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**Interim Report IR-09-001**

# On Costs and Benefits of Russia's Participation in the Kyoto Protocol

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**Approved by**

Arkady Kryazhimskiy
Leader, Dynamic Systems Program

July, 2009

## Foreword

This paper is the last IIASA publication by Leo Schrattenholzer, the initiator of the project presented here and leader of the research group.

The project was launched in 2003, when Russia, one of the biggest players in the global emission reduction process, was not participating in the Kyoto Protocol, and strong debates about potential costs of its participation and benefits from it were frequently emerging among politicians and among scientists with different scientific backgrounds. These debates were supported by numerous research efforts, especially in Russia. The authors used diverse methodologies and produced a wide spectrum of estimates and policy recommendations.

At that time, Leo Schrattenholzer, Leader of IIASA's Environmentally Compatible Energy Strategies (ECS) Program, suggested that IIASA, an independent international research center, should contribute to this hot scientific discussion using its own instruments and bringing a stronger spirit of systems analysis to it. A research group consisting of members of the ECS and DYN Programs and also representatives of IIASA's network of applied mathematicians, started to work on this. An important point in this collaborative activity was a meeting in the Russian Academy of Sciences in May 2005, in which the members of the project team presented their preliminary results to a group of Russian experts; a key observation was that Russia would hardly meet its Kyoto emission level before the year 2020 under a range of economic assumptions, which seemed quite realistic in that "pre-crisis" period.

The project was essentially finished by the end of 2006. However, some important research components, including parts of sensitivity analysis, were still missing, and the group continued its research effort, in a slower mode and in another format, in which ECS was no longer in IIASA's agenda and Leo Schrattenholzer was no longer affiliated with IIASA.

In the course of real economic development (passing through today's economic crises), the medium-term growth scenarios assumed in the project (as well as in a number of other earlier studies) never came to reality, and the generated emission projections for Russia had no chance to be proven or rejected. However, a methodological value of this research, which includes a strong modeling effort, an extended numerical sensitivity analysis, and a comparison with alternative estimates remains high and can, principally, be used in new IIASA projects connected to the Post-Kyoto process.

Since July 2008, the group has been selecting and putting together material for this paper. In March 2009, Leo Schrattenholzer wrote the Introduction and Section 2 (Recent development of Russia's E3 System). He passed away unexpectedly in April, and did not see this paper published. I have dared to edit the rest of the text stylistically and slightly reshuffle it, in the hope that this small editorial effort of mine would help to represent Leo's vision of this work in a clearer way – a way which was always in the spirit of systems analysis.

Arkady Kryazhimskiy – June, 2009

# Contents

# Abstract

The authors consider an application of MERGE, a large-scale non-linear optimization model, to the analysis of the development of the E3 (energy-economy-environment) system in Russia. A brief historical overview is followed by a short outline of related studies performed earlier by Russian research institutions. Original MERGE-based development scenarios for Russia are described. The simulation results are presented in detail and then partially compared with the projections given by other authors. The results of a sensitivity analysis of the model's outputs are presented.

# Acknowledgments

The authors would like to thank the late Prof. Alan S. Manne for having accompanied IIASA's work with MERGE with his untiring advice, and Gerhard Totschnig for his development work with MERGE-5I. The contribution of Yaroslav Minullin to the scenario development and his assistance in the data analysis are greatly appreciated. We also gratefully acknowledge the Tokyo Electric Power Company (TEPCO) for supporting the development of MERGE 5I.

## About the Authors

***Boris Digas*** is a research scholar at the Institute of Mathematics and Mechanics, Ural Branch of the Russian Academy of Sciences, Ekaterinburg, Russia. He graduated in mathematics and mechanics from Ural State University, Ekaterinburg, Russia, in 1993. In 1998, he was a participant of IIASA's Young Scientists Summer Program with the Dynamic Systems Project and the Risk, Modeling and Policy Project. In 2007, he defended his Ph.D. thesis in mathematical modeling, numerical methods and software systems. His research interests include inverse problems of dynamics, programming, and mathematical modeling.

***Vyacheslav Maksimov*** is Head of the Department of Ordinary Differential Equations at the Institute of Mathematics and Mechanics, Ural Branch of the Russian Academy of Sciences, Ekaterinburg, Russia. He graduated in mathematics and mechanics from Ural State University, Ekaterinburg, Russia, in 1972 and received his Candidate and Doctoral Degrees in Physics and Mathematics from the Ural Branch of the Russian Academy of Sciences, Ekaterinburg, Russia, in 1978 and 1992, respectively. Dr. Maksimov has been collaborating with IIASA since 1993. His research interests are primarily focused on control theory, distributed parameter systems, and mathematical modeling.

***Leo Schrattenholzer*** † had been affiliated with IIASA since 1973, after graduating from the Technical University of Vienna in mathematics. He received his Ph.D. in energy economics in 1979, also from the Technical University of Vienna. His Ph.D. thesis was on modeling long-term energy supply strategies for Austria. From 2000 to 2006 he was Leader of IIASA's ECS Program. The focus of his last work was on the application of large-scale energy-economy-environment models for the formulation of long-term global scenarios. Since 1981 Dr. Schrattenholzer had been serving as one of two co-directors of an international network of energy analysts, the *International Energy Workshop (IEW)*, a global network of analysts concerned with international energy issues. He was also Lead Author of IPCC's Second Assessment Report.

# On Costs and Benefits of Russia's Participation in the Kyoto Protocol

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## 1 Introduction

According to the Kyoto Protocol of the UN Framework Convention on Climate Change, signed at the Third Conference of Parties, in Kyoto, Japan, in December, 1997, the developed industrial countries must reduce their emissions of six greenhouse gases (GHG) in the period 2008–2012 by at least 5% from 1990 levels. Each Party to the Kyoto Protocol is assigned with an individual emission limit that must not be exceeded. In particular, the 15 Member States (as of 1997) of the European Union have a target of reducing their emissions by 8%; the USA by 7%; Japan and Canada by 6% each. Russia's emissions ceiling is set at the 1990 level.

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.

The work reported here was initiated before the Russian decision to ratify the Kyoto Protocol (KP). The aim was to provide a numerical and reproducible basis for the decision by estimating the economic consequences, costs or benefits, of Russia being bound by the limits stipulated in the KP.

In this respect, the work reported here can of course no longer serve the original purpose. The authors have nonetheless decided to publish this paper, mainly for two reasons. First, the scenarios developed with the Integrated Assessment (IA) model MERGE have been updated to the latest available information, that is, the information as of mid-2008[1]. The second – methodological – reason is that we believe that the work for Russia demonstrates the usefulness of MERGE for analyzing economic costs and benefits of environmental agreements in a large number of situations.

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[1] The Global Economic Crisis – under this name – became a major global concern in late 2008. At the time of this writing, the hope can still be entertained that after the end of the crisis, GDP development will "catch up" again, at least to some extent. In particular, given the strong methodological focus of this paper, the authors see no reason to change the future growth rates of potential economic growth. After all, also the oil price trajectories in the model are still the same as in 2006 despite the obvious possibility that they could have been considered very wrong at some point in between.

One peculiarity of the projections of the future evolvement of the Russian E3 (energy-economy-environment) system is that many variables used to portray this evolvement span rather wide ranges over the projection period, usually reaching to the year 2050. While it is of course acknowledged that major uncertainties surround any such projection, it appears unsatisfactory to simply take this situation as being the norm and for granted. In our opinion what should be done is that the different projections – in particular those on the high and low ends of the spectrum – should be qualified by identifying necessary and/or sufficient conditions under which each of the scenarios appears particularly plausible. This way, readers are in a position to form their subjective probabilities not solely on abstract ranges but also on sets of circumstances (so-called scenario variables), which may include variables better amenable to estimating probabilities and plausibility.

As an instrument for making the necessity or sufficiency of conditions plausible, we selected the MERGE model (Manne and Richels, 2004), one of the most well-known and widely accepted E3 models.

As a basis for our model-based analysis we first review Russia's current GHG emissions and their determinants in Section 2.

In Section 3, we discuss some background for our research – the future projections for Russia's E3 system, suggested by several Russian experts in the period preceding Russia's participation in the Kyoto Protocol; we notice, in particular, a visible diversification in the experts' estimates of the time, at which Russia's emissions will reach the level of 1990 – the Kyoto level for Russia. This diversification has motivated our research from a methodological perspective; in our study, we assess the experts' estimates using a global E3 model.

In Section 4, we first summarize the MERGE model and its variant MERGE-5I ('I' as in IIASA) to the extent we deem necessary to understand the scenarios and conclusions presented later. We then present our MERGE-based results and compare them with earlier experts' projections for Russia's E3 system.

In Section 5, we analyze the sensitivity of the model outcomes to variations in the values of the major parameters of Russia's economy.

## 2 Recent development of Russia's E3 system

### 2.1 Background

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. In addition, the fall of the "iron curtain" has made a significant intrusion into the economies of all successor states. For almost a decade, Russia's Gross Domestic Product was steeply decreasing. Only in 1998 it began to rise 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, for example, 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 crude oil and natural gas, the maintenance of existing and the construction of new pipelines are among the most crucial issues.

Also, 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).

