

# Dynamic Ecology-Economy Interactions Modeling

## *Some Experience and Perspectives of Application in Russian and German Context<sup>\*)</sup>*

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### ***Abstract***

Solution of environmental problems on global and regional levels urges creation of adequate approaches to study the development of the regional economy and its interaction with the natural environment. For this purpose a generalized input-output model is proposed, which includes: block of fixed assets dynamics; several kinds of linear and nonlinear production functions; algorithms for balanced forecasting of technological structures; nature block describing dynamics of the main environmental indicators (such as: air and water pollution, state of forests and soil, mineral and bio-resources etc.) with self- and artificial restoration, economic and anthropogenic influences taken into account. Nature-Economy Simulation SYstem (*NESSY*) is used as a basic software tool for building and investigating such models.

Application of the system to modeling scenarios of environmental-economic development of Russia is described. The model was built for 13 economic sectors and 8 basic natural resources. Three groups of scenarios were developed to illustrate business as usual, stabilization and “sustainable” future dynamics. These strategies were modeled by different investment policies, and, in particular, by proper distribution of funds for the purposes of nature restoration. It was demonstrated that development, which is both economically efficient, and environmentally sound, can be possible only with such an investment policy that provides considerable share of expenses for new technologies, and namely for low materials consuming and energy-saving ones.

A perspective of building a version of the nature-economy interactions model in German context is also discussed. First experience is considered where the analysis of air pollution dynamics is undertaken with the help of a non-linear dynamic input-output model, built on available statistical data for 58 economic sectors of Western Germany. The data was aggregated to 17 sectors with detailed representation of power industry sectors. Major air pollutants under consideration (both of industrial and households origin) were as follows: carbon dioxide, carbon monoxide, dioxide, nitrogen oxides, and volatile organic compounds. Production functions along with equations of both gross and air-cleaning fixed assets dynamics were estimated for each aggregated sector. Changes in emission coefficients for sectors were modeled as non-linear functions of fixed assets for air cleaning. This enables to follow effects of different investment policies on air pollution abatement and to forecast the required steps of technological changes in the ecologically unsound industries. Comparison of scenarios is provided to analyze costs of different environmental-economic development programs.

**Keywords:** *ecological-economic regional development, dynamic input-output models, technical change, air pollution, scenario analysis*

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## 1. Introduction

Effective control of the economy of a large region or state requires the up-to-date technology of constructing multivariate forecasts of economic development. Such technology is to be based on mathematical models and methods, as well as on the complex of information and software tools, which provide the realization of computational procedures with respect to these models.

The paper is devoted to construction and application of a dynamic input-output model for ecology-economy interactions analysis. Despite known simplifications, the input-output approach remains one of the few, which, along with sufficient simplicity of mathematical formalization, allows the development of operational models and economic policy mechanisms. It is widely used in applied investigations of macro-economic processes, as well as in the practice of prospective national and regional economic planning. Under the present conditions the development of market relations in Russia and other states of the former Soviet Union is being followed by the destruction of old economic ties, and hyperinflation. It is even argued whether I-O models can be still of use in the absence of the centrally planned system. But it appears that the methodology under study can acquire ever-growing significance, as it provides the possibility to analyze strategic directions of economic development, considering besides dynamic intersectoral links also the interaction between the sectors of economy and the natural environment. Such analysis is urgent for the development of the state regulation programs, which are an integral part of environmental-economic policy for any developed market system. In this concern it seems appropriate that the modeling approach used in this work is considered on applications to Russia and Western Germany.

## 2. Basic Dynamic Multisectoral Economy Model

Most of the macromodels considering the national economy as a multisectoral system are based on ideas of the input-output analysis (Leontieff, 1966). The sectors are assumed to exchange flows of intermediate production in accordance with the technologies available. Intersectoral links shaped in the course of production are simulated with the help of linear input-output balance equations:

$$X_i(t) = \sum_{j=1}^n a_{ij} X_j(t) + Y_i(t), \quad Y_i(t) = \sum_{j=1}^n d_{ij} I_j(t) + C_i(t) + S_i(t), \quad i = 1, n \quad (1.)$$

where  $X_i(t)$  denotes the gross output of the  $i$ -th sector,  $Y_i(t)$  - the final (net) product,  $I_i(t)$  - the investments to the  $i$ -th sector,  $C_i(t)$  - the final consumption,  $S_i(t)$  - the export surplus.  $A = \{a_{ij}(t)\}$  is the matrix of input-output coefficients, and  $D = \{d_{ij}(t)\}$  is the matrix of the technological structure of investments. It has nonzero rows only for those sectors (which are basically two: machinery and construction), that provide investment goods into other sectors.

The model assumes the fixed assets  $K_i(t)$  of the sectors to grow as a result of investment and to decrease due to physical wear and obsolescence. The assets changes are thus modeled by the following equations:

$$K_i(t+1) = (1 - m_i) K_i(t) + h_i I_i(t), \quad i = 1, n, t = t_0, T, \quad (2.)$$

Here  $\mathbf{m}$  is the depreciation coefficients vector for the fixed assets per annum; and  $\mathbf{h}$  is the ratio of the materialized investments to their present volume. Hereinafter  $t=t_0$  and  $t=T$  are the initial and the final year of modeling respectively.

The output of each sector is described by the production function

$$X_i(t) = F_i(t, K_i, L_i), \quad i = 1, n, \quad (3.)$$

which characterizes its maximal production capabilities with the given values of capital  $K$  and labor  $L$ . Time dependence is taken into account as an exogenous effect of technical change upon the production capability.

The model (1-3) can be used in simulation modes, where one group of variables is preliminary set, and the other are calculated by solving the system of recurrent equations, as well as it can be stated as an optimal control problem (Krotov, 1981, 1982). In order to recognize the effect of various economic as well as ecological factors, the model (1-3) can be appropriately changed, maintaining its general structure. Such an extension of the described basic input-output model is considered below.

### 3. Nature-Economy Model

The model addresses dynamic interactions between  $n$  sectors of economy and basic natural resources of the region (such as water, air, soil, forests, mineral and bioresources), described by  $m$  state-of-environment indicators (Gurman, 1981, 1990). Dynamics of each natural resource is subjected to economic use (impact), self- and artificial restoration. The composition of economic sectors and environmental indicators differs from particular region under investigation.

