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Global long-term energy–economy–environment scenarios with an emphasis on Russia*

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Abstract. This paper describes two research projects carried out by the International Institute for Applied Systems Analysis (IIASA) within the framework of IIASA Environmentally Compatible Energy Strategies (ECS) Program and IIASA's Dynamic Systems (DYN) Program in collaboration with leading groups in Russia. One project aims at elucidating Russia's opportunities and prospects stemming from participation in the Kyoto Protocol. The main results of this simulation-based study are that under a wide range of plausible assumptions concerning its economic development and its estimated energy supply, Russia's participation in the Kyoto protocol may hold the promise of economic and environmental benefits. The second project concerns the outlooks for the Russian natural gas sector. The MERGE global model, i.e. one of the most well-known and extensively used E3 models, is used in the study pertinent to the first project. The GASCOM dynamic optimization shell is used for research efforts within the second project aimed at optimization of investments into the gas lines. Although both projects are in their early phases, a set of relevant results have been obtained already.

1 IIASA, energy, and methodology

The International Institute for Applied Systems Analysis (IIASA) is a non-governmental research organization sponsored by scientific organizations in 16 countries and located in Austria. The institute conducts interdisciplinary scientific studies on environmental, economic, technological and social issues in the context of human dimensions of global change. IIASA's objective is to bring together scientists from various countries and disciplines to conduct research in a setting that is nonpolitical and scientifically rigorous. Because of its non-governmental status, IIASA is independent and can provide non-political and unbiased perspectives. This neutrality and impartiality is particularly valued by those utilizing the Institute's research findings.

Studying environmental, economic, technological, and social developments, IIASA researchers generate methods and tools useful to both decision makers and the scientific community. The work is based on original state-of-the-art methodology and on analytical approaches linking a variety of natural and social science disciplines. Since its inception in 1972, IIASA has been the site of successful international scientific collaboration in addressing areas of concern for all societies, such as global climate change, energy, acid rain, forest decline, water resources, the social and economic implications of population change, risk and the theory and methods of systems analysis.

Energy research in particular has been conducted – under various program names – since 1973. The work of IIASA's first Energy Systems Program culminated in a seminal work on the long-term development of the global energy system (Haefele 1981).

Today, the overall objective of IIASA's Environmentally Compatible Energy Strategies (ECS) Program work can be described as giving advice to public, private, and corporate

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[*] Material was presented originally at the International Conference MIEC-CGEMP 2005 "Energy relation between the European Union and Russia in the global context", Paris, France, 18–19 April, 2005.

decision makers on how to develop and build an energy system that serves the goal of ensuring future prosperity of all societies in an environmentally compatible fashion. The basis for such advice consists prominently of a wide range of global long-term E3 (energy–economy–environment) scenarios, which ECS builds with formal in-house and external models to ensure consistency and reproducibility. The global scenarios are usually based on 11 world regions, which together comprise the globe. As to the energy system, ECS work equally emphasizes the supply and the demand side. Each new scenario usually addresses one or more specific issues, for example, the transportation sector, energy supply security, or natural gas. Also, major countries and regions that are crucial for the evolvement of the global energy system are studied in more detail. Among these are major developed and developing countries such as China, India, and Russia. Whatever the focus, sustainable development is always an issue, and a global perspective is always maintained. To serve the international community, ECS offers its services as an independent analyst of the implications of alternative burden-sharing schemes in connection with global agreements such as the U.N. Framework Convention on Climate Change (UNFCCC).

ECS's research presented in this paper is carried out jointly with the IIASA's Dynamic Systems (DYN) Program. The area of DYN's scientific interest is methodology for applied research. Within this broad area, DYN's niche is determined by (a) general challenges in IIASA's research, (b) general challenges in the development of related mathematical techniques, and (c) the contents of particular projects within IIASA's Programs. The DYN Program generalizes IIASA's research challenges into significant new problems in applied mathematics, and conversely, applies specific mathematical techniques to particular IIASA's programs and projects. Maintaining such feedback between the methodological and the applied research areas improves the understanding of the key features of large-scale components of global development.

ECS and DYN have also joined forces with collaborators in Russia, who contribute to the two research projects described in this paper. In the sequel, we refer to this network of research groups as the "collaborative group", which is poised to keep collaborating on the continuation of these two projects. Currently, the "collaborative group" consists of the following institutions: Energy Research Institute of the Russian Academy of Sciences (ERI, Moscow); Energy Systems Institute, Siberian Branch of the Russian Academy of Sciences (ESI, Irkutsk), Urals State Technical University (USTU, Ekaterinburg); Moscow State University (MSU, Moscow) and Institute of Mathematics and Mechanics, Urals Branch of the Russian Academy of Sciences (IMM, Ekaterinburg).

2 Energy and Russia

After the break-up of the Soviet Union in 1991, its integrated fuel and energy complex, a part of centralized Soviet economy, was subject to major structural changes. Disturbance in fuel supplies from remote regions caused by geopolitical reasons was among the main factors to affect the stability (performance) of the energy system. In addition, the fall of the "iron curtain" has made a significant intrusion into the country's economy. Along with a sweeping switch from a planned to a market economy, this intrusion subsequently led to a dramatic depreciation of the national currency. For almost a decade, Russia's Gross Domestic Product (GDP) was steeply decreasing. Only in 1998 it began to increase again – from a level corresponding to 57% of 1990's GDP. Since then, GDP growth has been continuing at increasing rates, thus giving cause for expecting further economic growth.

Along with the stabilization of the economy and the sustained increase of economic output, Russia is facing new challenges, among which we would like to highlight the following. First, the issue of physical obsolescence of energy-related physical capital, in particular infrastructures built during Soviet times, is of increasing importance. Since one of the most important driving forces of Russian economic growth is the production, consumption, and export of oil and gas, the maintenance of existing and the construction of new pipelines are among the most crucial issues.

Second, Russia inherited a legacy of environmental problems from the Soviet Union. The Soviet Union's emphasis on heavy industrial production and little regard for the environment has left Russia with numerous environmental problems, from severe air pollution to radioactive contamination. Although numerous factories and heavy industry were shut down in the economic contraction in 90s, the country still has an economy that is heavily reliant on energy-intensive industries. Furthermore, Russia's ongoing transition to a market economy has led the government to promote economic growth rather than environmental protection. Yet, the environment is certainly a more pertinent issue in today's Russia than it was even 10 years ago. Such improvement can be supported – among other measures – by the country's Environmental Protection Law and the Law on Ecological Expert Review (both passed after the break-up of the USSR) and participation in the international environmental agreements (such as the Kyoto Protocol and the Methane to Markets Partnership).

This brief overview describes the setting for our study, which addresses Russia's options to deal with these interconnected and partially conflicting challenges aiming for a sustainable global development. Out of many real-world issues, we have selected two for the definition of two projects for which we present results of initial work in this paper: Russia's opportunities and challenges related to its participation in the Kyoto Protocol and the prospects for the country's natural-gas sector. The two projects are described in the following two subsections.

