# FORESIGHT
## AND STI GOVERNANCE

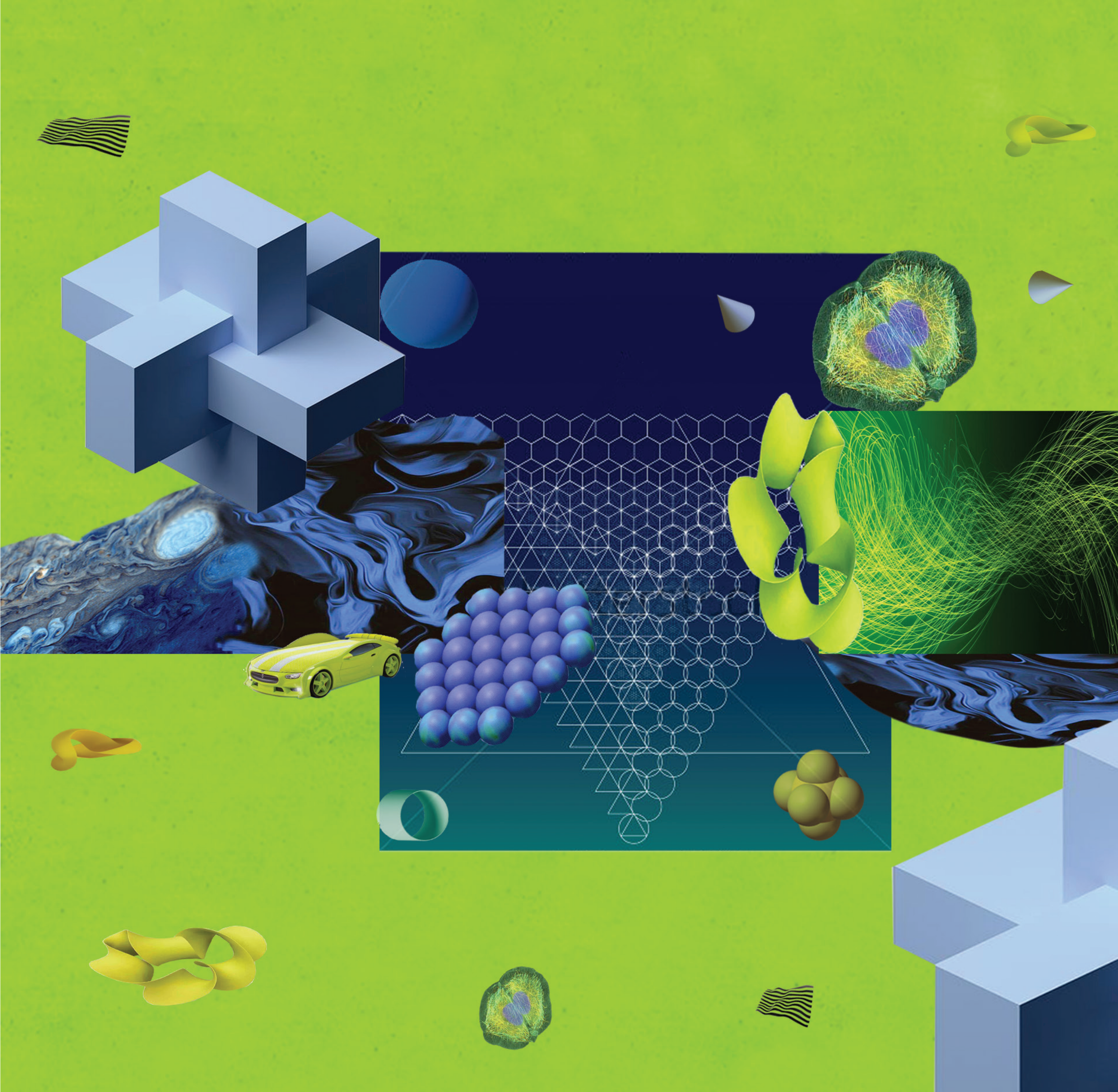
JOURNAL OF THE NATIONAL RESEARCH UNIVERSITY HIGHER SCHOOL OF ECONOMICS

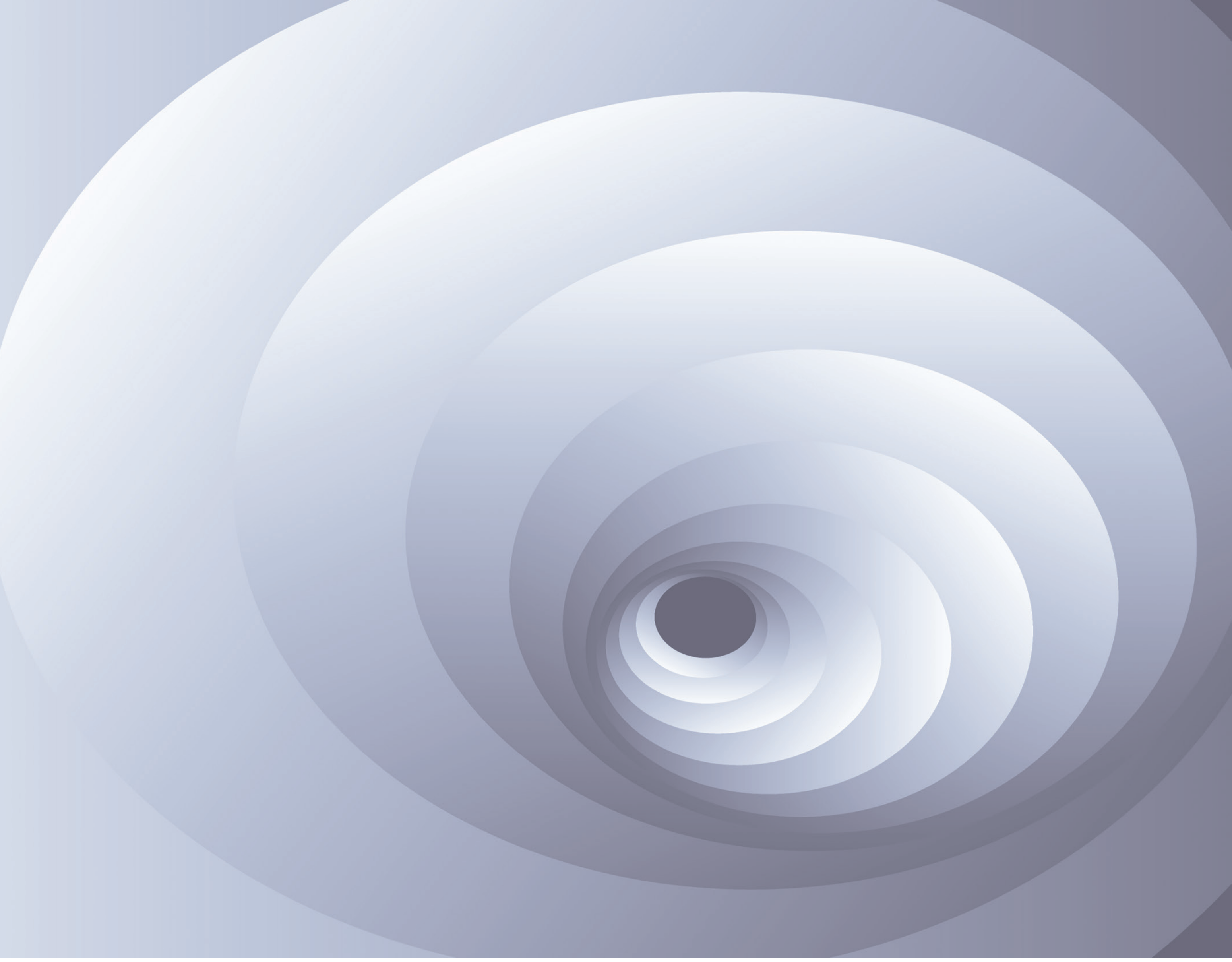
ISSN 2500-2597

2018
Vol.12 No 4

SPECIAL ISSUE

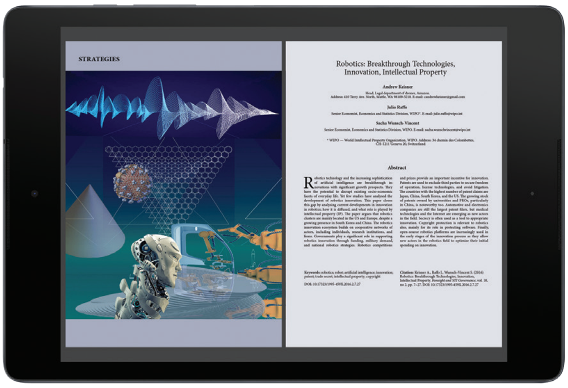
# FUTURE OF ENERGY







FORESIGHT
AND STI GOVERNANCE
JOURNAL OF THE NATIONAL RESEARCH UNIVERSITY — HIGHER SCHOOL OF ECONOMICS
FORESIGHT
2016. vol. 10. No. 2

STRATEGIES
Robotics: Breakthrough Technologies, Innovation, Intellectual Property
Abstract

# ABOUT THE JOURNAL

*Foresight and STI Governance* is an international interdisciplinary peer-reviewed open-access journal. It publishes original research articles, offering new theoretical insights and practice-oriented knowledge in important areas of strategic planning and the creation of science, technology, and innovation (STI) policy, and it examines possible and alternative futures in all human endeavors in order to make such insights available to the right person at the right time to ensure the right decision.

The journal acts as a scientific forum, contributing to the interaction between researchers, policy makers, and other actors involved in innovation processes. It encompasses all facets of STI policy and the creation of technological, managerial, product, and social innovations. *Foresight and STI Governance* welcomes works from scholars based in all parts of the world.

Topics covered include:

- Foresight methodologies and best practices;
- Long-term socioeconomic priorities for strategic planning and policy making;
- Innovative strategies at the national, regional, sectoral, and corporate levels;
- The development of National Innovation Systems;
- The exploration of the innovation lifecycle from idea to market;
- Technological trends, breakthroughs, and grand challenges;
- Technological change and its implications for economy, policy-making, and society;
- Corporate innovation management;
- Human capital in STI;

and many others.

The target audience of the journal comprises research scholars, university professors, post-graduates, policy-makers, business people, the expert community, undergraduates, and others who are interested in S&T and innovation analyses, foresight studies, and policy issues.

*Foresight and STI Governance* is published quarterly and distributed worldwide. It is an open-access electronic journal and is available online for free via:
https://foresight-journal.hse.ru/en/

## INDEXING AND ABSTRACTING

WEB OF SCIENCE™ CORE COLLECTION EMERGING SOURCES CITATION INDEX

SCOPUS™

RePEc RESEARCH PAPERS IN ECONOMICS

SSRN

ProQuest

GENAMICS™ JOURNALSEEK

EBSCO

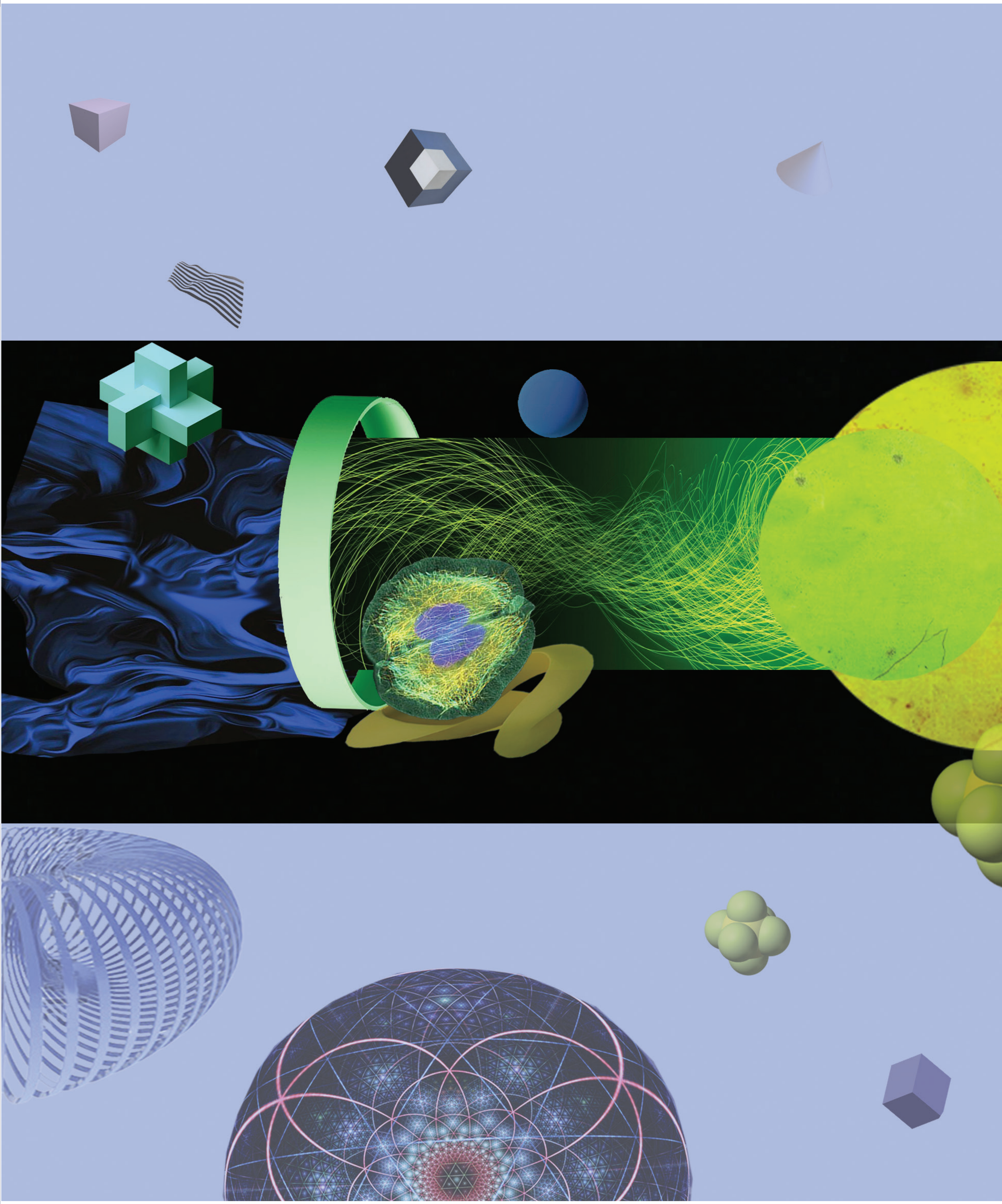
Academic Search Premier

OAJI .net Open Academic Journals Index

# CONTENTS

## SPECIAL ISSUE
## "FUTURE OF ENERGY"

**Vol. 12 No 4 2018**



# New Energy Sources, Technologies, and Systems: The Priority of Social, Climate, and Environmental Issues

**Jürgen-Friedrich Hake**
Professor, j.-f.hake@fz-juelich.de

Institute of Energy and Climate Research –IEK, Forschungszentrum Jülich, Wilhelm-Johnen-Straße, 52428 Jülich, Germany

**Liliana Proskuryakova**

Director, National Contact Centre for International Academic Mobility, lproskuryakova@hse.ru

Institute for Statistical Studies and Economics of Knowledge at the National Research University Higher School of Economics (HSE ISSEK), 11 Myasnitskaya street, Moscow, 101000, Russian Federation

## Abstract

The introductory article to the special issue "The Future of Energy" is devoted to promising areas of development of the global energy complex, the assessment of their contribution to overcoming global challenges, and ensuring sustainable development. The trends under consideration differ significantly in the rate of evolution. Prospective development trajectories present both opportunities and risks specific to the fuel and energy complex of particular countries. Success in using emerging advantages and leveling threats depends upon a combination of internal and external factors, including the choice of public policy measures and the effectiveness of their implementation.

