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Nuclear energy may help to overcome the restrictions on economic growth posed by climate change mitigation policies

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Abstract. This paper presents an analysis of available options of restructuring of energy sector within the broader context of economic development without undermining the global climate.

Such restructuring involves active implementation of emission free energy sources which ensure sustainable generation of electricity of standard quality in a climate-friendly way. Using available statistical data, the authors analyzed the dynamics of global energy consumption in relation to the level of economic development. **The hypothesis of saturation of energy demand during the transition to post-industrial economic development has been confirmed**. Saturation of energy demand creates opportunities for a wide scale utilization of innovative ecological methods of climate stabilization and environmental restoration. Restructuring of energy sector in environmentally-safe manner can be especially important in the conditions of fast economic growth of the world's largest developing economies (China and India). Economic growth in these countries is currently characterized by a rapid increase in energy consumption and greenhouse gas emissions. This paper provides quantitative estimates of the investments required for stabilization of global climate under the projections of future energy demands over the next three decades.

The proposed scenario of restructuring of energy sector can be economically feasible, and it is quite likely that electricity in the future will be mainly generated from renewable energy sources and nuclear energy. The numeric estimates and the analysis presented in this paper can be used in formulation of climate stabilization policies in a rapidly growing global economy.

Introduction. The transition to a post-industrial economy in the developing countries requires removing economic barriers and increasing the rate of energy consumption. Increasing energy demand during the transition period creates the risk that the climate-based greenhouse gas (GHG) emission caps are exceeded globally. The current structure and patterns of energy generation and consumption have been largely formed by economic development of China and India. The transition of these countries to the post-industrial energy saturation will be largely completed by 2050s. Until that time, their development will be associated with rapid increase of energy consumption. In order to conform to the strategic goals of long-term climatic stability, it is crucially important to reduce per capita GHG emissions by 50%, and this goal requires developing of emission–free energy production technologies in the current era of growing energy-intensive economy. The analysis of correlations among economic development and modern technologies of energy production and consumption provides a method to estimate the parameters and feasibility of future structure of global energy balance under the requirements to preserve the stability of earth's climate.

The development of energy networks on the basis of renewable energy sources (RES), wind and solar energy, sets up a number of technological and organizational tasks for the managers of local energy production facilities. The reliability and flexibility of standardized energy supply networks which utilize RES and serve the consumers beyond the local level will require development and implementation of powerful energy storage facilities to maintain continuity and avoid possible gaps in the energy production networks. Such energy-storing networks are 'smart' because they allow utilizing RES in a centralized and sustainable manner.

Nuclear energy appears to be most efficiently adapted to the current centralized power supply network which connects power generation facilities with the numerous consumers of energy. The sufficiency of the resource base of large-scale nuclear energy generation facilities is projected for hundreds of years, and it will rely on the industrial technology of closed-loop nuclear energy cycles [1]. Such technology combines the reactors on fast neutrons and thermal neutrons.

GHG emissions may be radically reduced on a global scale if the basic “backbone” nuclear power plants coexist with the traditional hydrocarbon energy generation networks during the transition of the developing economies to post-industrial development, while their local energy demands are predominantly met with RES.

Current trends in energy consumption and GHG emissions. During the transition to post-industrial economy, energy consumption linearly increases with GDP. Deviations from the linear dependency indicate that the relative input of materials in the production function decreases (“dematerialization of economy”) and the structure of per capita consumption changes as the well-being of the population increases. Such deviations indicate the conditions for technological and economical innovation. The current economic policy priorities shift towards knowledge-intensive technologies, leading to accelerated development of services in education, health care provision, and management.

The changes in energy intensity and accompanying GHG emissions during the transition to post-industrial economy have been reported in several studies of economic indicators and per capita GDP (Fig.1) [2-7].