2.1 *Implications of Russia's ratification of the Kyoto Protocol*

Following intensive and heated public discussions, the President of the Russian Federation signed the Federal Law "on the ratification of the Kyoto Protocol to the United Nations Framework Convention on Climate Change" on 4 November 2004. This law led to the ratification of the Protocol by Russia, which in turn led to the Protocol coming into force on 16 February 2005. Still, the debate about future costs and benefits of Russia being a Party to the Kyoto Protocol has continued.

The arguments used in these discussions aim at substantiating the advantages and disadvantages of the participation in the Kyoto Protocol. Indeed, for the country with an economy in transition it is crucial to assess the possible impact of any measures, which can have a negative effect on economic growth. However, after the decision was made, it would appear more rational – for proponents and opponents alike – to move from discussions about pros and cons to jointly searching for a way to maximize the benefits of the Kyoto agreement and to looking ahead in order to design strategies after the First Commitment Period, 2008–2012.

This was the motivation for the collaborative group introduced in section 1 to examine the implications of Russia's participation in the Kyoto Protocol from an economic and an environmental perspective.

The purpose of the analysis undertaken within the first project and presented in this paper is to contribute to formalizing the debate by quantifying the main drivers of economic growth, energy consumption, and environmental impact. As an instrument, IIASA has selected the MERGE model (Manne 2004), one of the most well known and most widely accepted E3 models. At this stage, we focus on methodology and on presenting illustrative first results.

2.2 *Natural-gas production, consumption, and exports*

The geopolitical importance of natural gas is expected to rise significantly in the coming decades. Being the environmentally most compatible fossil fuel and given its large resource base, natural gas has the potential to be a dominant energy source during the transition from the current oil and coal-based economy to a future system that does not rely on fossil fuels. According to various forecasts, the share of natural gas in the world energy consumption pattern would double in the next 30 years and contribute some 30% to the global primary-energy supply.

Owning 28% of the world natural-gas reserves, Russia enjoys enormous opportunities for natural-gas production and export, both to the more traditional markets in Europe and – in the near future – to East Asian countries who are expected to become major consumers of gas within the coming decades.

While natural-gas production, consumption, and exports are covered in aggregate terms in the global model MERGE to be introduced in the next subsection 3.1, the economic evaluation of gas pipeline projects warrants a separate, more detailed analysis. This was the motivation for the other field of study by the collaborative group, described in subsection 3.2.

3 Two modeling approaches and their results

In this section we describe the results of the two analyses introduced above. We begin with a description of the MERGE model and its application to the analysis of the economic consequences of Russia's participation in the Kyoto Protocol. The second subsection presents GASCOM, a dynamic-optimization framework for optimizing investments into gas pipelines, followed by the presentation of an illustrative application. Both descriptions emphasize methodological aspects of our modeling, thus emphasizing the preliminary character of our results.

3.1 *MERGE*

3.1.1 *Objectives*

The study was launched in early 2004, when the intentions of Russia's authorities to comply with the Kyoto Protocol were still uncertain and torn between the pressure from the European Union on Russia to ratify and the opposition of major scientific and industry groups from inside Russia.

One of the critical issues intensively discussed by those groups was the impact of environmental measures stipulated by the Protocol, which could significantly dampen the economic growth and therefore jeopardize the ambitious plans of the Russian Government to double the current GDP in 10 years.

Despite the difference in the arguments of various discussants they had important indicators in common. Among these are GDP growth rates, energy intensity, carbon intensity of energy, and others. Different assumptions about the future values of these indicators have led to drastically different results and policy recommendations. This observation motivated us to analyze the possible economic consequences of Russia's participation in the Kyoto Protocol with a formal model in which these driving forces can be quantified.

In our analysis we focus on the Former Soviet Union region (FSU), assuming that Russia's indicators describe the economy–energy–environment of the whole FSU region with reasonable accuracy. For the future, we plan to define and analyze Russia as a separate region.

The collaborative group set out to analyze possible future economical costs and benefits of Russia's participation in the Kyoto Protocol with the help of MERGE model. The following issues were considered important:

— identify the most sensitive model parameters describing the FSU region;
— determine the time period after which the FSU's GDP becomes lower in a "compliance case" compared with a business-as-usual case;
— identify circumstances and conditions under which the FSU carbon price becomes non-zero in the period from 2008 to 2012.

In our study we depart from a business-as-usual (BAU) case implying no Kyoto targets and no flexible mechanisms (Emission Trade, Clean Development Mechanisms). Relative to this case, benefits of ratification and benefits of carbon trade can be calculated separately both for Russia and its trading partners by comparing the BAU results with those for a case (with identical driving forces), where a carbon constraint is assumed. Although we are mainly interested in assessment of the First Commitment Period (2008–2012), we introduce the Kyoto constraints for the entire time horizon up to the year 2100.

In addition to studying economic consequences for Russia, the study also reports the changes in energy-economy balances for other world regions, and, therefore, the changes in energy imports and exports between the regions examined.

3.1.2 *MERGE "in a nutshell"*

The global optimization model MERGE (Manne 2004) describes the interaction between macroeconomic production, the energy system (demand and supply), pollutant emissions, and climate change. The model consists of three logical parts: a macroeconomic module, an energy supply part, and a climate module. It combines a top-down description of the economy and energy demand with a bottom-up description of the energy sector.

The macroeconomic module in MERGE defines an inter-temporal utility function of a single representative producer-consumer in each world region, which is then maximized. The optimal development of the GDP is defined through optimizing a sequence of savings, investments and consumption decisions. GDP for each region is described by a nested CES (constant elasticity of substitution) production function in the following way:

$$YN(t,rg) = [a \cdot (K(t,rg)^{KPVS} \cdot L(t,rg)^{1-KPVS})^{\rho} + b \cdot (EN(t,rg)^{ELVS} \cdot NN(t,rg)^{1-ELVS})^{\rho}]^{\frac{1}{\rho}} ,$$

$$\rho = 1 - \frac{1}{ESUB} ,$$

where

t – time index (the model's time horizon is split into 5 years periods);
rg – region;
YN – total output of economy (GDP);
a, b – scale coefficients;
K – capital;
L – labor;
EN – electric energy;
NN – non-electric energy;
$KPVS$ – capital value share (optimal value share of capital in the capital-labor aggregate);
$ELVS$ – electric value share (optimal value share of electricity in the energy aggregate);
$ESUB$ – elasticity of substitution between capital-labor and energy aggregates.

The optimal quantities of the production factors are determined by their relative prices. The energy module describes the technological options available to supply the energy needed as a production factor, and the climate module calculates the resulting GHG concentrations and global temperature.

MERGE was designed as an integrated-assessment model (IAM) to study global GHG mitigation scenarios and to conduct cost-benefit analysis. For analyzing the costs of the Kyoto Protocol for a set of realistic scenarios, IIASA-ECS extended and modified the original MERGE 5 model as described in the following subsection.

