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Business-as-usual, High Technology and Coalition Scenarios for Transboundary Pollution in the European Union

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Abstract

The paper addresses the issue of air pollution in the European Union (EU). The focus is on economic and environmental assessment of alternative pollution control scenarios. In order to derive policy-relevant conclusions, we develop an ecology-economy model of the EU by linking an environmental effect from countries' SO_2 (sulphur dioxide) abatement with their economic outcomes.

We consider SO_2 reduction strategies (GAINS) available for the EU member states during 2015-2020 and, compare environmental and economic impacts in two scenarios assuming that a base-line abatement technology and respectively, an advanced abatement technology are being used. Furthermore, we introduce elements of game theory and consider a possibility for cooperation in air pollution abatement among several Baltic countries (Finland, Sweden, Denmark and Latvia). The optimal choice of the technologies and corresponding levels of SO_2 reduction are determined for the given countries. The coalition scenario is shown to be superior to the baseline scenario. We study a positive externality effect and demonstrate that the neighboring countries, Estonia and Lithuania, receive the highest impact from pollution reduction. Possible free-riding by Latvia and Finland is considered. It has been proven that stability of cooperation is achievable.

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Business-as-usual, High Technology and Coalition Scenarios for Transboundary Pollution in the European Union

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1 Introduction

Stationary emissions sources, such as coal-fired and oil-fired power stations, and mobile sources, such as cars, ships and aircraft emit a complex mixture of pollutants, including sulphur dioxide SO_2 and nitrogen oxides NO_x (the precursors to acid rain). It is now well established that this air pollution is transported over hundreds or even thousands of kilometres. Consequently, when acidic pollution is finally deposited, its environmental impacts are felt in areas far removed from their sources.

In Europe acid rain became a major transboundary enviromental issue in the late twentieth century. Since the prevailing wind direction there is generally westerly or south-westerly, territories most affected by acidification are Scandinavia, Central and Eastern Europe. To cope with the transboundary air pollution problem, international treaties on a long range transport of atmospheric pollutants have been agreed, e.g., the Sulphur Emissions Reduction Protocol under the Convention on Long-Range Transboundary Air Pollution. In collaboration with the UN Economic Commission for Europe and in the context of the Geneva Convention on Long-Range Transboundary Air Pollution, an interactive model for air pollution and greenhouse gases (GAINS) has been developed at the International Institute for Applied Systems Analysis (IIASA), [1], [2]. This model explores synergies and trade-offs between control of local and regional air pollution and mitigation of global greenhouse gas emissions. Its European implementation covers 43 countries in Europe including the European part of Russia. GAINS estimates emissions, mitigation potentials and costs for six air pollutants (SO_2, NO_x, NH_3, etc.) and for the six greenhouse gases have been included in the Kyoto protocol. The model time coverage for scenario analysis is the period 1980–2030.

Over the past 50 years game-theory applications in environmental economics have largely focused on transboundary pollution problems, [3] – [6]. One of the first attempts to estimate actual spillovers from transboundary pollution was undertaken by [7] for the case of acid rain in Europe. The following examples of game-theoretic assessment [8] – [16] show that, as well as global warming and ozone depletion, problem of transboundary acid rain remains relevant, [17]. Important topics vary from analysis of energy scenarios and pollution control costs to estimation of transboundary acidification and its impact on ecology and health. Special attention is paid to negotiation and enforcement mechanisms of multilateral agreements.

The main research interest of the present paper is to derive new policy-relevant conclusions about available pollution control strategies. The goal is achieved by stepwise solving of 4 tasks:

- quantification of the geo-physical impact of acidification;
- calibration of the technology cost and environmental benefit functions associated with the establishing of an ecology-economy model in use;
- formation of a project of an agreement on acid rain in a group of the EU countries;
- economic and environmental assessment of alternative strategic scenarios for the EU member states.

Sections 2 and 3 suggest a method to compare two dissimilar facets of environmental benefits from pollution reduction and monetary costs, which is still missing in the current load of game-theoretic literature on international environmental agreements (IEAs). We specify an environmental effect from the countries' SO_2 reduction and then link it with the monetary payoffs by introducing cost/benefit ratios. Thus it allows us to resolve a crucial problem of consistency in dimension and design an economy-ecology model of the EU (basing on GAINS data about technology levels available for the EU state members and the air pollutant transportation coefficient matrix for 2020). In the framework of the introduced model we undertake a comparative analysis of environmental and economic aspects of a business-as-usual (BAU) scenario and a high technology (HighT) scenario for the period 2015-2020. See Section 4.

Further on, in Section 5 we introduce elements of game theory and consider a possibility for cooperation on air pollution reduction among several Baltic countries (Finland, Sweden, Denmark and Latvia) in the period 2015-2020. The choice of technologies and correspondent levels of SO_2 reduction, optimal for the considered group of countries, are determined and the coalition is shown to be superior to the baseline scenario in both environmental and economic aspects. Besides that, we study a positive externality effect and demonstrate that two neighboring countries, Estonia and Lithuania, receive the highest impact from pollution reduction. We reveal that the stability of the agreement can be threatened by free-riding incentives of Latvia and Finland. We use the concept of potential internal stability and consider a possibility to introduce a launch transfer mechanism to eliminate free-riding. Analytic solutions are accompanied by numerical analysis presented in figures and tables.

The paper intends to contribute to the initiative on the Fragility of Critical Infrastructures (www.iiasa.ac.at/Research/FCI).

2 Ecology-Economy Model

Consider N heterogeneous interdependent countries acting as players. Each player can choose a feasible strategy $q_i \in [\underline{q}_i, \bar{q}_i]$, $i = 1, \dots, N$, describing the size of a pollution reduction load ($\underline{q}_i$ and $\bar{q}_i$ are lower and upper bounds, respectively). Let $\mathbf{q} = (q_1, \dots, q_N)$ be a full pollution reduction vector. Then the payoff (net benefit) of each player i is given by

$$\pi_i(\mathbf{q}) = B_i(\mathbf{q}) - C_i(q_i), \tag{1}$$

here $B_i(\mathbf{q})$ is a monetary equivalent of the environmental benefit and $C_i(q_i)$ is the cost paid by player i for pollution reduction. Assume that the abatement cost function is quadratic:

$$C_i(q_i) = \frac{1}{2} c_i q_i^2, \tag{2}$$

the parameter $c_i > 0$ is the slope of the marginal cost function. The monetary equivalent of the environmental benefit gained by player i is given by

$$B_i(\mathbf{q}) = \lambda_i \sum_{k=1}^{N} T_{ki} q_k, \tag{3}$$

where $\sum_{k=1}^{N} T_{ki} q_k$ is the environmental benefit of the total pollution reduction load to the territory of player i, $T_{ki} \geqslant 0$ is a transport coefficient describing the acidification effect from a proportion of pollution of country k transported to country i.

To assign a monetary value to the environmental benefit, we introduce a parameter $\lambda_i \geqslant 0$, $i = 1 \ldots, N$, describing a cost/benefit ratio for each player $i, i = 1, \ldots, N$. The latter value can be described as a ratio of a unit change in the abatement cost function to the corresponding increment of the environmental benefit:

$$\lambda_i = x_i \frac{(1/2) c_i q_i^2}{\sum_{k=1}^{N} T_{ki} q_k} = x_i \frac{1}{\sum_{k=1}^{N} T_{ki} \sqrt{2/c_k}}. \tag{4}$$

Parameters x_i act as proportionality coefficients, and can be roughly estimated as $x_i \in [3, 20]$, $c_i = 1, \ldots, N$. In the following section we justify a choice of the introduced benefit and cost functions and further undertake a comparison of the baseline (or business-as-usual (BAU)) and high technology (HighT)) scenarios for the EU in the period 2015-2020, using GAINS model data.

3 Model Calibration

In this section we undertake calibration of the suggested ecology-economy model in such a way that policy-relevant conclusions about optimal pollution control can be derived. Focusing on the economic aspects of pollution control, we quantify the geo-physical impact of acidification and assign it a monetary value. To carry on the numerical analysis we use data of the GAINS model, which was developed at the International Institute for Applied System Analysis (IIASA). It estimates emissions, mitigation potentials and costs for six air pollutants (SO_2, NO_x, PM, NH_3, VOC) and for the six greenhouse gases included in the Kyoto protocol. GAINS European implementation covers 43 countries in Europe including the European part of Russia. In the present paper we tackle air pollutants, in particular SO_2, emitted and deposited on the territory of the EU: Austria, Belgium, Cyprus, Czech and Slovakia Republics, Germany, Denmark, Estonia, Spain, Finland, France, UK, Greece, Hungary, Ireland, Italy, Lithuania, Luxembourg, Latvia, Malta, Netherlands, Poland, Portugal, Sweden, Slovenia.