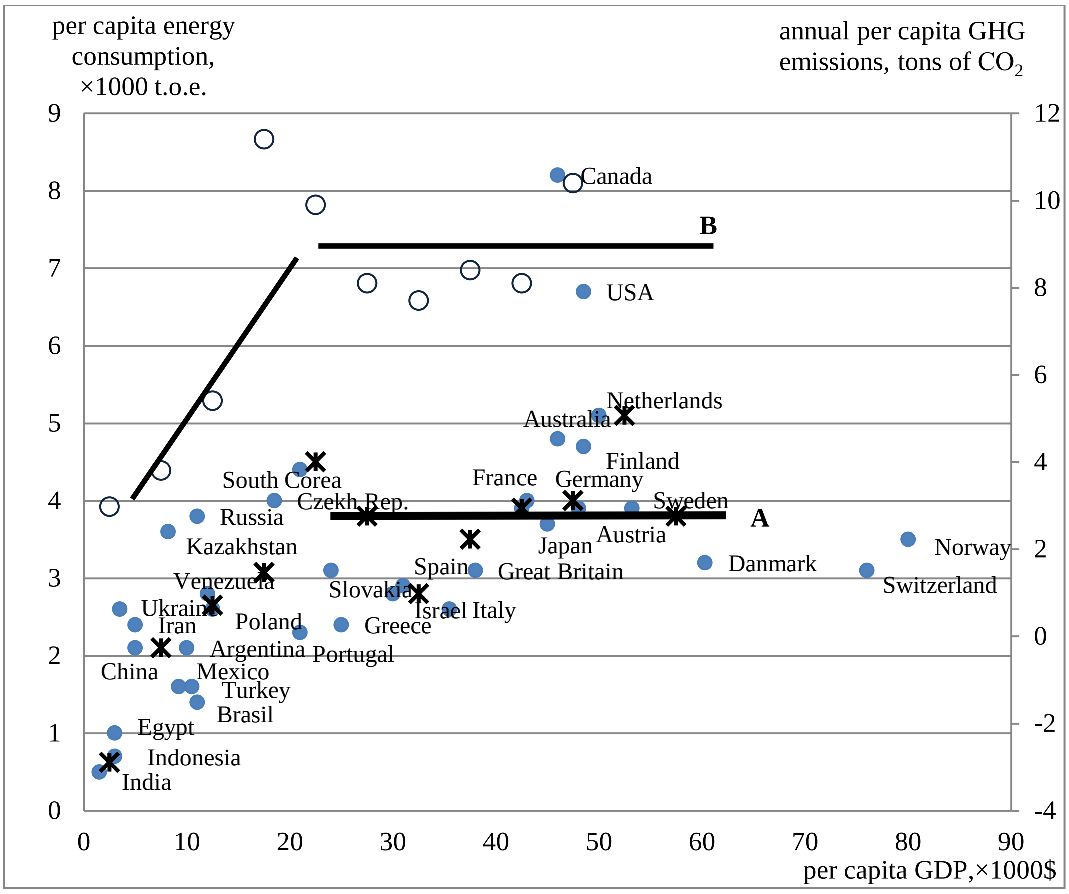

Figure 1. A: The distribution of per capita GDP and the regression model of changes in annual per capita energy consumption (thousand tons of oil equivalent); B: the regression model of changes in GHG emissions.

*) denotes per capita energy consumption and °) denotes per capita GHG emissions of per capita GDP. The county data were averaged within each $5000 interval of per capita GDP.

The post-industrial domination of services in GDP structure is reached at per capita GDP of 20,000-22,000 $. After this threshold, the relative share of services in GDP stays constant at 55–60% and economy grows faster than energy consumption (and accompanying GHG emissions). This is called energy saturation [5], and the growth in GDP beyond this point can be achieved with stabilized energy consumption. If the current trends in economic development continue, nearly all largest energy consuming countries, which constitute more than 60% of global population, will reach post-industrial stage of development by the middle of the 21st Century.