3.1.3 *IIASA extensions of MERGE*

In order to be able to model the important Parties to the Kyoto Protocol, the two MERGE regions CANZ (Canada, Australia, and New Zealand) and EEFSU (Eastern Europe and Former Soviet Union) were split into the four regions: Canada, ANZ (Australia and New Zealand), EEU (Eastern Europe) and FSU (Former Soviet Union). The model now includes 11 world regions.[*]

All five GHG categories (CO_2, CH_4, N_2O, short-lived fluorides, long-lived fluorides), with abatement options, and CH_4 leakages from natural gas pipelines are now included in the modeling of GHG emissions and the permit trade. Also, the limits on sequestration from forest management as given in the Marrakesh Accord were included.

The Clean Development Mechanism (CDM) is one of the Kyoto Protocols "flexible mechanisms", designed to reduce the economic costs (and to thus increase the global efficiency) of greenhouse gas abatement. Equations describing the CDM mechanism and a price-responsive CDM supply were incorporated into the model using an iterative approach to match the CDM supply and the carbon price.

MERGE-I[**] (see Schrattenholzer 2004) includes recent information on expected economic growth and energy consumption of the complying regions. The regional power sector options are restricted to the level of the year 2010 which excludes the possibility of generating unrealistic build-up rates of power plants. For Japan, we additionally assume that by 2010 in this country no more LNG terminals than in the Reference scenario will be available and thus Japan's natural-gas imports will not exceed those given by the Reference scenario.

3.1.4 *Sensitivity analysis*

To analyze the consequences of assuming different geopolitical scenarios guiding the implementation of the Kyoto Protocol, we formulate two "limiting cases". One limiting case is a business-as-usual case (BAU) without GHG emission constraints. The costs of GHG abatement (in a case including such constraints) are calculated relative to this scenario. The second limiting case is an extreme compliance case (DOM) in which the Parties to the Kyoto Protocol comply with their "Kyoto limits" by domestic measures only. Relative to this case, benefits of GHG emission trading (as well as CDM and JI) can be calculated. The third limiting case, called "Full trade" – in which all "flexible mechanisms" (carbon trading, Joint Implementation, and the Clean Development Mechanism) – will be implemented as one of the next steps of the collaborative group's work.

We selected an arithmetic difference between the values of realized GDP for the FSU region according to the BAU case and that of the domestic measures case (DOM) as the most important result, and we use the term GDPLoss to refer to it. This indicator displays the value of GDP that the country will lose or, if the indicator assumes a negative value,

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[*] All regions follow the same convention as US-EIA's International Energy Outlook (2004), with the only exception that we included the new Baltic EU members Estonia, Latvia, and Lithuania in EEU (and not in FSU).

[**] We use MERGE-I ("I" as in IIASA) to refer the new version of the original model.

gain as a consequence of observing the Kyoto limits. Note that even in the "domestic measures only" case realized GDP of the FSU will depend on the development of the E3 system in other world regions. For example, changes in Western Europe's (WEU) energy system due to observing the Kyoto constraints could have an impact on of energy imports from the FSU, which in turn will lead to a slight decrease of FSU's GDP. Such fluctuations of GDPLoss are expected to occur within the time horizon of our scenarios.

One other particularly interesting result of our model runs is the point in time, when a significant increase in the GDPLoss function will occur. This point in time describes a situation, in which the FSU will have its emission reduction reserves exhausted, and measures aimed at a restructuring of the industry and energy sector towards a low-emission system will be initiated.

Fig. 1 shows the dynamics of the FSU's GDP Loss, simulated by MERGE-I for a set of reference parameter values (see the Reference scenario, subsection 3.1.5).

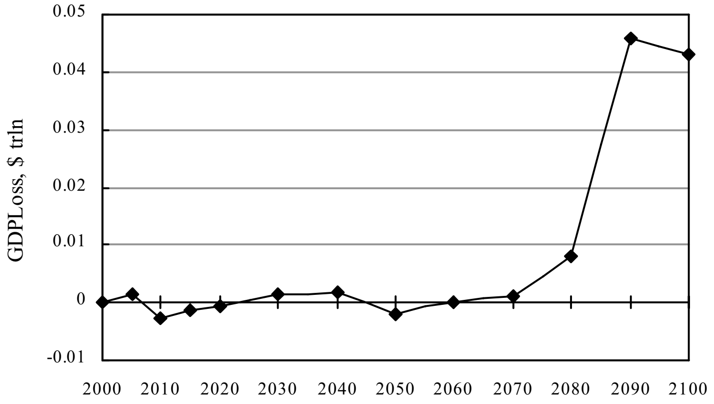

Fig. 1. GDPLoss of the Former Soviet Union (FSU), 2000–2100.

Over 100 simulations have been performed and over 600 plots have been generated to analyze the sensitivity of the GDPLoss to variations in the model's key parameters. One of the examples of such analyses, showing the sensitivity of the FSU's GDPLoss with respect to the FSU's capital value share (KPVS), is presented in fig. 2.

Having ranked more than 30 input parameters according to the degree of the sensitivity – with respect to them – of the FSU's GDPLoss curve in the Reference scenario (see subsection 3.1.5), we identified the following "most sensible" FSU's parameters which subsequently served as the basis for the design of "extreme" scenarios (see subsection 3.1.5, UNpesGL and UNpesGLC scenarios):

ESUB – elasticity of substitution between the capital-labor and energy aggregates;
KPVS – capital value share (optimal value share of capital in the capital-labor aggregate);
ELVS – electricity value share (optimal value share of electricity in the energy aggregate);
PRNEF – reference price for non-electric energy.

The following parameters varied according to the definition of each scenario:

AEEI – autonomous energy efficiency improvement rate, percent per year;
GROW – potential GDP growth rate, annual percent;
BCH4GAS – CH_4 leakage per ton of natural gas consumption, mln t.

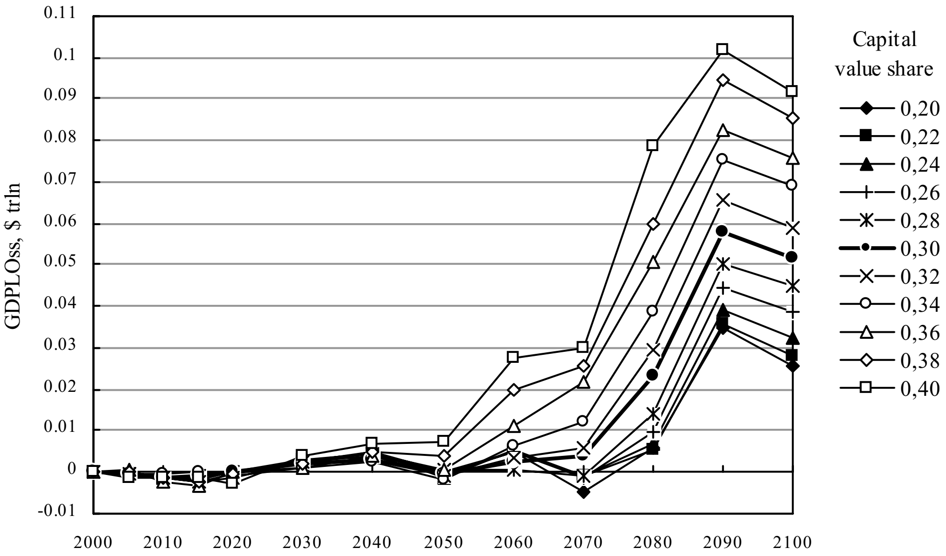

Fig. 2. The sensitivity of the FSU's GDPLoss with respect to the capital value share (KPVS).