3.1 Cost functions and cost/benefit parameters

To determine correlating parameters λ_i, $i = 1, \ldots, N$, we first approximate cost curves of each of 25 countries. Consider such pollutant as SO_2, which together with NH_3 and NO_x cause acidification of soil. Values $e_i^{SO_2}$, $e_i^{NO_x}$ and $e_i^{NH_3}$ denote correspondent pollutants emitted by player i, $i = 1, \ldots, N$, and then transported around the country and its neighbors' territory. Level of each emitted pollutant is linked to a certain choice of technology. Data containing costs of available technologies $\{c_i^p\}_{p=1}^{T_i}$ and correspondent pollution levels $\{e_i^p\}_{p=1}^{T_i}$, $i = 1, \ldots, N$, in 2020 can be found in the GAINS model. To approximate the SO_2 abatement cost functions, we translate and mirror the pollution cost curves provided by GAINS (the original curve is the blue one in Fig. 1 and the transformed one is the red one in Fig. 2):

$$q_i^p = e_i^{BAU} - e_i^p, p = 1, \dots, T_i,$$
$$C_i(q_i^p) = C_i^p - C_i^{BAU}, p = 1, \dots, T_i.$$

As you can see from Fig. 2, the curve describing relation between SO_2 reduction and the costs is concave[1] and can be approximated with the quadratic polynom: $C_i(q_i) = \frac{1}{2}c_i q_i^2$. We apply the least square method to determine relation of SO_2 reduction q_i and the correspondent costs $C_i(q_i)$ bared by countries $i = 1, \dots, N$. Thus parameters c_i can be found as a solution of the problem:

$$\min_{c_i} \sum_{p=1}^{T_i} \left(\frac{1}{2} c_i (q_i^p)^2 - C_i(q_i^p) \right)^2, i = 1, \dots, N. \tag{5}$$

In case of Finland, the minimization problem (5) is represented as follows

$$\begin{aligned} \min_{c_{Fin}} \big(&(0.106c_{Fin} - 0.25)^2 + (0.328c_{Fin} - 0.45)^2 + (4.651c_{Fin} - 1.8)^2 \\ &+ (8.364c_{Fin} - 3.05)^2 + (24.151c_{Fin} - 6.63)^2 + (26.064c_{Fin} - 7.03)^2 \\ &+ (28.956c_{Fin} - 8.15)^2 + (38.281c_{Fin} - 12.28)^2 + (51.613c_{Fin} - 17.76)^2 \\ &+ (91.937c_{Fin} - 33.1)^2 + (94.119c_{Fin} - 33.94)^2 + (106.434c_{Fin} - 39.78)^2 \\ &+ (117.505c_{Fin} - 63.51)^2 \big), \end{aligned}$$

and leads to $c_{Fin} = 0.409$ (Fig. 3 represents thus obtained SO_2 abatement cost curve of Finland, it is marked in green).

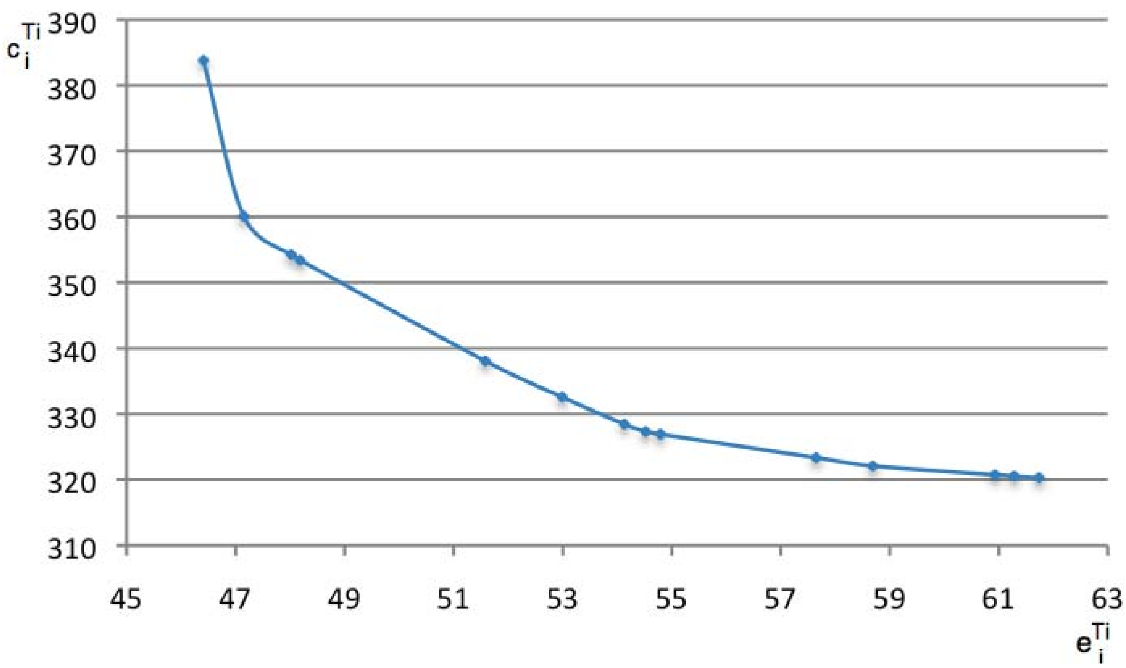


Figure 1: Technology cost curve of Finland in 2020

[1]This property holds for all 25 EU countries

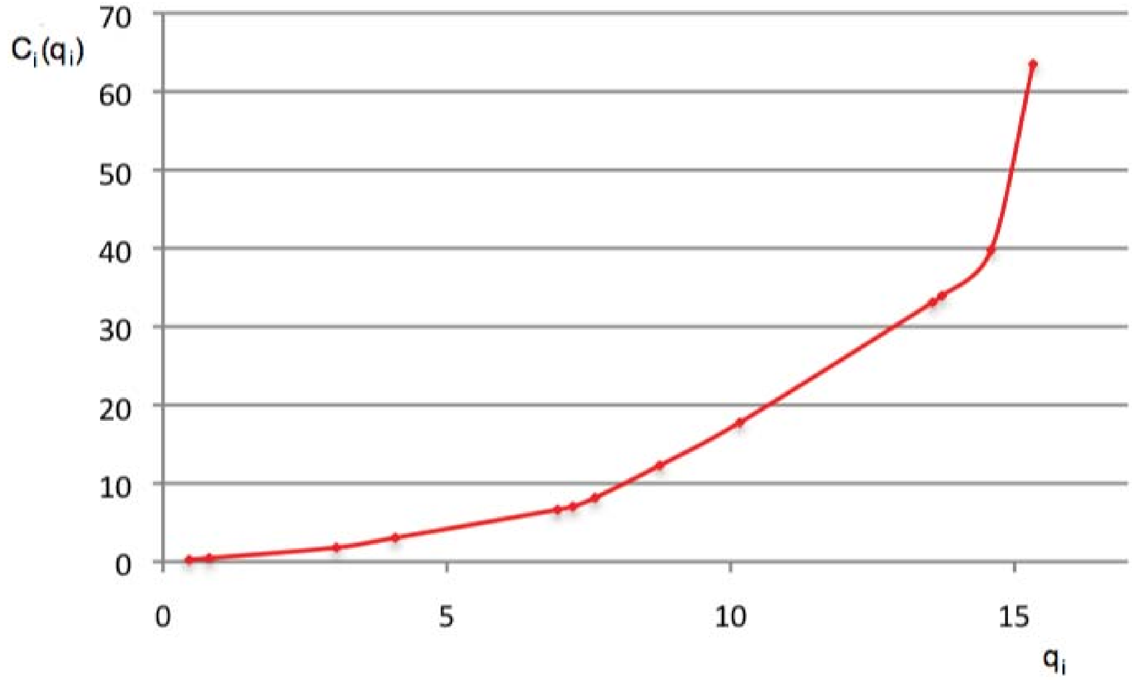


Figure 2: SO_2 reduction cost curve of Finland in 2020

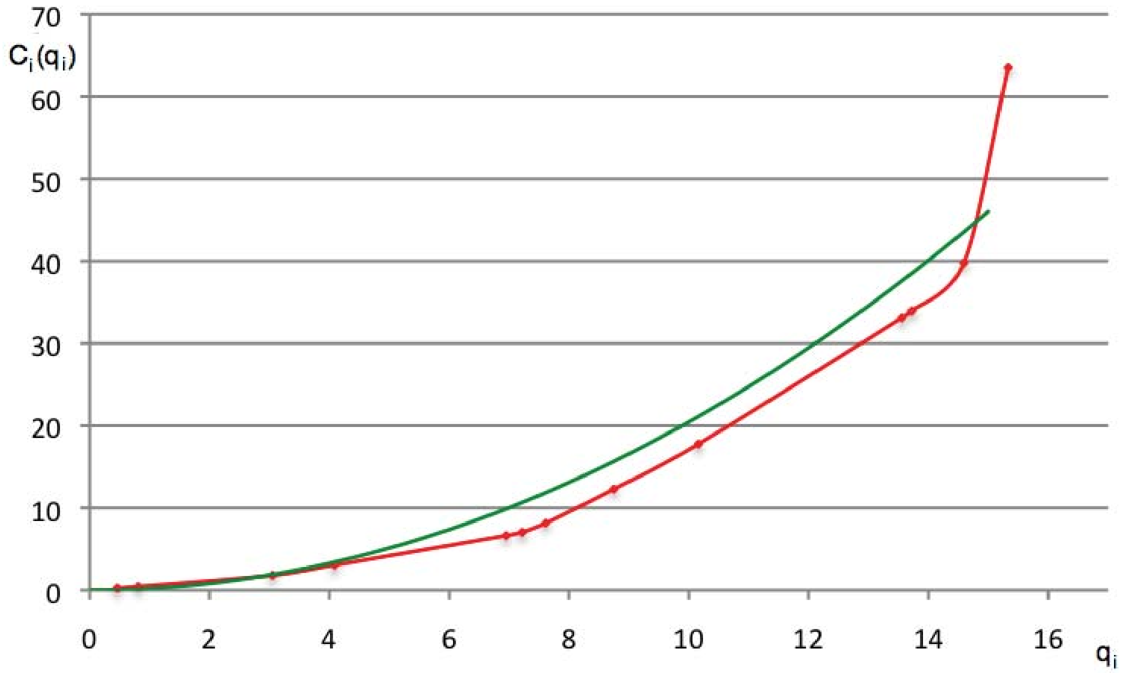


Figure 3: Approximation of the SO_2 reduction cost function of Finland in 2020

Table 1: Slopes of abatement cost curves of 25 EU countries

country	Austria	Belgium	Cyprus	Czech Rep.	Germany
c_i	1.24	0.099	1.058	0.21	0.061
country	Denmark	Estonia	Spain	Finland	France
c_i	1.556	0.52	0.011	0.409	0.018
country	UK	Greece	Hungary	Ireland	Italy
c_i	0.028	0.039	0.028	0.472	0.014
country	Lithuania	Luxembourg	Latvia	Malta	Netherlands
c_i	0.091	4.862	0.354	3.698	0.143
country	Poland	Portugal	Sweden	Slovenia	Slovakia Rep.
c_i	0.005	0.043	1.321	0.155	0.167