The region can be considered as the territory divided into several districts, connected by a transport network and by the possible migration of resources. Every district (subregion) is described by a standard model. The basic equations (blocks) of such a model are as follows:

#### Block of generalized intersectoral balance

$$X = AX + DI + A^Z z + D^Z I^Z + C - X^{imp} + X^{exp} \quad (4.)$$

#### Blocks of fixed assets dynamics for economy and nature restoration sectors

$$K_i(t+1) = (1 - m_i)K_i(t) + h_i I_i(t), \quad i = 1, n, \quad (5.)$$

$$K_j^Z(t+1) = (1 - m_j^Z)K_j^Z(t) + h_j^Z I_j^Z(t), \quad j = 1, m, \quad (6.)$$

#### Block of natural environment state variables dynamics

$$R(t+1) = Q(R(t) - R^*(t)) - (EX + E^I I + E^C C + E^Z I^Z + E^N N) + Jz + r^{imp} - r^{exp} \quad (7.)$$

#### Block of production functions

$$X_i(t) = F_i(t, K_i, L_i), \quad i = 1, n \quad (8.)$$

$$z_j(t) = F_j^Z(t, K_j^Z, L_j^Z), \quad j = 1, m \quad (9.)$$

#### Block of structure matrices dynamics

$$\begin{aligned} A(t) &= F_A\{t, A(t-1), \dots, A(t-t_1), X(t)\} \\ A^Z(t) &= F_{A^Z}\{t, A^Z(t-1), \dots, A^Z(t-t_2), z(t)\} \\ D(t) &= F_D\{t, D(t-1), \dots, D(t-t_3), I(t)\} \\ D^Z(t) &= F_{D^Z}\{t, D^Z(t-1), \dots, D^Z(t-t_4), z(t)\} \end{aligned} \quad (10.)$$

Here  $X, C$  are respectively the vectors of outputs and net consumption of products;  $z$  is intensity of artificial (exogenous with respect to environment) restoration of resources;  $K, K^Z$  - the fixed assets of economic sectors, and sectors of nature restoration respectively;  $m, m^Z$  are respective depreciation coefficients;  $I, I^Z$  are gross investments into fixed assets of economic sectors, and sectors of nature restoration respectively;  $R$  is the vector of the state variables of the natural environment (sometimes called 'resources' for simplicity)  $R = \{R_1, \dots, R_m\}$ ;  $R^*$  is the undisturbed (or "desired") state of the natural resources,  $r^{imp}, r^{exp}$  - are the migration of natural resources to/from the region;  $X^{imp}, X^{exp}$  are respectively imports and exports of products;  $A, A^Z$  - are the matrices of direct expenses per unit of  $X$ , and  $z$ ;  $D, D^Z$  - are the matrices of technological structure of investments;  $Q$  - is the matrix of self-restoration coefficients and mutual influence of natural resources;  $E$  - is the matrix of resource expenditures per the unit of  $X$ ;  $E^I, E^Z$  - are the matrices of fund-forming expenditures of resources;  $E^C$  - is the matrix of resource expenditures on net consumption of products.  $J$  is the diagonal matrix with elements equal +1 or -1, subject to whether the restoration of resource (flow of  $z$ ) leads to growth or decrease of the variable  $R$  (the latter - in the case of pollution);  $E^N$  is the vector of coefficients, which

account for the anthropogenic nonindustrial load on natural resources;  $N$  is the population of the region. Production functions  $F, F^Z$ , respectively for principal and restoration sectors, may also depend on the state of natural resources  $R$  (in general case  $F, F^Z$  are non-linear).

The description of the dynamics of environmental variables is accepted to be linear and so requires the minimum of information. This equation describes the region's environment in terms of deviation from some undisturbed natural state. With the absence of the economic impact through withdrawal and restoration of resources, the equations solution  $R(t)$ , in the limit, will tend to  $R^*$ .

The change of technological production processes, conditions of mining and prospecting of mineral resources, the increase of labor productivity, and other factors, which influence the specific expenditures of production and resources, are taken into account in the model by the introduction of the dependence on time of the matrices  $A, D, E, E^N, A^Z, D^Z$ . In the general case, these matrices may depend also on  $R$ . The dependence  $Q(R)$  accounts for the fact, that in the case of a strong disturbance of the natural environment, the latter may lose the ability of self-restoration.

The described nature-economy model can consider a region (country) with or without internal subdivision of the territory. Such a single-point model (possessing only sector and resource divisions) can be of interest, e.g., for macro estimating of possible development strategies for the interaction of the economy and the ecological environment.

#### **4. Nature-Economy Simulation System**

On the basis of the complex of multisectoral and multiresource models the Nature-Economy Simulation System (*NESSY*) was developed (Safonov, 1991). The main goal of the system is to provide a user with the complex of integrated tools for interactive construction and investigation of dynamic models of ecological-economic development and to serve for decision making support.

Users of the system may be conditionally divided into "system analysts" and amateur or "end-users". The first group of users can improve the system by adding new model blocks, modifying available ones by setting required model configurations, and in accordance with the problem to be solved, as well as they can interactive parameters estimating. These functions of the system are served by the Models building subsystem. The rest capabilities of the system, such as scenarios setting, calculations and data base control, plotting source and resulting information, etc. are available for all users. The system consists of the following functional and service components:

**The subsystem of models building** provides specification, identification and models linking out of blocks assigned by the user. The model is to be understood here is a computation procedure in its simulation or optimization statement while the blocks are modules realizing various stages of computation (or servicing). Thus, for example, computational algorithms, procedures of computing the right-hand sides of the differential equations systems, integration methods, computation of a generalized intersectoral balance, etc., all of them are organized in the form of separate blocks. Simultaneously the user creates the description of model global variables and attributes of their dimensions. To formalize the mathematical description of the problem and algorithms a special metaextension of *FORTRAN-77* and *C* is used as a modeling language. The corresponding preprocessor and libraries of subprograms are developed for this purpose which provide:

- dialogue access to the global variables of the model,
- interface between the model program and the database,
- automatization of model linking out of blocks.

The preprocessor translates the block program into *FORTRAN* or *C* source text. Translated (object) block modules are linked in a unified programs together with the integrated software providing computation experiments to be performed by a final (non-programming) user.

The following identification methods are used for the ecological-economic models under study:

1. *Regression methods*, based on statistical data. Methods for time-series processing and procedures of statistical estimation of parameters are used for the model blocks, described by linear and non-

linear regression equations. Application of these methods to a number of different production functions parameters estimation in NESSY is described (Safonov, 1996).