3.1.5 *Scenarios and simulations results*

We first compared four scenarios assuming different ranges for the FSU's GDP growth rate and for autonomous energy efficiency improvement indicator in 2000–2100[*]. Each scenario represents a variation of model input parameters used for the comparative analysis of the business-as-usual case (BAU) and domestic measures case (DOM) of the MERGE model.

1) *Reference scenario*. FSU's GDP growth rate varies from 4.5% (in 2000) to 2.2% (in 2100), per year, and energy efficiency improvement indicator varies from 3.9% (in 2000) to 1.1% (in 2100) per year.
2) *UNstd*. FSU's GDP growth rate and energy efficiency improvement are quantified as estimated in the Third National Communication of the Russian Federation (TNCRF) to UNFCCC, scenario III (UNFCC 2003). The annual GDP growth is fixed at the level of 4.5% for period 2000–2020. For the subsequent period, the Reference scenario values are used leading to a 2.2% growth rate in 2100. The rate of energy efficiency improvement is fixed at the level of 2.0% per year for period 2000–2020, and takes the Reference scenario values thereafter, thus reaching 1.1% in 2100.
3) *UNpes*. This scenario is defined similarly to UNstd, with the 2000–2020 growth rate values estimated as in Scenario I of the TNCRF to UNFCCC (UNFCC 2003). Namely, the FSU' GDP growth rate is fixed at the level of 3.3% per year for period 2000–2020 and takes the Reference scenario values in the subsequent period, reaching 2.2% in 2100. The rate of the energy efficiency improvement is fixed at the level of 2.5% per year for 2000–2020, and takes the Reference scenario values thereafter, reaching 1.1% in 2100.
4) *WorstGL*. This scenario assumes the highest FSU's GDP growth rate, 7% per annum in 2000–2020. The assumption agrees with the current plan of the Russian Government to double the GDP within 10 years. For the subsequent period the Reference scenario values for the GDP growth rate are assumed. The energy efficiency improvement

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[*] Other model parameters take conventional reference values, which we do not specify here.

indicator is defined according to the Reference scenario. An additional assumption is that there is no reduction of methane leakage, which is fixed at its year-2000 level, 27 kg CH_4/kWyr.

Fig. 3 and 4 show the simulated trajectories (in absolute values, $ trln) of the FSU's GDPLoss for four scenarios listed above. Fig. 4 shows relative (in percent) changes in the FSU's GDPLoss. In each scenario, minor fluctuations of the GDPLoss are noticeable in the beginning and a clear deviation from zero is seen in the middle of the period. This major deviation is most pronounced in the WorstGL scenario around 2020. This can be interpreted as a result of the combined effect of an unmitigated gas leakage, a rapid GDP growth, and slow improvement in energy efficiency. A combination of these effects leads to an increase of both energy demand and the share of the carbon-intensive GDP, and, as a consequence, to raising emissions. The Reference and UNstd scenarios are quite similar, and their impacts on the dynamics of the GDPLoss do not differ seriously. In both scenarios a significant rise in the FSU's GDPLoss starts around 2070.

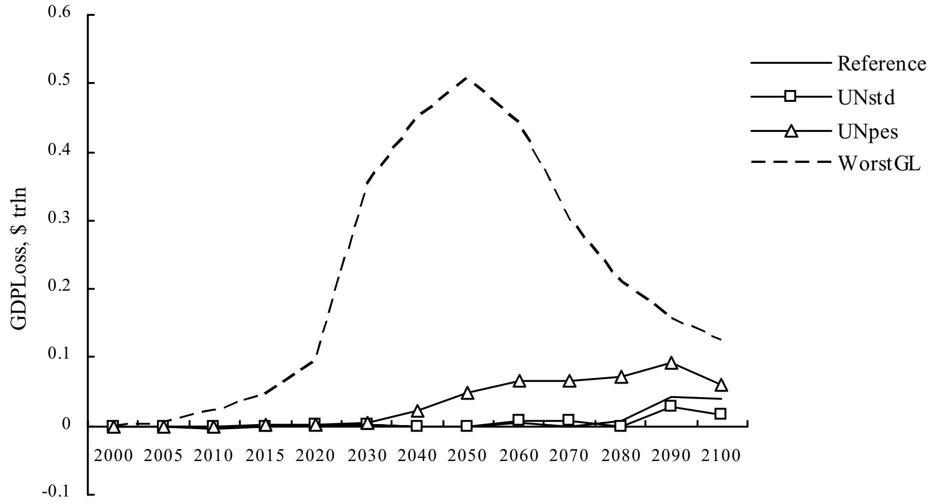

Fig. 3. FSU's GDPLoss in four scenarios.

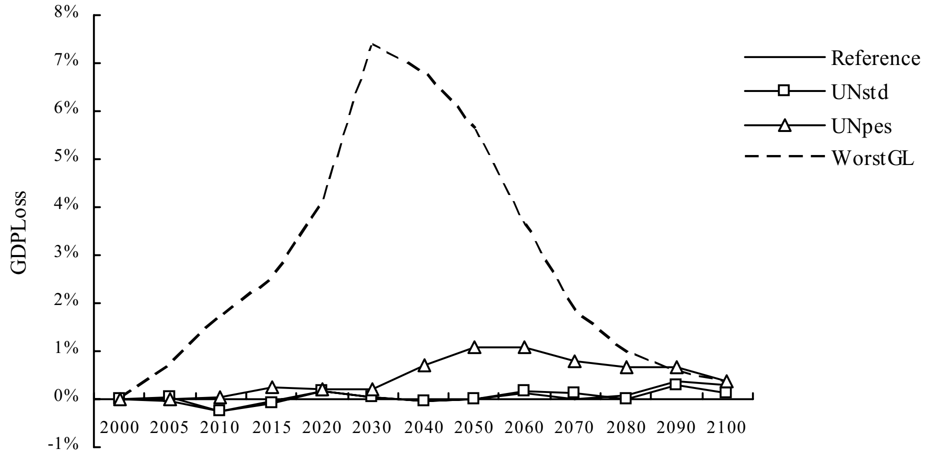

Fig. 4. FSU's relative GDPLoss in four scenarios.

