	47.50
PIT	agriculture interventions	0.77	1.28	1.69	1.90
	industry CCS and distr. main.	0.01	0.46	4.21	3.86
	chemical process optimization	0.48	0.73	0.91	1.01
	energy efficiency	2.65	3.62	4.31	4.99
	fuel efficiency	3.42	7.20	11.94	14.94
	mixed energy/fuel efficiency	0.27	0.64	0.98	1.16
	energy sector investments	3.55	10.71	16.10	20.06
Total PIT scenario		11.16	24.63	40.15	47.92

Table 14: Decomposition of the GDP change of the package (deviation from BAU in %)

Closure		2015	2020	2025	2030
Public consumption	agriculture interventions	-0.01	-0.02	-0.02	-0.03
	industry CCS and distr. main.	0	-0.13	-1.18	-0.42
	chemical process optimization	-0.07	-0.07	-0.07	-0.08
	energy efficiency	-1.74	-1.01	-0.12	0.12
	fuel efficiency	-0.14	-0.21	0.18	0.54
	mixed energy/fuel efficiency	-0.04	0.02	0.11	0.15
	energy sector investments	-0.15	-1.67	-1.31	-0.95
Total public consumption scenario		-2.13	-3.08	-2.42	-0.66
Social transfers	agriculture interventions	0	-0.01	0	0
	industry CCS and distr. main.	0	-0.05	-0.19	-0.12
	chemical process optimization	-0.03	-0.03	-0.04	-0.04
	energy efficiency	-1.34	-0.58	0.19	0.35
	fuel efficiency	-0.06	-0.03	0.55	1.05
	mixed energy/fuel efficiency	-0.03	0.04	0.12	0.15
	energy sector investments	-0.06	-1.23	-0.9	-0.71
Total social transfers scenario		-1.52	-1.89	-0.28	0.68
VAT	agriculture interventions	0	0	-0.01	-0.01
	industry CCS and distr. main.	0	-0.08	-0.79	-0.34
	chemical process optimization	-0.04	-0.05	-0.05	-0.06
	energy efficiency	-1.28	-0.57	0.11	0.18
	fuel efficiency	-0.06	0	0.58	0.97
	mixed energy/fuel efficiency	-0.02	0.03	0.12	0.15
	energy sector investments	-0.13	-1.13	-0.79	-0.73
Total VAT scenario		-1.53	-1.79	-0.83	0.16
PIT	agriculture interventions	0	-0.01	-0.02	-0.02
	industry CCS and distr. main.	0	-0.14	-1.67	-0.37
	chemical process optimization	-0.07	-0.07	-0.07	-0.07
	energy efficiency	-1.85	-0.8	0.02	-0.12
	fuel efficiency	-0.08	-0.07	0.47	0.71
	mixed energy/fuel efficiency	-0.02	0.03	0.12	0.13
	energy sector investments	-0.16	-1.32	-0.92	-0.89
Total PIT scenario		-2.18	-2.37	-2.07	-0.63

5.4 Macroeconomic impact of alternative energy packages

Apart from establishing the optimal scenario under given constraints we also consider twelve other energy mixes. Out of them four serve for sensitivity analysis. Remaining eight reflect different discretional policy choices of a government towards desired technological composition of an energy supply in the country. Below we present short description of each of chosen scenarios together with a comparison of their key economic characteristics.[1]

Wind+Solar In this scenario we assume that government is interested in promoting some types of renewable sources of energy i.e. wind and solar. Although there are not as good conditions in Poland to use wind energy as in the Netherlands nor the country can use as much solar energy as countries from the south of Europe, according to our assumptions it is still possible to install more than 700 MW of solar plants and more than 6.7 GW of wind plants till 2030. Apart from renewable resources and coal there are no other sources of energy installed. On the other hand it must result in higher costs as both solar and wind plants are much less efficient than coal. Indeed it comes at the huge cost of PLN 9 989 million which is more than 4 times larger than cost in optimal scenario.