2. *Methods of structural forecasting*, using model outputs, statistical and empirical (expert) data. Such methods (Stone, 1962; Sedelev *et.al.*, 1984; Safonov, 1996) are used to account for the structural parameters dynamics, (e.g.  $A, A^{(z)}, D, D^{(z)}$ ). This approach can also be called “dynamic” or “adaptive” identification as it uses also the data, obtained in the course of model calculations.
3. *Expert-analytical methods*. One of the most significant problems of ecological-economic models identification is the lack or weak systematization of the data required (basically concerned with environment and its interaction with economics). It can be obtained via original identification methods for ecological blocks (Gurman, 1990), built around the expert data, direct calculations and hypotheses on behavior of concrete physical, biological and other natural processes.

**The database management subsystem** provides data entry, correction, and processing in the form of a set of multidimensional arrays of various data types. The data bank of NESSY is constructed on the basis of the data bases management system *CubeMaster* (Adamovitch and Volkov, 1990), operating with three-dimensional arrays. Besides the dialogue shell (including also tools for table and graphic mapping), the DBMS *CubeMaster* contains a C-library for software interface between its data sets and user’s programs.

**The computations subsystem** enables a user to solve simulation and optimal control problems in the mode of interaction with the computer model. It provides possibility to stop and interrupt computations, to indicate variables traceable in the course of computations in special text and graphic windows and to change parameters of algorithm.

**The subsystem of information visualization** operates both autonomously and in the course of computation directly in the dynamics of algorithm operation. The layout of charts and tables can be compiled by the user from a wide variety of standardized forms.

**The dialogue monitor** maintains friendly user interface based on the Dialogue Constructor “*DiaCon*” (Salkinder, 1991) which supports computer-aided tools for creating and correcting the dialogue script in accordance with the user’s requirements, including also context-sensitive hypertext help subsystem and numerous servicing functions.

The software of NESSY is implemented for PCs under *MS DOS* using *Microsoft FORTRAN and C*.

## **5. Scenario Analysis of Russian Ecological-Economic Development**

The analysis of the former Soviet Union (FSU) ecological-economic development was performed (Safonov, 1992) for investigating the possibilities of the ecological situation stabilization in Russia and for elaborating appropriate strategies to achieve this goal.

The FSU economy was considered within the 13 basic sectors (Table 1). This classification of the obtained by aggregating the standard 18-sectors classification of the official governmental statistics. State of environment was described by 8 aggregated indicators (Table 2).

The model was built on the basis of economic statistics for the period of 1965-1988. The environmental blocks were identified using the data available in official documents as well as the estimates of experts. Appropriate retrospective analysis was held to verify the model parameters.

For the period of 1985-2005 several scenarios of economic development were created by forecasting the investments and labor resources regarded to the principal and nature restoring sectors. Three basic groups of scenarios were built to match the three goals respectively: Scenario 0 - “inertial extrapolation”, Scenario 1 - “ecological stabilization”, Scenario 2 - “complex nature-economic-social development”.

**Table 1. Sectors of industry:**

1. Machinery
2. Construction
3. Fuel
4. Electricity
5. Chemicals
6. Wooden materials
7. Construction materials
8. Light industries
9. Food
10. Other manufacturing
11. Agriculture
12. Transportation &
13. Trade, services, etc.

**Table 2. The environmental indicators:**

1. Aggregated concentration of water impurities [MPC - maximum permissible concentration]
2. Aggregated concentration of air impurities [MPC]
3. Quality of soil [site index]
4. Agricultural land square [ha]
5. Timber resources (stockpile of workable wood) [m<sup>3</sup>/ha]
6. Wood covered square [ha]
7. Aggregated stockpile of mineral resources [roubles]
8. Aggregated stockpile of biological resources [roubles]

The Scenario 0 (“business as usual”) assumed the 3% annual growth of the investments to economy sectors ( $I$ ) and no investments to nature restoration ( $I^Z(t)=0$ ). Allowing for the economic crisis in Russia during 90-s, we should mention that this investment scenario can be considered as the marginal one, illustrating the maximal economic load on the environmental system.

On the basis of the Scenario 0 there were built two others (1 and 2) in which a considerable amount of investments in nature restoration allocated at the initial 5 years of the forecasting period (see Fig.1)<sup>1</sup>. As it can be seen through Fig.2 - Fig.5, such environmental clean-up investments within Scenario 1 did provide some partial stabilization of environmental situation, but mainly during the period of intensive investment. To achieve goals of long-term stabilization (“sustainability”) of the ecological-economic development, Scenario 2 assumed that 15% of total investments into nature restoration were addressed to the technological change. The latter was modeled by decreasing dynamics of structural matrices (such as  $A$ ,  $D$ ,  $A^Z$ ,  $E^X$ , etc.) as function of such investments.

Processes in industrial sectors influence the development of other ones, which finally leads to changes in the general labor productivity, cost structure of the gross national product and other economic indicators. In the input-output model interconnections between sectors are performed by exchanging flows of production, so new kinds of production involved in these flows stimulate new technologies in the sectors concerned. This process can be called the intersectoral diffusion of technologies.

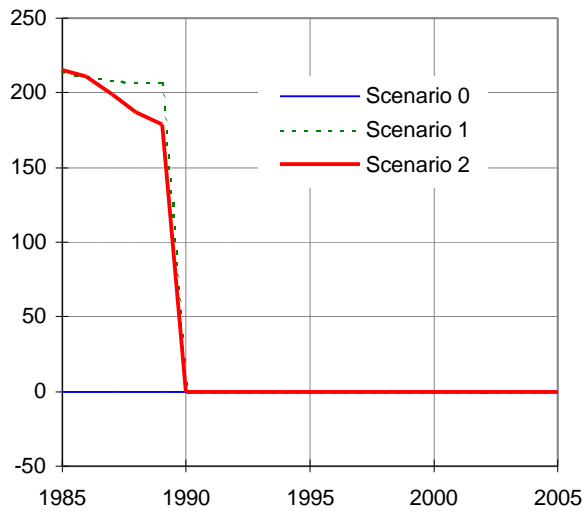
New technologies are more efficient because of at least two reasons. The first one is that in new technological processes new materials, new kinds of fuel and energy and new methods of production are mainly used. The other reason is that the cost of raw materials used in old technological processes is growing due to depletion of natural resources. Finally, new technologies are more competitive since their ratio of expenses to net income is lower than these of the old ones. From the other side, they are generally at the same time less ecologically harmful.