**Keywords:**
new energy sources; technology evolution; global challenges; trends; sustainable development; state energy policy

**Citation:** Hake J.-F., Proskuryakova L. (2018) New Energy Sources, Technologies, and Systems: The Priority of Social, Climate, and Environmental Issues. *Foresight and STI Governance*, vol. 12, no 4, pp. 6–9. DOI: 10.17323/2500-2597.2018.4.6.9

The growing demand for energy in the context of social, climatic, and environmental constraints requires new energy sources. Among a multitude of factors that shape the future development of our energy systems are the volatility of energy prices, the ongoing and expected technological breakthroughs, and geopolitical shifts. These uncertainties compel decision-makers and researchers to look into the upcoming developments in an attempt to foresee and forecast such changes, master the trends, and take over new markets.

Among the technological areas being developed, **thermonuclear fusion** has the highest potential. Despite the delays and the high costs, the ITER remains the most promising nuclear fusion project; the results are expected in the medium to long term. The reactor's launch and operation will allow one to test the viability of the suggested engineering solutions and to assess economic feasibility of their commercialization. If the research turns out to be successful, ITER-based technological solutions may be implemented at nuclear fusion reactors [*Rosanvallon et al.*, 2018]. The deployment of fourth-generation reactors is expected after 2030. The advantages of this approach include the development of a system comprising not only a reactor, but facilities for the disposal (recycling) of spent nuclear fuel, resulting in higher reliability and safety [*Lake*, 2002; *Grape et al.*, 2014]. New multipurpose nuclear energy systems will generate heat and power. The main uncertainty factor here is the project costs affecting their competitiveness with other types of power generation. International cooperation and an interdisciplinary approach to energy research are among the most important success factors.

Before the invention of hydrogen fuel cells, the application of **hydrogen** for energy-related purposes was limited by low profit margins, high explosion hazards, and a lack of economically viable storage and distribution systems. Hydrogen fuel cells provided a solution for all these problems. Hydrogen has a very high energy density and is safe in mixtures with liquids, which makes its transportation possible via already existing liquid fossil fuel distribution networks. Also, hydrogen fuel cells allow for storing large volumes of electricity and make it available to users not connected to the grid. The possibility and time required to overcome the barriers hindering the large-scale application of hydrogen remain uncertain: insufficient safety and durability of fuel cells and hydrogen storage systems; the lack of a decentralized infrastructure that would make hydrogen cars attractive to consumers; and the high costs of electrolyzers and hydrogen production [*Haseli*, 2018].

The technology for the extraction of **geothermal energy** from hot dry rocks has been developed in Russia for decades: research and development projects have been completed and the systems have entered the demonstration phase. They are based upon technologies for the extraction and use of heat accumulated in the hot dry rocks of the earth's crust to generate affordable power and heat with stable adjustable parameters to provide a steady energy supply in remote and poorly developed regions of the country, as all those areas that have a power deficit. The existing solutions are fully based upon equipment that was produced in Russia and tested at Russian industrial enterprises. Research centers, universities, and industrial companies participated in the development of geothermal energy systems, the experimental version of which may be applied as early as 2016-2020, and large-scale industrial application is expected in 2020-2025 and onwards. This clean energy resource is attractive because of the low energy production costs, close to zero emissions, and an opportunity to recuperate excessive heat (through establishing a closed-cycle system) [*Cui et al.*, 2017; *Huang et al.*, 2018].

Researchers have been working on increasing the efficiency of **solar energy** use as early as in the 1940s, when it was suggested that an automated space station be launched to redirect solar energy to Earth using microwaves or laser beams [*Asimov*, 1967]. Today India, China, the United States, and Japan are developing their own satellite-based robotic solar power stations that would wirelessly transfer huge volumes of clean renewable energy to Earth. The main barrier hindering the construction of such stations is the high costs of space launches required to place the satellites into orbit. Accordingly, the first such space-based solar power plant is estimated to cost up to $20 billion. Taking into account the declining space launch costs due to competition by private companies, this estimate may be revisited [*Matsumoto*, 2002; *Potter*, 2008].

**Dark matter**[1] remains the least researched potential energy source. This work is currently at the basic research stage. Experiments to discover this matter are conducted at the LHC proton accelerator at the European Organization for Nuclear Research (Switzerland). The potential for using dark matter as an energy source for spacecraft on long missions is being discussed [*Liu*, 2009]. If relevant hypotheses are confirmed, a unit of dark matter mass could emit 5 billion times more energy than a mass unit of dynamite [*Casalino et al.*, 2018].

The works published within the special issue of the *Foresight and STI Governance* "The Future of Energy" discuss in detail these and other aspects of energy technology development.

The article by **Daniel and Jennifer Sklarew** assesses the potential contribution of future energy systems to the achievement of sustainable development goals (SDGs) approved by the UN in 2015 [UN, 2015] that

[1] According to one of the hypotheses, the visible mass of the Universe accounts for about 5% of common matter; 70% is "vacuum energy", and 25% is dark matter – matter that is invisible, does not emit either light or other electromagnetic waves and does not huddle when affected by gravity [*Redd*, 2017].

address social concerns and security (resilience) issues [*Schlör et al.,* 2018], affordability, environmental and climate friendliness, particularly by means of the combined use of water, energy, and agricultural resources [*Märker et al.*, 2018]. Particularly, the 7th SDG directly addresses global energy challenges: ensuring universal access to affordable, reliable, and modern energy services; substantially increasing the renewable energy share in the global energy mix; and doubling the global rate of improvement in energy efficiency. Multiple other SDGs are also directly and indirectly related to the most pressing energy issues around the globe [*AIQattan et al., 2018*]. Importantly, the SDGs go beyond the public good: they could be very relevant for businesses, in particular, through the application of various sustainability frameworks [*Muff et al.,* 2017].

The requirements for energy changed dramatically with the onset of the next technological revolution. This process is discussed in detail in the article by **Sergey Filippov**. Foresight research of trends and technologies in the energy sector are carried out in many countries, particularly in North America, the European Union (EU), and the BRICS countries. Often, they are part of integrated systems of strategic planning at the national and international levels. The results obtained are taken into account in the development of science, technology, and innovation policy [*Proskuryakova* , 2017].

The foresight research methodology has made significant progress over the past ten years. The latest techniques are applied, including big data analysis using elements of artificial intelligence, advanced scenario planning, augmented by Delphi real-time surveys, and more [UNESCO, 2015; *Miles et al.,* 2016]. This topic was developed in the article by **Gilbert Ahamer**, which is dedicated to the formation of a global change database (Global Change Data Base) and its application in Energy Foresight, while the prospects for the wider application of renewables in selected countries were analyzed by **Nurcan Kilinc Ata.**

One of the marked changes that already takes place is the increase in the number of market actors: former consumers have begun playing an active role in energy generation, storage, and trade [*Zafar et al.,* 2018]. Citizens and enterprises are becoming prosumers and generate energy-related user innovations. Power-consuming and internet-connected home and industrial appliances and devices communicate with one another and power suppliers, thus regulating and optimizing their energy consumption without human intervention. The rapid growth of decentralized energy systems, smart grids of various sizes, and the Internet of Energy expansion are the trends that we witness today due to the aforementioned developments [*Hong et al.,* 2018; *Mahmud et al.,* 2018].

Another novelty that citizens in Tokyo, Berlin, Los Angeles, and in other metropolitan areas in Europe, America, and Asia note is the appearance of electric vehicle charging stations and hydrogen fueling stations [ICCT, 2017]. By 2020 the European Union aims to ensure that 10% of the transport *fuel in* every *member* country originates from renewable sources such as *biofuels*. The European producers already offer diesel with up to 7% Fatty Acid Methyl Esters (FAME) (B7) and petrol with up to 5% ethanol (E5). In 2015, the six EU member states with the largest ethanol content (10%) in petrol were Bulgaria, Finland, France, Germany, Lithuania, and Slovenia [European Commission, 2017]. The leading producers of biofuel are the United States and Brazil [RFA, 2018]. Some countries, like Russia, have vast underexplored potential in biofuel production and exports [IRENA, 2017]. Inter-fuel competition on the Russian automobile market is assessed by **Vyacheslav Kulagin et al.**

Despite the available estimates of fossil fuels' undiscovered reserves, it is quite difficult to establish their actual volume. Some forecasts maintain that there is a substantial amount of hydrocarbons and no shortage should be expected in the foreseeable future. The opposite view has also been substantiated in the literature. Whatever the situation may be, estimates of the available reserves serve as an important parameter for planning the development of the energy industry [U.S. EIA, 2015]. Uncertainty regarding the total volume of undiscovered reserves is further increased by the unknown volume of commercially recoverable reserves. The production of unconventional and hard-to-extract hydrocarbons may turn out to be unprofitable. Technologies used for, and the energy intensity of, the extraction, beneficiation, and processing of fossil fuels may also vary greatly. All the above factors directly impact the energy balance. The prospects for unconventional oil extraction are analyzed in the article by **Alexander Malanichev**.

The rates of development of the considered global trends differ. Creating thermonuclear rectors may take decades, while new ways of extracting unconventional oil and gas reserves have already significantly transformed the global energy markets. As soon as the cost and energy technology problems that determine their competitiveness are solved, new developments can provide a breakthrough in various areas of applied research: from energy storage to new materials. Promising paths of development not only open up opportunities, but also pose threats specific to specific countries and their fuel and energy complexes. Success in catching up with the opportunities and combating the threats depends upon a combination of internal and external factors, including the selection of public policy measures and the formation of mechanisms for their effective implementation.

*The research leading to these results received funding from the Ministry of Science and Higher Education of the Russian Federation (project ID: RFMEFI60117X0014).*

## References

AlQattan N., Acheampong M., Jaward FM, Ertem FC, Vijayakumar N., Bello T. (2018) Reviewing the numbers seven and eleven. *Renewable Energy Focus* , vol. 27, pp. 97–110.

Asimov I. (1967) *Is Anyone There? Speculative Essays on the Known and Unknown* , New York: Doubleday.

Casalino A., Rinaldi M., Sebastiani L., Vagnozzi S. (2018) Mimicking and GW170817. *Physics of the Dark Universe* , vol. 22, pp. 108-115.

Cui G., Rena S., Zhang L., Ezekiel J., Enechukwu C., Wang Y., Zhang R. (2017) . *Energy* , vol. 128, pp. 366–377.

The European *Parliament* (2017) *Directive 98/70 / EC for the European Parliament and the Council of Europe* ( COM (2017) 284 final). Brussels: European Commission. Available at: https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX%3A52017DC0284, accessed 10/23/2018.

Grape S., Svärd SJ, Hellesen C., Jansson P., Lindell M.Å. (2014) New nuclear energy systems to support nuclear disarmament. *Energy Policy* , vol. 73, pp. 815–819.

Haseli Y. (2018) Maximum conversion efficiency of hydrogen fuel cells. *International Journal of Hydrogen Energy* , vol. 43, no 18, pp. 9015–9021.

Hong B., Zhang W., Zhou Y. , Chen J., Xiang Y., Mu Y. ( 2018) Energy-Internet-oriented microgrid energy management system architecture and its application in China. *Applied Energy* , vol. 228, pp. 2153-2164.

Huang, W., Cao, W., Jiang, F. (2018) A geothermal energy exploitation. *Energy* , vol. 162, pp. 630–644.

ICCT (2017) *Developing a cell* phone for the transport of *vehicles and vehicles for a vehicle that is a status update*. Available at: https://www.theicct.org/sites/default/files/publications/Hydrogen-infrastructure-status-update_ICCT-briefing_04102017_vF.pdf, accessed 10/25/2018.

IRENA (2017) *Renewable Energy Prospects for the Russian Federation* ( ReMap Working Paper), Abu Dhabi: IRENA.

Lake J.A. (2002) The fourth generation of nuclear power. *Progress in Nuclear Energy* , vol. 40, no 3 - 4 , pp . 301 - 307.

Liu J. (2009) *Dark Matter as with the a the Possible the New Energy for the Source of Future Rocket Technology* ( ArXiv the Paper 0908.1429 [ astro - of ph . Co ]). Available at: https://arxiv.org/abs/0908.1429, accessed 09/19/2018.

Mahmud K., Town GE, Morsalin S., Hossain MJ (2018). *Renewable and Sustainable Energy Reviews* , vol. 82, part 3, pp. 4179–4203.

Märker C., SandraVenghaus S., Hake J.-F. (2018) IIntegrated governance for the food–energy–water nexus – The scope of action for institutional change. *Renewable and Sustainable Energy Reviews* , vol. 97, pp. 290–330.

Matsumoto H. (2002) Research on solar power satellites and Japan. *IEEE Microwave Magazine*, vol. 3, no 4, pp. 36–45.

Miles I., Saritas O., Sokolov A. (2016) *Foresight for Science, Technology and Innovation* , Heidelberg, New York, Dordrecht, London: Springer.

Muff K., Kapalka A., Dyllick T. (2017) The Gap Frame - Translating the SDGs into relevant national business challenges. *The International Journal of Management Education* , vol. 15, no 2, part 2, pp. 363–383.

Potter S., Henley M., Davis D., Born A., Howell J., Mankins J. (2008) *Wireless Power Transmission Options for Space Solar Power* . Paper Presented at NASA International Space Development Conference, Washington, DC, 29 May – 1 June 2008. Available at: https://ntrs.nasa.gov/archive/nasa/casi.ntrs.nasa.gov/20080036588.pdf , accessed 04/23/2018.

Proskuryakova L. (2017) Energy technology foresight in emerging economies. *Technological Forecasting and Social Change* , vol. 119, pp. 205–210.

Redd NT (2017) What is Dark Matter? *Space.com*, 14.11.2017. Available at : https://www.space.com/20930-dark-matter.html, accessed 12.04.2018.

RFA (2018) *Renewable Fuels Association Database* . Available at: https://ethanolrfa.org/resources/industry/statistics/#1454098996479-8715d404-e546, accessed 10/23/2018.

Rosanvallon S., Elbez-Uzan J., Cortes P. (2018) Safety Provisions for the ITER Facility. *Fusion Engineering and Design*, vol. 136, part A, pp. 540–544. Available at: https://doi.org/10.1016/j.fusengdes.2018.03.016, accessed 14.10.2018.

Schlör H., Venghaus S., Hake J.-F. (2018) The FEW-Nexus city index — Measuring urban resilience. *Applied Energy* , vol. 210, pp. 382–392. Available at: https://doi.org/10.1016/j.apenergy.2017.02.026, accessed 09.10.2018.

US EIA (2015) *Annual Energy Outlook 2015 with projections to 2040*, Washington DC: US Energy Information Administration.

UNESCO (2015) *World Water Scenarios to 2050. World Water Assessment Program (WWAP)*, Paris: UNESCO.