## 2.2 History

The dynamics of greenhouse gas emissions in Russia presented in the Third and Fourth National Communications of the Russian Federation (TNC RF, FNC RF) [4, 5] (see also [1, 12]) show a significant reduction of GHG emissions over this period (of 1990–2004) – nearly 30% without account of land use and forestation (see, Figure 1). If taking the sinks from land use and forestation into account, the reduction reaches 45% by 2004. Here we used the main estimates presented in 4, 5]**.**

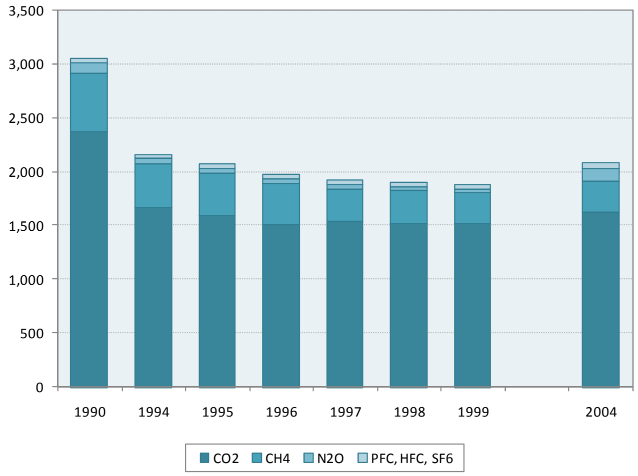

**Figure 1:** Greenhouse-gas emissions in Russia, 1990–2004, million tons of $CO_2$ equivalent ($MtCO_2$-equ.) without account of land use and forestation.
*Source: [4, 5].*

The shares of the six greenhouse gases in Russia correspond to those in most of industrialized countries: Nearly 78% is carbon dioxide, 14% methane, 5.7% nitrous oxide, and 2.3% fluorides.

Nearly 98% of direct anthropogenic $CO_2$ emissions are connected with the production, transport and use of fossil fuels, the remaining 2% originating from industry, mainly cement production. Conversely, $CO_2$ emissions from the beneficial use (combustion) of fossil fuel are about 99% of the total emissions related to fossil fuel. The remaining 1.2% originates from flaring and waste. The shares of $CO_2$ emissions from usage of fossil fuels are 50.8% from natural gas, 23.9% from oil, and 25.3% from coal. These shares differ from the world averages, which are 19.2%, 42.7% and 38.1% respectively. The large share of gas in the primary-energy balance of Russia is caused by active gas installation in urban areas in the last 30 years, by growth of gas usage in industry and for power generation as well as by significant increases in production in newly developed gas fields.

Russia's methane emissions are mainly caused by leakage during extraction, transportation and refining of petroleum and gas, by mining gas seepage, by livestock farming, by waste processing and disposal, as well as by forest fires. The nitrous oxide emissions are caused predominantly (almost 80%) by agriculture (fertilizer application); nearly 10% is connected with liquid wastes and 9% with fossil-fuel usage.

The main sources of fluorides (hydrofluorcarbons – HFCs, perfluorocarbons – PFCs, and sulfur hexafluoride – $SF_6$) emissions are the branches of industry connected with production of coolants, solvents and aerosols. $SF_6$ escapes during industrial processing of minerals (fluorites) and in high-voltage power engineering. PFCs escape in large amounts during production of aluminum.

The pattern of GHG emissions in Russia is represented by a number of source categories (Figure 2). The leading role in GHG emissions belongs to fossil fuel combustion (about 80% of total emissions).The share of large stationary energy sources (thermoelectric power stations, power objects at industrial plants) is above 50% of a country's total GHG emissions.

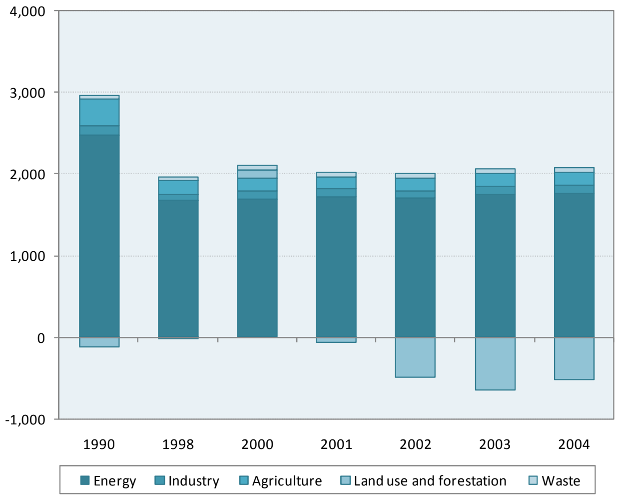

**Figure 2:** GHG emission pattern in Russia by source categories, 1990–2004, $MtCO_2$-equ. Negative values mean GHG absorption (sinks).
*Source: [5].*

Table 1 shows estimates for Russia's $CO_2$ emission from fuel combustion. Contributions of individual gases to Russia's total emissions are given in Table 2, and in Figure 3, which shows that despite a drastic change of the total emission value between 1990, 1998 and 2004 the shares changed only slightly.

**Table 1:** Russia's energy-related GHG emissions in 1990, 1998 and 2000–2004, in Mt of $CO_2$ equivalent. *Source: [5].*

| **Source and gas** | **Emissions, $MtCO_2$-eq p.a.** | | | | | | |
|---|---|---|---|---|---|---|---|
| | **1990** | **1998** | **2000** | **2001** | **2002** | **2003** | **2004** |
| Fuel combustion, $CO_2$ | 2.193 | 1.488 | 1.501 | 1.527 | 1.495 | 1.540 | 1.754 |
| Fuel combustion, $CH_4$ | 0.188 | 0.119 | 0.121 | 0.123 | 0.125 | 0.128 | 0.127 |
| Fuel combustion, $N_2O$ | 0.017 | 0.011 | 0.011 | 0.011 | 0.012 | 0.012 | 0.012 |
| Processing emissions and leakage, $CO_2$ | 19.346 | 12.994 | 13.954 | 14.182 | 21.250 | 20.742 | 24.255 |
| Processing emissions and leakage, $CH_4$ | 11.668 | 7.595 | 8.121 | 8.046 | 8.092 | 8.473 | 8.697 |
| Processing emissions and leakage, $N_2O$ | 0.0001 | 0.0001 | 0.0001 | 0.0001 | 0.0002 | 0.0002 | 0.0002 |

**Table 2:** Russia's industry-related GHG emissions in 1990, 1998 and 2000–2004, in Mt of carbon equivalent. *Source: [5].*

| **Source and gas** | **Emissions, $MtCO_2$-eq p.a.** | | | | | | |
|---|---|---|---|---|---|---|---|
| | **1990** | **1998** | **2000** | **2001** | **2002** | **2003** | **2004** |
| Processing of minerals, $CO_2$ | 41.606 | 16.464 | 20.939 | 21.861 | 23.200 | 24.967 | 27.420 |
| Chemical industry, $CO_2$ | 19.102 | 12.064 | 16.079 | 15.999 | 15.863 | 16.743 | 18.062 |
| Chemical industry, $CH_4$ | 0.063 | 0.019 | 0.028 | 0.032 | 0.034 | 0.040 | 0.043 |
| Chemical industry, N2O | 0.017 | 0.015 | 0.014 | 0.014 | 0.015 | 0.015 | 0.016 |
| Metallurgy, $CO_2$ | 9.865 | 3.816 | 4.319 | 3.867 | 3.913 | 4.821 | 5.159 |
| Metallurgy, fluorine-containing gases | 30.449 | 31.411 | 33.842 | 34.518 | 34.864 | 36.258 | 37.709 |
| Production and consumption of fluorine-containing gases | 8.031 | 9.474 | 10.128 | 10.134 | 10.139 | 10.144 | 10.148 |
| Utilization of solvents and other products, N2O | 0.0017 | 0.0017 | 0.0017 | 0.0017 | 0.0017 | 0.0017 | 0.0017 |

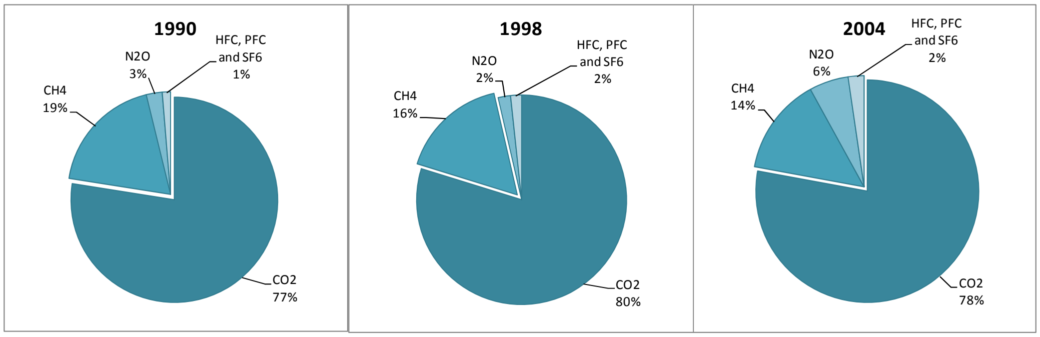

**Figure 3:** The distribution of the total equivalent emission among greenhouse gases in Russia in 1990, 1998 and 2004 (%). *Sources: [4] (1990, 1998), [5] (2004).*

# 3 Projections by Russian agencies

## 3.1 Brief overview

Medium- and long-term projections of Russia's economic development have been performed by several research centers in Russia. These include the Bureau for Economic Analysis [12], the Energy Research Institute of the Russian Academy of Sciences [6], the Russian Regional Environmental Center [3], and others. The projections suggest diverging results. According to some estimates, even under pessimistic scenarios for energy intensity (in which Russia's economic growth is still based on old technologies), Russia's emissions of greenhouse gases will not exceed the 1990 values within the first Kyoto Commitment Period (2008–2012) and thus remain within the "Kyoto limits". Other results assert the contrary. To illustrate a diversification of the experts' estimates, in this section we provide a brief overview of the results by the Russian Regional Environmental Center, the Third National Communication of the Russian Federation, and the Institute of Economic Analysis in Moscow. Note that these studies had been performed before Russia has joined the Kyoto Protocol, in a period in which many Russian scientists and politicians had been involved in strong debates about the costs and benefits for Russia from its participation in the Kyoto Protocol.