The preference of such innovation strategies is clearly illustrated by Fig.6, where the dynamics of consumption is plotted. Environmental restoration in Scenarios 1 and 2 requires considerable investment and respectively leads to deep decrease in value of total consumption. In practice this respectively tends to the policy of international credits, which in the end implies that the country will have to pay with its natural resources. But in the case of the Scenario 2, with appropriate distribution of investments to technological restructuring, such a policy pays off in quite an observable period, and the level of consumption is increasing due to more efficient technologies used.

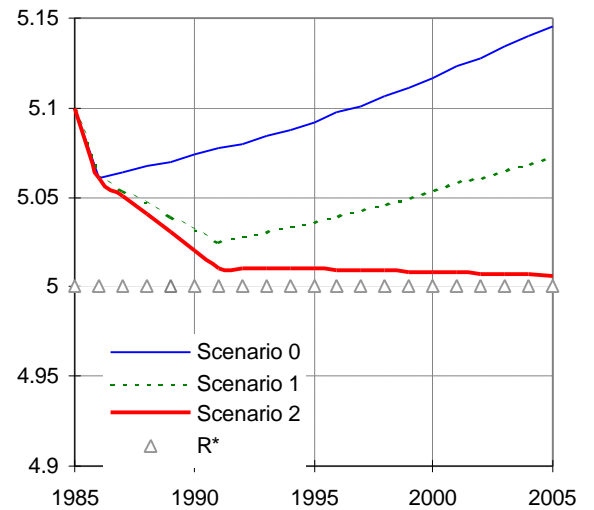
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<sup>1</sup> It should be noted that such a strategy of “forced” investments was derived from the preliminary optimization analysis on more simple models in terms of the general economic criterion enlarged with a penalty function on the nature use (Gurman, 1981).

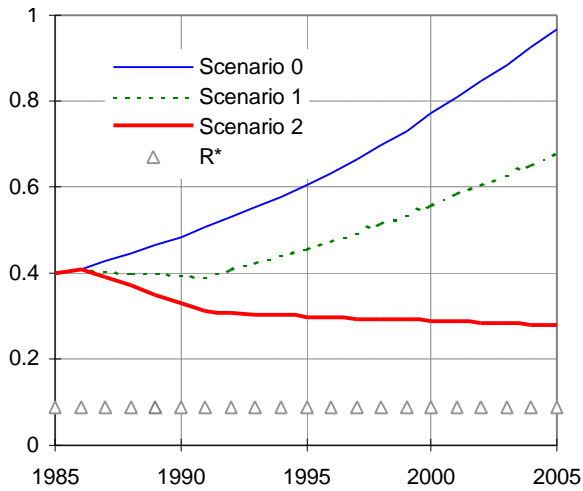
**Fig. 1 Total Investment in Nature Restoration (Mlrd. Rbl.)**



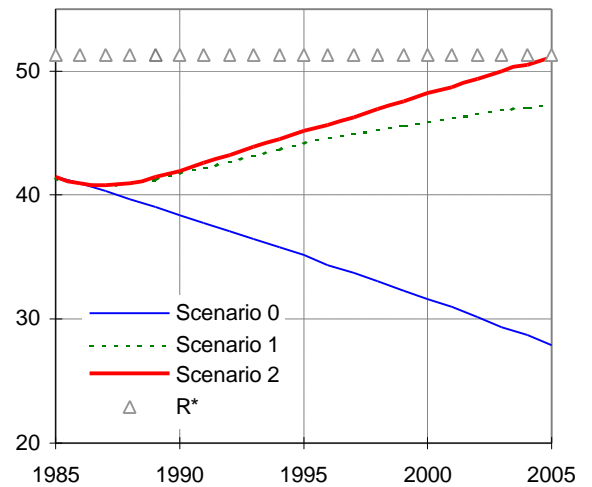
**Fig. 2 Water Pollution Average Concentration (MPC)**



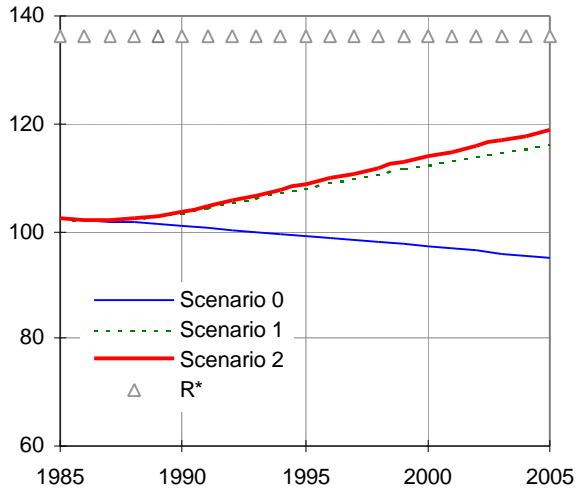
**Fig.3 Air Pollution Average Concentration (MPC)**



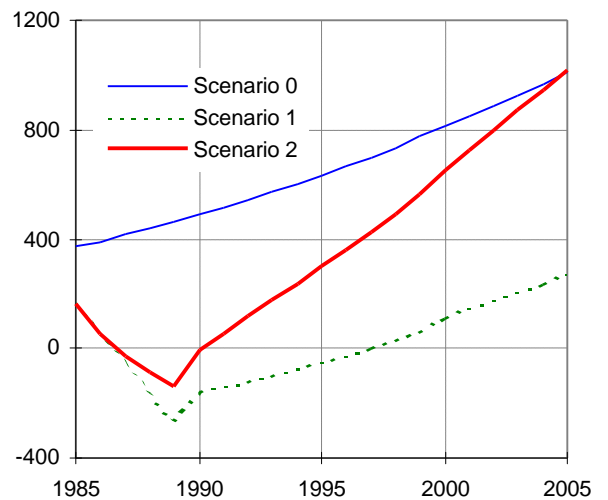
**Fig. 4 Quality of Soil (rank)**



**Fig. 5 Timber Resources (Stockpile of Workable Wood, m3/ha)**



**Fig. 6 Total Final Consumption (Mlrd.Rbl.)**



## **6. Discussion of Available Data for German Case Study**

A modification of the model for the German context has designed by the author during a short-term project at the Centre for European Economic Research (ZEW, Mannheim), Department of Environmental and Resource Economics, Logistics, in 1995.