UN (2015) *Resolution adopted by the General Assembly on 25 September 2015, A / RES / 70/1* , Geneva : United Nations. Available at: http://www.un.org/ga/search/view_doc.asp?symbol=A/RES/70/1&Lang=E, accessed 10/23/2018.

Zafar R., Mahmood A., Razzaq S., Ali W., Naeema U., Shehzada K. (2018) Prosumer based energy management and smart grid. *Renewable and Sustainable Energy Reviews*, vol. 82, part 1, pp. 1675–1684.

# Integrated Water-Energy Policy for Sustainable Development

**Daniel Sklarew**
Associate Professor, dsklarew@gmu.edu

**Jennifer Sklarew**
Adjunct Professor, jsklarew@masonlive.gmu.edu

College of Science, George Mason University, Fairfax, Virginia, USA

## Abstract

Numerous studies indicate the close interdependence between the water and energy industries, given that energy production is usually characterized by high water consumption while increasing water availability requires significant energy costs. The integration of energy and water policies at the global and national levels is seen as a tool for achieving sustainable development goals. The paper analyzes the opportunities for countries to ensure equal access to clean water and electricity provided by such integration. The case studies of India, Ghana, and Morocco illustrate how to achieve success when applying the nexus approach to water and energy policies.

This study offers unique contributions by providing a pioneering analysis of the relationship between global goals for energy and water access and national governments' abilities to develop synergistic energy and water policies. The proposed approach to integrating energy and water use could be applied to the full range of sustainable development goals and will be crucial for the success of countries in their implementation.

**Keywords:**
electricity access; clean energy; water access; clean water; Sustainable Development Goals; Energy-Water Nexus; natural resource management; United Nations

**Citation:** Sklarew D., Sklarew J. (2018) Integrated Water-Energy Policy for Sustainable Development. *Foresight and STI Governance*, vol. 12, no 4, pp. 10–19.
DOI: 10.17323/2500-2597.2018.4.10.19

The 1992 Rio Declaration established a global consensus that "human beings are at the center of concerns for sustainable development." This agreement, in turn, catalyzed unprecedented international collaboration towards addressing current and future generations' needs and well-being [United Nations, 2015]. Our success hereafter depends upon implementing certain enabling conditions, such as eliminating chronic thirst and providing reliable, clean energy for everyone, everywhere. At the same time, negative externalities, such as harm to other life and climatic instability from our greenhouse gas (GHG) emissions, must be mitigated.

These ends are among the 17 Sustainable Development Goals (SDGs) that United Nations members and their partners in 2015 agreed to realize by 2030 [*Sachs et al.*, 2018]:

1. No poverty
2. Zero hunger
3. Good health and well-being for people
4. Quality education
5. Gender equality
6. Clean water and sanitation
7. Affordable and clean energy
8. Decent work and economic growth
9. Industry, innovation, and infrastructure
10. Reduce inequality
11. Sustainable cities and communities
12. Responsible consumption and production
13. Climate action
14. Life below water
15. Life on land
16. Peace, justice, and strong institutions
17. Partnerships for achieving the above goals

How can these global goals for energy (SDG 7) and water (SDG 6) be achieved simultaneously and universally in the near future? Can we do so without irreparably impairing other ecosystem services (SDGs 13-15) upon which our life and collective prosperity depend?

Neither clean energy nor freshwater are in short supply on a global scale. Solar energy arriving to Earth's surface is some 7,500 times greater than our primary energy consumption of 450 EJ per year [World Energy Council, 2013]. Meanwhile, Lake Baikal in Russia alone contains more than tenfold the freshwater that humanity consumes annually [ILEC, UNEP, 1993; *Cosgrove, Rijsberman,* 2000]. By around 2015, we withdrew about one eighth of all readily available freshwater resources [UN, 2018, SDG 6.4.2]. Thus, our generation's challenge hereafter for both clean energy and clean water is not one of global scarcity, but of global access.

The period of 2000-2015 was a prerequisite with respect to improving this access by 2030. Over those fifteen years, humanity made remarkable strides towards global goals for universal access to clean energy and clean water.

Even as the global population grew by 38% from 2000 to 2015, the percentage of people with access to electric power increased by 10% to 87% [UN DESA, 2017; World Bank, 2018a]. At the same time, a steady 17% of total global energy consumption came from renewable sources – modern bioenergy, geothermal, hydropower, solar and wind, as well as traditional fuelwood and charcoal [World Bank, 2018a]. The net impact upon energy-related greenhouse gas (GHG) emissions was an increase of more than 40% over this period [IEA, 2018]. Thus, at the current development rate, we extrapolate that universal electricity access could be achieved before 2040. By contrast, *clean* energy for all, at least with respect to renewable energy without substantial GHG emissions, still appears generations away.

The World Health Organization/United Nations Children's Fund Joint Monitoring Program recognizes access to clean drinking water is expanding as well [WHO, UNICEF, 2017]. As with electricity, reliable on-site access to water grew by 10 percentage points, from 61% to 71% of the global population, during the 15 year period. An additional 20% of humanity could access "basic" water services (i.e., water from an improved source within a 30-minute round trip). Thus, we project that basic water access for all may be achieved around 2030. At the recent development rate, however, it may be closer to 2060 before all people have safely managed water on their premises.

While development is advancing rapidly, it is not yet at a pace that will sustain all humankind with clean energy and clean water by 2030. Accelerating our transition to clean energy and water systems for everyone, everywhere by 2030 cannot wait for the discovery of new technologies. Instead, we need to identify, emulate, and expeditiously scale-up viable solutions to simultaneously pursue both global goals and do so without further compromising our planet's ecological life support systems. The national case studies below show how an integrated approach to the SDGs for water and energy could provide a viable means for doing so.

The present article aims to guide this pursuit by examining the challenges and opportunities at the energy-water nexus of sustainable development. First, we examine historical sustainable development at this nexus. We then place this development in the context of integration across the scales of governance, from a local to national to international scale, using SDGs 6 and 7 as our framework. India, Ghana, and Morocco provide poignant case studies. Finally, we derive lessons and recommendations for how nations may utilize SDG targets as a means to unify, and thus hopefully expedite, national initiatives for clean energy and clean water for all.

## Sustainable Development at the Energy-Water Nexus

Realizing SDGs for energy and water access is premised upon harmonizing the energy and water policies on a national scale. In some cases, they are already well-aligned. In other cases, further attention to compatibility and integration is still needed to achieve the potential for success at the water-energy nexus by 2030.

Integrated policies recognize that energy and water systems are interdependent. For instance, it can be both energy- and water-intensive to manufacture the technologies needed to extract and refine natural resources for clean power and potable water (e.g., photovoltaic (PV) solar panels, pumps and pipes, wind and water turbines, and so on).

The United Nations attributes about 15% of global water withdrawals to energy production [UNESCO, 2018]. Accessing energy uses water in upstream energy resource collection processes and electricity production (e.g., [IEA, 2013; *Mekonnen et al.,* 2015; *Tan, Zhi,* 2016]). Interdependencies on the upstream side of energy production focus on the consumption and pollution of water to create fossil fuels, nuclear fuel, and corn-based biofuel. Thus, each of these primary energy sources include substantial quantities of "embodied water."

Water is also vital for large hydroelectric and thermoelectric power generators. Among the most water-intensive electricity generation technologies are concentrated solar power and coal-fired generating facilities with carbon capture and sequestration capabilities [*Macknick et al.,* 2012]. Such power plants consume the most water when using a recirculating cooling system. By contrast, non-thermal renewables, such as wind and hydropower, have the lowest water consumption factors. These renewable technologies have minimal embodied water and thus would be preferable in areas of ongoing water insecurity.

Thus, clean water also includes "embodied energy." Energy-water nexus studies focus on how accessing water uses energy for the diversion of flow upstream, purification and desalination, water temperature control, and wastewater treatment (e.g., [*Kahrl, Roland-Holst,* 2008; International Energy Agency, 2016; *Copeland, Carter,* 2017]). Some of these studies also explicitly highlight the relationship between these interdependencies and climate change (e.g., [*Rothausen, Conway,* 2011; *Pittock et al.,* 2015]), which threatens to disrupt historical water cycle patterns.

The global nature of the energy-water nexus supports the need for the integration of international goals for energy and water. Weitz, et al. assert that formulating integrated water, energy, and food SDGs will make them more cost-effective, while reducing the conflict between them and contributing to sustainable resource use [*Weitz et al.,* 2014]. Yumkella and Yillia posit the need for "a more coordinated approach to sustainable resources management, which in turn requires concerted action in all spheres of influence and at all levels of implementation" [*Yumkella, Yillia,* 2015, p. 8]. They urge the commitment of resources to implement concrete actions that realize the energy-water nexus approach. Weinthal, when analyzing the Sustainable Development Goals in global environmental politics, asserts that "Whereas the [UN Millennium Development Goals (MDGs) for 2015] were largely silent on such nexus issues, the implementation of the SDGs requires scholars to examine the implementation of the SDG for water in relation to the SDGs for energy" [*Weinthal,* 2018, p. 43].

Our Table 1 here responds to Weinthal's critique by aligning common national policy goals at the energy-water nexus with corresponding SDG targets [UN General Assembly, 2017]. The symmetry we present across energy and water targets provides a clear framework for governments to pursue more integrated policy-making with respect to universal access, natural resource quality, use efficiency, cooperation, and technology transfer. Policy integration at the energy-water nexus is also promoted by other SDG targets (e.g., 6.5, 6.6, 9.4, 12.2, 12.5, 13.2 and 15.9).

National attention to the energy-water nexus echoes this call for integrated policies, but largely without linking these national efforts to global frameworks. Many country case studies suggest the need for better national level coordination across energy and water policies and their implementation. For example, Scott, et al., employ case studies of US regions to examine the institutional and policy issues of the energy-water nexus on local and national scales [*Scott et al.,* 2011]. They highlight the importance of institutions in solving nexus challenges. Fan, et al.'s study of potentially synergistic energy, water, and climate policies in China suggests a similar need for an integrated policy framework [*Fan et al.,* 2018]. Using Israel as a case study, Teschner, et al., posit that integrated transition management of energy and water systems should recognize these systems' interdependencies [*Teschner et al.,* 2012]. Siddiqi and Anadon further propose integrated assessments of energy use in water-intensive industries in the Middle East region [*Siddiqi, Anadon,* 2011].

Pittock, et al. examine the role of national governance structures in policy and investment decisions to address the energy-water nexus and its relationship to climate, framing such policies and investments as

Table 1. **The UN Sustainable Development Goals for 2030 Provide Nations with Specific Policy Targets at the Energy-Water Nexus**

| National Policy Goals | 2030 Energy SDG Targets | 2030 Water SDG Targets |
|---|---|---|
| Universal access to affordable energy and water | 7.1 Ensure universal access to affordable, reliable, and modern energy services | 6.1 Achieve universal and equitable access to safe and affordable drinking water for all |
| Energy and water quality | 7.2 Substantially increase the share of renewable energy in the global energy mix | 6.2 Improve water quality by reducing pollution, eliminating dumping and minimizing the release of hazardous chemicals and materials, halving the proportion of untreated wastewater, and substantially increasing recycling and safe reuse globally |
| Energy and water-use efficiency | 7.3 Double the global rate of improvement in energy efficiency | 6.3 Substantially increase water-use efficiency across all sectors and ensure sustainable withdrawals and supply […] |
| International cooperation and technology transfer | 7.4 Enhance international cooperation to facilitate access to clean energy research and technology […] | 6.4 Expand international cooperation and […] support to developing countries in water- and sanitation-related activities and programs, including […] technologies |

*Source*: [UN General Assembly, 2017].

necessary for sustainable development [*Pittock et al.,* 2015]. Hussey and Pittock assert that national-level policy fragmentation is exacerbating challenges facing energy and water sectors [*Hussey, Pittock,* 2012]. They cite an *Ecology and Society* special feature dedicated to case studies that examine energy and water system interdependence, identifying the lack of and need for integrated policies and highlighting barriers to such integration. The authors of the studies in the special feature examine cases of energy-water interdependence challenges in the United States, the Netherlands, Italy, and elsewhere [*Stillwell et al.,* 2011; *Bonte et al.,* 2011]. These challenges parallel those introduced above, including water consumption by thermal power plants, GHG emissions from electricity use in water treatment plants, risks of underground thermal energy storage to groundwater supplies, and energy and water use in biomass production [*Bonte et al.,* 2011; *Dalla-Marta et al.,* 2011]. Based on a comparison of water consumption from energy production for over 150 countries, Spang, et al., also emphasize the need for improved data quality and reporting standards on a global scale [*Spang et al.,* 2014].

A few studies link the need for national and local integration of energy and water policies with nations' abilities to meet international goals (e.g., [*Rasul,* 2016; *Biermann et al.,* 2017; *Rivera et al.,* 2017]). Rasul asserts that in South Asia, "poor sectoral coordination and institutional fragmentation have triggered an unsustainable use of resources and threaten the long-term sustainability of food, water, and energy security in the region and also posed challenges to achieving the Sustainable Development Goals (SDGs)" [*Rasul,* 2016, p. 14]. Biermann, et al., assert that the SDGs' success depends upon institutional factors such nations' formalization of commitments, integration of sectoral policies, and "effective translation between global and national aspirations" [*Biermann et al.,* 2017, p. 28]. Rivera et al. examines the potential for the application of global sustainability standards at the city level, using Bogota, Colombia, as a case study. Their findings: global standards and goals can help to legitimize local actors and sustainability programs [*Rivera et al.,* 2017]. These studies highlight the need for an examination of how the energy and water SDGs intersect with national and local-level integration of energy and water policies.

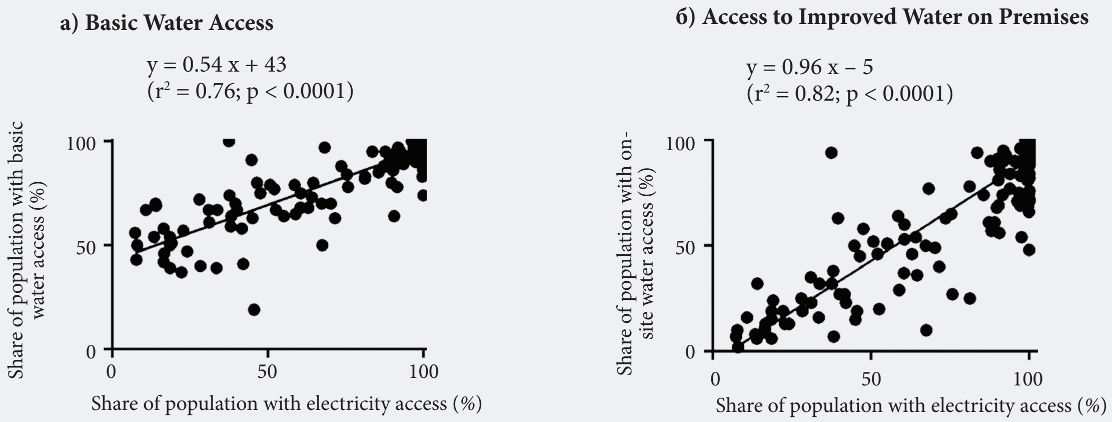
## National and Local Focus on Mutually Reinforcing Energy-Water Initiatives

At the local to regional levels, activities that advance energy access may as a byproduct reduce water access and vice-versa. Mining and refining fossil and nuclear fuels, irrigating biofuel crops, and thermoelectric power generation, as noted above, all consume and/or pollute nearby water. Conversely, energy is expended to desalinate, treat, pressurize, and pump water across human settlements.