Thus, one may assume that in the Reference scenario, the values of the input parameters are set in accordance with the country's vision of its energy–economy–environment development. As the UNpes scenario shows, assuming higher potential GDP growth rates may shift the initial point of steep growth of the GDPLoss to 2040. Finally, we equip the UN scenarios with "extreme" parameter values, and thus define the "extreme" UNpesGL and UNpesGLC scenarios (see below).

5) *UNpesGL*. In addition to the UNpes scenario it is assumed that there is no improvement in gas leakage.
6) *UNpesGLC*. Based on the results of the sensitivity analysis (subsection 3.1.4), we modify the UNpesGL scenario by choosing "much worse" (in terms of earlier occurrence of steep GDPLoss growth) parameter values: 0.33 for KPVS, 0.35 for ESUB and 5 for PRNEF versus, respectively, 0.3, 0.4 and 2.5 assumed in the Reference scenario.

Fig. 5 shows that, as expected, the UNpesGL and UNpesGLC scenarios give rise to substantially higher values for FSU's GDPLoss. A positive point is that the GDPLoss curves decline substantially after the year 2050. This illustrates the begin of a successful transition to an environmentally compatible global energy system.

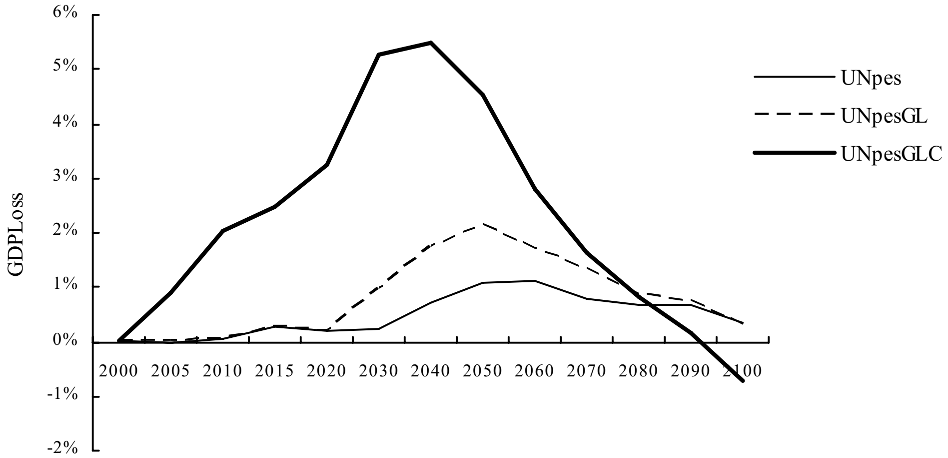

Fig. 5. The UNpes, UnpesGL and UNpesGLF scenarios: the persentage of the FSU's GDPLoss.

3.1.6 *Summary of the results of the first phase of the study and future plans*

Our analysis reveals significant sensitivities of the FSU's GDPLoss with respect to several important economic parameters including the GDP growth rate, the capital-value share (KPVS), and the elasticity of substitution (ESUB). While a GDP growth rate is a well-defined "scenario assumption", the other two are to a considerable extent uncertain (identifying realistic values for these parameters would be extremely helpful for specifying the major trends in the FSU's future economic development).

The starting point in the period of steep growth of the FSU's GDPLoss is strongly dependent on the FSU's assumed GDP growth rate. In the Reference scenario, the steep part of the FSU's GDPLoss curve begins near 2070, whereas in the most extreme scenarios that starting point is close to 2020. None of the scenarios demonstrate significant growth in the FSU's GDPLoss in period 2008–2012. The highest value of the relative GDPLoss (occurring around 2035), 7%, is observed in the worst-case WorstGL scenario assuming that the FSU's GDP quadruples between 2000 and 2020. In none of the scenarios, the

FSU's total GHG emission exceeds the 1990 level, implying that the "Kyoto Forever" constraint is not binding in all those scenarios.

The future plans of the collaborative group include the following tasks:

- — to disaggregate the FSU region and describe Russia separately;
- — to analyze the carbon intensity of Russia's present and future GDP, as earlier studies suggest that the "decarbonisation" of the Russian economy may be proceeding faster than assumed;
- — to reflect the inherent uncertainty that surrounds in the evolution of the driving forces, and define a range of plausible emissions will be determined and discussed;
- — to identify, in the spirit of "risk analysis", combinations of input parameter values that would lead to the increase of Russia's total carbon emission level above the Kyoto target in the period from 2008 to 2012;
- — to analyze whether the "risky" parameter values identified through Task 4 are in the plausible range and thus to assess whether the excess of Russia's total GHG emissions over the Kyoto limit appears plausible during the first commitment period (2008 –2012);
- — to build scenarios and perform simulations with a full carbon trade mode;
- — to formulate a scenario that limits temperature change to 2K.

3.2 *GASCOM*

A second project undertaken by the collaborative group introduced in section 1 is a joint effort to develop and implement a decision support system that provides a dynamic-optimization framework for optimizing investments into gas pipelines, estimating economic perspectives of specific pipeline operations taking into consideration the changes in world energy balances, economic activity, and financial indicators in relation to variations in key economic determinants. In this connection, the project also examines the rational dynamics of the international gas network development in Northeastern Asia taking into account possible synergies with other IIASA projects on world energy markets, Kyoto Protocol requirements and E3 (energy–economy–environment) development scenarios for Russia and China.

3.2.1 *Goals*

GASCOM (Gas Market Competition) is a gaming model aiming at decision makers and energy market analysts for whom it provides an assessment of the market and potential competitors from an economic perspective.

The model describes competition between investors/managers of gas pipeline projects within one natural-gas market, which may emerge in a region (e. g., a country). Competition arises at both stages of decision-making: planning investment and operation on the market. The model deals with agents (investors/managers) who make decisions concerning investment options and define supply policy. The competing agents act as players in a game. It is assumed that every agent makes decisions on the following:

- — a *start-of-construction time* and a *start-of-operation time* – points in "slow time" on the timescale at which this agent would start making investments into a pipeline, and would start operation on market, respectively;
- — *supply* – the volume of natural gas delivered to the market at each point in "fast time" of operation.

The model is optimized at two levels: *strategic planning* (investment) and *operation* (supply).