## 3.2 Projections based on Russia's official energy strategy till 2020

One of the forecasts was performed by the Russian Regional Environmental Center (RREC) [3] on the basis of the "Energy Strategy of Russia till 2020" approved by the Government of the Russian Federation [13]. The reference assumptions of this Strategy, concerning the economic growth dynamics of Russia are represented in Figure 4. According to these assumptions, the country's GDP will increase by a factor of approximately two between 2000 and 2012. The RREC's long-term forecast on production and consumption of primary energy resources in Russia is represented in Figure 5. The pattern of production and consumption of primary fuel-energy resources in Russia and medium-term GHG emission projection corresponding to these forecasts are illustrated in Figures 6 and 7.

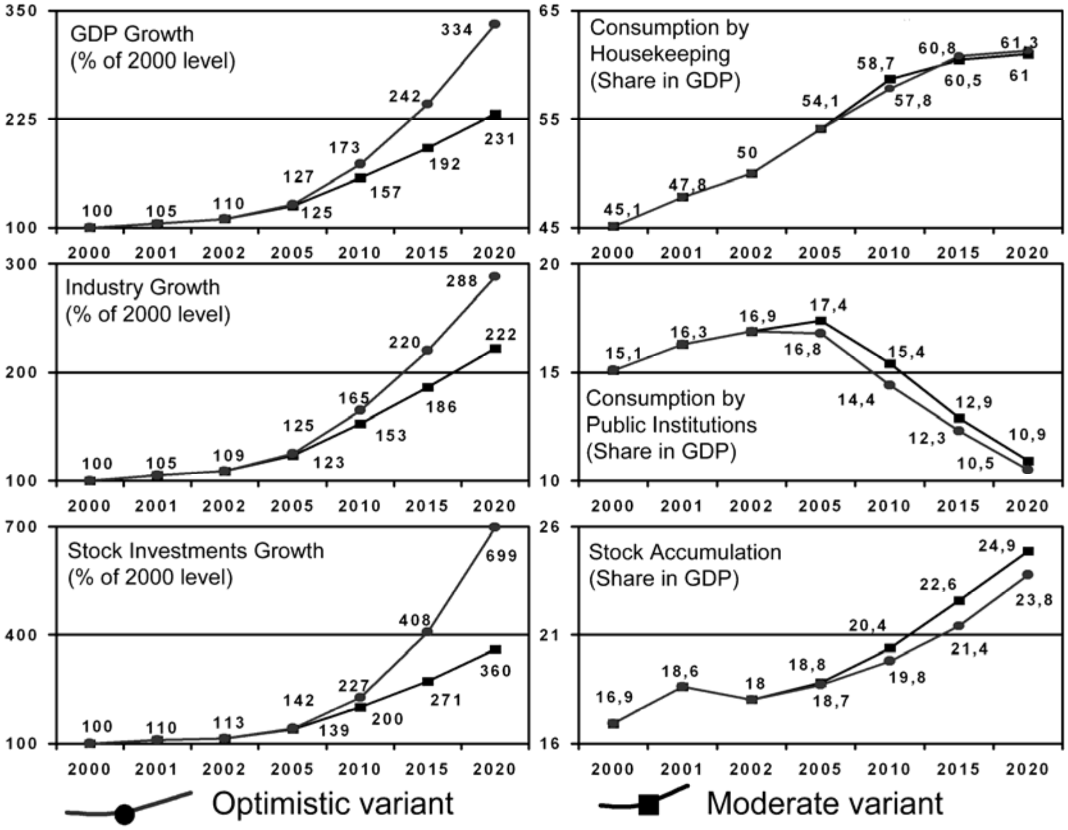

**Figure 4:** Basic assumptions on the development of Russia's economy until 2020, approved by the Government of the Russian Federation on 28 August, 2003. *Source: [13].*

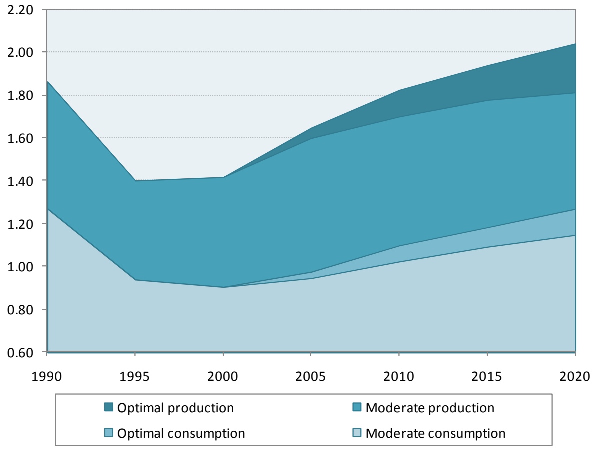

**Figure 5:** Medium-term projections for production and consumption of primary energy in Russia by the Russian Regional Environmental Center, in Gt of coal equivalent (Gtce). *Source: [3].*

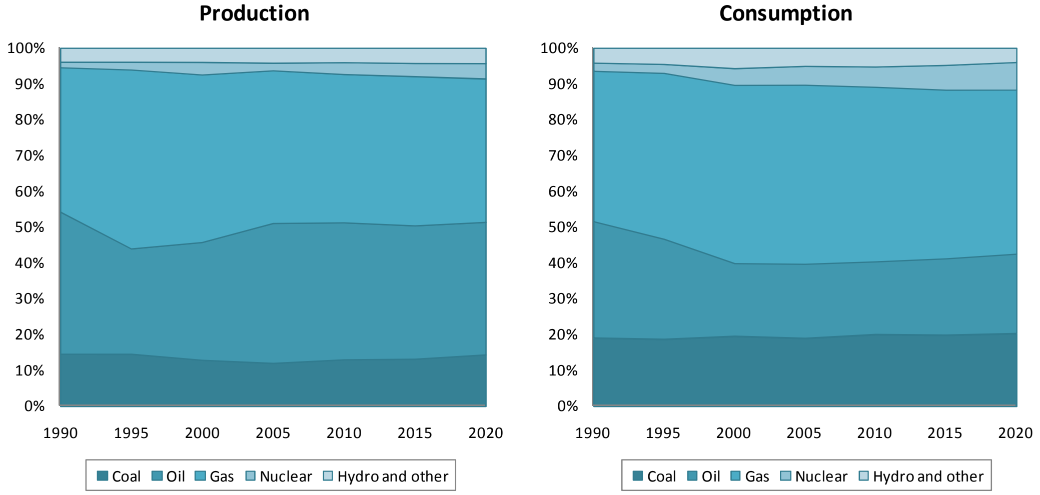

**Figure 6:** Long-term projections for pattern of production and consumption of primary energy in Russia by the Russian Regional Environmental Center.
*Source: [3].*

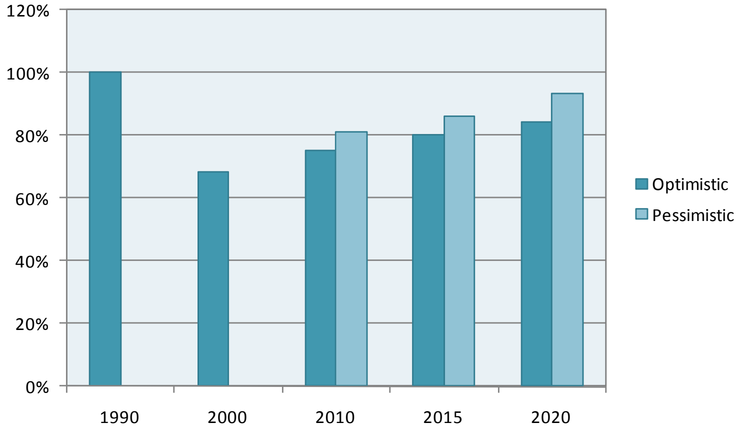

**Figure 7:** Medium-term GHG emission forecast for Russia by the Russian Regional Environmental Center.
*Source: [3].*

Note that RREC's emission projections (see Figure 7) show that Russia's emissions will remain below the level of 1990 till 2020, which corresponds with our simulation results.

## 3.3 Other projections from Russian sources

A significant amount of emission estimates for Russia rests upon the Third National Communication of the Russian Federation (TNC-RF) [4] approved by the Inter-Agency Commission of the Russian Federation on Climate Change[2].