Nonetheless, when the SDGs were launched in 2015, access to water and electricity were rising in tandem across the 191 reporting nations. Figure 1 charts this relationship. In nations with minimal access to electricity, only about 40% of residents had basic water access, Figure 1(a). Meanwhile, Figure 1(b) shows that access to improved water on one's own premises was nearly absent until electricity reached 5% or more of a nation's population. Thereafter, both basic and on-site water access converged upon 100% of people in nations with the greatest electricity access. These data support the notion of the advantages offered by conscientious, coordinated policy-making and the implementation across sectors and scales of government influencing the energy-water nexus.

Ways to leverage energy and water system interdependencies tend to focus on either the local, national, or regional level (e.g., [*Servert et al.,* 2016; *Sklarew, Sklarew,* 2017; *Kumar et al.,* 2018]). Al-Kharaghouli, et al. examine site-specific parameters for desalination powered by wind and solar in the Arab region [*Al-Kharaghouli et al.,* 2009]. Servert, et al. analyze the synergies of solar-powered desalination of seawater for mining operations in Chile, focusing on cost comparisons with desalination using grid-supplied electricity [*Servert et al.,* 2016]. Sklarew and Sklarew note the critical role of local and national institutional support in enabling the deployment of hydropower micro-turbines that can produce electricity from water flowing through drinking water pipes or storm water mitigation systems [*Sklarew,*

Figure 1. **Percentages of People with Access to Electricity versus Different Kinds of Water Access (%)**




*Note*: data provided across 191 nations reporting in 2015.
*Sources*: [UNICEF, 2017; World Bank, 2018b].

*Sklarew,* 2017]. Others have reviewed the local nexus benefits of "floatovoltaics," tethered photovoltaic power plants floating atop reservoirs and other surface waters [*Kumar et al.,* 2018; *Sengupta,* 2017].

None of these studies explain how global frameworks for energy and water systems should combine with local, national, and regional policy frameworks. The existing work does establish a foundation for examining ways in which global goals for energy and water access *could* influence national governments' abilities to develop synergistic energy and water policies. The current study offers a first analysis of this relationship and the implications for policies that leverage energy-water complementarities and interdependencies to advance universal access to both clean electricity and clean water in the future.

## Influence of Sustainable Development upon Governments' Energy and Water Policies

A quarter century passed between the drafting of the Rio Declaration and the establishment of the United Nations Sustainable Development Goals in 2015. During this period, the portion of humanity with access to electricity rose 17 percentage points, from 71% to 87% [World Bank, 2018b]. Meanwhile, access to improved water sources increased by 15 percentage points, from 76% to 91%.

Many nations that demonstrated greater progress on electricity access and clean water access from 1990 to 2015 accomplished these advances largely through separate initiatives to address energy and water. The top twenty performers included India and Ghana. Both nations are on track to achieve SDGs for energy and water access *before* 2030. Their governments' programs reveal the global need for linkages between energy and water access policies to more efficiently and effectively improve electricity and clean water access hereafter.

Over 25 years, basic water access expanded from 70% to 94% of Indians [*Ritchie, Roser,* 2018]. The portion with electricity access doubled, from 43% to 88% [World Bank, 2018a]. To accomplish these advances, India's government established the Rajiv Gandhi National Drinking Water Mission in 1991, which emphasized community participation in improving clean water access. The Bharat Nirman Program, established in 2005, shifted access from wells and boreholes to pipe systems. Concurrently, to promote increased electricity access, the Indian government implemented programs for grid connections and projects for renewable energy expansion. Connectivity programs have included a 1989 single-point connection program for households below the poverty line, as well as the Electricity Act of 2003, which obliged the government to supply electricity to rural areas through grid extension and distributed generation. Following this mandate, in 2005 the government established the Rajiv Gandhi Grameen Vidyutikaran Yojana (RGGVY) rural electrification program [*Nath,* 2011].

Ghana provided water access to one third more of its people in 2015 (89%) than in 1990 (56%). At the same time electricity access climbed remarkably from 24% to 76%. To achieve this progress, the Ghanaian government based its water policies on the year 2000's successful MDG target to halve the proportion of people without access to safe drinking water by 2015 [United Nations, 2015]. Ghana's improvements to water access have relied upon groundwater technologies such as boreholes, hand-dug wells, and community pipe systems. Meanwhile, electricity access improvements have emerged from large-scale and small-scale grid connections, as well as off-grid solar installations. In 1988, the government collaborated with the utilities agencies to connect all of the regions and districts in the country through the National Electrification Programme. In 1989, the government established the National Electrification Fund and the Self-Help Electrification Programme (SHEP), which offered to connect communities within 20 kilometers of the existing grid. Communities provided the low voltage wooden distribution poles [*Clark et al.,* 2005].

Aligned with SDG targets in Table 1, both the Indian and Ghanaian governments have implemented some integrated policies and initiatives that jointly promote water conservation and electricity access. These policies have also advanced energy-related greenhouse gas emissions reduction goals.

For example, the Indian government initiated national-level renewables projects that do not consume large quantities of water. Investments include large-scale wind power, family biogas plants, and solar streetlights, lanterns, and PV systems. Some of the government's sponsored projects – micro-hydropower plants – leverage existing waterways without contributing to water pollution or consumption [*Arora et al.,* 2010]. After the introduction of the SDGs, Prime Minister Modi announced the Saubhagya Scheme in 2017, with the goal of electrifying all households in India by December 2018 and a budget of $2.5 billion to achieve it [Government of India, 2017]. A slew of related policies also emerged, including several introduced in 2017 to advance the development of mini-grids based on renewable energy. In conjunction with private sector firms, local governments are implementing renewables-based mini-grids, reverse osmosis water purification projects and the floatovoltaics prototype noted above. Several government programs introduced in 2018 promote biomass, wind, and solar power generation as well.

Ghana continues to grapple with electricity access and water security challenges. The Ghanaian government's policies have included a Sustainable Energy for All Action Plan launched in 2012. The plan includes the 2010 goal of 100 percent access by 2020 [Energy Commission of Ghana, 2012]. In 2011, the government passed the Renewable Energy Act to shift electricity generation away from large hydropower production by 2020. The Act established the legal framework for the creation of policy tools such as feed-in tariffs and net metering [IEA, 2014]. In 2013 and 2016, the government implemented, then updated, feed-in tariffs for wind, solar photovoltaics, small hydropower, biomass, biogas, and geothermal power. Following the introduction of the SDGs, Ghana's government implemented a 2018 rollout of a national rooftop solar program aiming to install 200 MW of rooftop solar across the country. Some local Ghanaian projects that leverage energy-water complementarities include solar-powered water pumps as an alternative to piped water.

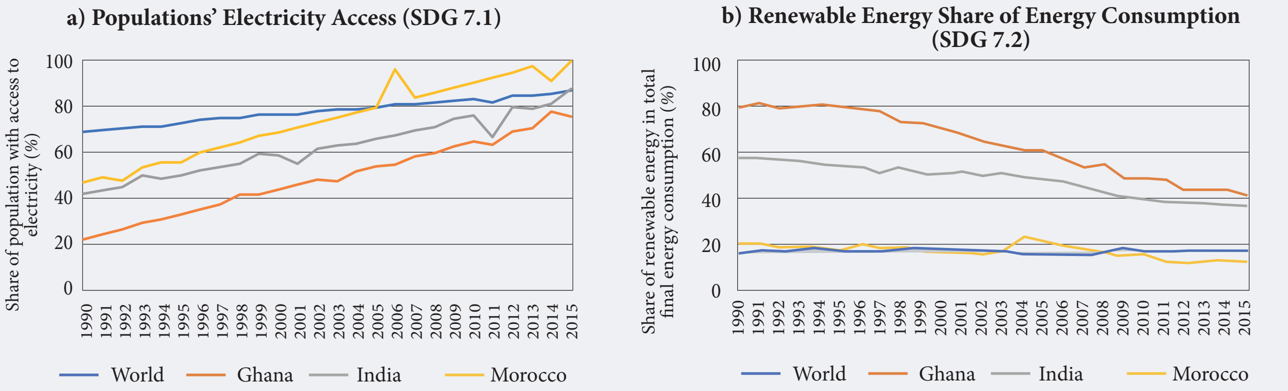
Having achieved universal access to electricity in 2015, Morocco demonstrates how such an accomplishment can help to support water access as well. Moroccans pushed through government policies that began to jointly address clean water and electricity access even before the introduction of the SDGs. Although energy and water policies are handled by separate government offices, some of their policies reflect efforts to coordinate across the single ministry that houses them. Following the launch of the Global Rural Electrification Plan in 1995, the National Office of Electricity aimed to connect most villages to the national grid, while using off-grid renewable energy systems to provide electricity for remote communities. These systems are powered by wind, hydropower, or PV. In 2004, a public-private partnership emerged to develop and manage 15 photovoltaic drinking water pumping systems to serve isolated communities. The government's 2009 Renewable Energy Law provides policy support and a regulatory framework for solar PV, solar thermal, and wind power production and commercialization. In 2015, the government adopted Law 58-15, which introduced net metering for solar PV and onshore wind plants connected to the centralized grid.

To promote clean energy use in irrigation systems, in 2013, Morocco's Ministry of Energy, Mining, Water, and Environment initiated the National Program for Solar Pumping in Irrigation Water Saving Projects. The project aims to reduce butane use by offering grants to small and mid-sized farms to purchase solar pumps for small-scale irrigation [Government of Morocco, 2016]. Following the introduction of the SDG, and Morocco's hosting of the Climate Change Conference of the Parties (COP 22) in 2016, the Moroccan government has focused on advancing the use of solar energy. Morocco's Renewable Energy and Energy Efficiency National Development Agency is working in partnership with the United Nations Development Programme. UNDP has committed "to establish quality standards for solar pumping, advocate for the adoption of photovoltaic pump systems for irrigation and promote investment in renewable energy technologies" [UNDP, 2017a].

## Preparing More Integrated Solutions for Future Energy-Water Development

India, Ghana, and Morocco all have actively and seriously invested in meeting the clean water and electricity needs of their people over the past generation. To varying extents, they are reducing the water embodied in their power production and the energy embodied in their drinking water in order to achieve one (Morocco) or both SDG targets 6.1 and 7.1 for universal access. Still, these nations' leaders and their counterparts elsewhere are not advancing infrastructure at a sufficient pace to ensure all citizens receive "safely managed" water in their own homes by 2030. Furthermore, despite technological advances and price drops, each has substantially *decreased* the share of renewable energy in their energy mix from 1990 to 2015. Figure 2 illustrates that we are still losing ground with respect to sustaining people with clean energy. This has disastrous implications for future climate mitigation (SDG 13), sustainable infrastructure

Figure 2. **1990-2015 Worldwide Trends and Those for Three Case Studies: Ghana, India and Morocco**




*Source*: [World Bank, 2018a].

(SDG 9), and responsible consumption and production (SDG 12) as well. What can be done to turn this trend around?

Nations that continue to struggle to achieve electricity and clean water access can derive lessons from these countries' experiences. India, Ghana, and Morocco demonstrate that the integration of clean energy access and water security policies at the national level can encourage local projects that address local communities' unique electricity and water needs. However, just as these local initiatives require national frameworks to support them, national policies can benefit from supportive global goals such as the SDGs if they are designed to highlight complementarities and minimize conflicts for nations striving to achieve them.

In assessing national-level progress on SDG 7, affordable, reliable, and modern energy for all, the United Nations recognizes that "national priorities and policy ambitions still need to be strengthened to put the world on track to meet the energy targets for 2030" [UN, 2018]. The United Nations Development Programme (UNDP) has committed itself to supporting nations' progress on meeting the SDG goals. The UNDP's 2018-21 Strategic Plan outlines two support platforms through which UNDP will provide such support for the national achievement of integrated policies to meet SDG targets [UNDP, 2017a]. These platforms bridge global and national goals. The country-support platform will "help countries design and carry out integrated solutions, where problems require action across economic, social, and environmental issues" [UNDP, 2017b]. The global development advisory and implementation services platform aims to "provide technical and policy advisory support to country platforms and UNDP country programmes; and support UNDP global knowledge, innovation and partnership-building efforts within the UN development system (UNDS), as well as with international financial institutions (IFIs) and other partners" [UNDP, 2017b].

## Conclusion

If the trends of the past quarter century are a reliable predictor, we find that virtually all of humanity should have access to clean water within a thirty-minute trip from home and back by 2030. Electricity should be essentially universal within a decade after that. Getting both into every home, however, may be yet another generation away.

Doing so will be critical to realizing the promise of sustainable development, i.e., to meet human needs in perpetuity. For instance, Costa et al. [*Costa et al.*, 2009] found that providing rural Ghanaian women such access decreases their "time poverty," providing them more time to pursue paid work. Thus, integrated access to clean water (SDG 6) and clean energy (SDG 7) in homes may ultimately help alleviate poverty (SDG 1). Poverty alleviation is also a primary goal for international agencies like UNDP and the World Bank. Thus, they have a strong interest in expediting the full achievement of SDG 6 and 7 targets by 2030 (if not sooner).

We assert that the integrative energy-water nexus approach should play a central role in accelerating clean energy and clean water access globally. In the most basic sense, this approach entails managing the amount of embodied energy used to develop and deliver clean water and, reciprocally, the quantity of clean water consumed or fouled in order to develop and deliver our energy to us. The energy-water nexus also challenges us to think beyond tradeoffs between energy access and water access. Instead, we seek for both axes of access to continue rising together in "win-win" scenarios (Figure 1). To do so, these interrelated systems must be transformed by government policies that catalyze joint energy-water infrastructure, for example, floatovoltaics on reservoirs, hydropower micro-turbines in water pipes, desalination plants fueled by sewage treatment plant methane, and hydrogen fuel cell batteries that reconstitute clean water from fresh air.

To raise the persistently low portion of renewable energy in our growing energy use (Figure 2), nations need to think intelligently about development along the energy-water nexus. It would not suffice for India to double its 2016 renewable energy supply in two to three years or for Morocco to increase its own from 13% of installed power in 2015 to 42% in 2020 [World Energy Council, 2018]. Their policy and technology choices additionally need to incorporate impacts and opportunities associated with water security and other ecosystem services (e.g., SDGs 13-15).

The framework of the policy goals and SDG targets presented in Table 1 above provides a model for nations to operationalize SDG priorities in national policymaking. SDG targets serve as criteria to evaluate national policies in a more integrated multi-sectoral manner. Still, this set of criteria – affordable access, quality, efficiency and technical cooperation – is illustrative, not normative. Natural resource development agencies are encouraged to adapt or build upon this set in order to create their own framework to facilitate policy integration at the energy-water nexus.