At the level of *strategic planning* the objective is to determine, for all agents, their start-of-construction and start-of-operation times so that one of two optimality criteria, maximization of net present value (NPV) and minimization of the time passed from the beginning of operation to payback, hold for all agents simultaneously. The start-of-construction and start-of-operation times are found as Nash equilibrium choices in a *game of timing* played out between the investors (who act without cooperation). An exceptional feature of the Nash equilibrium choices is acceptability for every player, or robustness to variations in individual choices: for every agent, a deviation from the Nash choice implies loss in optimality. Another interpretation is that in a Nash equilibrium situation each agent's choice is a *best response* to the choices of all other agents. Therefore, we view the Nash equilibrium start-of-construction and start-of-operation times as either reasonable approximations to most probable future structures of the gas market, or starting points for negotiations between the investors. Thus, finding Nash equilibrium solutions helps the investors answer the following questions:

- When to start the construction of a gas pipeline and when to enter the market considering that the behavior of the competitors is not fixed in advance?
- What will be the optimal Net Present Values (NPV) of the gas pipeline projects at the end of their lifetimes and what will be the optimal payback times?

At the level of *operation* (supply) a "fast time" *supply game* is analyzed, in which each agent controls the volume of gas currently delivered to the market so as to maximize the annual revenue due to sales of gas. The outcome helps the managers answer such questions as

- Which volume of gas it is rational to deliver to the market at each point in "fast" time?
- What gas-price dynamics will evolve on the market?

The "fast time" supply game played out at each "fast time" t is conditional to a set I of agents operating on the market at time t. Our methodology assumes that the supply game is solved for every time t and for every (hypothetic) group of operating agents, I, at the first stage of analysis. The obtained equilibrium supply paths provide a set of conditional forecasts for the market dynamics, which are used to solve the game of timing.

3.2.2 Market operation: supply game

t – time;
I – set of agents (pipelines) operating on the market at time t;
$C_i(t)$ – overall cost of delivering a unit of gas through pipeline i (i in I) at time t;
M_i – maximum capacity of pipeline i;
$G(t)$ – GDP, national income;
e_y – GDP elasticity of demand;
e_p – price elasticity of demand;
$P_{LNG}(t)$ – price of LNG at time t;
λ – annual discount coefficient;
i – index of pipeline project ($i = 1, 2, \ldots, n$).

In the supply game each agent i (in the group I) finds the volume of supply, y_i, through pipeline i so as to maximize the agent's annual revenue, r_i, due to sales of gas. The latter is defined as

$$r_i = y_i\,(p - C_i(t)),$$

where p is the price of gas. The market price formation mechanism defines p as a function of the total gas supply at time t, $y = \sum y_j$ (j runs through I), as well as of the endogenous parameters: GDP ($G(t)$), the elasticity parameters (e_y and e_p), and annual discount coefficient (λ)*. In result, for the given values of the endogenous parameters, the revenue

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[*] In some situations it is reasonable to assume that the price of gas is regulated and use price forecasts.

r_i is represented as a function of the exogenous parameters: the total supply y and the agent's supply y_i. This structure defines a multi-player supply game among the agents in group I. The natural constraints are

$$0 \le y_i \le M_i;\ p \le P_{LNG}(t).$$

A Nash equilibrium point in the supply game provides the set of equilibrium values of supply through the pipelines operating on the market at time t: $y_i^*(t)$ (i ranges within I). These values determine the equilibrium price of gas $p^*(t)$ and, for every agent i in I, the equilibrium annual revenue $r_i^*(t)$. Thus, the output parameters include:

$p^*(t)$ – equilibrium price of gas at time t;
$y_i^*(t)$ – equilibrium supply through pipeline i (i in I) at time t;
$r_i^*(t)$ – equilibrium annual revenue for agent i (i in I) at time t.

3.2.3 *Strategic planning: game of timing*

In the game of timing, the input parameters include conditional forecasts for the market dynamics, and construction data.

Each conditional forecast for the market dynamics is provided under the assumption that a certain group I operates on the market. This forecast is represented as the set of the trajectories of the agents' equilibrium annual revenues, $r_{iI}^*(t) = r_i^*(t)$ (i in I), which are among the outcomes of the supply games for group I (note that in order to form such forecast trajectories, one needs to solve the supply games for all t beforehand). For computing the values of the optimality criteria, the annual discount rate, λ, is also used.

The construction data include the construction costs, $W_i = W_i(t_i^0, t_i)$, as functions of the start-of-construction and start-of-operation times, t_i^0 and t_i, for every agent i. If one assumes that construction times, Δt_i, are fixed, then $t_i = t_i^0 + \Delta t_i$ and W_i are functions of the start-of-construction times, t_i^0, only. If the start-of-construction and start-of-operation times, t_i^0 and t_i, are restricted to relatively short intervals, the construction costs W_i can be constant. The construction data include also the end point for the pipelines' lifetime periods, $\vartheta_i = \vartheta_i(t_i)$.

Thus, the input data include:

$r_{iI}^*(t)$ – trajectories of the equilibrium annual revenues for all agents i in I under the assumption that group I operates on the market (for all groups I);
λ – annual discount rate;
$W_i = W_i(t_i^0, t_i)$ – construction costs for all pipelines I;
$\vartheta_i = \vartheta_i(t_i)$ – end points for the lifetime periods for all pipelines i.

In the game of timing, each agent i chooses a start-of-construction and a start-of-operation times, t_i^0 and t_i, so as to maximize the given optimality criteria. We consider two optimality criteria, U_i and T_i: U_i is the NPV for the pipeline project i at the end of its lifetime, and T_i is the payback time, i.e., the length of the time interval between the start-of-operation time t_i and the time, at which the construction cost, W_i, is compensated via sales of gas.

The input data is such that whenever all agents i choose their start-of-construction and start-of-operation times, t_i^0 and t_i, we find the unique values for the criteria U_i and T_i. Namely, ordering the start-of-operation times, $t_{i_1} \le \ldots \le t_{i_n}$, we identify the agent's groups sequentially occupying the market,

$$I_1 = \{i_1\},\ I_2 = \{i_1, i_2\},\ \ldots,\ I_n = \{i_1, \ldots, i_{n-1}\} = \{1, \ldots, n\},$$

and select those including agent i: I_k, I_{k+1}, … , I_n. We see that the annual revenue $\overline{r}_i(t)$ for agent i takes the values $r_{iI_k}^*(t)$, $r_{iI_{k+1}}^*(t)$, ... , $r_{iI_n}^*(t)$ for $t_{i_k} \le t \le t_{i_{k+1}}$, $t_{i_{k+1}} \le t \le t_{i_{k+2}}$, … , $t_{i_n} \le t \le \vartheta_i$, respectively. The accumulated revenue for agent i is therefore given by

$$R_i = \int_{t_i}^{\vartheta_i} e^{-\lambda t} \overline{r}_i(t) dt ,$$

and the NPV by $U_i = R_i - W_i$. The payback time ξ_i is found as the minimum of all $\xi \geq t_i$ such that the accumulated revenue gained between t_i and ξ,

$$R_i(\xi) = \int_{t_i}^{\xi} e^{-\lambda t} \overline{r}_i(t) dt ,$$

is not smaller than the construction cost: $R_i(\xi) \geq W_i$.