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[2] The National Communication has been prepared under specific provisions of the specially developed Federal Target Programme "Prevention of Dangerous Changes of Climate and Their Adverse Effects",

The main assumptions used in TNC-RF and based on the Energy Strategy of Russia described in the previous subsection are the following (here we follow [4]):

a) In Scenario I, Russia's GDP is expected to grow by a factor of 3–3.15 (corresponding to an average annual growth rate of 5.0–5.2%) between 2001 and 2020 as a consequence of an assumed favorable overall development of its economy. In parallel with Scenario I, Scenario II and Scenario III assuming lower GDP growth rates (3.3% and 4.5% per year on average, respectively) are considered. Scenario III follows a statement from the Second National Communication of the Russian Federation, which suggests that there is a certain probability for approximately 4.5% annual GDP growth along with a 2% average annual decrease in the energy intensity of GDP.

b) In Scenario I, it is assumed that available investments into efficiency improvements of the energy sector will suffice to introduce all measures as planned by the Russian government under the Federal Target Programme. In this case, during the period 2001–2020 the energy intensity of GDP can be reduced by a factor of 2.1 (corresponding to an average annual decline rate of 3.7%). Under less favorable conditions, this rate can be as low as 2.5% per year or 2.0% per year as assumed in Scenario II and in Scenario III, respectively.

c) The carbon index of energy demand (the ratio of $CO_2$ emissions to the total domestic energy resources consumption) is determined by the expected evolution of the country's primary-energy mix. According to the Energy Strategy [13], by the year 2020, the share of gas in primary-energy consumption will decrease from 48% to 42–45%; the share of oil will be stable over this period (22–23%); the share of coal will increase from 20% to 21–23%; the share of nuclear power will grow to 5.7–6.0%; and the share of non-conventional renewable energy sources (such as solar, wind, geothermal, biomass) will increase to 1.1–1.6%. Thus, in spite of a decrease in the gas share and an increase in the coal share, the carbon index of energy demand is expected to be approximately constant over the time period in question due to an increase in the share of carbon-free power sources.

Table 3 summarizes detailed characterizations of the scenarios.

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authorized by the approval of the Government of the Russian Federation of October 19, 1996, with the purpose of implementation of the commitments under the UN FCCC and prevention of negative consequences of climate change on the health of population and on the national economy. Information for National Communication has been submitted by nearly forty ministries, agencies, institutions, and institutes of Russia.

**Table 3:** Growth rates for the major drivers of Russia’s domestic energy demand and $CO_2$ emissions in 2001–2020 according to TNC-RF (% per year). *Source: [4]*

| | Scenario I | Scenario II | Scenario III |
|---|---|---|---|
| GDP growth rate | 5.2% | 3.3% | 4.5% |
| Energy efficiency improvement rate | 3.7% | 2.5% | 2.0% |

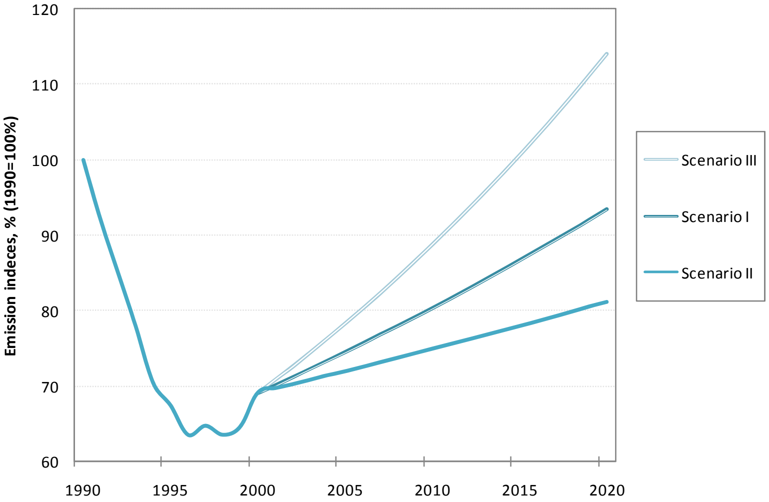


**Figure 8:** $CO_2$ emission projections for Russia for TNC-RF’s scenarios (1990 = 100%). *Source: [4].*

Russia’s projected $CO_2$ emissions for three TNC-RF’s scenarios are given in Figure 8. The figure shows that even in the worst of the TNC-RF’s scenarios, the 1990 $CO_2$ emission level will not be exceeded before 2015, which, principally, agrees with the RREC’s forecast depicted in Figure 7.

A different view is taken by the Institute of Economic Analysis (IEA) in Moscow considering four GDP growth scenarios for Russia. IEA’s estimates [2] are summarized in Table 4 and in Figure 9.

**Table 4:** IEA’s forecasts for the times of exceeding the 1990 level of $CO_2$ emission by Russia. *Source: [2]*

| | Scenario 1 | Scenario 2 | Scenario 3 | Scenario 4 |
|---|---|---|---|---|
| GDP growth rate | 5.0% | 6.2% | 6.7% | 7.2% |
| Energy efficiency improvement rate | 2.0% | 2.0% | 2.0% | 2.0% |

We see that under the assumption that Russia's GDP growth rate remains relatively high whereas the energy efficiency improvement rate remains relatively low, the IEA's experts expect Russia to exceed the 1990 level of carbon dioxide emissions before the end of the First Kyoto Commitment Period – the year 2012.

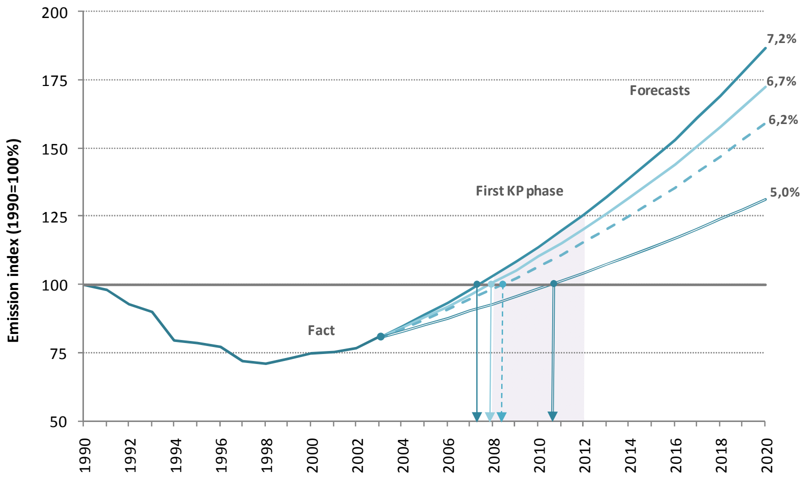


**Figure 9:** Actual (1990–2003) and projected by IEA (2004–2020) $CO_2$ emissions in Russia for four GDP growth scenarios
*Source: [2]*

### 3.4 Summary on experts' estimates

Although the studies outlined above deal with various aspects of the development of Russia's E3 system in a medium-term prospect, the Kyoto Protocol constraints play a central role in all of them. A key question addressed in all these studies is whether Russia will exceed its 1990 level of carbon dioxide emissions before the end of the First Kyoto Commitment period – the year 2012.

The Russian Regional Environmental Center (RREC), following the official "Energy Strategy of Russia till 2020", states that Russia's carbon dioxide emissions will remain below the level of 1990 till 2020.

The Third National Communication of the Russian Federation (TNC-RF), considering three medium-term scenarios for Russia's economic development, comes to the conclusion that Russia will exceed the 1990 emission level not earlier than in the year 2015.

Finally, the Institute of Economic Analysis (IEA) in Moscow has found that Russia will exhibit a relatively high rate of economic growth and a relatively low energy efficiency improvement rate and can exceed the 1990 level of emissions around the year 2010.

In the next section, while presenting the results of our research, we will also refer to the estimates suggested by the Energy Research Institute of the Russian Academy of

Sciences, which will be closer to those by RREEC and TNC-RF rather than those by IEA.

The diversification of the estimates provided by different Russian experts (which vary from, roughly, 2020 to 2010) has appealed for assessing these domestic estimates by using tools elaborated for analysis of the global E3 system, in which Russia acts as one of the parties.

This challenge has motivated our research. We used the global E3 MERGE model to generate future projections for Russia's E3 system. To complement the studies outlined above, our simulations show in particular, that only strongly pessimistic scenarios of economic development can admit that Russia exceeds its 1990 level of carbon dioxide emissions before the end of the First Kyoto Commitment Period.

The next two sections present our results.

# 4 MERGE-based Analysis of E3 Scenarios for Russia

## 4.1 The MERGE-5I Model

The selection of the model was preceded by a comprehensive review of the existing integrated assessment models, which could be used in the projected exercise. For this purpose the authors have reviewed over 30 world-known models and chose the MERGE model developed in the mid-1990s (a Model for Evaluating Regional and Global Effects of GHG reduction policies) [7, 8]. MERGE provides an IA (Integrated Assessment) framework for studying scenarios of the interaction between the economy, the energy system, and climate change. The model is very well suited to explore – in a quantitative and reproducible way – alternative views on a range of issues, e.g. costs, damages, valuation, and discounting. The purpose of using MERGE is to reflect these alternative views by sets of model inputs, one at a time. The last version of the MERGE model – MERGE-5 [9] – was modified by the ECS Program at IIASA. This resulted in the creation of a new model version, named MERGE-5I ('I' stands for 'IIASA') [10].

The global-optimization model MERGE [9] 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* defines an inter-temporal utility function of a single representative producer-consumer in each of the model's world regions, which is then maximized by MERGE subject to given constrains. The main variables of this module are the production factors capital stock ($K$), available labor ($L$), and energy inputs (electric, $EN$, and non-electric, $NN$), which together determine the total output of an economy according to a nested CES (constant elasticity of substitution) production function.