Following the least square method (5) we determine slopes of abatement cost curves of all 25 EU countries, see Tab. 1. Fig. 4 present the transposed matrix of SO_2 transport coefficients[2], where each element T_{ik} of row i specifies acidification impact, caused by the fraction of the correspondent type of pollution e_k of region k being deposited in region i. Given the parameters c_i and T_{ki} we can now determine correlating cost/benefit parameters λ_i (Tab. 2).

[2]GAINS extrapolations for 2020

Table 2: Cost/benefit parameters λ_i of 25 EU countries

country	Austria	Belgium	Cyprus	Czech Rep.	Germany
λ_i	9.229	2.049	2389.139	4.033	4.094
country	Denmark	Estonia	Spain	Finland	France
λ_i	15.015	77.385	44.246	96.71	7.946
country	UK	Greece	Hungary	Ireland	Italy
λ_i	12.16	58.795	14.758	13.548	22.66
country	Lithuania	Luxembourg	Latvia	Malta	Netherlands
λ_i	26.081	5.196	43.283	0.8	1.137
country	Poland	Portugal	Sweden	Slovenia	Slovakia Rep.
λ_i	4.182	43.286	34.687	21.494	9.839

3.2 Benefit function

Assume the environmental damage, caused by these pollutants, is described as a sum of deposition impacts (GAINS):

$$D_i^{env}(\mathbf{e}^{SO_2}, \mathbf{e}^{NO_x}, \mathbf{e}^{NH_3}) = \sum_{k=1}^{N} \left(T_{ki}^{SO_2} e_k^{SO_2} + T_{ki}^{NO_x} e_k^{NO_x} + T_{ki}^{NH_3} e_k^{NH_3} \right) + \kappa_i, \ i = 1, \ldots, N. \quad (6)$$

Pollutant loads $e_k^{SO_2}$, $e_k^{NO_x}$ and $e_k^{NH_3}$ measured in kilotons (Kt), parameter κ_i is background deposition impact (it reflects pollution flow from the area outside of the considered European territory), measured in[3] $mEq(H+)/hectar/year$. The transport coefficients $T_{ki}^{SO_2}$, $T_{ki}^{NO_x}$ and $T_{ki}^{NH_3}$ are measured as $mEq(H+)/hectar/year/Kt$, and the environmental damage $D_i^{env}(E_i)$ has dimension $mEq(H+)/hectar/year$.

Let $q_i = e_i^{SO_2,Y} - e_i^{SO_2,X}$, $i = 1, \ldots, N$, denote players' strategies, describing SO_2 reduction during period $[Y, X]$ (from moment Y to moment X). We shall specify the benefit functions $B_i(\mathbf{q})$, $i = 1, \ldots, N$, from reduction of pollution loads $\mathbf{q}$, using given in GAINS environmental damage functions $D_i^{env}(\mathbf{e}^{SO_2}, \mathbf{e}^{NO_x}, \mathbf{e}^{NH_3})$, $i = 1, \ldots, N$, (6):

$$\begin{aligned} B_i(\mathbf{q}) &= \lambda_i(D_i^{env}(\mathbf{e}^{SO_2,X}, \mathbf{e}^{NO_x,X}, \mathbf{e}^{NH_3,X}) - D_i^{env}(\mathbf{e}^{SO_2,X}, \mathbf{e}^{NO_x,X}, \mathbf{e}^{NH_3,X})) \\ &= \lambda_i \textstyle\sum_{k=1}^N \left(T_{ki}^{SO_2} e_k^{SO_2,X} + T_{ki}^{NO_x} e_k^{NO_x,X} + T_{ki}^{NH_3} e_k^{NH_3,X} \right) + \lambda_i \kappa_i \\ &-\lambda_i \textstyle\sum_{k=1}^N \left(T_{ki}^{SO_2} e_k^{SO_2,Y} + T_{ki}^{NO_x} e_k^{NO_x,X} + T_{ki}^{NH_3} e_k^{NH_3,X} \right) - \lambda_i \kappa_i \\ &= \lambda_i \textstyle\sum_{k=1}^N T_{ki}^{SO_2} \left(e_k^{SO_2,X} - e_k^{SO_2,Y} \right) = \lambda_i \textstyle\sum_{k=1}^N T_{ki}^{SO_2} q_k. \end{aligned}$$

We shall further omit upper index SO_2, thus obtaining identical to (3) representation

$$B_i(\mathbf{q}) = \lambda_i \sum_{k=1}^{N} T_{ki} q_k, \quad i, k = 1, \ldots, 25.$$

The SO_2 abatement benefit is calculated over the cost/benefit parameters given in Tab. 2, and the transfer coefficients given in Fig. 4.

[3]The dimension is milliequivalents of acid per hectar, per kiloton of pollutant, per year.

Figure 4: Transport matrix T_{ki}, $i, k = 1, \ldots, 25$ of EU in 2020

	Aust	BELG	CYPR	CZRE	GERM	DENM	ESTO	SPAI	FINL	FRAN	UNKI	GREE	HUNG
AUST	0.1314	0.0032	0.0000	0.2050	0.0583	0.0012	0.0000	0.0000	0.0000	0.0008	0.0007	0.0000	0.0000
BELG	0.0026	0.8399	0.0000	0.0353	0.1465	0.0070	0.0000	0.0000	0.0001	0.0077	0.0096	0.0000	0.0000
CYPR	0.0000	0.0000	0.0000	0.0001	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
CZRE	0.0177	0.0090	0.0000	0.7350	0.1073	0.0024	0.0000	0.0000	0.0001	0.0009	0.0013	0.0000	0.0000
GERM	0.0114	0.0376	0.0000	0.1323	0.3675	0.0078	0.0000	0.0000	0.0001	0.0033	0.0035	0.0000	0.0000
DENM	0.0015	0.0046	0.0000	0.0248	0.0433	0.1132	0.0000	0.0000	0.0004	0.0004	0.0018	0.0000	0.0000
ESTO	0.0001	0.0010	0.0000	0.0030	0.0033	0.0010	0.0000	0.0000	0.0022	0.0001	0.0002	0.0000	0.0000
SPAI	0.0004	0.0039	0.0000	0.0041	0.0074	0.0005	0.0000	0.0003	0.0000	0.0038	0.0020	0.0000	0.0000
FINL	0.0001	0.0006	0.0000	0.0028	0.0019	0.0005	0.0000	0.0000	0.0047	0.0000	0.0002	0.0000	0.0000
FRAN	0.0018	0.0829	0.0000	0.0216	0.0651	0.0030	0.0000	0.0000	0.0001	0.0235	0.0074	0.0000	0.0000
UNKI	0.0008	0.0236	0.0000	0.0106	0.0298	0.0072	0.0000	0.0000	0.0001	0.0019	0.0753	0.0000	0.0000
GREE	0.0002	0.0002	0.0000	0.0014	0.0009	0.0000	0.0000	0.0000	0.0000	0.0001	0.0001	0.0000	0.0000
HUNG	0.0054	0.0012	0.0000	0.0548	0.0092	0.0009	0.0000	0.0000	0.0001	0.0002	0.0003	0.0000	0.0002
IREL	0.0003	0.0080	0.0000	0.0040	0.0108	0.0028	0.0000	0.0000	0.0000	0.0012	0.0343	0.0000	0.0000
ITAL	0.0015	0.0010	0.0000	0.0095	0.0071	0.0001	0.0000	0.0000	0.0000	0.0005	0.0003	0.0000	0.0000
LITH	0.0003	0.0007	0.0000	0.0048	0.0046	0.0017	0.0000	0.0000	0.0005	0.0000	0.0002	0.0000	0.0000
LUXE	0.0042	0.0796	0.0000	0.0528	0.2850	0.0041	0.0000	0.0000	0.0001	0.0106	0.0048	0.0000	0.0000
LATV	0.0002	0.0004	0.0000	0.0037	0.0034	0.0012	0.0000	0.0000	0.0006	0.0000	0.0001	0.0000	0.0000
MALT	0.0003	0.0004	0.0000	0.0029	0.0027	0.0000	0.0000	0.0000	0.0000	0.0004	0.0002	0.0000	0.0000
NETH	0.0022	0.3940	0.0000	0.0311	0.1730	0.0093	0.0000	0.0000	0.0001	0.0032	0.0091	0.0000	0.0000
POLA	0.0021	0.0021	0.0000	0.0498	0.0195	0.0027	0.0000	0.0000	0.0002	0.0002	0.0006	0.0000	0.0000
PORT	0.0002	0.0015	0.0000	0.0014	0.0026	0.0002	0.0000	0.0000	0.0000	0.0010	0.0008	0.0000	0.0000
SWED	0.0006	0.0012	0.0000	0.0098	0.0106	0.0073	0.0000	0.0000	0.0010	0.0001	0.0007	0.0000	0.0000
SLOV	0.0102	0.0014	0.0000	0.0502	0.0110	0.0005	0.0000	0.0000	0.0000	0.0005	0.0004	0.0000	0.0000
SKRE	0.0051	0.0016	0.0000	0.0790	0.0105	0.0011	0.0000	0.0000	0.0001	0.0002	0.0003	0.0000	0.0001