The study was aimed at building and analyzing a dynamic input-output model allowing for major environmental impacts, for which statistical data was available. Since the information on air pollution and related to it issues occurred to be the best represented in the official German and Eurostat statistics, this study was focused on analysis of air-emissions induced by economic activities and household consumption.

Three types (or groups) of air-polluting substances could be distinguished (Zylicz, 1991): (1) SO<sub>2</sub>-like (i.e., toxic migrating) pollutants, (2) toxic nonmigrating pollutants, and (3) nontoxic migrating pollutants.

Group 1 consists of substances, which behave like SO<sub>2</sub>, i.e., directly cause damage due to their toxicity and may easily migrate over vast distances. Nitrogen oxides (NO<sub>x</sub>) and suspended particulates also belong to this group.

Group 2 consists of several gaseous pollutants. The non-migrating pollutants can be labeled as such either because they quickly fall down (as the dust does) or because they decay (or get neutralized in another way) before being transferred very far from the source. Carbon monoxide (CO) is an example of the latter category, as it transforms to nontoxic CO<sub>2</sub>.

Group 3 consists of substances that are non-toxic but yet seriously disturb the biosphere. Two such pollutants have been the focus of scientists' attention worldwide at least since the 1970s. These are carbon dioxide (CO<sub>2</sub>) and chlorofluorocarbons (CFCs), a whole family of chemicals also known as "freons" after their trade name. There are two major sources of SO<sub>2</sub> releases into the atmosphere: biomass degradation, e.g., resulting from deforestation of the Earth, and fossil fuel combustion.

In this section a draft configuration of the model is discussed as concerns data requirements and identification problem.

The economic development model is based on the basic input-output tables for 58 sectors, available at the German Federal Statistical Office (Statistisches Bundesamt) for 9 statistical years from 1978 to 1990 (Stat. Bund., 1989b, 1990a, 1992). Necessary information on dynamics of main input-output matrix, gross outputs, net consumption, investments and also export and import of products was obtained from these tables.

The block of fixed assets dynamics was built on the basis of data on capital stocks and its growth for 57 sectors from 1960 to 1995 (Stat. Bund., 1995c). Comparing with 58-sector classification, sector "Other mining products" includes data about crude petroleum and natural gas. The matrix of the technological structure of investments was available only for 1987 for 51 sectors from the publication of ifo-Institut für Wirtschaftsforschung, München (Gerstenberger et al., 1989). Due to this fact the constant structure of investments was used for the observing period of time. Labor statistics necessary for production functions identification was available for 58 sectors from 1978 to 1990 for 11 statistical years (Stat. Bund., 1989a). Also forecasts of employment from 1995 up to 2010 (Hofer et al., 1995) for 37 sectors were used. Such a difference in classification of industries in various sources required proper comparison and processing of available statistical data.

All information is available in current prices or in fixed prices. By means of price indices for gross outputs and fixed assets (Stat. Bund., 1995b) all data base was recalculated in prices of 1990.

On the basis of the 58-sector classification an aggregated one was built, representing main economic activities within only 17 enlarged sectors, at the same time sufficiently detailed, to follow main important environmental impacts (Table 3). Aggregated total indicators, characterizing main macroeconomic dynamics, are represented in the Table 4.

**Table 3. Economic sectors for Western Germany**

Original sectors from 58-classification are given in the right column for each aggregated sector

1. Agriculture, Forestry and Fishing	1, 2	11. Wooden and paper materials	30-34
2. Electric power, steam, hot water	3	12. Light industries and other products	35-37
3. Gas, Water	4,5	13. Food, Drinks, Tobacco	38-40
4. Coal products	6	14. Construction	41,42
5. Mining and other fuels	7,8	15. Trade wholesale and retail	43, 44
6. Refined petroleum products	10	16. Transportation	45-48
7. Chemical products	9,11-12	17. Services, Communication and other sectors	49-58
8. Construction materials	13-15		
9. Iron, Steel, and other Metallurgy	16-19		
10. Machinery	20-29		

**Table 4. Dynamics of macroeconomic indicators in 1978-1990**

Years	X (Mln. DM)	Y (Mln. DM)	C (Mln. DM)	I (Mln. DM)	K (Mln. DM)	L (Tsd.)
1978	3468251	1983831	1216297	350709	7564306	26130
1979	3571311	2042365	1240210	368004	7812729	26568
1980	3674370	2100899	1264122	385298	8081297	26980
1981	3634406	2089702	1262038	365572	8354423	26951
1982	3594442	2078506	1259955	345845	8603353	26630
1983	3671648	2120273	1277517	349750	8827250	26251
1984	3748853	2162040	1295080	353655	9059682	26293
1985	3858392	2219620	1324406	350573	9283508	26489
1986	3980132	2267716	1368656	355180	9502710	26856
1987	4020761	2317876	1409934	364841	9729473	27050
1988	4229138	2380897	1437263	375644	9960007	27261
1989	4443074	2498283	1483329	400410	10203815	27658
1990	4657010	2615669	1529395	425176	10466882	28479
Average annual growth rates, %	2.51	2.34	1.93	1.69	2.74	0.73