The core of the *energy module* is a comparatively simple Reference Energy System (RES) describing the technological options available to supply the energy needed as a production factor.

The *climate module* takes greenhouse gas (GHG) emissions, converting them systematically into atmospheric GHG concentrations and temperature change. The equations for calculating the radiative forcing and the temperature change are derived from the IPCC Third Assessment Report [11]. For $CO_2$, the radiative forcing is proportional to the logarithm of the ratio of the current to initial level of atmospheric concentrations. The outputs of the climate module include trajectories of GHG emissions, atmospheric concentrations, and temperature change.

The information flow through the model is depicted in Figure 10.

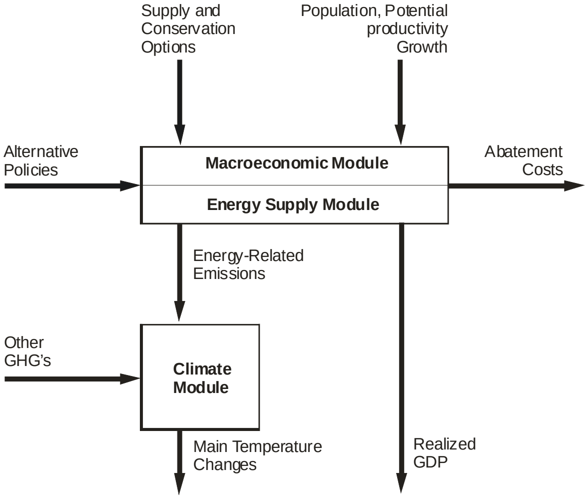


**Figure 10:** An overview of MERGE.

MERGE was designed as an integrated-assessment model (IAM) to study global GHG mitigation scenarios and to conduct cost-benefit analysis. In order to use MERGE to make a first step towards analyzing the economic consequences of the Kyoto Protocol for Russia, IIASA-ECS extended the original MERGE 5 model. The main parts of the extension were the splitting of two original MERGE regions into five new world regions, the improved treatment of non-$CO_2$ GHGs, and the inclusion of the Clean Development Mechanism (CDM). To distinguish the new version from the original model, we use the name MERGE 5I ('I' as in IIASA) for the new version.

In the original MERGE 5, Canada belongs to the model region CANZ (Canada, Australia and New Zealand) and Eastern Europe to EEFSU (Eastern Europe and Former Soviet Union). Since Eastern Europe and the Former Soviet Union play separate roles in this study and Australia did not ratify the Kyoto Protocol, these two world regions were split in the following way: In view of the small share of New Zealand's 1990 emissions in total CANZ emissions, we decided to split CANZ into Canada and ANZ (Australia and New Zealand). The split of EEFSU into the three parts, EEU (Eastern Europe), RUS (Russia), and NRFSU (other FSU) was obvious. The years 2007 and 2012 were also added.

In the original MERGE 5, data on $CO_2$, $CH_4$, $N_2O$, SLF and LLF are included. This means that the three "Kyoto gases" HFCs, PFCs, and $SF_6$ have been combined under the two categories SLF and LLF, that is, short-lived fluorinated gases (SLF) and long-lived fluorinated gases (LLF). Most emissions of the four non-$CO_2$ greenhouse gases are not related to the energy system. They are therefore given as external inputs to MERGE with the exception of $CH_4$ leakage resulting from natural gas production, which is treated endogenously. For each gas, 11 abatement cost categories and abatement volumes are defined in the form of step functions.

In the original MERGE 5, the emissions of these gases are used to calculate global temperature change, but only $CO_2$ emissions (and their abatement) are used to model the Kyoto Protocol. In MERGE 5I, the model was modified so that now, all five GHG categories, their abatement options, and $CH_4$ leakage are included in the modeling of the Kyoto Protocol. Also, the forest management thresholds (sinks) as given in Appendix Z of the Marrakech Accord [16] were included so that sequestration from forest management can only be accounted for until the thresholds of Appendix Z are reached. This may be important for competent readers.

### 4.2 Limiting cases and definition of GDP loss

To analyze consequences of different geopolitical scenarios guiding the implementation of the Kyoto Protocol for Russia, we consider two "limiting cases". Our reference case, R0, assumes no GHG emission constraints.

The second limiting case, R1, assumes that the Parties to the Kyoto Protocol comply with their "Kyoto limits" using domestic measures only. In this limiting case, we follow a hypothetic "Kyoto forever" scenario by extending the Kyoto constraints until the end of the 21st century.

The so-called "Full trade" case, was supposed to be implemented as the next step in our analysis.

We define the country's GDP loss to be the arithmetic difference between its GDP in the reference case, GDP(R0), and that in the domestic measures case, GDP(R1), and use notation GDPLoss to refer to it:

$$GDPLoss = GDP(R0) - GDP(R1)$$

This indicator shows the value of GDP that the country will lose or gain as a consequence of observing the Kyoto limits.

Note that even in the R1 case implying the use of domestic measures only; Russia's GDP depends on the development of the E3 system in other world regions. For example, a possible decrease in Western Europe's GDP due to observing the Kyoto constraints would affect energy imports from Russia, which in turn will result in a slight decrease in Russia’s GDPLoss. Moreover, fluctuations in GDPLoss’s values over time are expected to occur in our scenarios. One of the most distinctive results of our model runs is the point in time at which these fluctuations switch to a clear tendency to growth the GDP loss. This point in time describes a situation, in which Russia will have exhausted its energy efficiency potential (“hot air”), and a process of restructuring the industry and energy sectors towards a low-emission system will be initiated.

### 4.3 MERGE-5I scenarios for Russia

The main aim of our numerical experiment is to compare the temporal dynamics of important output MERGE-5I variables for Russia and the expert forecasting estimates by the Energy Research Institute of the Russian Academy of Sciences [14], which will be referred to as “the expert” further on in this section. The indices under investigation include the sizes of Russia’s $CO_2$ emissions, GDP, TPES (Total Primary Energy Supply), and the structure of TPES.

We consider four scenarios for development of Russia’s economy and energy sectors in the period 2005–2020: a Reference Scenario and three scenarios based on estimates from Russian sources.

A brief description of the scenarios is as follows:

1. The **Reference Scenario** (REF) rests upon a standard set of values assigned in MERGE-5I and incorporates the forecasts for Russia, suggested by the Energy Information Administration [15]. REF assumes that Russia’s annual GDP growth rate declines gradually from 4.5% in 2005 to 3.4% in 2020, and the energy efficiency improvement rate declines from 4.0% in 2005 to 2.4% in 2020, per year. The gas leakage level is assumed to decrease by 20% per decade.

2. In the **Governmental Scenario** (GOV), the annual GDP growth rate is fixed at the level of 6.2% for 2005–2020 (this corresponds to the RF Government’s forecast for Russia’s annual growth). The energy efficiency improvement rate declines from 5.3% in 2005 to 4.1% in 2020, per year. In both GOV and REF scenarios, indicator AEEI is calculated on the base of Arnulf Grübler’s assumption adopted in MERGE-5I [17]. The same assumption on gas leakage as in REF scenario is adopted.

3. The **Doubling Russia’s GDP within 10 Years Scenario** (DBL) illustrates the goal, announced by President V.V. Putin, to double Russia’s GDP within 10 years. This goal being translated into an annual average GDP growth rate in Russia gives 7.2%. The rate of energy efficiency improvement is set at the level of 2.0% per year. In addition, the DBL scenario assumes no improvement on gas leakage since 2000.

4. In the **Pessimistic Scenario** (PES), the annual average GDP growth rate is fixed at the level of 4.5% for 2005–2020. The energy efficiency improvement rate is fixed at the level of 2.0% per year. The same assumption on gas leakage as in DBL scenario is adopted.

Table 5 summarizes the key features of the scenarios.

**Table 5:** MERGE-5I scenarios.

| | Scenario REF | Scenario GOV | Scenario DBL | Scenario PES |
|---|---|---|---|---|
| GDP growth rates | 4.5-3.4% | 6.2% | 7.2% | 4.5% |
| Energy efficiency improvement rate | 4.0–2.4% | 5.3–2.1% | 2.0% | 2.0% |

From the perspective of emission reduction, the REF scenario and GOV scenario can be viewed as rather favourable ones; they assume relatively high energy efficiency improvement rates and medium and, respectively, quite high GDP growth rates for Russia. The DBL and PES scenarios assuming low energy efficiency improvement rates and quite high (in the case of the DBL scenario, very high) GDP growth rates are less favourable in this context. Note that the PES scenario assuming, roughly, the same GDP growth rate as the REF scenario, suggests, in a sense a less energy efficient variant of the latter scenario. Moreover, in the PES scenario, some of the macroeconomic parameters for Russia are defined to be "less favourable" for the country than in the other scenarios. Table 6 shows the values of some macroeconomic parameters for Russia, used for simulation.