Wind + Biomass In wind + biomass scenario government aims at maximizing the production of energy from these two sources in a similar manner to Wind + Solar scenario. Biomass can be used in small power plants which may supply the energy to small towns or villages. It should be noted here, however, that due to a small efficiency of biomass and wind plants they cannot provide electricity to bigger cities. Therefore, the extent to which biomass can be used is limited and still some new large coal or nuclear plants will be needed. The latter ones are more likely because of their efficiency. The main component of biomass is biomass CCS plants which is desirable from CO2 emission point of view. It is also the share of biomass CCS which mostly differentiates this scenario from the optimal one. Although biomass plants amount together to roughly 25% of whole energy production they cannot substitute for coal plants - some new coal IGCC will be needed.

Gas The next scenario takes a deeper dive into the policy in which government intervenes on the market in order to achieve higher share of gas in the electric energy mix than it is the case in optimal scenario. Thus, constraints on share of gas plants are violated. This exercise can be of special interest due to recent decreases in gas prices. As result the structure from table 5 is obtained. It shows that apart from coal gas and wind become main sources of energy in Poland in this scenario. It provides smaller CO2 emission reduction (40%) but at considerably smaller cost (annually from 2015 to 2030 PLN 2 147 million) which equals 76% of the cost of optimal scenario.

---

[1] GHG reductions are presented in relation to BAU 2030 value

CCS Taking into account strategic coal resources in Poland and the strength of coal lobby the government may be interested in implementing the technology which allows both high usage of coal as energetic resource and reduction of CO2 emission. CCS scenario represents such an option. In this scenario not only CO2 produced by coal plant is captured and stored but also from biomass and gas (however from the latter to much less extent). As it can be seen from the table CCS can be used as important source of reducing the CO2 emissions (48.3% comparing to BAU) though it comes at a considerable cost - government has to spend PLN 8 874 million which is more than 3 times more than it was the case in optimal scenario.

Nuclear The next scenario investigates the impact of higher usage of nuclear plants. As a result of this simulation renewable fuels play relatively smaller role in this scenario whereas nuclear energy contributes to 20% of total electricity production in 2030. It comes at the annual cost of PLN 3 341 million with the reduction of CO2 emission equaling to 48.7%.