Source: Statistisches Bundesamt

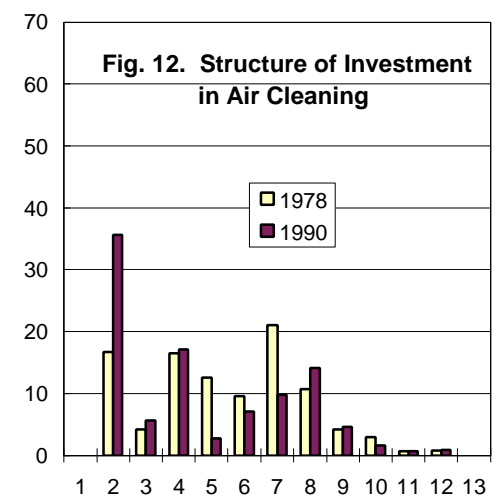
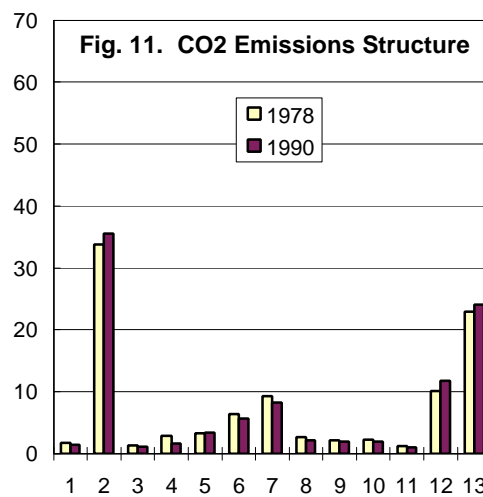
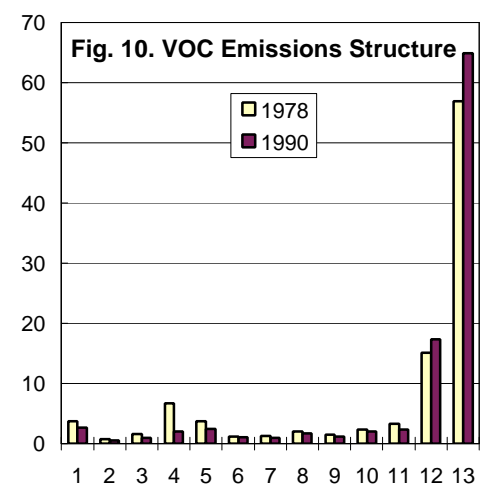
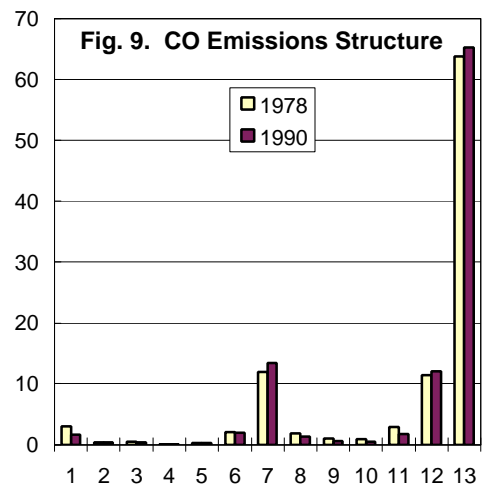
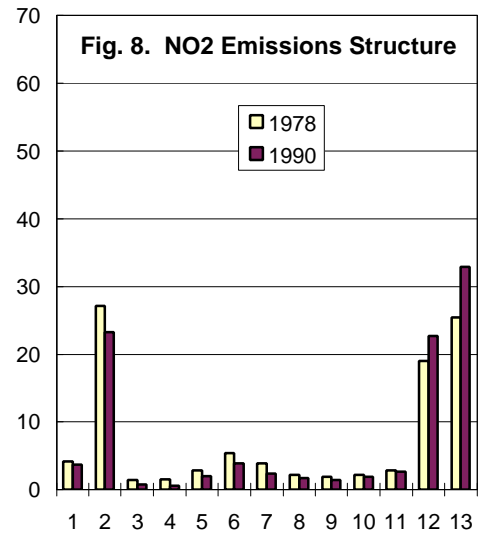
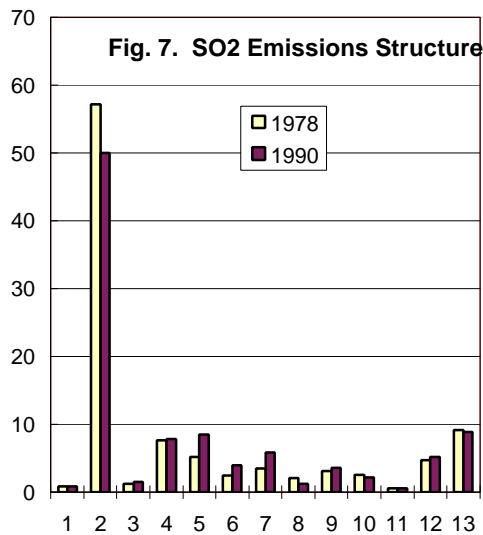
Nature block of the model is built on the basis of data on dynamics of fixed assets, investments, input-output matrices from 1978 to 1990 for 11 sectors of Manufacturing and State (Stat Bund., 1995a). Data is available for environmental restoration in the whole and for air cleaning separately. It was also recalculated in prices of 1990.

Major air pollutants under consideration in the model are as follows:

1. CO<sub>2</sub> - emission of carbon dioxide (KTonnes)
2. SO<sub>2</sub> - emission of sulfur dioxide (KTonnes)
3. NO<sub>x</sub> - emission of nitrogen oxides (KTonnes)
4. CO - emission of carbon monoxide (KTonnes)
5. VOC - emission of volatile organic compounds (KTonnes)

Information on emissions of these pollutants is available from 1978 to 1990 for 58 economy sectors (Hohmeyer, Walz et al., 1992). The data was aggregated 13-sectors, according with available classification of investment for environmental restoration.

Due to distribution of emissions among sectors, those that cause the largest damage to environment were marked out. Among such sectors are Electricity, Chemical industry, Construction materials industry, Metallurgy and also State and Households. The influence of these sectors on air-pollution and relationship between investments for air cleaning and volume of emissions are to be considered.

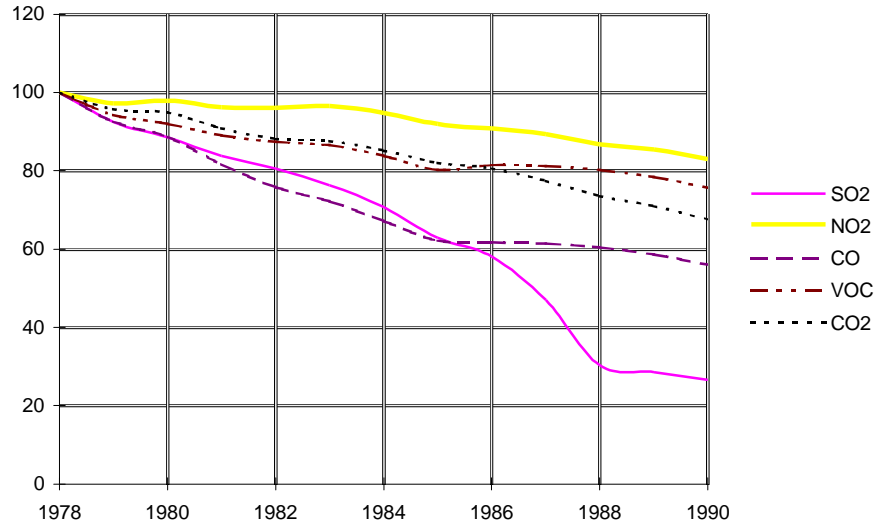


- 1 Agriculture, Forestry and Fishing
- 2 Electric power, Steam, Gas, Water
- 3 Mining and other fuels
- 4 Refined petroleum products
- 5 Chemical products
- 6 Construction materials
- 7 Iron, Steel, and other Metallurgy