**Table 6:** The values of some macroeconomic parameters for Russia used for simulation.

| Scenario | Capital value share | Elastisity of substitution between capital-labor, and electric-nonelectric energy pairs | Reference price of non-electric energy (USD per GJ) |
|---|---|---|---|
| REF | 0.3 | 0.4 | 2.5 |
| GOV | 0.3 | 0.4 | 2.5 |
| DBL | 0.3 | 0.4 | 2.5 |
| PES | 0.33 | 0.35 | 5 |

## 4.4 Emission projections

Here we compare the temporal dynamics of key output MERGE-5I variables for Russia in the four scenarios described above, and the expert forecasting estimates [14] (note that in this section "the expert" is the Energy Research Institute of the Russian Academy of Sciences).

In Figures 11-17, the expert forecast is marked «forecast» or «expert estimation» and the modeling results corresponding to the scenarios are denoted by the abbreviations used for the scenarios: REF, GOV, DBL (or DOUBLE) and PES, respectively. Each scenario is implemented in cases R0 and R1 with identical input parameters. Recall that case R0 does not suggest any GHG emission constraints, and case R1 assumes that GHG emission reductions in the world regions bound by the Kyoto Protocol are achieved using domestic measures only.

In Figure 11 we see that in case R0 the expert forecast and scenarios REF and GOV suggest that Russia's $CO_2$ emissions do not reach the level of 1990 (the Kyoto level for Russia) even in 2020, whereas for scenarios DBL and PES the Kyoto level is reached before the end of the First Kyoto Commitment Period – the year 2012. Considering a radical difference in the behaviors of the simulated emission trajectories for scenarios REF and PES in case R0, we come to a remarkable qualitative observation. Note that (Table 5) both the REF and PES scenarios assume roughly the same (medium-size) GDP growth in Russia, whereas these scenarios essentially differ in assumptions on the energy efficiency growth rates in Russia: a drift from 4.0% to 2.1% in scenario REF opposes 2.0% in scenario PES (here we neglect the differences in the values of some macroeconomic parameters in scenarios REF and PES, given in Table 6). We see therefore that a strong and timely increase in the country's energy efficiency improvement rate ("a switch from PES to REF") can radically improve its medium-term emission trajectories and, in particular, shift the time of crossing the Kyoto level from the beginning of the First Kyoto Commitment Period to far beyond it.

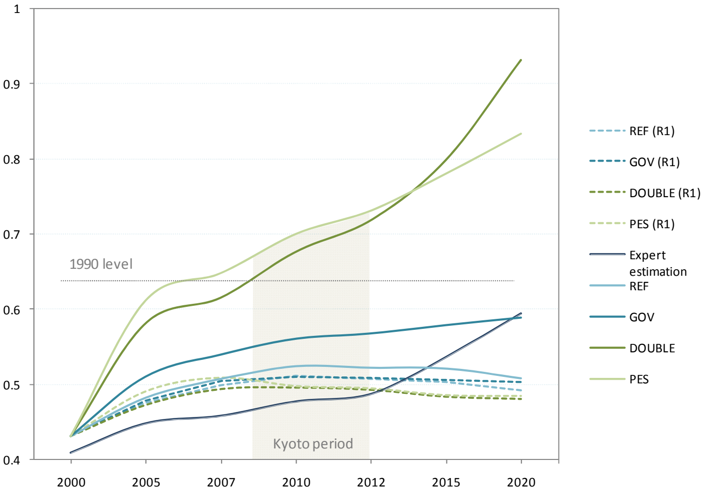


**Figure 11:** Russia's $CO_2$ emissions in Gt of carbon equivalent; for the four MERGE-5I scenarios in case R0 (no emission constraints).

Also, Figure 11 shows us that in case R1, Russia's Kyoto level remains high above its simulated medium-term emission trajectory for each of our four scenarios. In this context, it is remarkable that the implementation of domestic measures for reducing emissions by all Kyoto Parties drastically improves Russia's emission trajectories even in the most non-favorable scenarios, DBL and PES, assuming that Russia crosses its Kyoto level before the end of the First Kyoto Commitment Period in case R0.

Finally, Figure 11 demonstrates that in case R1 the diversification in Russia's emission trajectories across the scenarios is significantly lower than in case R0, which, principally shows that in the case of Russia, the implementation of domestic measures for reducing emissions by all Kyoto Parties may act as a strong factor for raising the robustness of the country's output emission trajectory with respect to fluctuations in parameters of its economic development.

In Table 7 we bring together the estimates for the years Russia's reaches its Kyoto (1990) emission level, as suggested by the Third National Communication of the Russian Federation (TNC-RF), the Institute of Economic Analysis in Moscow (IEA), and by our group. Table 7 is based on Tables 3, 4 and 5, and on Figures 8, 9 and 11.

**Table 7:** The years, in which Russia reaches its Kyoto (1990) carbon emissions level in case R0; estimates by the Third National Communication of the Russian Federation (TNC-RF), Institute of Economic Analysis, Moscow (IEA), and MERGE-5I.

| | TNC-RF | | | IEA | | | | MERGE-5I | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | Scenarios | | | Scenarios | | | | Scenarios | | | |
| | I | II | III | 1 | 2 | 3 | 4 | REF | GOV | DBL | PES |
| GDP growth rate | 5.2% | 3.3% | 4.5% | 5.0% | 6.2% | 6.7% | 7.2% | 4.5%-3.4% | 6.2% | 7.2% | 4.5% |
| Energy efficiency improvement rate | 3.7% | 2.5% | 2.0% | 2.0% | 2.0% | 2.0% | 2.0% | 4.0%-2.4% | 5.3%-4.1% | 2.0% | 2.0% |
| Year of reaching 1990 emission level (before 2020) | - | - | 2015 | 2011 | 2009 | 2008 | 2007 | - | - | 2008 | 2006 |

The results summarized in Table 7 are, in general, mutually complementary rather than inconsistent. The TNC-RF and IEA give their estimates for two non-intersecting intervals of medium-size and relatively high GDP growth rates in Russia, respectively, and in this sense complement each other. Here, we see that Russia's critical year (the year, in which it reaches its 1990 emission level) moves backward while the assumed GDP growth rate in Russia increases. Note that the TNC-RF's estimate for Russia's critical year in Scenario III, 2015, indicates (in combination with the outcomes for Scenarios I and II) that lowering the energy efficiency improvement rate can rapidly shift Russia's critical year backwards.

In Table 7, our (MERGE-5I) assumptions on the country's GDP growth rates and energy efficiency improvement rates partially intersect, to some extent, with those by the TNC-RF and IEA and partially complement them. Our REF scenario is quite close to the TNC-RF's Scenario I, and in both scenarios Russia's critical year falls beyond 2020. Our DBL scenario is similar to the IEA's Scenario 4 and these two scenarios suggest roughly similar estimates for Russia's critical year (the years 2008 and 2007 in the former and latter scenarios, respectively). In these two situations the final estimates obtained independently, based on two different methodologies practically coincide and thus support each other.

In Table 7, our REF scenario relates to the IEA's Scenario 1 very much like the TNC-RF's Scenario I does: assuming approximately the same GDP growth rate as in the IEA's Scenario 1, the REF scenario suggests a higher energy efficiency improvement rate for Russia. Here, we see the effect we noticed earlier in the relationship between the TNC-RF's Scenario I and the IEA's Scenario 1: lowering the energy efficiency improvement rate (from the value assumed in IEA's Scenario 1 to the one assumed in our REF scenario) can rapidly shift Russia's critical year backwards. We arrive at the same effect if we compare our GOV scenario and the IEA's Scenario 2.

Table 7 shows also a pair of seemingly inconsistent estimates: the TNC-RF's Scenario III and our PES scenario assume similar GDP growth rates and similar energy efficiency improvement rates for Russia, and suggest different estimates for Russia's critical year: 2015 (in the TNC-RF's Scenario III) and 2006 (in the PES scenario). Understanding the reasons for this discrepancy requires a deeper analysis of similarities and dissimilarities in the assumptions and methodologies used by the TNC-RF and by our group. One of the possible reasons could be a non-standard set of macroeconomic parameter values in scenario PES (see Table 6).

## 4.5 GDP loss

In Figure 12 we see that for all modeling scenarios under our model assumptions, in the period before the year 2020, Russia's GDP loss grows at approximately constant rates, which essentially differ. In scenario REF and in scenario GOV, the growth rates of Russia's GDP loss are insignificant and reach no more than 2% in the end of the period, whereas in scenario DBL and in scenario PES this indicator is approximately five times higher and exceeds 12% by the end of the period. Thus, the latter two scenarios turn out to be much less favorable for the country in terms of both the time of crossing the Kyoto level in case R0 (Figure 11) and GDP loss caused by a switch from case R0 to case R1.

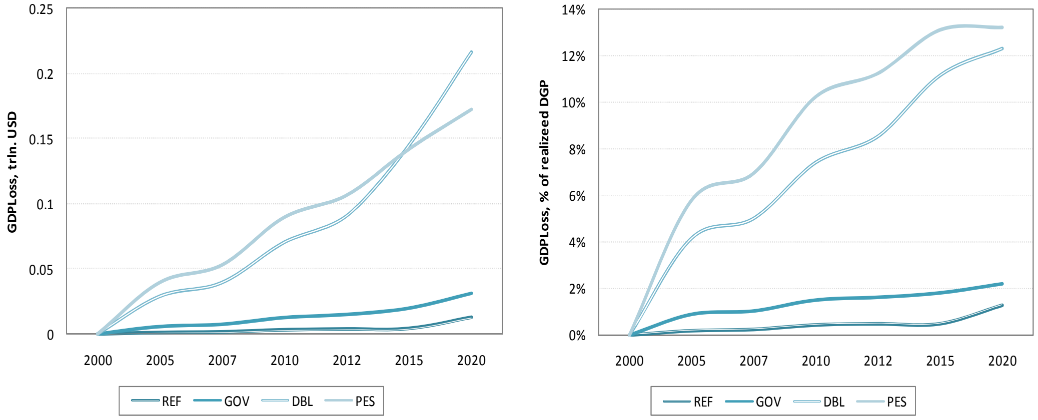


**Figure 12:** Russia's GDP loss, GDPLoss, due to the implementation of domestic abatement measures in trln. year-2000 USD (left) and as a percentage of GDP (right).