The energy-water nexus scholarship to date has identified the interdependencies on global and national scales, the challenges arising from them, and the need for effective, unified national policies to address these challenges. This study recommends the development of such integrated national policies in the context of existing global frameworks such as the SDGs. Such framing will align national energy and water policies under broader goals, enabling policymakers to recognize conflicts and leverage complementarities. This global framing for national efforts requires coordination between national governments and international agencies such as the UNDP and the World Bank. UNDP has pledged support for national goals. This needs to include education, capacity-building, and tools that can enable national governments to effectively integrate their clean energy and water access policies. UN support for the methodological integration of sustainable development across SDGs targets, as illustrated above for the energy-water nexus, will be critical to nations' success in achieving SDGs targets for 2030 and ultimately realizing sustainable development globally in perpetuity.

## References


Al-Karaghouli A., Renne D., Kazmerski L.L. (2009) Solar and wind opportunities for water desalination in the Arab regions // Renewable and Sustainable Energy Reviews, vol. 13, no 9, pp. 2397–2407.

Arora D.S., Busche S., Cowlin S., Engelmeier T., Jaritz J., Milbrandt A., Wang S. (2010) *Indian Renewable Energy Status Report: Background Report for DIREC 2010* (NREL/TP-6A20-48948, 991558), Golden, CO: National Renewable Energy Laboratory. Available at: http://www.ren21.net/Portals/0/documents/Resources/Indian_RE_Status_Report.pdf, accessed 12.08.2018.

Bieber N., Ker J.H., Wang X., Triantafyllidis C., van Dam K.H., Koppelaar R.H.E.M., Shah N. (2018) Sustainable planning of the energy-water-food nexus using decision making tools. *Energy Policy*, vol. 113, pp. 584–607. Available at: https://doi.org/10.1016/j.enpol.2017.11.037, accessed 25.09.2018.

Biermann F., Kanie N., Kim R. (2017) Global governance by goal-setting: The novel approach of the UN Sustainable Development Goals. *Current Opinion in Environmental Sustainability*, vol. 26–27, pp. 26–31. DOI: 10.1016/j.cosust.2017.01.010.

Bonte M., Stuyfzand P.J., Hulsmann A., Van Beelen P. (2011) Underground Thermal Energy Storage: Environmental Risks and Policy Developments in the Netherlands and European Union. *Ecology and Society*, vol. 16, no 1, article 22 [online]. Available at: http://www.ecologyandsociety.org/vol16/iss1/art22/, accessed 18.12.2017.

Clark A., Davis M., Eberhard A., Gratwick K., Wamukonya N. (2005) *Power Sector Reform in Africa: Assessing the Impact on Poor People* (Report Prepared by the Graduate School of Business, University of Cape Town), Washington, D.C.: World Bank.

Copeland C., Carter N.T. (2017) *Energy-Water Nexus: The Water Sector's Energy Use*, Washington, D.C.: Congressional Research Service.

Cosgrove W.J., Rijsberman F.R. (2000) *World Water Vision: Making Water Everybody's Business*, London: Earthscan Publications.

Costa J., Hailu D., Silva E., Tsukada R. (2009) *The Implications of Water and Electric Supply for the Time Allocation of Women in Rural Ghana* (Working Paper no 59), Brasilia: International Policy Centre for Inclusive Growth, United Nations Development Programme.

Dalla-Marta A., Natali F., Mancini M., Ferrise R., Bindi M., Orlandini S. (2011) Energy and Water Use Related to the Cultivation of Energy Crops: A Case Study in the Tuscany Region. *Ecology and Society*, vol. 16, no 2, article 2 [online]. Available at: http://www.ecologyandsociety.org/vol16/iss2/art2/, accessed 17.10.2018.

Energy Commission of Ghana (2012) *Sustainable Energy for All Action Plan*, Accra: Energy Commission of Ghana.

Fan J.-L., Kong L.-S., Zhang X. (2018) Synergetic effects of water and climate policy on energy-water nexus in China: A computable general equilibrium analysis. *Energy Policy*, vol. 123, pp. 308–317. Available at: https://doi.org/10.1016/j.enpol.2018.09.002, accessed 18.12.2017.

Government of India (2017) *Guidelines for Pradhan Mantri Sahaj Bijli Har Ghar Yojana (Saubhagya)*, Delhi: Ministry of Power, Government of India.

Government of Morocco (2016) *Programme for Large-scale Deployment of Solar Pumping in Irrigation Water Saving Projects*, Rabat: Ministry of Energy, Mining, Water and Environment, Government of the Kingdom of Morocco.

Hussey K., Pittock J. (2012) The Energy–Water Nexus: Managing the Links between Energy and Water for a Sustainable Future. *Ecology and Society*, vol. 17, no 1, article 31 [online]. Available at: http://dx.doi.org/10.5751/ES-04641-170131, accessed 18.12.2017.

IEA (2013) *Renewable Energy Act. Law 13-09*, Paris: International Energy Agency. Available at: https://www.iea.org/policiesandmeasures/renewableenergy/?country=Morocco, accessed 18.12.2017.

IEA (2014) *Renewable Energy Act 2011*, Paris: International Energy Agency. Available at: https://www.iea.org/policiesandmeasures/pams/ghana/name-130043-en.php, accessed 18.12.2017.

IEA (2016) *World Energy Outlook 2016: Water-Energy Nexus*, Paris: International Energy Agency.

IEA (2018) *Global Energy and CO2 Status Report 2017*, Paris: International Energy Agency. Available at: https://www.iea.org/publications/freepublications/publication/GECO2017.pdf, accessed 10.05.2018.

ILEC, UNEP (1993) *Data Book of Lake Environments: A Survey of the State of World Lakes*, Otsu, Japan: International Lake Environment Committee, United Nations Environmental Programme.

Kahrl F., Roland-Holst D. (2008) China's water–energy nexus. *Water Poli*cy, vol. 10, pp. 51–65. Available at: https://doi.org/10.2166/wp.2008.052, accessed 10.05.2018.

Kumar N.M., Kanchikere J., Mallikarjun P. (2018) Floatovoltaics: Towards improved energy efficiency, land and water management. *International Journal of Civil Engineering and Technology*, vol. 9, pp. 1089–1096.

Macknick J., Newmark R., Heath G., Hallett K.C. (2012) Operational water consumption and withdrawal factors for electricity generating technologies: A review of existing literature. *Environmental Research Letters*, vol. 7, article 045802 [online]. Available at: https://doi.org/10.1088/1748-9326/7/4/045802, accessed 17.10.2018.

Mekonnen M., Gerbens-Leenes, P.W., Y. Hoekstra, A. (2015) The consumptive water footprint of electricity and heat: a global assessment. *Environmental Science: Water Research & Technology*, vol. 1, pp. 285–297. Available at: https://doi.org/10.1039/C5EW00026B, accessed 17.10.2018.

Nath A. (2011) India's Progress Toward Achieving the Millennium Development Goals. *Indian Journal of Community Medicine*, vol. 36, no 2, pp. 85–92.

Pittock J., Hussey K., Dovers S. (2015) *Climate, Energy and Water,* New-York: Cambridge University Press.

Rasul G. (2016) Managing the food, water, and energy nexus for achieving the Sustainable Development Goals in South Asia. *Environmental Development*, vol. 18 (April), pp. 14–25.

Ritchie H., Roser M. (2018) *Water Access, Resources & Sanitation* [online]. Available at: https://ourworldindata.org/water-access-resources-sanitation, accessed 10.06.2018.

Rivera J.M., Munoz M.J., Moneva J.M. (2017) Revisiting the Relationship Between Corporate Stakeholder Commitment and Social and Financial Performance. *Sustainable Development*, vol. 25, no 6, pp. 482–494.

Rothausen S.G.S.A., Conway D. (2011) Greenhouse-gas emissions from energy use in the water sector. *Nature Climate Change*, vol. 1, pp. 210–219. Available at: https://doi.org/10.1038/nclimate1147, accessed 10.06.2018.

Sachs J., Schmidt-Traub G., Kroll C., Lafortune G., Fuller G. (2018) *SDG Index and Dashboards Report 2018*, New York: Bertelsmann Stiftung and Sustainable Development Solutions Network (SDSN).

Scott C.A., Pierce S.A., Pasqualetti M.J., Jones A.L., Montz B.E., Hoover J.H. (2011) Policy and institutional dimensions of the water–energy nexus. *Energy Policy*, vol. 39, pp. 6622–6630. Available at: https://doi.org/10.1016/j.enpol.2011.08.013, accessed 15.09.2018.

Sengupta D. (2017) NTPC installs India's largest floating solar PV plant in Kerala. *The Economic Times*, 10.03.2017. Available at: https://economictimes.indiatimes.com/industry/energy/power/ntpc-installs-indias-largest-floating-solar-pv-plant-in-kerala/articleshow/57577004.cms, accessed 28.06.2018.

Servert J., Cerrajero E., Fuentealba E. (2016) *Synergies of solar energy use in the desalination of seawater: A case study in northern Chile*. Paper presented at the SOLARPACES 2015: AIP International Conference on Concentrating Solar Power and Chemical Energy Systems. Available at: https://aip.scitation.org/doi/10.1063/1.4949232, accessed 28.06.2018.

Siddiqi A., Anadon L.D. (2011) The water–energy nexus in Middle East and North Africa. *Energy Policy*, vol. 39, pp. 4529–4540. Available at: https://doi.org/10.1016/j.enpol.2011.04.023, accessed 10.06.2018.

Sklarew J.F., Sklarew D.M. (2017) *Empowering Resilience in Energy and Water Systems: Addressing Barriers to Implementation of Urban Hydroelectric Micro-turbines* (The CIP Report), Fairfax, VA: George Mason University.

Spang E.S., Moomaw W.R., Gallagher K.S., Kirshen P.H., Marks D.H. (2014) The water consumption of energy production: An international comparison. *Environmental Research Letters*, vol. 9, no 10, article 105002. Available at: http://iopscience.iop.org/article/10.1088/1748-9326/9/10/105002/pdf, accessed 15.06.2018.

Stillwell A.S., King C.W., Webber M.E., Duncan I.J., Hardberger A. (2011) The Energy-Water Nexus in Texas. *Ecology and Society*, vol. 16, no 1, article 2 [online]. Available at: http://www.ecologyandsociety.org/vol16/iss1/art2/, accessed 19.07.2018.

Tan C., Zhi Q. (2016) The Energy-water Nexus: A literature Review of the Dependence of Energy on Water. *Energy Procedia*, vol. 88, pp. 277–284. Available at: https://doi.org/10.1016/j.egypro.2016.06.154, accessed 24.08.2018.

Teschner N., McDonald A., Foxon T.J., Paavola J. (2012) Integrated transitions toward sustainability: The case of water and energy policies in Israel. *Technological Forecasting and Social Change*, vol. 79, no 3, pp. 457–468.

UN (2015) *Millennium Development Goals Report 2015*, New York: United Nations Publications.

UN (2018) *The Sustainable Development Goals Report 2018*, New York: United Nations Publications.

UN DESA (2017) *World Population Prospects: The 2017 Revision* [online]. Available at: http://www.un.org/en/development/desa/population/publications/database/index.shtml, accessed 10.05.2018.

UN General Assembly (2017) *Work of the Statistical Commission pertaining to the 2030 Agenda for Sustainable Development* (A/RES/71/313). Available at: http://ggim.un.org/documents/A_RES_71_313.pdf, accessed 24.08.2018.

UNDP (2017a) *Country programme document for the Kingdom of Morocco*, Geneva: United Nations.

UNDP (2017b) *United Nations Development Programme Strategic Plan 2018–21*, Geneva: United Nations.

UNESCO (1992) *The Rio Declaration on Environment and Development,* Paris: United Nations Educational, Scientific and Cultural Organization.

UNESCO (2018) *The United Nations World Water Development Report 2018: Nature-Based Solutions for Water*, Paris: United Nations Educational, Scientific and Cultural Organization.

UNICEF (2017) *Drinking Water* [online database]. Available at: https://data.unicef.org/topic/water-and-sanitation/drinking-water/, accessed 10.05.2018.

UNSD (2018) *SDG Indicators* [online database]. Available at: https://unstats.un.org/sdgs/indicators/database, accessed 10.05.2018.

Weinthal E. (2018) The Sustainable Development Goals in Global Environmental Politics. *A Research Agenda for Global Environmental Politics* (eds. P. Dauvergne, J. Alger), Cheltenham: Edward Elgar Publishing, pp. 39–49.

Weitz N., Nilsson M., Davis M. (2014) A Nexus Approach to the Post-2015 Agenda: Formulating Integrated Water, Energy, and Food SDGs. *SAIS Review of International Affairs*, vol. 34, pp. 37–50. Available at: https://doi.org/10.1353/sais.2014.0022, accessed 17.09.2018.

WHO, UNICEF (2017) *Joint Monitoring Programme for Water Supply, Sanitation and Hygiene. Program Data* [online database]. Available at: https://washdata.org/data accessed 10.06.2018.

World Bank (2018a) *Tracking SDG7: The Energy Progress Report 2018*, Washington, D.C.: World Bank. Available at: https://trackingsdg7.esmap.org/, accessed 22.10.2018.

World Bank (2018b) *World Bank Development Data Group Open Data* [online database]. Available at: https://data.worldbank.org/, accessed 10.06.2018.

World Energy Council (2013) *World Energy Resources 2013 Survey*, London: World Energy Council.

World Energy Council (2018) *World Energy Trilemma Report 2018*, London: World Energy Council.

Yumkella K.K., Yillia P.T. (2015) Framing the Water-Energy Nexus for the Post-2015 Development Agenda. *Aquatic Procedia*, vol. 5, pp. 8–12. Available at: https://doi.org/10.1016/j.aqpro.2015.10.003, accessed 17.09.2018.

# New Technological Revolution and Energy Requirements

**Sergey Filippov**
Director, fil@eriras.ru

Energy Research Institute of Russian Academy of Sciences, 31–2, Nagornaya str., Moscow, 117186, Russian Federation

## Abstract

The new technological revolution is radically changing the shape and development conditions of the world energy industry. The increase in demand for energy, alongside with changes in its structure, require the development of breakthrough technologies and the supply of new energy resources, which is associated with significant costs. To optimize them, a timely anticipation of the expected socio-economic changes and future energy requirements is needed.

This paper analyzes the possible implications of the new technological revolution for the global and domestic energy industries. It evaluates current and prospective trends, such as changes in energy consumption due to growing demand from the service sector and households while reducing the needs of large-scale industry, digitalization, the formation of "mobile", "portable" energy, and so on.

Russia will maintain demand for a centralized energy supply while increasing the demand for distributed generation and cogeneration with the involvement of renewable energy sources, smart grid technologies, and other solutions. The current structure of the national fuel and energy complex is vulnerable to the large-scale electrification of transport and decarbonization of world energy.

**Keywords:** scientific & technological progress; new technological revolution; post-industrial economy; post-industrial society; energy; energy demand; requirements to energy; energy technology; distributed energy; mobile energy

**Citation:** Filippov S. (2018) New Technological Revolution and Energy Requirements. *Foresight and STI Governance*, vol. 12, no 4, pp. 20–33. DOI: 10.17323/2500-2597.2018.4.20.33

A new technological revolution is unfolding in the world. Numerous and impressive scientific and technological advances and the mass marketing of radically new, innovative products provide ample evidence of that. These changes cannot help but affect the energy sector, because only new energy technologies and carriers will allow one to meet growing demand. Developing them requires significant resources, so anticipating forthcoming changes in the economic and social fields along with the future requirements for the energy industry becomes a particularly relevant task.