- 8 Machinery
- 9 Wooden and paper materials, Light industry
- 10 Food, Drinks, Tobacco
- 11 Construction
- 12 Transport and Services
- 13 Households

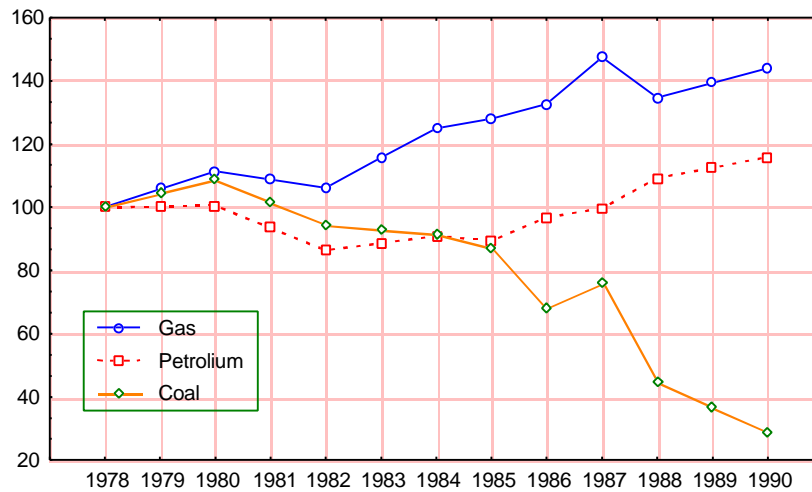
separately for each pollutant (see Fig. 7-12). According with the general dynamics of air-pollution abatement in the economic activities (Fig.13) during the statistical period, the coefficients of the matrix of emissions structure (emissions per unit of gross output) can be modeled as a function of accumulated investment (capital stocks) in air-cleaning in each sector:  $E(K^Z) = a_1 / (K^Z(t)^{a_2} + a_3)$ .

**Fig. 13.** Dynamics of emission coefficients  
1978 = 100%.



Household emissions, which come mainly from burning fuels for heating and while using private cars, can be described as a sum of pollution coming from consumption of respectively gas, coal and petrol. Fig. 14. illustrates statistical dynamics of total consumption of these three fuels, where process of substitution of coal by gas is can be clearly seen.

**Fig. 14. Growth Rates of Energy Consumption**  
(1978=100%)



## 7. Dynamic Input-Output Model for Air Pollution Analysis

Thus the modification of the input-output model from paragraph 3, used for the German air pollution dynamics study is as follows:

$$\begin{aligned}
 X_i(t) &= \sum_{j=1}^n a_{ij}(t)X_j(t) + \sum_{j=1}^n d_{ij}(t)I_j(t) + C_i(t) + S_i(t), \quad i = 1, n, \\
 I_i^Z(t) &= \mathbf{q}_i(t) \sum_{j=1}^n I_j, \quad i = 1, n', \\
 \begin{cases} K_i(t+1) = (1 - \mathbf{m}_i)K_i(t) + \mathbf{h}_i I_i(t), & i = 1, n, \\ K_i^Z(t+1) = (1 - \mathbf{m}_i^Z)K_i^Z(t) - \mathbf{h}_i^Z I_i^Z(t), & i = 1, n', \end{cases} \\
 \bar{K}_i(t) &= (K_i(t) + K_i(t+1)) / 2, \quad i = 1, n, \\
 X_i(t) &= F_i(t, K_i, L_i) = \mathbf{s}_i \bar{K}_i(t)^{a_i} L(t)^{1-a_i} e^{r_i(t-t_0)}, \quad i = 1, n, \\
 \begin{cases} E_{ij}^X(t) = I_j^1(t) / (\bar{K}_i^Z(t)^{I_{ji}^2(t)} + I_j^3(t)), & i = 1, \tilde{n}, j = 1, m, \\ E_{ij}^C(t) = \left| (\mathbf{g}_j^1(t) / ((t-t_0)^{\mathbf{g}_j^2(t)} + \mathbf{g}_j^3(t))) \right|, & i \in \mathbf{I}_E = \{3,4,6\}, j = 1, m, \end{cases} \\
 R_j(t) &= \sum_{i=1}^{\tilde{n}} E_{ij}^X(t) \tilde{X}_i + \sum_{i \in \mathbf{I}_E} E_{ij}^C(t) C_i + r_j^{imp} - r_j^{exp}, \quad j = 1, m
 \end{aligned} \tag{11.}$$

Here  $X$ ,  $C$  are respectively the vectors of outputs and net consumption of products;  $S$  - is the surplus of export plus change of production stocks;  $I$ ,  $I^Z$  are the gross investments into development of main and air-cleaning fixed assets);  $K$ ,  $K^Z$  main and air-cleaning fixed assets of sectors;  $r^{imp}$ ,  $r^{exp}$  are the transboundary pollutions within German territory;  $E^X$  is the matrix of emission structure (pollution per unit of  $X$ ),  $E^C$  is the vector of coefficients of households pollutions;  $F$  are production functions,  $R$  - is a vector of 5 types of emission. Aggregation of  $n$  (17) sectors to  $n'$  (12) is used for unification of classifications of economic and air-cleaning statistics.

The model enables to analyze dynamic emissions and to run comparative analysis of the investment scenarios, performing different strategies of environmental-economic development.