## 4.6 Energy sector

In Figure 13, we present the simulated temporal dynamics of Russia's Total Primary Energy Supply (TPES) and the expert forecast for TPES. It is evident that the expert forecast for TPES is much closer to the simulation results for scenarios DBL and PES than for scenarios GOV and REF. Note that the perspectives for Russian power engineering from the viewpoint of the Energy Information Administration and from the viewpoint of Russian experts are essentially different (e.g. the energy supply in 2020 for scenario DBL is almost twice the size of scenario REF) [13, 15].

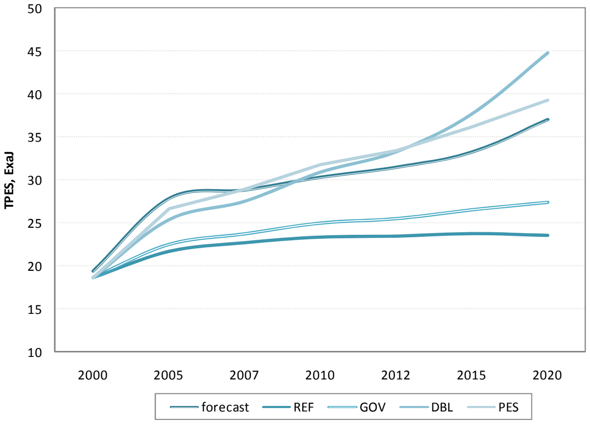


**Figure 13:** Russia's Total Primary Energy Supply (TPES, both electric and non-electric, in EJ), case R0 (no emission constraints).

Analyzing the structure of the energy sector of Russia (Figure 14), we see that at least till 2020, natural gas plays a definitive role in Russia's TPES for all the model scenarios as well according to the expert forecast. For the model scenarios, its share in 2020 is larger than 50%. The share of oil and coal (existing processing technologies) decreases in time for all scenarios. Further calculations demonstrate a sharp fall in shares of these resources, which can be explained by reserve depletion. One can expect that in a time perspective, new coal processing technologies and renewable energy sources will come to the forefront.

Note that the model dynamics presented in Figures 11–14 is optimal (as suggested by MERGE-5I) on the whole time interval; this fact may be a reason for the deviations of the modeling results from the expert forecast at specific moments. However, summarizing the results presented above (see Figures 11–14), we can conclude that the expert forecast holds an intermediate position between the modeling results for scenarios DBL and GOV.

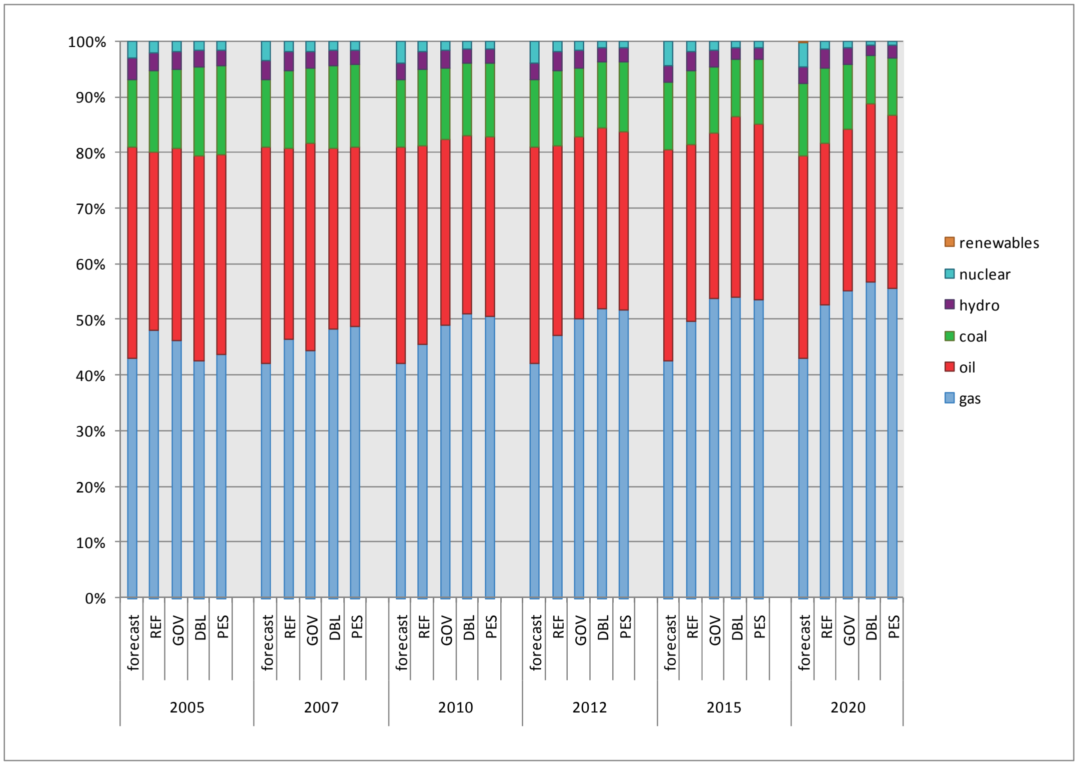


**Figure 14:** Russia's TPES structure (fuel mix) for the four MERGE-5I scenarios in case R0 (no emission constraints).

To study the dynamics of the structure of Russia's energy sector and world-regional primary-energy exports by Russia, we choose scenario GOV, which, on the one hand, reflects the Russian governmental forecast for the country's economic development, and on the other hand, as follows from aforementioned, is close to the expert estimates.

MERGE-5I suggests two energy categories – electric energy and non-electric energy. According to the basic model scenario, REF, global electricity demand grows approximately sixfold in the 21st century – from 49 EJ in 2000 to almost 300 EJ in 2100. This corresponds to an average annual growth rate of 1.8%. Total demand for non-electric energy in the 21st century grows at a significantly slower pace than that for electricity, it roughly triples from 250 to 740 EJ, which corresponds to an average annual growth rate of 1.1%. The modeling results for scenario GOV in case R0 (no emission constraints) are presented in Figures 15, 16.

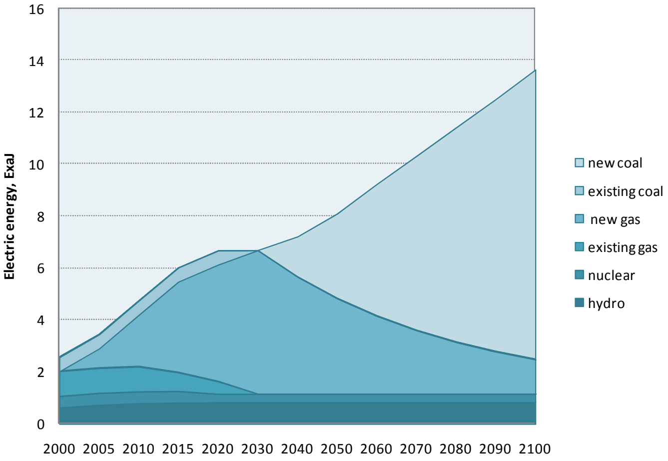


**Figure 15:** The dynamics of the electric energy mix in Russia, scenario GOV, case R0 (no emission constraints).

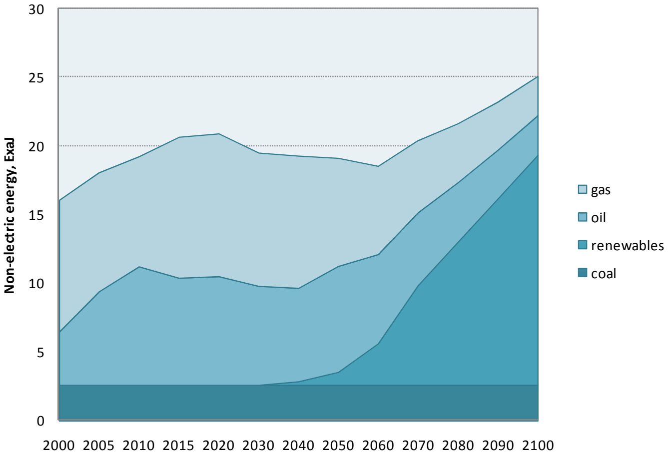


**Figure 16:** The dynamics of the non-electric energy mix in Russia, scenario GOV, case R0 (no emission constraints).

We see from the figures that Russia's electricity demand for the GOV scenario grows from 2.57 EJ in 2000 to 13.64 EJ in 2100 (corresponding to an average annual growth rate of 1.7%), and demand for non-electric energy grows from 16.1 to 25.1 EJ (corresponding to an average annual growth rate of 0.45%). These rates are comparable with those for global demands simulated by MERGE. We can also observe other tendencies similar to the global behavior. The generation of the electricity mix is characterized by hydro and nuclear keeping their absolute contributions at almost constant levels. In the early years, their combined share is significant and it falls below 10% in 2100 (down from 42% in 2000). Natural gas plays a bridging role in Russia. Its contribution to electricity generation peaks around the middle of the century and then declines as a consequence of resource constraints. In the long run, new coal is the fuel of choice for electricity production. Russia's non-electric energy mix rests on a constant base (2.6 EJ) supplied by coal and its thermal uses. Oil and natural gas increase their dominance until the middle of the century, when resource constraints on these two fossil fuels begin to push renewable energy into the market.