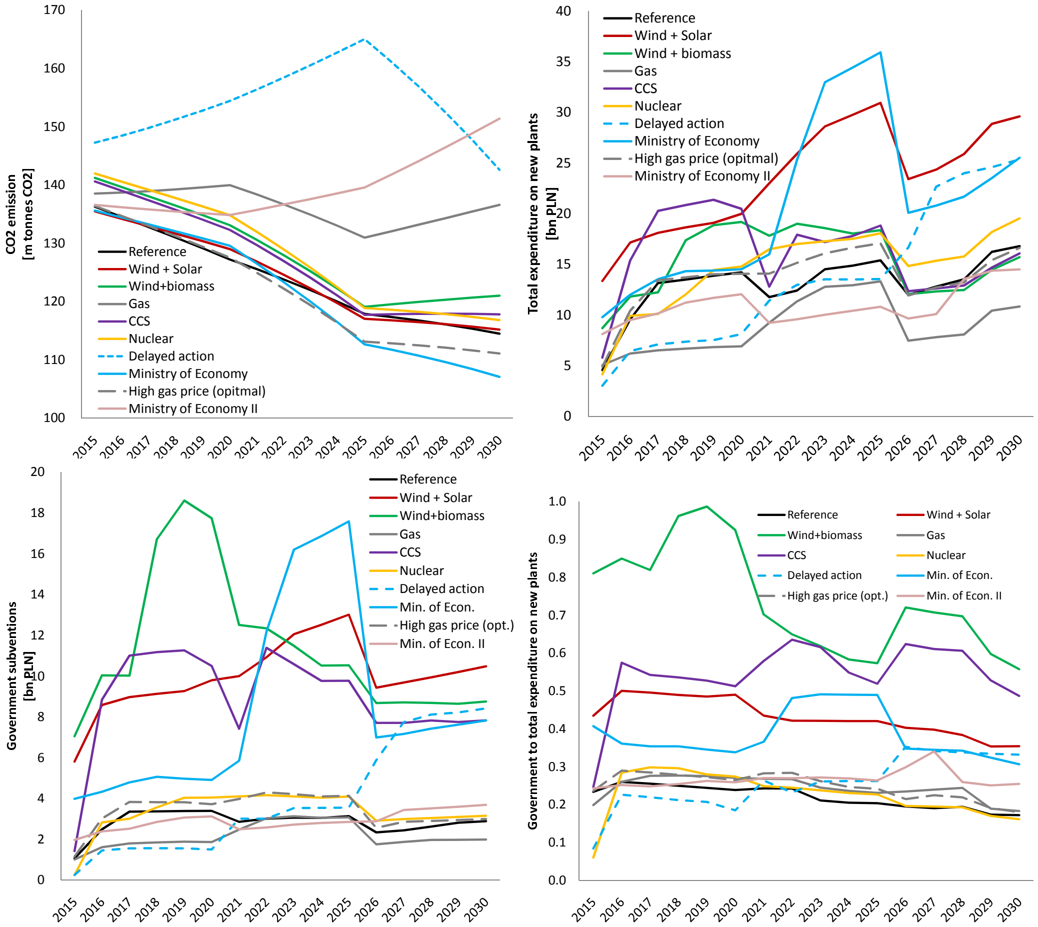
Delayed action In this scenario it is assumed that the government postpones its actions till 2015. After that it decides to reach the same goals as described earlier and undertakes optimal policy to reach them. It turns out that in this case average costs of participation of the government in new power plants rise to PLN3 932 million whereas the reduction declines to 36.7%. It is caused by the fact that the government has to influence the market to invest in less efficient (and more costly) technologies (like coal CCS) which are necessary to approach the reduction target.

Ministry of Economy - I In this case we took the energy mix from the Polish Ministry of Economy targets expressed in document "Energy Policy 2030". Taking into account our baseline projections of a total energy production volume we incorporated in this scenario the EP2030 GWh values for renewable and nuclear energy plants directly. As our business as usual scenario predicts smaller energy consumption than it is stated in the EP2030 document, we had to adjust the conventional coal capacity from original MoE assumptions downwards, in order to meet our baseline forecasts. In other words in this scenario production capacity of nuclear and renewable plants is exactly the same as in the MoE EP2030 scenario, whereas the production capacity of conventional coal power plants is smaller. In consequence this scenario would costs PLN 8 362 million and cause the reduction of CO2 emission in the energy sector by 53% which is the highest number from all scenarios.

Ministry of Economy - II Similarly to the previous case we have taken the structure of the energy mix from the Ministry of Economy document "Energy Policy 2030". In this case however, we took the exact structure of the electric energy mix and not the absolute capacity of individual technologies. In consequence, in this scenario total GWh that are to be installed in new types of power plants (i.e. wind, biofuels, solar and nuclear) are much smaller than in the previous case. Consequently the conventional coal share after the year 2020 is much larger than in the other considered scenarios. This results both in the larger emissions and smaller costs comparing to the previous variant.