## 8. Scenarios for Western German Air-Pollution Forecasting

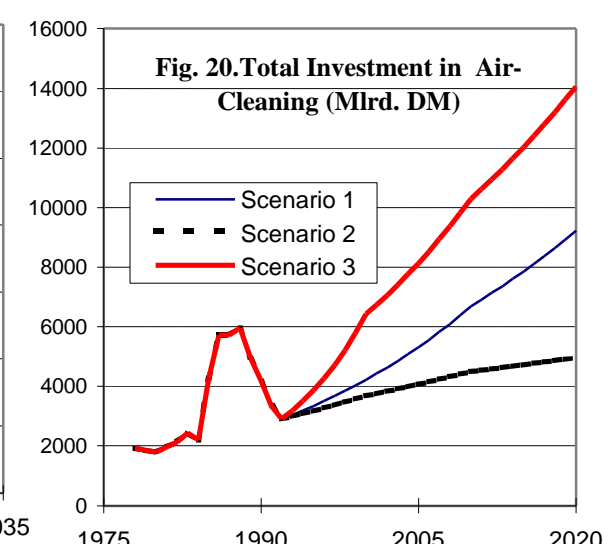
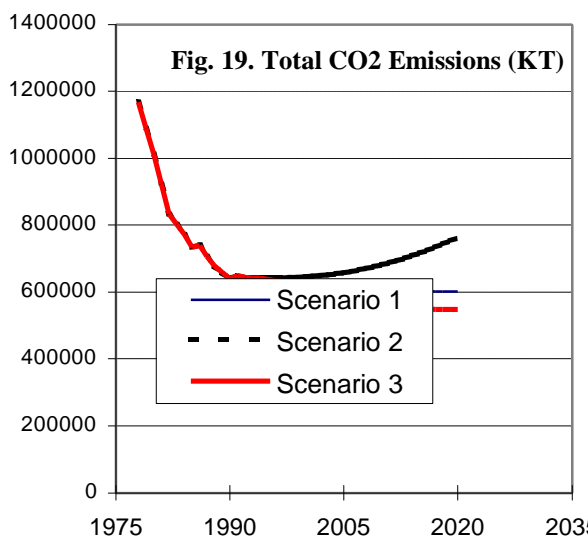
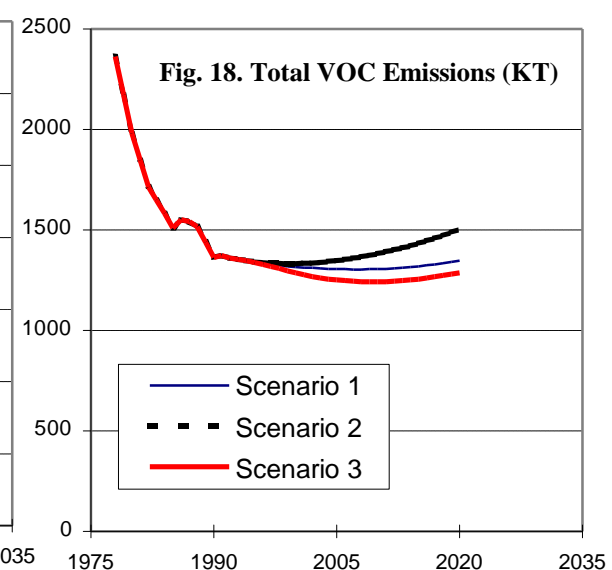
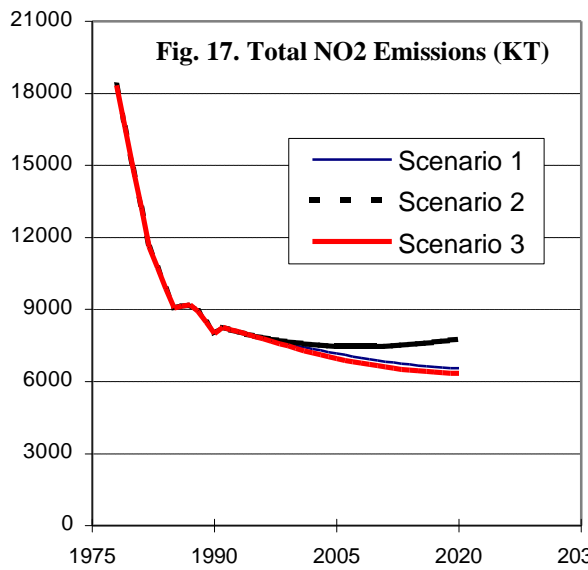
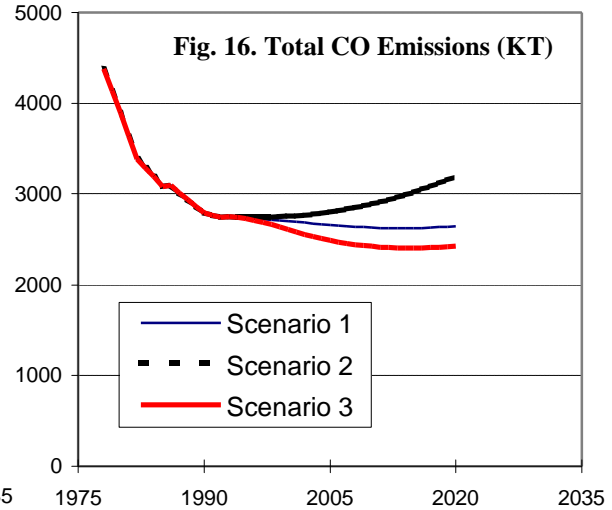
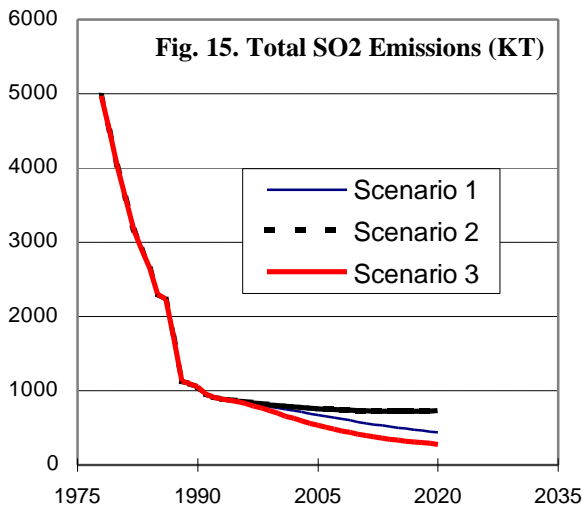
In the Fig 15-19 three scenarios are plotted for the values of 5 types of air pollution and respective programs of investments into air-cleaning:

*Scenario 1* is a basic scenario with extrapolation of economic activities and moderate growth rates of investment into air-cleaning (see Fig. 20).

*Scenario 2* is a sort of a "heavy industrial" development with 5% growth rate of total investment into economy with minimal share of investments into air-cleaning.

*Scenario 3* has the same economic development program, as the Scenario 1, but it applies intensive investment into air-cleaning assets.

General draft conclusion of the analysis (to be continued in future versions of the paper) is that cost of maintaining the same level of German air pollution abatement is rather high.



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