Forecasting has always been based upon analyzing previous experience, in this case – previous technological revolutions and their impacts upon the energy industry. Numerous attempts have been made to scientifically explain technological revolutions and conceptualize technological development. Some of the proposed concepts include the wave principle, technological structures, innovation waves, technological ages, technological cycles, and so on [*van Gelderen,* 1913; Šmihula, 2011; *Zvorykin et al.*, 1962; *Kondratiev*, 1989; *Glaziev*, 1993]. Researchers tried to explain the high rate of scientific and technological progress (STP) [*Šmihula,* 2011; *Kurzweil*, 2005; *Vinge*, 1993] by increased access to education and scientific information as well as economic demand for innovations [*Koh, Leung*, 2003]. The results of the above studies help create visions of the possible future economy and society.

At the same time the currently observed S&T transformations are so rapid and profound, analyzing their consequences for the global and Russian energy industries requires additional effort. A deeper understanding of these processes would help reduce uncertainty associated with the industry's technological development and successfully deal with the so-called "black swan" challenges, unexpected events leading to significant consequences [*Taleb,* 2007]. Events of this kind cannot be ruled out even in such a highly inertial industry as energy. Regular monitoring, careful analysis of S&T advances including thoses in related areas, and the development of technological foresight techniques specifically for the energy industry [*Filippov, Dilman,* 2018] would help identify black swans in a timely manner. System analysis methods also remain relevant and are successfully applied to accomplish various research objectives [*Kaganovich et al.,* 1989], along with physical, technical, and at a later stage, feasibility analyses. The development of these approaches may benefit from the application of procedures for the timely detection of emerging technologies through ongoing scanning of the R&D sector using advanced analytical techniques such as big data analysis.

The technological revolution in question is particularly important for the Russian energy industry, as a major exporter of energy resources (about 50% of the total domestic output). Accordingly, we are primarily interested in how the new technological revolution affects global energy demand and international fuel markets, though it does not make estimating possible changes in domestic demand irrelevant either.

Power generation plays key role in the technological development of the energy industry as the world's largest fossil fuel consumer. In Russia, its share amounts to about 40% of natural gas and 50% of coal. Fuel industries also have to take into account developments in the electric power industry. The transport sector is the main consumer of oil-based motor fuels, but in the foreseeable future it could experience a fundamental transformation. Therefore, the roles of electricity and motor fuels in the future economy deserve special attention.

## Technological Revolutions: Previous Experience

Over the course of the previous three centuries, the world has experienced several technological revolutions that have affected various areas of human activities and led to various other, industry-specific revolutions: industrial production, energy, transport, agriculture, and other fields. The massive application of revolutionary innovations resulted in the rapid development of relevant industries, explosive growth of productivity, and energy intensity. In most cases, technological revolutions led to the emergence of new technological structures in relevant industries, which were usually defined as sets of closely interconnected, in physical and functional terms, technologies and relevant control systems.

Technological and industrial revolutions are frequently seen as one and the same, despite the fact that quite different interpretations exist, based on chronology, technological content, and actual results [*Toffler*, 1970; *Toffler, Toffler*, 2006; *Bell*, 1973]. And, of course, all industrial revolutions were radically different in terms of their energy component.

The first industrial revolution (the first half of the $17^{th}$ to early $19^{th}$ centuries) amounted to moving from manual labor to machine production. It was based on the wide application of steam and steam engines in industry; the substitution of charcoal with coal coke in metallurgy; and the conversion of rail and marine transport to steam engines. It allowed for mechanizing basic technological processes, sharply increasing labor productivity, cutting production and transportation costs, and stepping up product exchanges. Underground mining and the marketing of high-calorific coal eliminated limitations on where major production facilities could be located. Coal became the basic fuel.

The second industrial revolution (the second half of the $19^{th}$ to early $20^{th}$ centuries) involved the emergence of conveyor belt production, leading to the mass manufacture of affordable products. This created strong demand for "high-density" energy carriers (electricity and oil-based fuels) and new powerful engine types (electric motors and internal combustion engines (ICE)) and promoted the development of high-tonnage organic chemistry, first of all coal-based. Electric motors allowed for achieving high labor productivity even at small-capacity facilities. ICEs promoted the further development of rail and water transport and the emergence of new transport modes including road-based and aviation. As a consequence, the geography of raw material supplies and product sales greatly expanded while population mobility increased. Advances in chemistry allowed one to significantly extend the range of available materials for industrial production and everyday use as well as led to the "green revolution" in agriculture due to the application of mineral fertilisers and weed and pest killers. Thus, basic industries of the present-day economy emerged: industrial production, transport, and agriculture.

The third industrial revolution (the mid-20th to early 21st centuries) is associated with flourishing mass production, the mass application of electronics, the automation of technological processes, computer equipment, information and communication technologies (ICT), the emergence of the internet, and the beginning of the digital revolution [*Toffler, Toffler*, 2006]. ICT has permeated all spheres of production activities and everyday life. Their application allowed one to radically improve production processes, cut costs, increase end products' quality, and change work conditions and organization. Large corporations gained competitive advantages, international division of labor became more efficient, leading to the globalization of production and the emergence of global product and service markets, including those for energy resources, power engineering equipment, oil services, and so on [*Toffler, Toffler*, 2006; *Bell*, 1973].

Colossal changes happened in the social sphere. Urbanization, mobility, and motorization have all accelerated. The concentration of industrial production fuelled the growth of cities, leading to the emergence of megacities. Standards and quality of life greatly improved and lifestyles have radically changed. The service sector grew by an unprecedented amount, with medicine, education, and entertainment becoming the key industries of the modern economy. The most important attribute of the consumer society [*Baudrillard*, 1998] that emerged due to the above factors was the unbridled growth in demand for energy, primarily in deeply processed forms such as motor fuels and electricity.

The response to the exponential growth of energy consumption and concentration of industry was the construction of powerful generating facilities, the concentration of energy production at large companies (mining, processing, and generating ones), the construction of major electrical grids and pipeline networks, and the development of a radically new energy source – the fission of heavy unstable uranium nuclei, i.e., nuclear energy.

## The New Technological Revolution and its Specific Features

The next technological revolution will again be based upon new management and control systems, materials, production and transportation technologies, frequently closely interconnected, and thus creating significant synergies when applied together. Technological innovations affect all industries of the economy, among other things by changing demand for energy and requirements for energy carriers and thus ultimately changing the very vector of the energy industry's development.

### Scientific Advances and their Possible Consequences

In any technological revolution, the development of new technologies and materials is based upon scientific advances, first of all, in basic research. When a new technological structure is emerging, the trend towards the accelerated creation of new knowledge and its commercialization, is likely to remain in place. Mathematics, material science, robotics, and especially life sciences (physics, chemistry, molecular and cellular biology, neurobiology, bionics, etc.) will play a major role here. Advances in genomics may lead to the creation of synthetic life [*Richardson et al.*, 2017] and the development of neuroinformatics will help to speed up the creation of neural networks and neurocomputers [*Gorban*, 1998]. Hopes associated with the further development of ICT and information security systems are based upon the creation of quantum computers and the development of quantum cryptography techniques [*Ladd*, 2010].

The hypothesis concerning the approaching era of technological singularity is quite popular in the literature: a relatively short period of time will see an extremely high rate of scientific and technological development [*Kurzweil*, 2005; *Vinge*, 1993]. Humans and machines are expected to merge together at that time, through the integration of machine technologies and the human biological "shell", thus blending people's mental abilities with the potential of artificial intelligence, leading to the emergence of cybernetic organisms (cyborgs) and their communities. Further advances in life sciences may lead to the creation of androids – synthetic humanoid live organisms, or humanoid robots. High-quality chemical energy carriers that will serve as power sources for them, among other things for energy-intensive components such as artificial muscles which will make androids mobile and enable them to do useful work. Glucose could be suitable for this purpose – the most universal energy source for metabolic processes of all live organisms including humans. Glucose is a high-energy substance (about 15.7 MJ/kg) and is efficiently produced from readily available raw materials (hydrolysis of starch or cellulose), or from $CO_2$ using photosynthesis, as it occurs naturally. However, it is difficult to fully appreciate the real prospects of creating (and the risks associated with the mass introduction of) such innovations today and their impact upon the subsequent development of human civilization, economy, society and, in particular, the energy industry.

**New Control Systems**

New control systems (commonly referred to as cyber-physical ones) are expected to blend the physical and digital worlds into a virtual reality using smart network technologies and sensors [*Lee*, 2008; *Khaitan, McCally*, 2014]. Embedded systems should play a key role in this process, controlling a large number of various objects in real time on the basis of high-performance algorithms, microprocessor equipment, micro- and nano-size electric and biomechanical actuators, smart meters, and (bio)sensors embedded into the controlled objects [*Heath*, 2003; *Elk*, 2016]. This will make management and control smarter, i.e., it will minimize the need for human involvement due to AI-based analytical, prognostic, and decision-making functionality.

Communications based on next-generation mobile networks with data transfer rates measured in tens of gigabits per second will play a major role, making device-to-device (D2D) communication universally available. Smart machine-to-machine (M2M) interfaces and automated identification technologies, in particular radio frequency identification (RFID), will be widely applied. Extended RFID functionality due to integrated sensors will allow one to manufacture smart products. Increased computational power and data storage capacity, combined with more efficient algorithms for processing large volumes of diverse data and ensuring its security (such as blockchain technology, etc.) will also be among the major accomplishments of the digital revolution.

Embedded systems can monitor the state of various objects (products) in real time, predict their key characteristics such as the remaining service life, determine the optimal mode of interaction with the environment, and decide whether to continue using the object, develop (upgrade), or decommission it. In the latter case, the object will be automatically sent for processing or disposal at the right time, with its valuable components (metals, plastics, etc.) recycled in the most efficient way possible to minimize the consumption of non-renewable natural resources (including energy), and any other negative environmental impact.

Ensuring an adequate level of cybersecurity may turn out to be a real problem with the mass application of new control systems. The conventional objective of data protection in this case is supplemented with a new one that is an order of magnitude more complex: protecting the control systems themselves. Unauthorized covert penetration (which would not involve significant energy or financial costs) would be fraught with colossal damage, all the way down to complete destruction of a facility; an example is the destruction of centrifuges at the Iranian uranium enrichment plant.

The new (fourth) industrial revolution which is based upon embedded systems (it is occasionally referred to as Industry 4.0 [*Hermann et al.*, 2015]) is expected to dramatically increase productivity and reduce the need for natural resources, including energy. New industry will emerge on the basis of numerous new technologies, mainly "nature-like" ones, i.e., environmentally and climate friendly – though this term should not be taken literally. A wide range of conditions apply in nature, from "soft" (the evolution of living organisms, mineralization, leaching, etc.) to extreme ones (such as mineral formation at ultrahigh temperatures and pressure, etc.), along with numerous impacts (mechanical, physical-chemical, electro-physical, etc.).

Prospective production technologies include the following:

- bioengineering ("live production systems")
- machine-free shaping and forming techniques based on additive technologies and surface engineering by subjecting substances to a variety of high-energy impacts (radiation in various frequency ranges, high-intensity electric and magnetic fields, high-energy ions, etc.), leading to radically improved product quality, increased productivity, and resource efficiency;
- smart industrial (bio)robots for the final assembly of components in unmanned production cycles;
- high-performance separation of gaseous and liquid media;
- highly sensitive sensors for comprehensive 4D control of physical fields' parameters, properties, and chemical composition of various media and biological objects ("technical vision", "electronic nose", etc.);
- micro- and nano-size electromechanical systems and miniature power sources for them, "biochemically powered" biomechanical devices ("artificial muscle"), etc.

"Smart" factories and "lights out" production facilities are expected to emerge on the basis of the above technologies, i.e., those that do not require human involvement (and therefore do not need lighting either), which are fully automated and robotic and allow one to manufacture products by individual orders at low costs. This will cut down on the unnecessary use of natural resources (which is typical of the present-day mass production: much of the output remains unsold and subsequently is simply recycled). Smart factories and products will allow one to fully control the entire production cycle, from product development to disposal. In a more distant future, it would become possible to create "self-replicating machines" (*Freitas, Merkle*, 2004), "growing" the necessary components, and assembling them "on site" using advanced biotechnologies.

Revolutionary changes are also expected in the scope of the agricultural technology platform. Robotization of tillage, improved cropland monitoring systems (among other things, using drones and spacecraft), the development of new sensor types to monitor the state of soil and crops, all of these advances fit into the concept of precision agriculture [*Zhang et al.*, 2002; *McBratney et al.*, 2005; *Balabanov et al.*, 2013; *Yakushev*, 2016]. Robots, adjustable-spectrum lighting systems, and transparent structures with high thermal resistance open new opportunities for round-the-year hothouse farming. Precision agriculture combined with robotized animal farming make up the smart farming concept. In the longer term, the mass application of technologies for producing high-quality natural protein-rich foods (such as milk, meat, etc.) from vegetable matter using artificial organisms can be expected, including the functional elements of farm animals. Relevant technologies are already being actively developed.

New production technologies will lead to a significant shift in the energy mix towards electricity and the introduction of stricter requirements for the quality and reliability of energy supply.

### New Materials

Scientific advances combined with new production technologies will contribute to the emergence of a whole range of innovative structural and functional materials with unique properties. Due to the widespread adoption of stricter environmental legislation, they would have to comply with new requirements such as "nature imitation" (i.e., being environmentally friendly), biocompatibility, and biosafety if subjected to prolonged exposure to the elements (i.e. (bio)degrading into safe components (waste) in a relatively short period of time). This should create very high demand for biomaterials and their precursors (biological raw materials for subsequent industrial processing into manufactured goods, food, pharmaceuticals, etc.). "Smart" materials have a high potential (with properties changing under external impact, i.e. "chameleon materials") to adapt to environmental conditions.

The energy industry has dire need for various innovative materials. Heat-resistant alloys and thermal barrier coatings currently being developed will allow for bringing gas temperature at gas turbine inlets to 1,700-1,900 °C, which will increase the efficiency of combined-cycle plants to 66-68%, and steam temperature at the steam turbine inlets to 720-750 °C. The result will be an increase in steam turbines' efficiency to 53-55%. The application of 3D printing in power engineering requires dispersed narrow fractional composition materials, including refractory ones (nanopowders, nanoink, etc.).

The electric power industry has demand for materials of extremely high conductivity to make new classes of conductors, including "warm superconductors", that is, materials with superconducting properties at room temperature. Their use will help reduce the loss of electricity in grids. There is demand for semiconductor and optical materials for photoconverters and power electronics, electrocatalysts to increase electrochemical generators' efficiency and battery capacity, and highly porous materials for more effective thermal insulation.

Mining hard-to-recover hydrocarbons requires new materials for the construction of wells (to reduce the viscosity of fluids and increase the porosity of host rocks). "Slippery" plastics and ceramics (materials with high hydrophobicity, low coarseness, and strong adhesion to structural materials) will allow for significantly reducing the hydraulic resistance of pipelines and therefore energy consumption for pumping oil and other liquids through them. In oil and gas chemistry there will be demand for new high-performance catalysts for all basic processing operations and for membrane materials with adjustable characteristics for the highly selective separation of liquid and gas media.

Increasing the safety of nuclear technologies and achieving thermonuclear fusion requires new radiation-resistant materials. Here there are high expectations for alloys based upon the adjusted isotopic composition of the initial components.