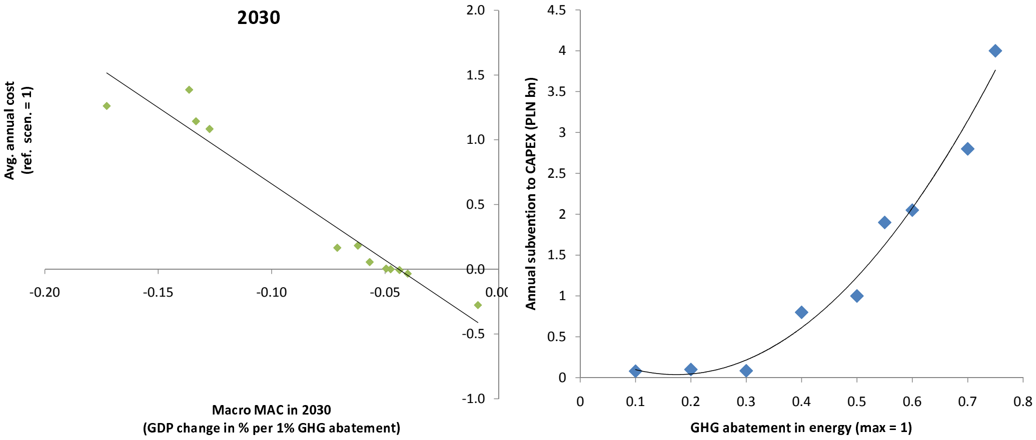
High gas price The high level of volatility of commodities and energy resources is a well-known phenomenon. The example of gas prices which shrank dramatically in 2009 are very instructive. In reference scenario we assumed that current, low, level of gas prices is going to be kept. In this scenario we remove this assumption and investigate the optimal structure of energy mix when gas prices rise to the historical 2009 level. It turns out that the new optimal solution is by 20% more expensive for the government than the reference one and the average annual cost for it amounts to PLN 3 398 million. The reduction stays on similar level of 49.3%. As could be expected - the main difference between high gas price scenario and optimal one is the share of gas in the energy mix structure. In this scenario this share drops to 0 what is compensated mainly by higher share of coal IGCC technology.

Figure 9: Alternative energy scenarios



All of alternative energy mixes are characterized by similar reduction of GHG emissions with an exception of the Delayed action, Gas and Ministry of Economy II scenarios. The first case is due to delayed start of implementing GHG abatement policies and necessary time - to build for new less emitting plants. The second and the third are caused by relatively high GHG intensity of respectively gas and coal plants in comparison to other technologies. They also differ one to another with respect to the path of capital expenditure (CAPEX), government subventions to CAPEX and their share in the total investments of the energy sector. The Wind + Solar and the first of Ministry of Economy scenarios are the most expensive options due to the usage of expensive solar plants. Moreover, they are also the most demanding with respect to the government subsidies. They require almost all the time more than half of capital spent on the new plants by private sector, whereas in optimal scenario this ratio equals to 0.2. On the other hand Ministry of Economy II belongs to the cheapest options, which is due to the much less ambitious investment programme than in the Ministry of Economy I scenario. This scenario in contrast to other options have positive dynamics of GHG emissions after 2020, because rising demand for electric energy in this period is covered to the large extent by conventional coal plants.

Figure 10: CAPEX and macroeconomic impact



There exists a clear relation between the average annual CAPEX in a given scenario and its Macro MAC in 2030. There is only one scenario that violates this correlation - namely the "delayed action" package. This is due to the different time sequence of capital expenditures in this scenario and other packages. In fact the GDP diminishing effects of the "delayed action" variant reach their (negative) maximum in the year 2030 when CAPEX also crest. In case of other packages those peaks are located five or ten years earlier. Moreover, only the unconstrained gas scenario performs better than the reference case. It is however unable to deliver the desired level of GHG abatement both in 2020 and 2030 and therefore violates one of the important constraints. Similar claim can be raised with respect to the Ministry of Economy II scenario, that is much cheaper than its first version, however at the price of much higher carbon dependance at the end of the considered period.

Table 15: GDP change in alternative energy packages (deviation from BAU in %)