The simulated dynamics of world-regional primary-energy (namely, oil and gas) exports by Russia for the GOV scenario in cases R0 and R1 is shown in Figure 17. We see starting from 2055 Russia's gas export in case R1 is smaller than in case R0, which can be explained by the fact that Russia's internal need for a less carbon-intensive fuel increases as a result of the implementation of  the Kyoto constraints.

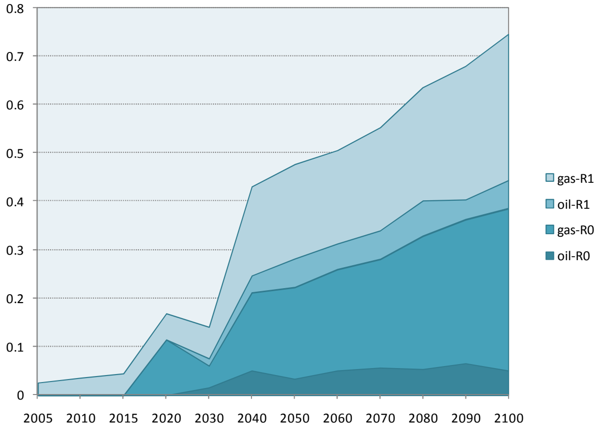


**Figure 17:** Oil and gas exports by Russia in trln. year-2000 USD, scenario GOV, cases R0 (no emission constraints) and R1 (domestic measures for emission constraints).

## 5 Sensitivity Analysis

In our numerical analysis demonstrated in Section 4, the MERGE-5I model is configured based on a set of standard reference parameter values [8, 9], which may, generally, be inaccurate due to various types of uncertainties in data and in experts' estimates. While taking possible inaccuracies of that kind into account, we found that the sensitivity of our estimates to variations is the values of some of the model parameters.

Here we show the results of our analysis of the sensitivity of Russia's GDP loss to the variations of the following major model parameters for Russia:

| | |
|---|---|
| ESUB | capital value share (optimal value share of capital in the capital-labor aggregate) |
| KPVS | electric value share (optimal value share of electricity in the energy aggregate) |
| ELVS | elasticity of substitution between capital-labor and energy aggregates |
| AEEI | energy efficiency improvement rate |
| KGDP | initial capital-to-GDP ratio |
| DEPR | annual depreciation rate |
| INTPR | international oil price |
| OGPD | oil-gas price differential |
| PNREF | reference price of non-electric energy |
| DECF | maximal annual decline factor for the capacities of electric and non-electric technologies |
| NSHF | maximal market share for electric and non-electric technologies |
| REIS | coefficients describing the energy-intensive sectors |
| ABMLT | parameters quantifying restrictions on abatement measures, namely, abatement quantity multipliers |

| | |
|---|---|
| ABLIM | abatement limits at alterative cost levels |
| AppendixZ | limits on sinks forestation |

We varied each parameter value, $V$, within the interval $[0.7V_0, 1.3V_0]$ with a step size of $0.1V_0$, where $V_0$ is the initial reference parameter value. An exception was parameter DECF whose reference value was 0.98. We varied the DECF values within the interval [0.9, 1.0] with a step size of 0.01. Let us note in passing that changing PNREF (reference price of non-electric energy) requires an appropriate change of PEREF (reference price of electric energy) as well.

For each parameter, $V$, and for each time period, $TP$, we find an instant sensitivity of Russia's GDP loss in period $TP$ to variations in $V$, $IS(V,TP)$, as the maximum over all $V_i$s, the perturbed values of $V$ within the chosen grid in the predefined variance interval, of the deviation of the value of Russia's GDP loss in period $TP$ for the perturbed parameter value $V_i$, $GDPLoss(V_i,TP)$, from that for the reference value $V_0$, $GDPLoss(V_0,TP)$, related to the reference value of the country's GDP in this period, $GDP(V_0,TP)$:

$$IS\ (V,TP) = \max_i \frac{GDPLoss(V_i,TP) - GDPLoss(V_0,TP)}{GDP(V_0,TP)}$$

Given an initial time period, $ITP$, and a final time period, $FTP$, we find a global sensitivity of Russia's GDP loss over the time interval $[IP,FP]$ to variations in $V$, $GS(V, [ITP,FTP])$, as the maximum of the absolute values of the instant sensitivity $IS(V,TP)$ overall $TP$s located between $ITP$ and $FTP$:

$$GS\ (V,[ITP,FTP]) = \max_{ITP \le TP \le FTP} |\, IS(V,TP)\,|$$

Figure 18 shows the values for the global sensitivities of Russia's GDP loss over the time intervals $[IP,FP]$ for scenario REF as functions of the final time period, $FP$, running from the initial time period, $IP$, the year 2005, to the year 2100.

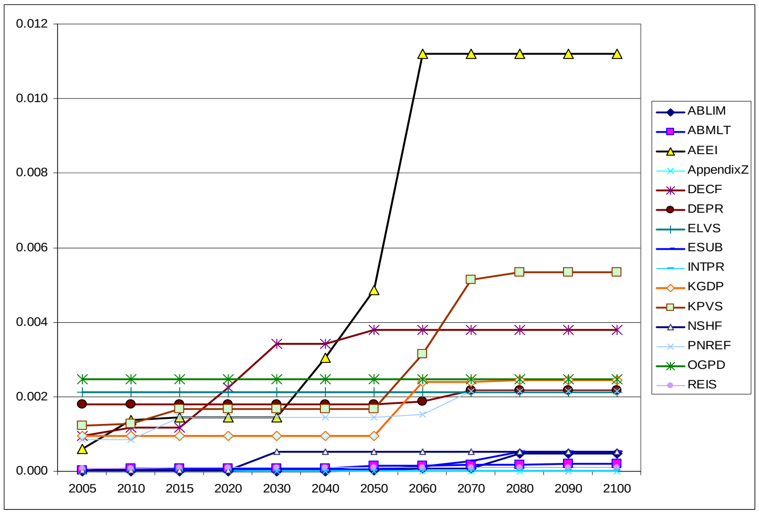
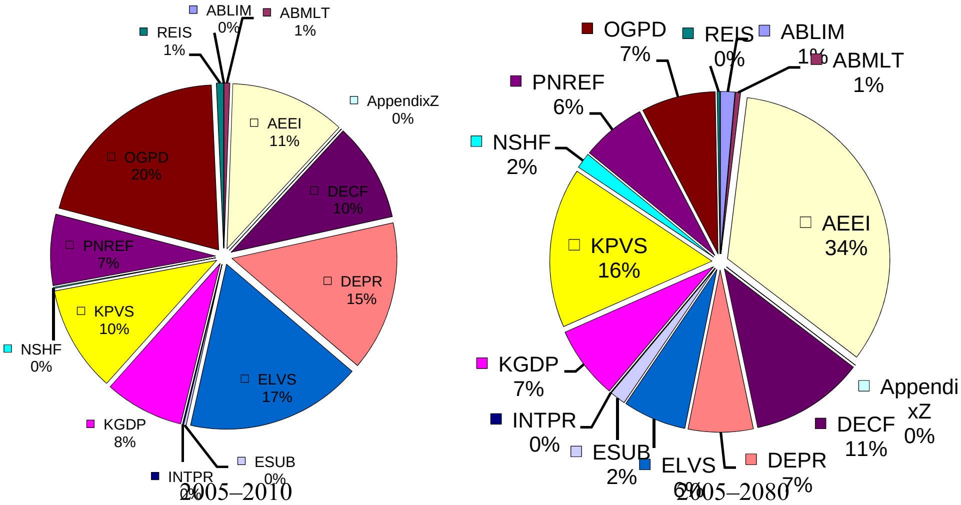


**Figure 18:** The global sensitivities of Russia's GDP loss over the time intervals [*IP*,*FP*] as functions of the final time period, *FP*, running from the initial time period, *IP*, the year 2005, to the year 2100; scenario REF.

Figure 19 displays the shares of the individual global sensitivities of Russia's GDP Loss *GS*(*V*,[*ITP*,*FTP*]) over the time intervals [*ITP*,*FTP*] = [2005,2010] and [*ITP*,*FTP*] = [2005,2080] in the overall global sensitivities on these intervals.



2005–2010 2005–2080

**Figure 19:** The shares of the individual global sensitivities of Russia's GDP Loss over the time intervals 2005–2010 and 2005–2080 in the overall global sensitivities on these intervals; scenario REF.

Figures 18 and 19 show the degree, to which each of the varied parameters influences the values of Russia's GDP loss. We see that Russia's GDP loss is most sensitive to variations in the energy efficiency improvement rate (AEEI) and capital value share (KPVS), whereas it is strongly robust to variations in ABLIM, ABMLT, Appendix Z, INTPR, ESUB, NSHF and REIS. The latter robustness property reveals the constraints that may not be binding for the country.

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