The development of new structural materials raises hopes for achieving radically higher levels of energy saving. For example, next-generation composite materials based on synthetic biopolymers, very durable and lightweight, promise a revolution in the automotive and aircraft industries, leading to significantly reduced energy consumption by vehicles. An example is "biosteel" currently being developed by the AmSilk company – a biopolymer, a synthetic analogue of spider silk. The advantage of such materials is that they are biodegradable and environmentally friendly, synthesized by genetically modified bacteria in a bioreactor with a nutrient medium at a temperature of about 37 °C [*Sadowy*, 2018].

The development of most of the new materials involves the active application of electrophysical and electrochemical processes, leading to increased demand for electricity. Large-scale production of various carbon-based plastics and other carbon-containing materials requires powerful sources of carbon. This can be obtained from fossil organic fuels (coal, natural gas, oil) and from biomass of natural or artificial origin. Using complex biomass bio-molecules as precursors of industrial biomaterials allows one to save energy by synthesizing them from simple components.

### New Transportation Technologies

The main trends associated with the new technological revolution in transportation include the following:

- increased transportation volumes and speed, for people and cargo alike;
- wide dissemination of electric and hybrid vehicles, primarily in cities, to reduce anthropogenic pressure on the environment;

- rapidly increasing number of "light" personal electric vehicles such as electric scooters, etc.
- active use of air space by personal (air cars), light public (air taxis), and low-tonnage cargo (drones) transport vehicles;
- increased use of unmanned vehicles.

These trends become stronger as newer transport technologies and traffic control systems become available, including for unmanned vehicles in a 4D environment (in real road and air traffic conditions in real time) [OECD, IEA, 2017]. The world's leading car manufacturers have already started a new technology race [Toyota, 2017], focused on developing fully electric (with externally rechargeable batteries) and hybrid (with electricity generated *in situ* using hydrogen fuel cells) cars. Similar power supply schemes are suggested for light passenger and cargo aircraft. While the development of new diesel engines for passenger cars is being phased out, the use of traditional urban electric transport is expanding (underground and ground vehicles alike), which makes the issue of finding an optimal balance between public and private transport ever more relevant.

The emergence of smart products and the further development of online trade combined with robotic delivery vehicles can fundamentally alter logistics schemes in industrial production and other domains. Smart products provide more opportunities for tracking their dissemination in time and space, which radically changes production and sales planning, the collection and recycling of used products and waste management, leading to increased resource saving and more efficient environment protection. The mass application of smart logistics would lead to the transformation of existing and the emergence of new markets.

The further development of conventional urban electric transport, mass production of electric cars and personal light vehicles will lead to increased electricity consumption in cities and require a radical transformation of the urban electric grid infrastructure. The mass construction of expensive "rapid charging stations" will be in order (based on direct high-amperage current, powerful batteries, and power electronics), along with strengthening urban power grids and increasing their reliability; greatly increasing cities' electricity generation capacities; and applying new technologies for managing complex power modes.

## Post-Industrial Society

The role of industrial production in the economy is steadily falling against the background of the overwhelming growth of the service sector, especially the healthcare, education, beauty, and entertainment industries. These trends allow one to call the future society a post-industrial one [*Bell*, 1973]; numerous synonymous terms are also used such as post-industrial economy, knowledge-based economy, and knowledge society.

Technologies such as the internet of things (IoT) or services (IoS) are transforming the entire service and household appliance landscape. Robots may gradually replace people even in the yet hard-to-algorythmize "manual" labor niche, such as nursing, childcare (nannies, junior kindergarten personnel), social care (various kinds of social workers), etc. Further robotization of everyday life and homes can be expected, the nature of services changing with the emergence of smart products ultimately transforming our entire way of life. People will have more free time, their mobility will increase, and as a consequence, so will the demand for transportation services.

Improved living standards associated with better housing, the wider application of electrical household appliances, lighting, and climate control technology providing a comfortable environment regardless of the season and geographical location will lead to increased demand for electricity, affecting the seasonal dynamics of energy consumption. Thus, new technologies can once again radically transform the anthropogenic environment, making it more friendly which is a primary, albeit quite difficult, task. At the same time, the mass robotization of services and everyday life, the introduction of smart home systems, and remotely controlled household appliances make the cybersecurity issue increasingly relevant. The concept of a "smart and safe city" may provide an answer.

A prominent trend of a post-industrial society's development is the mass application of all sorts of portable gadgets (for information, communication, entertainment, and other purposes), whose market has reached a colossal size. In 2016, about 5 billion mobile phones were in active use globally, i.e., more than 68% of the world's population had them [*Ahonen,* 2016]. About half of these phones were smart ones and their share is steadily growing. Global smartphone sales in 2017 amounted to 1.46 billion units, and the revenues exceeded $300 billion. Consumers have spent about $60 billion more on applications. By 2020, the number of actively used smartphones is expected to reach 6 billion, or 76% of the world's population. In addition to mobile phones, people are using more than 1 billion notebook computers and 230 million tablets. In 2017, global notebook sales exceeded 162 million units [T-Adviser*,* 2018a].

Russia is also following these global trends. In 2017, about 28.5 million smartphones were sold in the country, for a total amount of $3.6 billion [T-Adviser, 2018b]. The number of actively used phones exceeds 100 million. Notebook sales in 2017 amounted to 2.5 million units at 79.9 billion rubles [T-Adviser, 2018a].

Taken together, portable gadgets' batteries consume huge amounts of electricity, making up the backbone of the so-called portable energy industry. They promote the growth of mobile traffic, which requires the further development of mobile networks and, accordingly, energy supply systems for them.

## Energy Industry in the Post-Industrial Period and Conditions for its Development

Important consequences of the new technological revolution for the energy industry include a) the continued electrification of the production sector, transport, and everyday life and b) the increased segmentation of demand for energy by different strata with different growth rates and structures. In turn, the technological structure of the energy sector will be subjected to further segmentation in order to meet future demand as efficiently as possible. This trend will be most obvious in the electric power industry, which can be divided into portable and mobile energy, distributed generation, and centralized power supply. Clearly, these segments will need completely different technologies.

### Electrification of the Economy and Society

A key indicator of countries' economic development and standard of living is per capita electricity consumption, especially by the end use sector and its "constituents", i.e., households. In these terms, Russia significantly (1.5-2.5 times) lags behind the more developed countries (Table 1), which means demand for electricity has significant growth potential.

The significant spread of the values under consideration in various Russian regions is worthy of note (Table 2). Russia has a powerful fuel and energy sector (FES) with traditionally high energy consumption. Various FES industries, first of all oil production, use about a third of all electricity generated in the country, while in the Urals Federal District the relevant figure is more than 50%.

In most of the leading countries, demand for electricity grows at a higher rate compared with secondary energy carriers. Russia is no exception here, but due to active automobilization, the demand for motor fuels also displays a quite high growth rate (Fig. 1).

A traditional feature of the Russian energy industry is a significant level of centralized heat supply. Heat energy prevails in secondary energy carriers' consumption structure: its share exceeds 42%, though it is steadily decreasing (in 2000, it was more than 53%). The planned active housing construction may reverse the trend of falling demand for centralized heat supply, since households are its main consumers (their share is about 37%).

Further development of the Russian energy sector directly depends upon correctly identifying the prospects for cogeneration and the requirements for new cogeneration plants, which in turn depend upon the balance of demand for electric and heat energy. The trend of this balance shifting in favor of electricity can be expected to remain in place: since 1990, the ratio of these two values grew 80% (Fig. 2). New cogeneration technologies should provide not only a higher fuel utilization factor, but also higher electrical efficiency.

Table 1. **Unit Electricity Consumption by Country: 2015**

| Country | Population (*million*) | Land area (*million km²*) | Population density (*people/ km²*) | Power density (*kWh/km2 per year*) | Grid losses (*%*) | Per capita electricity consumption (*thousand kWh per person per year*) | | | |
|---|---|---|---|---|---|---|---|---|---|
| | | | | | | Total | FES | End use sector | Out of that, households |
| **Developed countries** | | | | | | | | | |
| US | 320 | 9.5 | 33.6 | 454 | 5.9 | 13.5 | 1.7 | 11.8 | 4.4 |
| Canada | 36 | 10.0 | 3.6 | 61 | 10.0 | 17.0 | 3.0 | 14.0 | 4.7 |
| Japan | 128 | 0.4 | 338.6 | 2738 | 4.1 | 8.1 | 0.7 | 7.4 | 2.1 |
| Germany | 82 | 0.4 | 228.9 | 1678 | 4.0 | 7.3 | 1.0 | 6.3 | 1.6 |
| France | 64 | 0.5 | 117.8 | 912 | 6.4 | 7.7 | 1.1 | 6.6 | 2.4 |
| Korea | 51 | 0.1 | 513.7 | 5575 | 3.4 | 10.9 | 1.1 | 9.8 | 1.3 |
| **Developing countries** | | | | | | | | | |
| Russia | 147 | 17.1 | 8.6 | 62 | 10.1 | 7.2 | 2.3 | 5.0 | 1.0 |
| Brazil | 206 | 8.5 | 24.2 | 72 | 16.0 | 3.0 | 0.6 | 2.4 | 0.6 |
| South Africa | 55 | 1.2 | 45.3 | 202 | 8.1 | 4.5 | 0.9 | 3.6 | 0.5 |
| China | 1397 | 9.6 | 145.6 | 608 | 5.1 | 4.2 | 0.7 | 3.5 | 0.5 |
| India | 1309 | 3.3 | 398.1 | 421 | 18.6 | 1.1 | 0.3 | 0.8 | 0.2 |
| **World** | **7383** | **137.4** | **53.7** | **176** | **8.2** | **3.3** | **0.5** | **2.7** | **0.7** |

*Source*: ERI RAS.

Table 2. **Unit Electricity Consumption by Russian Regions: 2017**

| Russian regions | Population (*million*) | Land area (*million km²*) | Population density (*people/ km²*) | Power density (kWh/km². per year) | Grid losses (%) | Per capita electricity consumption (thousand kWh per person per year) | | | |
|---|---|---|---|---|---|---|---|---|---|
| | | | | | | Total | FES | End use sector | Out of that, households |
| **Russia** | **146.9** | **17 125.2** | **8.6** | **64** | **9.5** | **7.4** | **2.3** | **5.1** | **1.1** |
| **Federal districts** | | | | | | | | | |
| Central | 39.3 | 650.2 | 60.5 | 346 | 10.2 | 5.7 | 1.3 | 4.5 | 1.1 |
| North-Western | 14.0 | 1687.0 | 8.3 | 68 | 9.3 | 8.2 | 2.0 | 6.2 | 1.1 |
| Southern | 16.4 | 447.8 | 36.7 | 154 | 16.0 | 4.2 | 1.2 | 3.0 | 1.0 |
| North Caucasus | 9.8 | 170.4 | 57.6 | 145 | 8.5 | 2.5 | 0.7 | 1.8 | 0.7 |
| Volga | 29.5 | 1037.0 | 28.5 | 194 | 7.1 | 6.8 | 2.3 | 4.5 | 0.9 |
| Urals | 12.4 | 1818.5 | 6.8 | 102 | 8.0 | 15.0 | 8.3 | 6.7 | 1.2 |
| Siberian | 19.3 | 5145.0 | 3.7 | 43 | 12.1 | 11.5 | 2.7 | 8.8 | 1.2 |
| Far Eastern | 6.2 | 6169.3 | 1.0 | 8 | 14.7 | 7.9 | 2.9 | 5.0 | 1.4 |
| **Russian regions** | | | | | | | | | |
| Moscow Region | 7.5 | 44.3 | 169.4 | 1065 | 14.3 | 6.3 | 1.6 | 4.6 | 1.1 |
| Leningrad Region | 1.8 | 83.9 | 21.6 | 236 | 10.5 | 10.9 | 3.5 | 7.5 | 1.4 |
| Moscow | 12.5 | 2.6 | 4810.2 | 21 783 | 7.9 | 4.5 | 0.8 | 3.8 | 1.1 |
| St. Petersburg | 5.4 | 1.4 | 3822.8 | 20 146 | 12.6 | 5.3 | 1.0 | 4.3 | 1.0 |

*Source*: ERI RAS.

The growth of electricity consumption in the post-industrial period will be primarily determined by the increased number of portable devices, electrification of everyday life and transport, the increased use of electrophysical and electrochemical processes in industry, and increased electrical intensity of agriculture. Increased electricity consumption and its wider use in the scope of the "electric world" concept formulated a quarter of a century ago implies that humanity's basic energy needs will be met specifically with electricity [*Kaganovich et al*., 1989].

## Portable Energy

The current portable energy boom is a consequence of the mass proliferation of various devices, monitoring and security systems, ICT, and mobile communications. Portable devices can be stationary or wearable. Their power sources should meet the relevant requirements; originally chemical batteries were used for these purposes, but subsequently in many cases they were replaced by electrochemical ones.

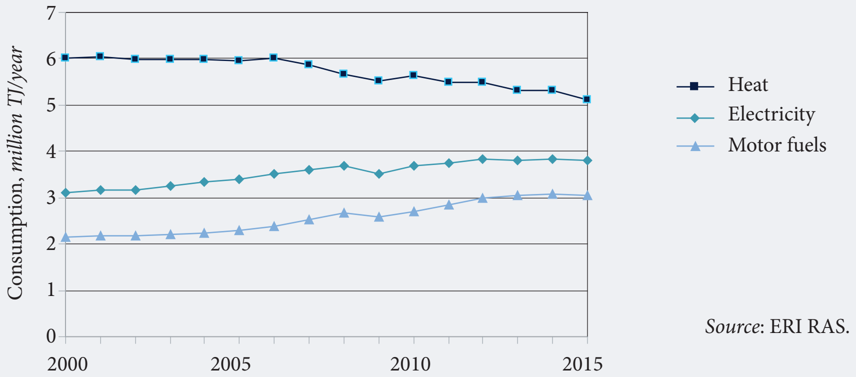
The total global battery capacity of the more popular portable devices types (mobile phones and notebook computers) is almost equally divided between these two groups: 50 and 40-50 GWh, respectively. Charging them takes about 10 and 15 TWh of electricity per year, respectively. The replacement of previous-generation mobile phones with large-screen smartphones increases the requirements for battery capacity and power consumption. In Russia, the battery capacity of mobile phones in active use is approximately 1 GWh and of notebook computers – 0.8 GWh, which in annual terms amounts to about 0.2 and 0.25 TWh, respectively.

The introduction of new control systems with their numerous smart sensors and actuators will provide additional powerful momentum for the development of portable energy, along with the growing entertainment industry which implies the use of all sorts of electronic devices.

Portable energy takes the lower segment in the generating capacities' power ranking, varying between fractions of and hundreds of watts (Fig. 3). Technologically, it is based upon next-generation chemical power sources, electrochemical batteries, super condensers, low-temperature hydrogen fuel cells which hold hydrogen in a bound state (in intermetals, carbon nanomaterials, etc.), or under high pressure in cylinders. Methanol fuel cells are also being actively developed.