Closure	Scenario	2015	2020	2025	2030
Public consumption	Reference (optimal, low gas price)	-0.15	-1.68	-1.31	-0.95
	Wind + Solar	-2.33	-3.66	-4.73	-3.42
	Wind + Biomass	-1.91	-5.03	-2.94	-2.43
	Gas (low gas price)	0.03	-0.45	-0.93	-0.13
	CCS	-0.89	-3.53	-3.16	-2.52
	Nuclear	0.09	-2.07	-1.58	-1.37
	Delayed action	0.12	-0.92	-1.91	-4.19
	Ministry of Economy	-1.16	-1.78	-6.15	-2.78
	Ministry of Economy II	-0.94	-1.46	-2.10	-1.64
	Optimal (high gas price)	-0.50	-2.08	-1.91	-1.29
Closure	Scenario	2015	2020	2025	2030
Social transfers	Reference (optimal, low gas price)	-0.06	-1.23	-0.89	-0.71
	Wind + Solar	-1.63	-2.53	-3.37	-2.42
	Wind + Biomass	-1.20	-3.34	-1.54	-1.79
	Gas (low gas price)	0.10	-0.26	-0.58	-0.02
	CCS	-0.75	-2.19	-1.91	-1.82
	Nuclear	0.10	-1.63	-0.99	-1.06
	Delayed action	0.13	-0.72	-1.44	-3.18
	Ministry of Economy	-0.68	-1.14	-4.55	-1.86
	Ministry of Economy II	-0.55	-0.93	-1.55	-1.10
	Optimal (high gas price)	-0.37	-1.54	-1.33	-1.00
Closure	Scenario	2015	2020	2025	2030
VAT	Reference (optimal, low gas price)	-0.14	-1.13	-0.78	-0.73
	Wind + Solar	-1.63	-2.56	-3.14	-2.55
	Wind + Biomass	-1.20	-3.13	-1.66	-1.94
	Gas (low gas price)	0.07	-0.29	-0.39	-0.07
	CCS	-0.87	-1.98	-1.91	-1.99
	Nuclear	-0.02	-1.54	-0.90	-1.12
	Delayed action	0.06	-0.75	-1.37	-3.12
	Ministry of Economy	-0.70	-1.16	-3.90	-2.12
	Ministry of Economy II	-0.57	-0.95	-1.33	-1.25
	Optimal (high gas price)	-0.45	-1.49	-1.19	-1.08
Closure	Scenario	2015	2020	2025	2030
PIT	Reference (optimal, low gas price)	-0.16	-1.33	-0.92	-0.89
	Wind + Solar	-1.81	-2.98	-3.77	-2.92
	Wind + Biomass	-1.43	-4.31	-1.98	-2.25
	Gas (low gas price)	0.03	-0.37	-0.54	-0.19
	CCS	-0.69	-2.64	-2.37	-2.34
	Nuclear	0.06	-1.80	-1.07	-1.34
	Delayed action	0.08	-0.81	-1.44	-3.56
	Ministry of Economy	-0.89	-1.37	-5.12	-2.43
	Ministry of Economy II	-0.72	-1.13	-1.75	-1.43
	Optimal (high gas price)	-0.45	-1.66	-1.40	-1.27

One should also note that due to the technological constraint the more ambitious is the desired abatement level in 2030, the higher investment costs must be beard as more expensive technologies must be involved in the energy mix. In consequence, although 30percent reduction of emission level relative to BAU can be achieved easily at low micro- and macro- economic costs, more ambitious goals will demand much higher and exponentially growing effort from the society.

6 Summary

In the article we have shown that the suite of simulation methods composed of purely econometric estimates of business as usual scenario, financial assessment of alternative investment options and macroeconomic projections can be successfully utilized in the climate policy assessment. In particular we stressed that the DSGE macro modeling framework can integrate the microeconomic, technological bottom-up approach presented among others in the widely known reports of McKinsey&Company with purely macroeconomic general equilibrium modeling traditionally represented in the field by the static and dynamic CGE models.

We argued that as long as many GHG mitigation options are more costly that their ”less green” counterparts their implementation will unavoidably generate fiscal costs for the economy. In other words many ”climate friendly” technologies need to be be subsidized by the government in order to equalize their NPV with coal related alternatives. In particular this remark concerns investments in non-emitting electric energy power plants that on one hand demand substantial investments but in the other can deliver large chunk of ultimate reductions in CO2 emission level. Therefore, in the fiscally constrained environment, Poland cannot afford to invest in the high cost, low carbon technologies. In result optimal energy mix that at the same time guarantees desired mitigation, produces enough energy for the growing economy, and is the cheapest although technologically viable option should include coal, gas, wind, water and nuclear power plants.