For each agent, i, a choice of t_i^0 and t_i is a *strategy* and the value of U_i (or T_i) is a *benefit*. This defines the game of timing completely. Let us recall that we look for a Nash equilibrium solution, in which each agent's choice responds best (for the given criterion) to the choices of the other agents.

The game of timing has no trivial solutions. To make it clearer, let us consider the NPV criterion, U_i. An early commercialization of a pipeline i (i.e., the choice of a relatively small start-of-operation time, t_i), may imply high revenues for agent i in the starting period when the other pipelines are still not operating and pipeline i dominates on the market. Thus, on the one hand, the "first mover" annual revenues may provide a crucial contribution to the final NPV. On the other hand, in the starting period gas demand may be low, and the "first mover's" advantage may not be so significant, whereas in a time perspective gas demand may grow significantly, and a late commercialization (implying the choice of a large start-of-operation time, t_i) may result in a much higher contribution to the final NPV even if agent i is the "last mover" in the game. An optimal decision should balance these opposite trends. A similar argument applies for the payback criteria, T_i.

3.2.4 *Solution methods*

We use analytic and numerical approaches to finding Nash equilibrium solutions in the game of timing. Within the framework of the analytic approach, the major results rigorously obtained so far characterize the locations the agent's best responses and state the existence of Nash equilibrium solutions. It has been shown that for the NPV optimality criteria, U_i, the agent's best responses are, generically, restricted to a finite set of points in time, and these points can be identified in advance using properties of the construction costs, W_i, and conditional forecasts for the annual equilibrium revenues, $r_{iI}^*(t)$. In particular, it has been proved that in the game of two agents, neither of which strongly dominates in resources (and each of which has a fixed start-of-operation time), every agent has two choices for the best response start-of-operation times only, "fast" and "slow", and their locations are fixed on the time axis. Moreover the game of timing has precisely two Nash equilibrium solutions, which are formed by the asymmetric "fast-slow" and "slow-fast" combination of best responses (Klaassen 2004). In other words, in competition of two agents whose resources do not differ too strongly, the agents should decide who of them is the "first mover" (if one of the agents is much stronger in resources, the Nash equilibrium solution is unique and the stronger agent is the "first mover" automatically). This mathematical result has been generalized for the "nearly symmetric" game of n agents sufficiently close in resources (Brykalov 2004).

The numerical approach is universal and aimed at practical finding Nash equilibrium solutions in the game of timing (Klaassen 2001; Golovina 2002; Klaassen 2003). We use the method of iterated best responses (the agents update their best responses one by one). If the obtained sequence of the agent's choices converges, the limit point constitutes a

Nash equilibrium solution. Theoretically, the method may not converge and/or miss some Nash equilibrium solutions (even if many initial points in the iterations are tried); however, practically, in all tests with data on the Turkish gas market (see below) the method converged.

A full description of the case for Turkey is given in (Golovina 2002; Klaassen 2003). To illustrate the model' capabilities, we reproduce the most instructive graphics below.

3.2.5 *Highlights of GASCOM's application to the Turkish gas market*

This research was initiated in 2001, when Turkey's situation with respect to gas infrastructures could be described, in brief, as follows (see Nikonov 2002). "The routing of oil and gas pipelines in Asia and especially the Caspian region is at the center of the geopolitics of energy. One of the most promising markets in the region is Turkey not in the least because Turkey constitutes a gateway from Asia to Europe. Official forecasts suggest that Turkey's gas demand might quintuple by 2010. Various countries in the Caspian region are interested to export gas to Turkey. Gazprom proposes to build the "Blue Stream" pipeline under the Black Sea to expand its current gas deliveries to Turkey, Turkmenistan is heading for the Trans-Caspian gas pipeline to deliver gas to Turkey. It seems that some of these countries are moving ahead fast so as to preempt the investments decisions of others making it unattractive to build a new transmission pipeline since the market might not be big enough. Currently, natural gas (around 30% of Turkey's demand in 1999) is imported in the form of LNG from Algeria and Egypt. The remaining 70% comes through pipelines from Russia via Bulgaria." Fig. 6 illustrates the situation.

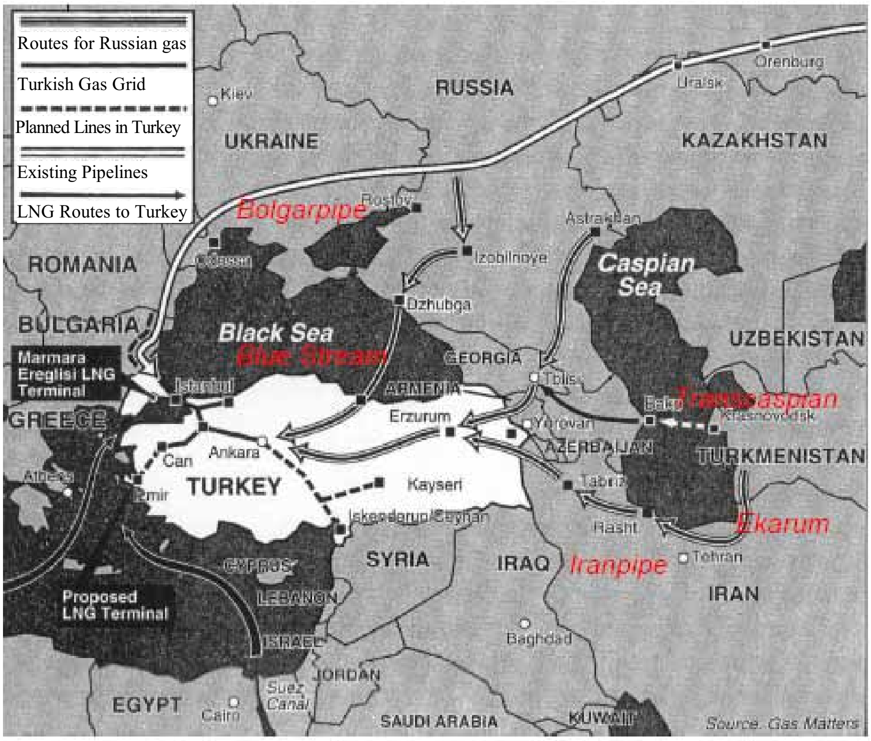

Fig. 6. Gas pipeline routes to Turkey (Source: Gas Matters).

The following gas transmission projects were considered as competitors in the game of timing:

— "Blue Stream": a direct connection between Russia and Turkey under the Black Sea;
— "Trans-Caspian": delivering gas from Turkmenistan to Turkey through Azerbaijan and Georgia;
— "Ekarum": importing gas from Turkmenistan to Iran and then to Turkey;
— "Iranpipeline": an alternative to the "Blue Stream", going directly from Iran.

Table 1 presents the major data used in our analysis. In this run, net present value (NPV), U_i, was maximized.