	IREL	ITAL	LITH	LUXE	LATV	MALT	NETH	POLA	PORT	SWED	SLOV	SKRE
AUST	0.0005	0.0002	0.0001	0.1243	0.0001	0.2189	0.0148	0.0297	0.0000	0.0013	0.0000	0.0302
BELG	0.0059	0.0002	0.0001	0.6225	0.0001	0.0394	1.1194	0.0111	0.0000	0.0031	0.0000	0.0017
CYPR	0.0000	0.0000	0.0000	0.0000	0.0000	0.0097	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
CZRE	0.0008	0.0001	0.0003	0.2416	0.0002	0.0979	0.0416	0.0751	0.0000	0.0025	0.0000	0.0267
GERM	0.0022	0.0002	0.0002	0.6020	0.0001	0.0860	0.2446	0.0361	0.0000	0.0043	0.0000	0.0051
DENM	0.0012	0.0000	0.0006	0.1199	0.0003	0.0466	0.0325	0.0278	0.0000	0.0289	0.0000	0.0017
ESTO	0.0001	0.0000	0.0003	0.0520	0.0009	0.0218	0.0061	0.0067	0.0000	0.0040	0.0000	0.0007
SPAI	0.0022	0.0002	0.0000	0.1044	0.0000	0.2222	0.0102	0.0017	0.0005	0.0004	0.0000	0.0006
FINL	0.0002	0.0000	0.0002	0.0445	0.0005	0.0284	0.0027	0.0051	0.0000	0.0051	0.0000	0.0005
FRAN	0.0047	0.0008	0.0001	0.6914	0.0000	0.2616	0.1580	0.0066	0.0000	0.0016	0.0000	0.0015
UNKI	0.0165	0.0000	0.0001	0.1114	0.0001	0.0374	0.1059	0.0067	0.0000	0.0033	0.0000	0.0008
GREE	0.0001	0.0001	0.0001	0.0070	0.0000	0.3759	0.0003	0.0019	0.0000	0.0000	0.0000	0.0017
HUNG	0.0002	0.0001	0.0002	0.0241	0.0001	0.1827	0.0047	0.0363	0.0000	0.0014	0.0000	0.0613
IREL	0.3411	0.0000	0.0000	0.1971	0.0000	0.0707	0.0330	0.0027	0.0000	0.0014	0.0000	0.0003
ITAL	0.0003	0.0064	0.0000	0.0540	0.0000	0.8206	0.0029	0.0031	0.0000	0.0002	0.0000	0.0028
LITH	0.0001	0.0000	0.0079	0.1026	0.0014	0.0457	0.0055	0.0271	0.0000	0.0053	0.0000	0.0017
LUXE	0.0033	0.0003	0.0001	0.5443	0.0001	0.0939	0.2272	0.0122	0.0000	0.0025	0.0000	0.0025
LATV	0.0001	0.0000	0.0014	0.1015	0.0044	0.0377	0.0031	0.0146	0.0000	0.0049	0.0000	0.0012
MALT	0.0002	0.0006	0.0000	0.0175	0.0000	33.8670	0.0008	0.0013	0.0000	0.0000	0.0000	0.0013
NETH	0.0049	0.0001	0.0001	0.0950	0.0001	0.0268	3.8123	0.0126	0.0000	0.0034	0.0000	0.0018
POLA	0.0003	0.0000	0.0008	0.0510	0.0003	0.0722	0.0133	0.2127	0.0000	0.0037	0.0000	0.0222
PORT	0.0009	0.0001	0.0000	0.0589	0.0000	0.1198	0.0046	0.0006	0.0380	0.0001	0.0000	0.0002
SWED	0.0005	0.0000	0.0004	0.1019	0.0003	0.0515	0.0073	0.0132	0.0000	0.0482	0.0000	0.0010
SLOV	0.0003	0.0004	0.0001	0.0502	0.0001	0.2057	0.0063	0.0202	0.0000	0.0009	0.0000	0.0186
SKRE	0.0003	0.0001	0.0002	0.0304	0.0001	0.1261	0.0067	0.0523	0.0000	0.0017	0.0000	0.1489

4 Business-as-usual and High Technology scenarios

Let us consider period 2015-2020 and calculate and compare the environmental and economic outcomes of two 'opposing' scenarios. According to the first one, Business-As-Usual scenario (BAU), the EU countries choose the least expensive of available technologies (base-line level), which is associated with highest SO_2 emission. Currently, the EU member states are following this scenario. The second scenario is High Technology (HighT), which would, if adopted, prescribe high technological standards and low pollution. Let us first consider BAU scenario. In the second and third columns of Tab. 3 we summarize GAINS extrapolations of SO_2 pollution reduction q_i and pollution control costs $C_i(q_i)$ of 25 EU member states[4] Using model equations (1) – (4) calibrated in Sections 3.1 and 3.2, we calculate the benefits $B_i(\mathbf{q})$ and the payoffs $\pi_i(\mathbf{q})$ of the EU countries during 2015–2020. Results of the calculations are presented in Tab. 3. Graphical illustration of abatement efforts and associated payoffs is exhibited in Fig. 5 and 6, respectively. Fig. 5 shows that the largest SO_2 abatement in BAU scenario is undertaken by Poland, United Kingdom and Spain.

Poland provides a good example of the transboundary effect of air pollution: Being one of the largest pollutant together with Italy, France, Spain and Germany, Poland undertakes highest reduction of SO_2 during 2015-2020, making a substantial positive impact on the neighboring countries Czech and Slovakia republics and Lithuania (see Fig. 6). Another example of positive externality is Finland, Denmark and Sweden, who also benefit by SO_2 reductions undertaken by Germany and Poland.

It is interesting to notice that some countries, like Netherlands, Belgium and Portugal, receive negative payoffs. In BAU scenario during 2015–2020 Netherlands lowers costs of pollution control and increases SO_2 production. Air pollution spreads across Netherlands border and leads to environmental losses on both Netherlands and Belgium's territories, thus resulting in negative payoffs for both countries. Portugal, due to its geographical location on oceanside in the south-west of the EU, is exposed to transboundary pollution threat to much smaller degree than other EU members and it would be better off by abating smaller amount of SO_2 or not abating at all.

Now let us turn to the HighT scenario during 2015-2020: SO_2 reduction and costs of 25 EU member states can be found in the second and third columns of Tab. 4. Using model equations (1)–(4), we calculate the benefits and the payoffs of the EU countries during 2015–2020 in high technology scenario (see the forth and fifth columns in Tab. 4). Fig. 7 and 8 represent comparison of abatement efforts (Kt) and the payoffs (Mln. E) of the 25 EU countries during 2015–2020 in the BAU and HighT scenarios. Though majority of the countries are better off in the HighT scenario, it would be premature to conclude its superiority over the BAU scenario since its enforcement needs to be guaranteed by all 25 EU countries. As we can see from Fig. 8, the HighT costs of such countries as Poland, Germany, Spain, France, Italy (these are the largest pollutants), as well as Greece and Portugal, are substantially larger than benefits, which makes this scenario unprofitable to those 7 countries and thus can hardly be accepted. In the following section we are going to suggest alternative scenario based on partial cooperation among EU countries, which fills the gap between the BAU and the HighT scenarios, delivering higher abatement levels and acceptable economic outcomes.

[4]Pollution characteristics of Malta, Greece and Cyprus can be inaccurate due to complexity of measurements justification. Acidification impact of these countries is rather small and can be omitted.