Global stabilization of energy consumption is partly caused by a downward trend in population growth in the post-industrial economies. Family planning is influenced by the costs of education and the number of school-years needed to increase (or maintain) the attained level of well-being. The projected global energy consumption will reach 19-21 gigatons of oil equivalent (Gt.o.e) by the turn of the 21st Century, if the above estimates hold true and the population growth follows the scenario outlined in [2]. This is nearly twice as much as the current level of global energy consumption.

The dynamics of GHG emissions generally reflects the changes in energy consumption as the economy grows, taking in account the structure of energy consumption in each individual country (Figure 1B). The climate stabilization goal requires that the share of emission-free energy sources reach 40-45% of total energy balance by 2050s, to ensure energy-sufficient economy in the post-industrial world, and to meet the abovementioned GHG emission reduction target.

Nuclear energy and CO2 emission reductions. The required reductions of emissions of greenhouse gases should be achieved in the conditions of further growth of energy consumption during the transition to a post-industrial economy. Nuclear energy technologically coexists with the traditional generation from fossil fuels, which creates the need to increase the share of nuclear energy in global energy balance, with the goal to reduce carbon emissions in the energy sector.

The development of other types of emission-free energy sources and the provision of reliable and continuous supply of energy of standard quality will require radical changes in the existing infrastructure of energy distribution and consumption. Systemic and large-scale exploitation of RES which convert solar, wind and hydro-energy to electricity leads to fragmentation of the network structure. Utilization of RES is only possible with the extensive network of energy accumulation devises, which becomes the main functional feature of spatially distributed power generation, with a stable power output. Under these assumptions, the share of RES in energy balance may reach 15-20%.

The estimated cost of capital investments per unit of installed power generation capacity is greatly influenced by the choice of the structure, scale and technology of the projects in energy sector. The estimates of the investment costs in RES projects are highly volatile. The authors summarized these estimates after reviewing the published reports of ETA, the Institute of Energy Research of Russian Academy of Sciences [9] and the number of commercial organizations (Table 1).

Table 1. Costs per unit of installed capacity

Energy sources	Nuclear	Natural gas	Coal	Wind	Solar	Network energy storage devises
EUR per kW of installed capacity	1570	570	1000	715-1 000	1000 - 1450	1000 – 1860

The meaningful comparisons of investment costs should include the development of logistic infrastructure, including seaports, railways, pipelines, etc. Such categories of costs are comparable to power generation costs in the traditional fossil fuel-based energy.

RES (wind and solar generation) are widely used at the local level of power supply. On the regional level, utilization of RES requires investing in the network power storage devises (SmartGrid), which doubles the associated investment costs (Table 1). Such devises are needed to ensure a reliable supply of high-quality electricity. Another barrier to widespread implementation of RES in the regional power grids comes from the limited number of recharge cycles: the modern Li-ion storage batteries can only work for five years in the modern power grids.

Nuclear energy can provide a viable long-term solution for the problem of depleting energy resources for hundreds of years. A closed-loop technology of utilization of nuclear energy is currently available as a combination of fast neutron reactors and thermal neutron reactors. Nearly 100% utilization of energy of fission of natural Uranium in the electric power grids in Russia, France, Japan and India can be attained by years 2020-2025.

The required 50% reduction in the anthropogenic per capita GHG emissions can be achieved if the following structure of global energy balance is reached by 2050s: 40% share of traditional generation of electricity from fossil fuels; 40% share of basic nuclear energy stations; 20% share of solar, wind and small hydro-power plants which serve predominantly the local and off-grid customers.

An increase in the share of nuclear energy up to 40% of the world energy balance will require installation of 2300 GW of nuclear power generation capacities. This would secure the attainment of climate-justified reductions of GHG emissions and attract about 7.5-8 trillion USD of investments in the development of nuclear energy until the turn of this Century. This amount of investments is equivalent to 10% of today's global GDP. The required reductions of carbon intensity of electricity generation can be implemented if the currently available nuclear power technologies are transferred to the developing countries which have the highest rates of GDP growth.

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