Our business-as-usual scenario (BAU) projections show that Poland’s overall 2020 targets probably will not be very hard to meet, but due to forecasted strong economic growth one should expect that further significant carbon abatement would require much more demanding policy measures in the future. At the same time the macroeconomic impact of the micro-package varies strongly with time. In the investment phase, when expenditures on abatement technologies concentrate one can even expect about 5percent deviation of GDP from its BAU level. This value strongly depends on the government fiscal strategy and the projected scope of investment. The energy intensive sectors mainly power and heavy industry are expected to be hit hardest. In the long term however many of potential GHG mitigation levers start to benefit the economy. This especially concerns the fuel and energy efficiency measures that, over the long term, tend to improve productivity true better factor utilization. It must however be stressed that although the efficiency agenda is very promising as a economically attractive climate policy tool its actual implementation will not be easy. We argue that although additional fiscal costs will probably be necessary to materialize those measures, their negative impact over the long-term should not dominate generally positive influence on economic growth.

References

[1] Bergman, Lars 2005. "CGE Modeling of Environmental Policy and Resource Management," Handbook of Environmental Economics, in: K. G. Mäler and J. R. Vincent (ed.), Handbook of Environmental Economics, edition 1, volume 3, chapter 24, pages 1273-1306 Elsevier.

[2] Bukowski Maciej, Dyrda Sebastian and Pawel Kowal 2008, Assessing Effects of Joining Common Currency Area with Large-Scale DSGE model: A Case of Poland, IBS working paper 03/2008.

[3] Energsys 2008, Impact of the Proposed EU Energy and Climate Policy on the Polish Energy Security", Synthesis 2008

[4] Fischer, Carolyn and Newell, Richard G., 2008. "Environmental and technology policies for climate mitigation," Journal of Environmental Economics and Management, Elsevier, vol. 55(2), pages 142-162, March.

[5] Heal, Geoffrey 2008. "Climate Economics: A Meta-Review and Some Suggestions," NBER Working Papers 13927, National Bureau of Economic Research, Inc.

[6] IPCC, Climate change 2007: Impacts, adaptation and vulnerability. Technical report. IPCC

[7] Kowal Pawel, 2005. "An Algorithm for Solving Arbitrary Linear Rational Expectations Model," GE, Growth, Math methods 0501001, EconWPA, revised 12 Jun 2005.

[8] McKinsey and Company, "Assessment of Greenhouse Gas Emissions Abatement Potential in Poland by 2030", Non technical report 2009

[9] Mortensen, Dale *The persistence and indeterminancy of unemployment in search equilibrium*, Scandinavian Journal of Economics **91** (1989), no. 2, 347–70.

[10] Murchison, Stephen, Rennison, Andrew and Zhu Zhenhua, *A structural small open-economy model for canada*, Tech. report, 2004.

[11] Nordhaus, William D. 2006. "The Stern Review on the Economics of Climate Change," NBER Working Papers 12741, National Bureau of Economic Research, Inc.

[12] Pissarides, Christoph *Unemployment and the persistence on employment shocks*, Tech. report, 1990.

[13] Smets, Frank and Raf Wouters, 2003. "An Estimated Dynamic Stochastic General Equilibrium Model of the Euro Area," Journal of the European Economic Association, MIT Press, vol. 1(5), pages 1123-1175, 09.

[14] Stern, Nicholas 2006. "What is the Economics of Climate Change?," World Economics, World Economics, Economic and Financial Publishing, PO Box 69, Henley-on-Thames, Oxfordshire, United Kingdom, RG9 1GB, vol. 7(2), pages 1-10, April.

[15] Werf van der, Edwin 2007. "Production Functions for Climate Policy Modeling: An Empirical Analysis," Kiel Working Papers 1316, Kiel Institute for the World Economy.