Table 3: BAU scenario: SO_2 reduction (Kt) and payoffs (Mln. E) of EU member states during 2020-2015

countries	GAINS	GAINS	Estimation (BAU)	Estimation (BAU)
	SO_2 Reduction Kt	Cost Mln. E	Benefit Mln. E	Payoff Mln. E
Austria	1.241	2.652	83.368	80.716
Belgium	2.296	11.325	8.087	−3.238
Cyprus	7.001	7.845	16.080	8.235
Czech Rep.	14.409	−41.023	99.099	140.122
Germany	16.479	−17.867	54.979	72.846
Denmark	2.855	−26.889	89.235	116.124
Estonia	3.226	−4.455	91.617	96.072
Spain	33.243	23.529	27.932	4.403
Finland	−1.333	14.42	87.184	72.764
France	11.108	−45.649	23.307	68.956
UK	62.206	1.237	76.226	74.989
Greece	24.381	23.347	21.289	−2.058
Hungary	15.373	2.403	104.849	102.446
Ireland	4.83	7.04	59.445	52.405
Italy	19.501	−21.81	20.543	42.353
Lithuania	4.556	2.307	118.951	116.644
Luxembourg	−0.002	4.728	38.342	33.614
Latvia	1.62	−1.097	108.838	109.935
Malta	7.959	0.88	0.257	−0.623
Netherlands	−3.066	34.2	−5.449	−39.649
Poland	160.465	−0.783	147.684	148.467
Portugal	3.394	32.987	9.626	−23.361
Sweden	1.686	−17.566	89.186	106.752
Slovenia	3.187	−14.335	91.982	106.317
Slovakia Rep.	5.128	15.515	103.179	87.664

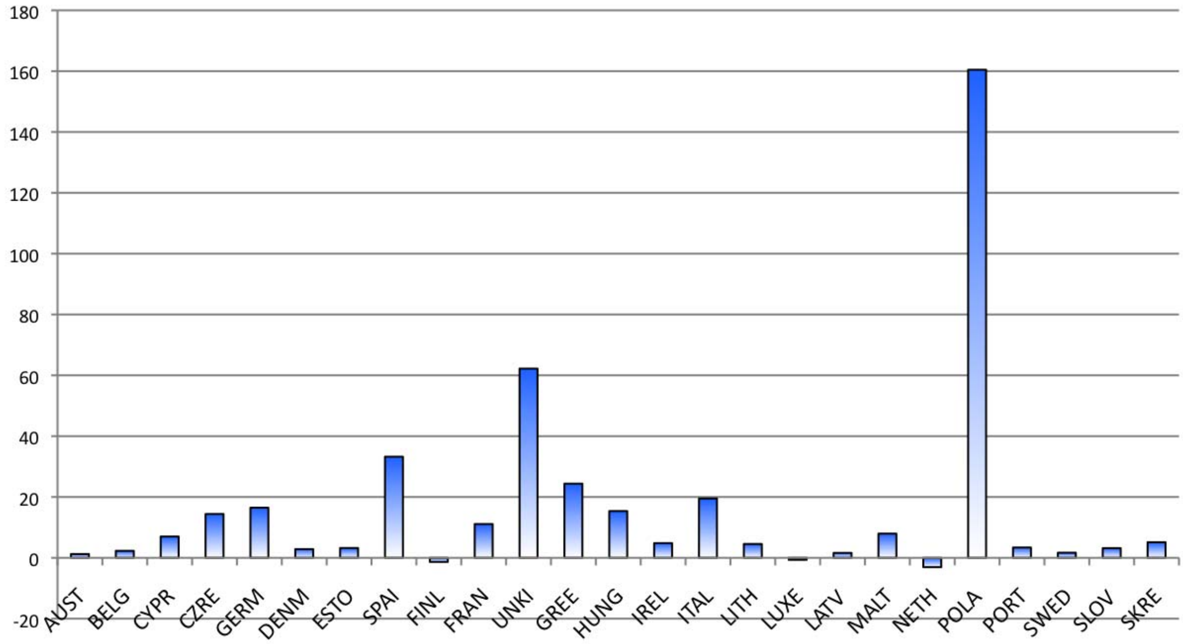


Figure 5: BAU: SO_2 reduction of EU member states during 2020-2015, Kt

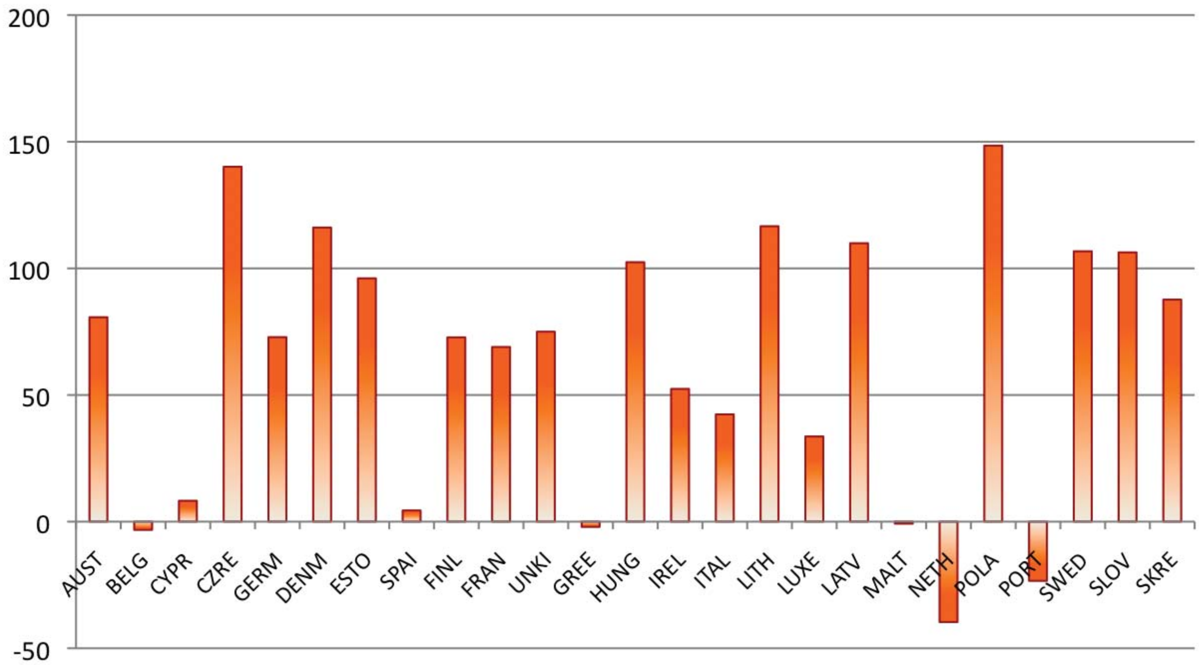


Figure 6: BAU: payoff of EU member states during 2020-2015, Mln. E

Table 4: HighT: SO_2 reduction (Kt) and payoff (Mln. E) of EU member states during 2020–2015.

Countries	GAINS	GAINS	Estimation (HighT)	Estimation (HighT)
	SO_2 Reduction Kt	Cost Mln. E	Benefit Mln. E	Payoff Mln. E
AUST	5.729	15.492	320.041	304.549
BELG	34.939	79.515	165.826	86.311
CYPR	12.266	27.902	61.749	33.847
CZRE	41.361	71.853	354.826	282.973
GERM	128.497	546.406	330.687	−215.719
DENM	6.996	−12.116	365.176	377.292
ESTO	9.729	9.357	354.708	345.351
SPAI	213.142	293.865	168.011	−125.854
FINL	14.002	77.929	334.283	256.354
FRAN	207.341	428.951	206.529	−222.422
UNKI	155.59	158.774	284.312	125.538
GREE	93.994	167.819	79.000	−88.819
HUNG	84.498	45.516	372.176	326.660
IREL	13.516	32.793	195.409	162.616
ITAL	187.399	252.406	103.979	−148.427
LITH	21.055	18.738	423.732	404.994
LUXE	1.298	9.537	293.423	283.886
LATV	7.055	6.717	390.031	383.314
MALT	9.331	7.406	1.173	−6.233
NETH	18.85	77.569	134.733	57.164
POLA	547.696	561.236	511.346	−49.890
PORT	50.907	106.986	57.019	−49.967
SWED	12.674	67.029	352.655	285.626
SLOV	13.517	−2.303	334.710	337.013
SKRE	25.357	67.599	368.285	300.686

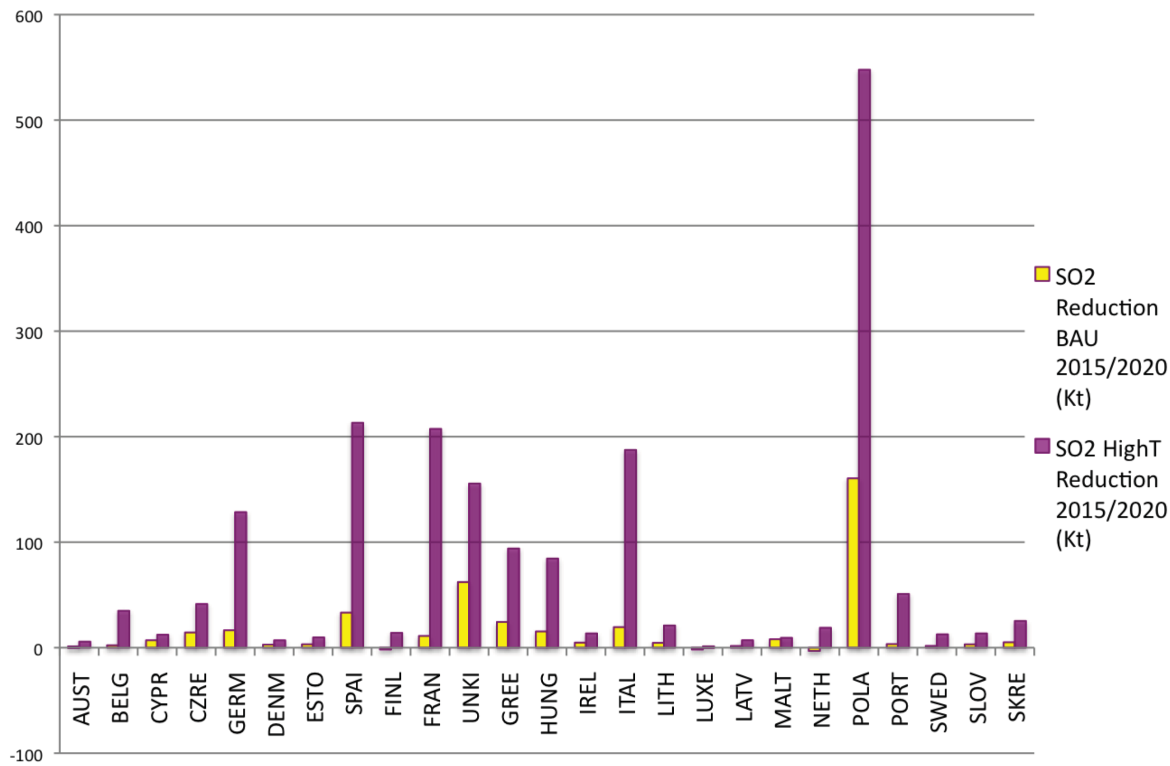


Figure 7: Comparison of BAU and HighT: SO_2 reduction of EU member states during 2020-2015, Kt