Some of the data presented in table 1 were obtained using IIASA's MESSAGE model (Klaassen 2001). Data for the starting year, capacity, length and investment (construction) costs were based on (EIA 1999a; EIA 1999b; Ignatius 2000; Zhao 2000). Operation and maintenance costs (in our simulations these recurring expenses relate to the transportation costs) were based on data of the MESSAGE model and were equal to 10% of the investment (Strubegger 1995). Data for transit fees were estimated on the basis of the existing transit fees from Russia through Ukraine and the length of the transit route (Sagers 1999). Distribution costs include domestic distribution and storage costs to the residential, industrial and conversion sectors (Golombek 1995). GDP forecasts for Turkey were derived from the SRES-B2 scenario assuming that Turkey would follow the same development path in terms of GDP growth rates per capita as the Middle East and North Africa (Riahi 2000). The world market price for LNG was derived from the IIASA median scenario (B2) developed for the IPCC Special Report on Emission Scenarios (Nakićenović 2000).

Table 1. Data on the Turkey gas market (2001).

Origin	Russia	Turkmenistan	Turkmenistan	Iran
Pipeline's name	Blue Stream	Trans-Caspian	Ekarum	Iranpipe
Estimated (planned) start of operation	2002	2002	2009	2010
Percentage constructed in 1998	0	0	54	58
Final capacity, bln m^3/year	14.16	31.15	28.30	28.00
Length, miles	1220	1696	2172	2400
Investment, $ bln	3–4.3	2–3	3.8–4	3.9–4.1
Transportation costs, $ bln/bln m^3	14	8	30	30
Distribution costs, $ bln/bln m^3	33	33	33	33
Transit fees, $ bln/bln m^3	0	16.9	21.6	0

In the central case based on different estimates for the price elasticity, the price elasticity of demand, e_p, was estimated as –0.7 and income (GDP) elasticity of demand, e_y, as 1.25 (the GDP elasticity value fits with the GDP elasticity in developing countries, and the price elasticity value fits with Turkish data).

The agent's iterated best responses converged to the Nash equilibrium start-of-operation years shown in table 2 (the last row shows also the planned start-of-operation years: an extraction from table 1).

Thus, the Nash equilibrium scenario, as compared to the planned scenario, implies that it is optimal to delay building the "Blue Stream" by one year only, whereas the start-of-operation times for the "Trans-Caspian" should be delayed by eight years, and for the "Ekarum" by 16 years. Therefore, for the "Trans-Caspian" and the "Ekarum", in contrast with the "Blue Stream", it is important that in 8–16 years the investment costs would be lower and gas demand (and, consequently, the annual revenues) higher. The “Iranpipe” would still proceed as currently planned (start in 2010). Recall that this analysis was carried out while competition between the “Blue Stream” and the “Trans-Caspian” as potential “first movers” still continued. The fact that investment into the “Trans-Caspian” was frozen soon, suggests that our analysis led to a correct short-term forecast that the “Blue Stream” would be the “first mover” in the game.

Table 2. The Nash equilibrium and planned start-of-operation years for the Turkey gas market.

Pipeline’s name	Blue Stream	Trans-Caspian	Ekarum	Iranpipe
Nash equilibrium start of operation	2003	2010	2025	2010
Planned start of operation	2002	2002	2009	2010

Fig. 7 illustrates the simulated trajectories of the accumulated profit for the “Blue Stream” and the “Trans-Caspian” for the Nash equilibrium and planned scenarios. We see that the Nash equilibrium scenario, as compared to the planned scenario, brings higher total profits (NPV) to both projects in 2045 and later (whereas for the “Blue Stream” this holds over the entire operation period).

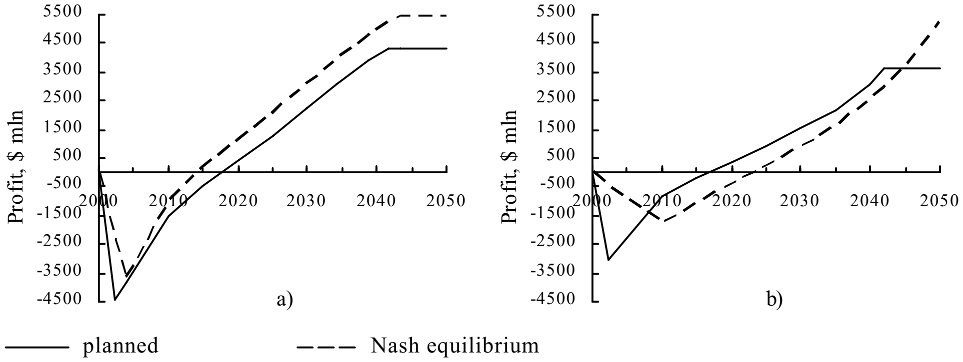

Fig. 7. The simulated trajectories of the accumulated profit for the “Blue Stream” (a) and the “Trans-Caspian” (b) for the Nash equilibrium and planned scenarios.

When the research was still in progress (in the beginning of 2001), PSG International Ltd. (an affiliate of GE Capital and Bechtel Enterprises) – one of the major investors of the “Trans-Caspian” project – has quit the project, leaving it in a “frozen” state. In late 2002 (a year after the research was finished) the “Blue Stream” project management announced the final stage of construction, and in the beginning of 2003, the “Blue Stream” started delivering gas to Turkey. After a year of operation, during which Turkey’s natural-gas demand has been stably increasing (Is this true indeed?..) the investors showed their interest in renewing the “Trans-Caspian” project, what, principally, agrees with our analysis.

4 Conclusions

The future evolvement of Russia’s energy–economy–environment (E3) system is crucial for global E3 development, which implies that Russia’s E3 system will remain in the focus of IIASA's work. This paper describes two research projects carried out within the framework of IIASA's Environmentally Compatible Energy Strategies Program and IIASA's Dynamic Systems Program in collaboration with leading groups in Russia.

One project aims at elucidating Russia's possible advantages and disadvantages within the rules of the Kyoto Protocol and the country's strategic prospects for any future global scheme serving the purposes of the Framework Convention on Climate Change. The main results of this simulation-based study are that under a wide range of plausible assumptions concerning its economic development and its estimated energy supply, Russia's participation in the Kyoto Protocol may hold the promise of economic and environmental benefits.

Assuming, for illustrative purposes, an extension of the "Kyoto limits" beyond the First Commitment Period (2008–2012), the hypothetical extrapolation of the continuation of the Kyoto limits ("Kyoto Forever") suggests that even then, Russia will suffer significant GDP loss only under a part of those sets of assumptions that include high economic growth. Add to this that any future global environmental obligations will only be the result of international agreements, Russia appears well poised to contribute to global environmental protection without risking major damage to its economy.

The second Russia-related project concerns the strategically important natural-gas sector, which is crucial not only for Russia's economy, but also for the global environment. Within this second project, a modeling tool was developed that has a potential to help optimize the design, the timing, and the operation of gas pipeline projects in Eurasia.

Although both projects are in their early phases, a set of relevant results have been obtained already, and further research work is in progress.

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