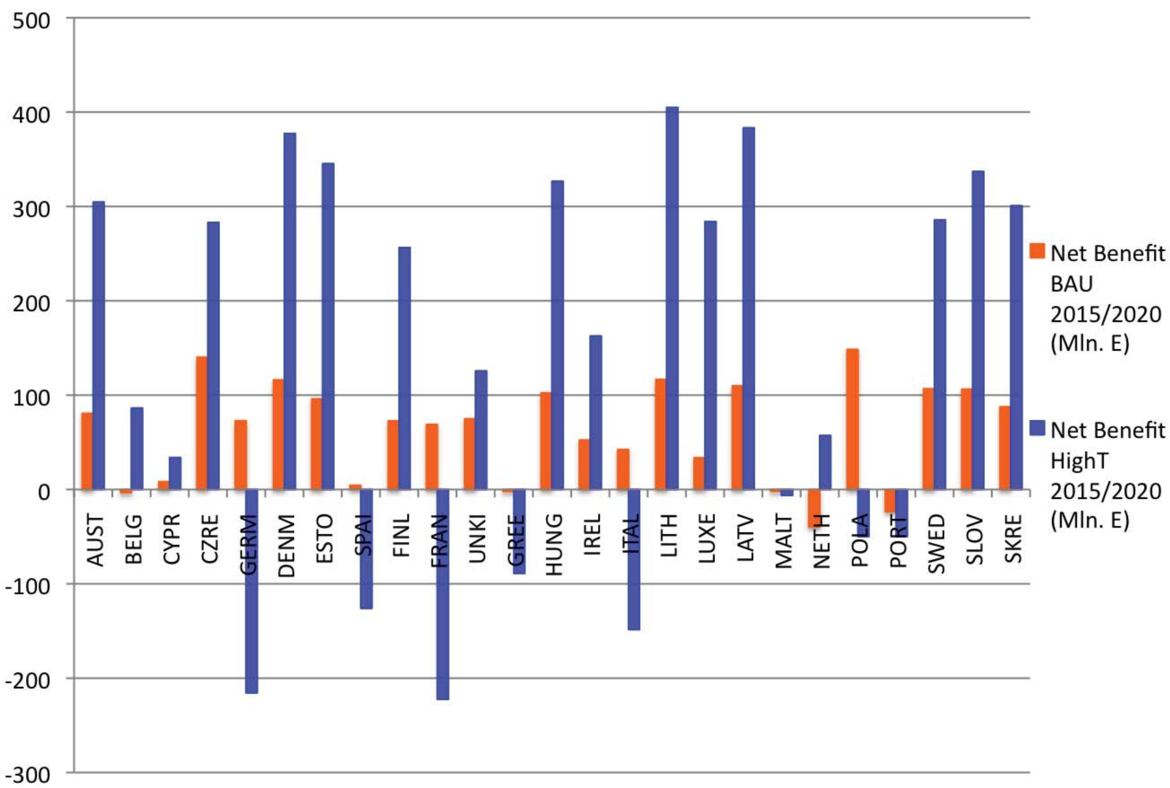


Figure 8: Comparison of BAU and HighT: payoff of EU member states during 2020-2015, Mln. E

5 Business-as-usual and Coalition scenario

In this section we are going to introduce elements of non-cooperative game theory and suggest another strategical scenario of SO_2 reduction in the EU. Let $\mathcal{N} =$ be a set of N heterogeneous players, e.g. countries, each of which follows its BAU scenario and emits pollutant that damages a shared environmental resource. We suppose that players decide on additional pollution reduction efforts $q_i^S \in \Omega_i = [0, \bar{q}_i], \quad \bar{q}_i > 0$, being aware of the transboundary effect of pollution and knowing that reduction achieved by one player benefits all players. Let vector $(1, \ldots, s)$ denote players, which joined the agreement (signatories of the coalition S) and act cooperatively to reduce pollution. Vector $(s+1, \ldots, N)$ describes players, who prefer to act independently (free-riders form set $F = \mathcal{N} \setminus S$) and follow BAU scenario. Within the suggested framework we interpret multilateral agreement formation as a static game $\Gamma(S) = \langle \mathcal{N}, \{q_i^S\}_{i \in S}, \{\pi_i^S(\mathbf{q}^S), \pi_j^F(\mathbf{q}^S)\}_{i \in S, j \in F} \rangle$, where q_i^S is strategy (additional abatement effort) of a player i, $i = 1, \ldots, N$; $\mathbf{q}^S$ is a vector of strategies of all players given that the agreement is presented by the coalition S, and $\pi_i^S(\mathbf{q}^S)$ and $\pi_j^F(\mathbf{q}^S)$ are the payoffs of the signatories and free-riders, respectively, [19], [20]. We call vector $\mathbf{q}^S$ feasible if $q_i^S \in \Omega_i$, $i = 1, \ldots, N$.

The payoff of each signatory depends on its own abatement decision as well as on the correspondent decisions of others and can be given as difference between pollution reduction benefit and abatement cost

$$\pi_i^S(\mathbf{q}^S) = B_i(\mathbf{q}^S) - C_i(q_i^S), \quad i = 1, \ldots, s. \tag{7}$$

Following the BAU scenario, free-riders bare no extra abatement cost ($q_j^S = 0, j = s+1, N$) and their payoffs are

$$\pi_j^F(\mathbf{q}^S) = B_j(\mathbf{q}^S), \quad j = s+1, \ldots, N.$$

The benefit and cost functions are such that

$$B_i' \geq 0, B_i'' \geq 0, B_i(0) = 0, \tag{8}$$

$$C_i' \geq 0, C_i'' \geq 0, C_i(0) = 0. \tag{9}$$

Properties (8) and (9) of the benefit and cost functions guarantees existence and uniqueness of maximum of payoffs $\pi_i^S(\mathbf{q})$ (7), where $\mathbf{q}^S \in \Omega = \prod_{i=1}^N \Omega_i$.

Typical set up for $\Gamma(S)$ is a two stage game. In the first stage players decide (here, simultaneously) whether to participate in an agreement or not. It is assumed that this is binary choice: 'join' and 'do not join'. In the second stage players choose their pollution reduction level. The problem is solved backwards. Suppose members of the coalition S choose abatement targets according to the group optimality principle:

$$\max_{q_i^S} \sum_{i \in S} \pi_i^S(\mathbf{q}^S), \quad i \in S, \tag{10}$$

$$\text{w.r.t. } 0 \leqslant q_i^S \leqslant \bar{q}_i. \tag{11}$$

To characterize the coalition S, we apply the concept of internal and external stability, also known as *self-enforcing*, [18]. It says that the coalition S, characterized by vector $(1, \ldots, s)$ of signatories, is self-enforcing if it is internally stable

$$\pi_i^F(\mathbf{q}^{S \setminus i}) \leq \pi_i^S(\mathbf{q}^S), \quad i \in S, \tag{12}$$

and externally stable

$$\pi_j^S(\mathbf{q}^{S\cup i}) \leq \pi_j^F(\mathbf{q}^S), \quad j \in F. \tag{13}$$

Inequality (12) sets condition of internal stability, *i.e.* no member of S prefers to withdraw from the agreement (thus its payoff of a free-rider reduces given the coalition $S \setminus i$). This phenomena occurs because the players, remaining in the coalition, rationally react on free-riding of the former signatory and recalculate their optimal strategies. As a result the payoff of the free-rider can become smaller than it was when the player was a signatory. Foreseeing the following (indirect) punishment from other coalition members, none of the signatories withdraws. Similarly, condition (13) of external stability guarantees that no free-rider from set F prefers to join the coalition S (thus becoming a member of the coalition $S \cup i$ the player receives smaller payoff). Together conditions (12) and (13) ensure that no player unilaterally deviates.

The coalition stability concept receives the following extension by introducing a sharing rule (or side payments within the coalition), [21], [22]. Let Δ^S, where

$$\Delta^S = \sum_{i\in S} \Delta_i^S = \sum_{i\in S} \left(\pi_i^S(\mathbf{q}^S) - \pi_i^F(\mathbf{q}^{S\setminus i})\right), \tag{14}$$

be the surplus, obtained by the members of the coalition S. Applying a certain sharing rule, Δ^S can be reallocated among signatories with certain weights coefficients α_i, $\sum_{i\in S} \alpha_i = 1$, so that the payoff of each coalition member becomes

$$\sigma_i^S(\mathbf{q}^S) = \pi_i^F(\mathbf{q}^{S\setminus i}) + \alpha_i \Delta^S. \tag{15}$$

Formula (15) means that each signatory receives as much as it could get unilaterally deviating from S, plus individual share of the common surplus. The coalition S is thus called *potentially self-enforcing* if

$$\Delta^S \geq 0,$$

and

$$\pi_j^S(\mathbf{q}^{S\cup i}) \leq \pi_j^F(\mathbf{q}^S), \quad j \in F.$$

Suppose such Baltic countries as Denmark, Finland, Sweden and Latvia start cooperation towards additional reduction SO_2 pollution. It implies that the coalition S consists of 4 players and the rest of 21 players are free-riders from set F. The payoffs of the signatories are as follows:

(1) Denmark
$\pi_1^S(\mathbf{q}^S) = 15.015(0.1132q_1^S + 0.0004q_2^S + 0.0003q_3^S + 0.0289q_4^S) - 0.778(q_1^S)^2$,

(2) Finland
$\pi_2^S(\mathbf{q}^S) = 96.71(0.0005q_1^S + 0.0047q_2^S + 0.0005q_3^S + 0.005q_4^S) - 0.205(q_2^S)^2$,

(3) Latvia
$\pi_3^S(\mathbf{q}^S) = 43.283(0.0012q_1^S + 0.0006q_2^S + 0.0044q_3^S + 0.0049q_4^S) - 0.177(q_3^S)^2$,

(4) Sweden
$\pi_4^S(\mathbf{q}^S) = 434.687(0.0073q_1^S + 0.001q_2^S + 0.0003q_3^S + 0.0482q_4^S) - 0.661(q_4^S)^2$.

When deciding on SO_2 reduction strategies, each signatory faces technological limitations: they can choose one of the available level of technology from BAU to HighT. This limitation also outlines feasible strategy sets Ω_i. The upper bound is $\bar{q}_i = q_i^{HighT}$, $i = 1, \dots, 4$

(according to GAINS). Thus $\Omega_1 = [0, 6.996]$, $\Omega_2 = [0, 14.002]$, $\Omega_3 = [0, 7.055]$, $\Omega_4 = [0, 12.674]$. To determine equilibrium strategies q_i^S, $i = 1, \dots, 4$, we solve the problem (10):

$$\max_{q_1^S, q_2^S, q_3^S, q_4^S} \big(4.973q_1^S + 0.921q_2^S + 0.374q_3^S + 22.082q_4^S \\ -0.778(q_1^S)^2 - 0.205(q_2^S)^2 - 0.177(q_3^S)^2 - 0.661(q_4^S)^2\big),$$

w.r.t.

$$0 \leqslant q_1^S \leqslant 6.996,$$
$$0 \leqslant q_2^S \leqslant 14.002,$$
$$0 \leqslant q_3^S \leqslant 7.055,$$
$$0 \leqslant q_4^S \leqslant 12.674.$$

System (5) can be solved using quadratic programming method, Tab. 5. We remind that strategies q_i^S describe additional to the BAU reduction of SO_2, hence total SO_2 abatement of the signatories in coalition scenario is equal to $q_i^{Coal} = q_i^{BAU} + q_i^S$. In Fig. 9 we present comparison of SO_2 reduction in the BAU, HighT and Coalition scenarios. As we expect, optimal SO_2 reduction of coalition scenario fills the gap between BAU and HighT scenarios and thus prescribes choice of higher than BAU technology level (TL) for all 4 countries: Denmark – TL 2/3 (of 13 available), Latvia – TL 4/5 (of 16 available), Finland – TL 3/4 (of 14 available), Sweden – TL 2/3 (of 12 available).

The Coalition scenario is practicable only if stability of the coalition S is guaranteed. Let us explore free-riding incentives of the coalition members. According to definition of a self-enfocing coalition, it is necessary to consider coalitions $S \setminus i$, $i = 1, \dots, 4$, and compare payoffs of the players if they leave the coalition S with their payoffs if they remain signatories of S (see formula (12)). In a similar manner as for the coalition S we find group optimum $\mathbf{q}^{S \setminus i}$, $i = 1, \dots, 4$. Tab. 6 presents abatement strategies of Denmark, Finland, Latvia and Sweden given 5 different coalitions:

Table 5: Coalition scenario: additional SO_2 pollution reduction (Kt) during 2020-2015

player	strategy
Denmark	$q_1^S = 0.7$
Finland	$q_2^S = 2.123$
Latvia	$q_3^S = 1.282$
Sweden	$q_4^S = 1.322$

Table 6: Coalition scenarios: additional SO_2 pollution reduction (Kt) during 2020-2015

country	LDSF	LDF	LDS	LFS	DFS
Denmark	0.700	1.160	1.290	0	1.288
Finland	2.123	1.199	0	1.267	1.214
Latvia	1.282	0.669	0.576	0.689	0
Sweden	1.322	0	1.754	1.794	1.963
SUMMA	5.428	3.027	3.620	3.751	4.465

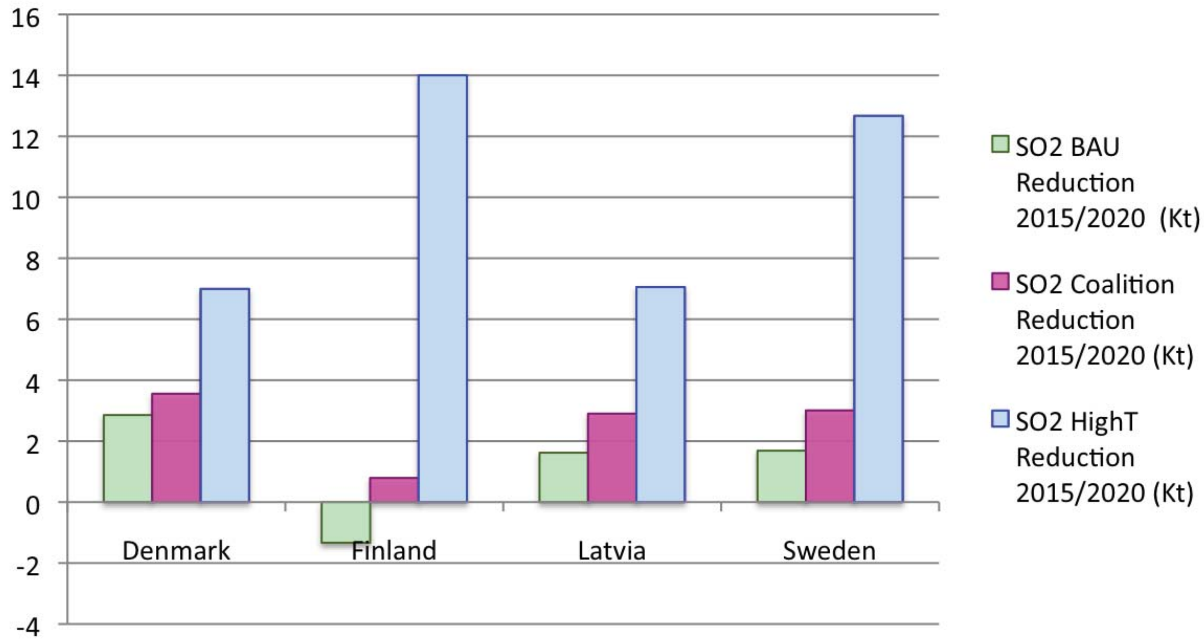


Figure 9: Comparison of BAU, HighT and Coalition scenarios: SO_2 reduction during 2020-2015, Kt

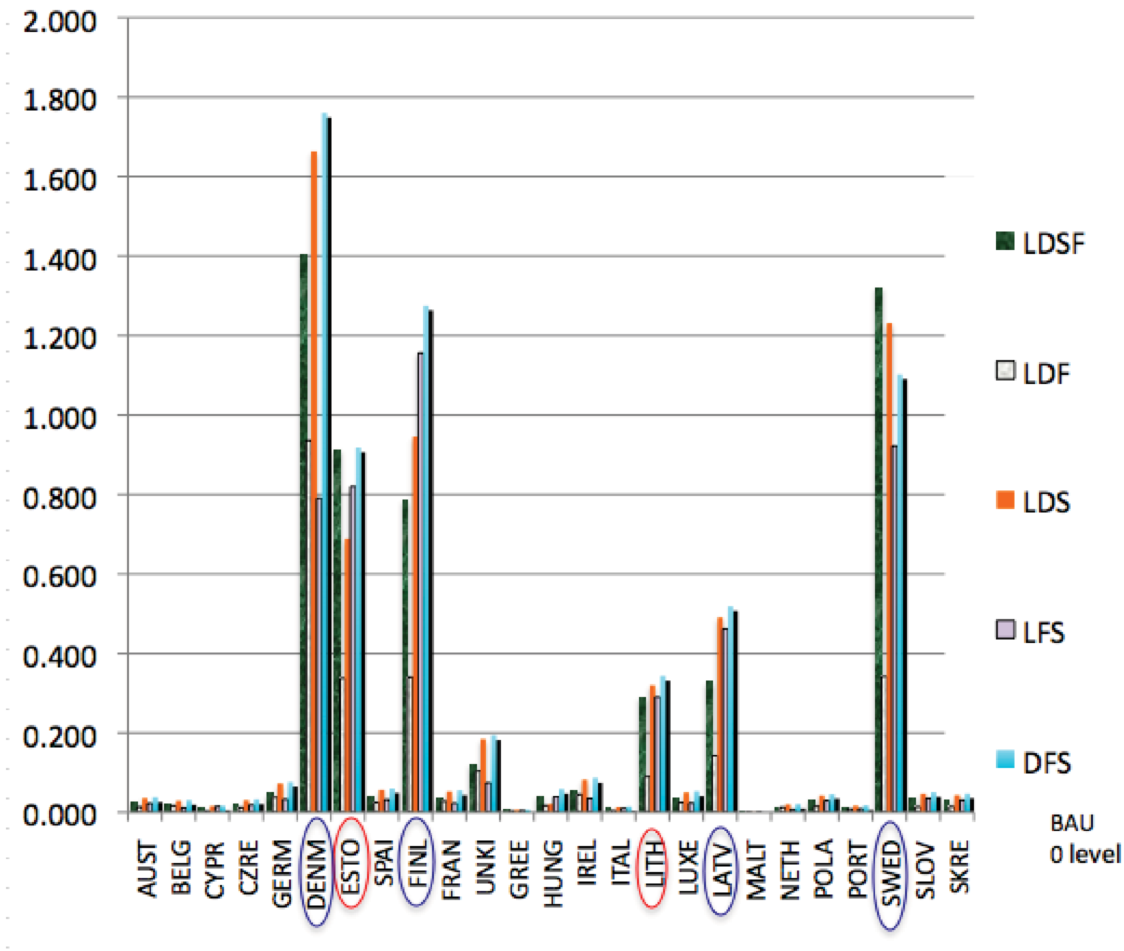
- LDSF= Latvia+Denmark+Sweden+Finland;
- LDF= Latvia+Denmark+Finland;
- LDS= Latvia+Denmark+Sweden;
- LFS= Latvia+Finland+Sweden;
- DFS= Denmark+Sweden+Finland.

Bigger coalition LDSF delivers higher SO_2 reduction and thus more preferable from environmental point of view. Payoffs of all 25 EU countries in case of the Coalition scenario are presented in Fig. 10 and 11. First of all it is important to point out that Coalition scenario is profitable for all EU member states (it increases their payoffs in comparison to BAU) and that neighboring countries, Estonia and Lithuania, experience strong positive externality. Secondly, it reveals that there is potential free-riding problem: internal stability condition (12) holds for Denmark and Sweden , Finland and Latvia have incentives to leave the coalition. To get rid of free-riding, a transfer scheme can be introduced to act as a 'carrot' mechanism by reallocating the coalition surplus and provide potential coalition stability.

Figure 10: Payoffs in Coalition scenarios during 2020-2015 (Mln. E)

	LDSF	LDF	LDS	LFS	DFS
AUST	0.025	0.01	0.04	0.02	0.04
BELG	0.019	0.02	0.03	0.01	0.03
CYPR	0.013	0.00	0.02	0.01	0.02
CZRE	0.022	0.01	0.03	0.02	0.03
GERM	0.048	0.04	0.07	0.03	0.08
DENM	**1.402**	0.94	1.66	**0.79**	1.76
ESTO	0.912	0.34	0.69	0.82	0.92
SPAI	0.039	0.03	0.06	0.03	0.06
FINL	**0.783**	0.34	**0.95**	1.16	1.27
FRAN	0.034	0.03	0.05	0.02	0.06
UNKI	0.119	0.10	0.18	0.07	0.19
GREE	0.006	0.00	0.01	0.00	0.01
HUNG	0.040	0.02	0.02	0.04	0.06
IREL	0.053	0.05	0.08	0.03	0.09
ITAL	0.010	0.00	0.01	0.01	0.01
LITH	0.288	0.09	0.32	0.29	0.34
LUXE	0.033	0.03	0.05	0.02	0.05
LATV	**0.328**	0.14	0.49	0.46	**0.52**
MALT	0.000	0.00	0.00	0.00	0.00
NETH	0.013	0.01	0.02	0.01	0.02
POLA	0.032	0.01	0.04	0.03	0.05
PORT	0.011	0.01	0.02	0.01	0.02
SWED	**1.318**	**0.34**	1.23	0.92	1.10
SLOV	0.035	0.01	0.05	0.04	0.05
SKRE	0.032	0.01	0.04	0.03	0.05
COAL_SURPLUS	**1.235**				

Figure 11: Payoffs in Coalition scenarios during 2020-2015 (Mln. E)



6 Concluding Remarks

Air pollution of sulphur dioxide (SO_2) in the European Union (EU) is a central issue of the present paper. This problem has a transboundary nature, since emitted air pollution is transported by winds across the borders and, when acidic pollution is finally deposited, its environmental impacts are felt in areas far removed from their sources.

In the present paper we address and analyze the following problems: (1) quantification of the geo-physical impact of acidification, introduction of cost/benefit parameters; (2) calibration of technology cost and environmental benefit functions, establishing of an ecology-economy model; (3) formation of an international environmental agreement on acid rain among a group of the EU countries; (4) economical and environmental assessment of different strategic scenarios available to EU member states.

Stepwise solution of these 4 tasks allows us to derive new policy-relevant conclusions about available pollution control strategies, regarding the Business-as-usual, High Technology and Coalition scenarios. To extend and improve numerical assessment of the pollution control scenarios, further extension of the present analysis can be suggested

- generalize ecology-economy model by introducing NH_3 and NO_x pollutant flows into consideration;

- undertake sensitivity analysis of λ_i, $i = 1, \dots, N$ (and assess heterogeneity of proportionality coefficients x_i);
- introduce alternative benefit curve assessment: using statistical data of GDP and amounts of emitted pollutants of the EU member states, build a mathematical model, which expresses a particular functional dependence of access of relative growth of GDP (growth speed of GDP) on relative emission (emission per unit of GDP);
- develop advanced game theoretic framework of the Coalition scenario: consider other optimality principles (i.e., Stackelberg, Nash equilibrium) and construct set of stable agreements basing the self-enforcing principle, detect possible threats for agreement stability and introduce incentive mechanisms (carrots) and sharing rules to eliminate free-riding incentives.

References

[1] http://www.iiasa.ac.at/rains/index.html

[2] *L. Hordijk* (1986) Acid rain in Europe: an energy-environmental impact study, Papers in Regional Science, 60, N0. 1, pp. 107-123.

[3] *Vorobiev N.N.* (1985) Games Theory, Nauka, Moscow (in Russian).

[4] *L. Petrosjan, V. Zakharov* (1997) Mathematical models in environmental policy analysis. Nova Science Publishers. New York, USA, pp. 262.

[5] *M. Finus* Game Theory and International Environmental Cooperation (New Horizons in Environmental Economics)// Edward Elgar Publishing Ltd., 2001. 416 p.

[6] *S. Barrett* Environment and Statecraft The Strategy of Environmental Treaty-Making//Oxford University Press, 2003. 456 p.

[7] Mäler, K.-G. (1989) The acid rain game, in H. Folmer and E. van Ierland (eds), Valuation Methods and Policy Making in Environmental Economics, Amsterdam:Elsevier, pp. 231–52.

[8] *Welsch,H.* (1990) Cost-effective control strategies for energy-related transboundary air pollution in Western Europe, Energy Journal, Vol. 11, pp. 87–104.

[9] *Kaitala,V.,M.Pohjola and O.Tahvonen* (1991) An analysis of SO_2 negotiations between Finland and the Soviet Union, Finnish Economic Papers, 4, pp. 104–112.

[10] *Kaitala, V.,M.Pohjola and O.Tahvonen* (1992) Transboundary air pollution and soil acidification: a dynamic analysis of an acid rain game between Finland and the USSR, Environmental and Resource Economics, Vol. 2, pp. 161–181.

[11] *Martin,W.E.,R.H.Patrick and B.Tolwinski* (1993) A dynamic game of a transboundary pollutant with asymmetric players, Journal of Environmental Economics and Management, Vol. 24, pp. 1–12.

[12] *P.W. Kennedy* (1994) Equilibrium pollution taxes in open economies with imperfect competition, Journal of Environmental Economics and Management, Vol. 27, No. 1, pp. 49–63.

[13] *A. Nentjes* (1994) Control of reciprocal transboundary pollution and joint implementation, in G.Klaasen and F.R.Førsund (eds.), Economic Instruments for Air Pollution Control, Economy and Environment, Vol. 9, Dordrecht: Kluwer, pp. 209–230.

[14] *Brian R. Copeland, M. Scott Taylor* (1995) Trade and Transboundary Pollution, The American Economic Review, Vol. 85, No. 4, pp. 716–737.

[15] *M. Germain, PH.L. Toint* (2000) An Iterative Process for International Negotiations on Acid Rain in Northern Europe Using a General Convex Formulation, Environmental and Resource Economics, Vol. 15, pp. 199 – 216.

[16] *S. Rubio, B. Casino* (2001) International cooperation in pollution control, Working Paper WP-AD 2001-21.

[17] *The Swedish NGO Secretariat on Acid Rain*, Acid Rain News, March 2005, No.1, http://www.acidrain.org/pages/publications/acidnews/2005/AN1-05.asp

[18] *C. d'Aspremont, A. Jacquemin, J. A. Weymark* (1983) On the Stability of Collusive Price Leadership, Canadian Journal of economics, Vol. 16, pp. 17 – 25.

[19] *E. Diamantoudi, E. S. Sartzetakis* (2006) Stable International Environmental Agreements: An Analytical Approach, working paper, Journal of Public Economic Theory, Vol. 8, No. 2, pp. 247 – 263.

[20] *M. McGinty* (2006) International Environmental Agreements among Asymmetric Nations, Oxford Economic Papers, New York, Vol. 59, No. 1, pp. 45 – 62.

[21] *J. Eyckmans, M. Finus* (2004) An Almost Ideal Sharing Scheme for Coalition Games with Externalities, Katholieke Universiteit Leuven, Center for Economic Studies, Working Paper 2004-14.

[22] *H.-P. Weikard, M. Finus, J.-C. Altamirano-Cabrera* (2006) The impact of surplus sharing on the stability of international climate agreements, Oxford Economic Papers, Vol. 58, pp. 209 – 232.