The mass use of electric cars, light personal and industrial electric vehicles, and industrial and household robots give grounds to speak about the emergence of "mobile" (transport) energy. Technologically, it will be based upon electrochemical batteries, low-temperature fuel cells, and super condensers, while energy-wise it will be based upon electricity (clean cars) and hydrogen (hybrid vehicles). Hydrogen may be supplied externally or produced "onboard" from hydrocarbons, spirits, ethers, or other hydrogen-containing energy carriers. The required capacity of mobile energy generating plants ranges between hundreds of watts (personal electric vehicles, "light" robots, etc.) to hundreds of kilowatts (electric cars, industrial transportation vehicles, and "heavy" robots).

Figure 1. **Consumption of Secondary Energy Carriers in Russia (*million TJ/year*)**




*Source*: ERI RAS.

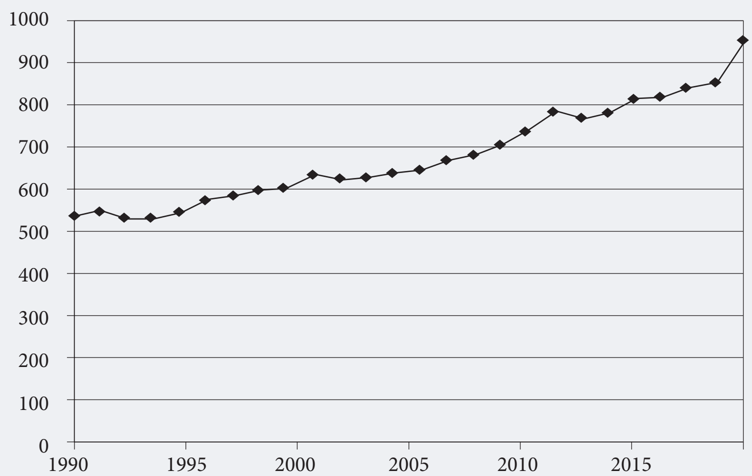
The growth of mobile energy generation implies the development of relevant energy infrastructure such as electric and hydrogen charging/filling stations, hydrogen logistics, and so on. New types of electrical devices, power electronics (current and voltage converters, communication equipment, etc.), and control systems for them will be needed. The future role of hydrogen remains uncertain due to problems with ensuring adequate safety if it becomes widely used. This provides impetus for the search for alternative hydrogen-containing energy carriers for mass application in transport.

Over time, mobile energy can surpass "big" power generation in terms of total electric power and start playing a significant role in its development and operations. Today, the total engine power of passenger cars in Russia exceeds 5 TW, while total electric power of all power plants in the country is about 0.27 TW. Thus, if only 5%-10% of passenger cars are replaced with electric ones and the latter are connected to the power grid in reverse mode, they will become a significant factor in power system management (in economic terms, too). Electric vehicle batteries can be charged with cheaper electricity at night or during periods of surplus generation from renewable energy sources (RES), returning electricity back into the grid during peak load times (when the price goes up). Thus, electric cars can effectively combine the functions of consumer regulators and peak generators, creating a unique niche in the electric power system. Smoothing the grid load curve with their help will favorably affect the operations of thermal and nuclear power plants.

Connecting a large number of electric vehicles to the electric power system may also require radically changing the power generation structure and grid configuration, and not just technologically but also spatially. Most of the vehicles will be concentrated in cities, where the power management issue is already extremely dire.

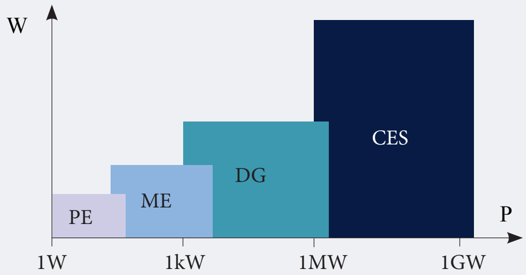
Mobile energy development is fraught with dramatic changes on the oil and motor fuel markets. The latter will be gradually replaced by electricity and hydrogen, given the large-scale adoption of electric vehicles,

Figure 2. **Balance of Electric (E) and Heat (Q) Energy Consumption in Russia (*kWh/Gcal*)**




*Source*: ERI RAS.

Figure 3. **Unit Capacity (P) of Generating Facilities in Various Power Energy Segments and their Overall Use (W)**




*Legend*: PE – portable energy; ME – mobile energy; DG – distributed generation; CES – centralized energy supply

*Source*: ERI RAS.

leading to sharply reduced demand with disastrous consequences for the global oil market. Many of the projects currently being actively promoted in Russia may lose their relevance – such as the production and processing of heavy oil or the development of the hydrocarbon reserves on the Arctic shelf, which is extremely capital-intensive and questionable in terms of economic feasibility.

## Distributed Generation

Generally, distributed generation means all kinds of power plants with 25 MW or less capacity, which:

- work autonomously (decentralized power supply);
- are integrated into electricity generation systems (EGS) (vertical power management);
- operate in the "island" mode, i.e., autonomously, but are connected to EGS in order to provide backup capacity, meet peak loads by using the grid, or return their surplus output to it;
- operate as part of microgrids (horizontal power management).

Electric accumulators, both "network" (integrated into the grid complex and designed for accomplishing system objectives), and "consumer" ones (uninterruptible power sources, backup capacities, electric cars, etc.) also act as a kind of distributed generation facilities. Sometimes autonomous and distributed generation are also distinguished from one another.

In Russia, about 18 GW of electric power is concentrated in the "decentralized zone". Significant distributed generation capacities are integrated into the centralized power supply system: approximately 7 GW come from gas turbines and 3 GW more from low-power steam turbines [*Filippov et al.*, 2015]. The so-called grey zone includes low-power diesel and gas piston power plants, which are poorly reflected in the statistics and are mostly used as backup and peak load power sources. Just between 2001-2007, about 13.4 GW of such generators were installed in the country, compared with 9.7 GW of "big energy industry" capacities installed during the same period [*Filippov*, 2009].

The following factors favorably affect the development of distributed generation:

- increased economic activity in sparsely populated areas with correspondingly low demand for electricity;
- infrastructural limitations in areas with centralized energy supplies (lack of technological potential to connect new consumers);
- the need to improve the quality and reliability of electricity supply (uninterrupted power, backup capacities, etc.)
- the development of renewable energy generation based on universally available sources such as sun, wind, and biomass;
- reduced energy costs due to the exclusion of the so-called "network" component and more efficient generation;
- the economic development of new areas with no transport and energy infrastructure.

Huge parts of Russian territory meet these criteria, with low population density and power consumption compared with many leading foreign countries (see Table 1 above). Eastern regions in particular stand out in this respect (see Table 2 above). About two-thirds of the country's territory do not have a centralized power supply and three quarters lack a centralized (pipeline) gas supply. Building large power grids there is economically unfeasible and would involve large energy losses.

The decentralization of industrial production and the growth of agriculture would also promote distributed generation. In particular, having large reserves of mineral and other resources, as well as significant generating capacities, opens wide opportunities to Russia for developing the high-technology production of new, high value added, and research-intensive materials. The country has the chance to become a world leader in this field. The development of small-scale production does not require building huge factories, so it may become an attractive area for implementing distributed generation technologies. Distributed generation also allows for cutting energy costs in centralized energy supply zones due to more efficient production and the elimination of the so-called "network" component.

Mobile communications and big data processing are turning into new, rapidly growing sectors of the economy which also looks attractive for distributed generation. The deployment of fourth-generation mobile internet networks has created conditions for the rapid growth of mobile traffic, primarily due to multimedia content. Mobile traffic tripled in Russia in 2015-2017, almost reaching the Western European levels [T-Adviser, 2018b]. The commissioning of much more productive, but also more energy-intensive, 5G networks is not far off. The further development of mobile communications will promote the demand for low power autonomous power sources (less than 100 kW) and more stringent requirements for their working life and reliability.

The growing demand for remote ("cloud") data storage, entertainment, computing, and other resources led to a surge in the number of data processing centers, along with the amount of electricity they consume. According to EvoSwitch, in 2015 data centers' electricity consumption reached 416 TWh or approximately 3% of the overall global consumption [*Lebedev*, 2018]. Due to the rapidly growing volumes of "heavy" data (streaming entertainment videos, the internet of things, security systems, monitoring of industrial facilities, etc.), data centers' demand for electricity (apart from everything else, they are burdened with very strict reliability and quality requirements) is expected to triple in the next decade. Having backup power sources (electric generators and/or electricity storage devices) and air-conditioning systems becomes necessary for them. All these tasks require the development of power electronics, electrical equipment, and energy storage facilities.

Serious global restrictions concerning greenhouse gases emissions exacerbate the uncertainty of the energy industry's technological future. Forthcoming changes may affect the mix of primary energy resources and accelerate the transition from large-scale generation based on organic fuels to distributed generation based on carbon-free RES.

## Centralized Energy Supply

Centralized power supply systems form the basis of modern power industry and are operated by almost all developed countries. In present-day Russia, about 93% of the power generating capacities (249 GW) is concentrated in the centralized zone, 88% (236 GW) of which are integrated into the Unified Electric Power System.

The expected decentralization of energy demand and the active development of distributed generation will not lead to abandoning centralized power supply in the foreseeable future. Demand for it will primarily come from large-scale industry and major urban agglomerations, i.e., areas with a high-density energy load where centralized supply remains favorable for economic and environmental reasons.

A significant proportion of today's large-scale industrial enterprises (metallurgical, mechanical engineering, chemical and petrochemical, pulp-and-paper, etc.) are likely to remain in business, and stay competitive for a long time to come. Currently this sector accounts for about 20% of electricity consumption in Russia, though this group of consumers is extremely price-sensitive and, given sufficient financial resources, often start their own (distributed) power generation.

Ongoing global urbanization may make a significant contribution to preserving centralized power supply. No noticeable increase in population is expected in Russia, which cannot be said about the small settlement residents' tendency to move into major metropolitan areas and megacities. Power density in Moscow and St. Petersburg exceeds 20,000 kWh/km$^2$ per year (Table 2). In industrialized regions adjacent to megacities or incorporated into them (the Moscow Region) it decreases to 1,000 kWh/km$^2$ per year and in areas with a high population density, to 150-200 kWh/km$^2$ per year. Meanwhile in, for example, the Far Eastern Federal District this value does not even reach 10 kWh/km$^2$ per year. Generating significant amounts of "clean" energy in megacities along with electric power and developing electric transport can provide a radical solution for the environmental problem – apart from a specific aspect, namely an acceptable level of electromagnetic pollution and the electromagnetic compatibility of relevant instruments and devices, which requires a separate effort.

Distributed generation provides realistic technological alternatives to centralized power supply in large cities and metropolitan areas, associated with the development and mass application of environmentally friendly fuel cells on natural gas and electrochemical batteries [*Bredikhin*, 2017]. The greatest effect can be achieved by using cogeneration plants integrated into intelligent microgrids. However, first of all, the most complicated S&T problem must be solved, namely radically reducing the costs of the relevant equipment and extending its working life.

The need for centralized power supply may increase with the emergence of large volumes of highly efficient renewable energy resources in the energy balance, located far away from consumption centers. Modern RES-based installations do have sufficient unit capacity, while network solutions make it possible to efficiently transmit electricity over long distances (in particular, using ultrahigh voltage alternating- and direct-current power lines ranging between 800-1,000 kV and more). Accordingly, powerful (tens and hundreds of megawatts) "wind farms" and "solar fields" are now being set up in areas with high concentrations of high-potential RES, for integration into centralized electric power systems. Such "network" installations currently account for the bulk of RES-based generation growth.

The possible introduction of stringent, legally binding international restrictions on greenhouse gas emissions will require the accelerated decarbonization of the global energy industry and the Russian industry as well. Achieving this would require switching to carbon-free natural energy sources, namely nuclear fusion and RES. Thermonuclear power plants are unlikely to find commercial applications in the coming decades, as well as generation technologies based on organic fuels with $CO_2$ capture, since no effective methods for reliable and long-term (on a geological scale) utilization of the huge amounts of carbon dioxide have yet been proposed. The situation is further complicated by the bad reputation nuclear power has in many countries, so the talk about its "renaissance" has to be seen as somewhat premature. Replacing organic fuels by renewable energy sources on a comparable scale, in turn, requires developing deserts and large coastal water areas, which implies creating a global electric power system and developing regional centralized energy systems. Providing 1,500 kV voltage and putting in place appropriate submarine cables would be a technological challenge.

The development of the electric grid complex leads to increased network losses over the course of the transmission and transformation of electricity. Developed countries with high power density have managed to reduce such losses to 4%-6% (see Table 1 above). In Russia this figure is about twice as high (about 10%) and varies greatly across the country (see Table 2 above).

The operation and development of an electric grid complex involves significant costs, whose share in the price of electricity that end users pay today often exceeds 50%–60%. Hopes for a significant reduction in such costs due to the elimination of the "network" component of electricity prices are associated only with certain technologies. A breakthrough can be expected from the mass application of low-cost "warm" superconductors (operating at room temperature), though the development of the necessary materials is progressing very slowly.

## Conclusions

All technological revolutions radically affected the energy industry, both directly (the emergence of new energy technologies) and indirectly, by shaping energy demand including its volume, structure, and requirements regarding energy carriers' quality. The new technological revolution will be no exception: together with the post-industrial economy and society emerging on its basis, it will place new demands upon the energy sector. First of all, we are referring to significantly increased demand for electricity and stricter requirements for the quality and reliability of its supply.

The further segmentation of the energy sector's technological structure should be expected in order to meet future demand for energy as efficiently as possible. This trend will be most obvious in the electric power industry, which can be divided into portable and mobile energy, distributed generation, and centralized power supply. The growth of direct current (DC) generation and consumption in the first three segments and the creation of powerful backbone DC networks in the latter may revive interest in DC power supply systems.

Demand for a centralized energy supply may be associated with concentrated energy loads by large-scale industry, urbanization, and the emergence of megacities. The further development of centralized energy may be promoted by the requirements for the decarbonization of the energy industry. In this case, it will become necessary to develop RES in remote locations such as deserts and coastal waters of distant seas and possibly step up the development of nuclear energy.

Decentralization, economic activities in regions with low energy density, economic development of new territories, and the widespread application of available RES will promote the development of distributed generation. The expected mass proliferation of electric cars, light personal electric vehicles, and autonomous robots of various functionalities may lead to the explosive growth of mobile energy. Integrating millions of electric vehicles into electric power systems will strongly affect the development of the "big" energy industry, since it will require a substantial adjustment of its technological and spatial structure. The increased use of various gadgets and other low-power autonomous devices will promote the development of portable energy and subsequently the production of electrochemical batteries, which in turn is fraught with causing a shortage of certain materials and a jump in their prices. The digitization of the energy industry will exacerbate the issue of ensuring the cybersecurity of energy facilities and systems.

Russia's specific features, such as the structure of its energy demand, harsh climate, and vast territory, impose additional requirements on the technological development of the country's energy industry.

In particular, centralized power supply systems will remain in demand, but demand for distributed generation technologies, including those based on renewable energy sources, will also grow. Developing cogeneration on the basis of electrochemical generators, smart grid technologies, and so on remains among the most important objectives.

The current structure of the Russian fuel and energy complex is extremely vulnerable to the large-scale electrification of transport and the decarbonization of the global energy industry. The wide proliferation of electric vehicles, broad use of RES across the world, and the resulting decrease in demand for oil may have a devastating effect on the global hydrocarbon market, which will have a negative impact upon the country's energy sector and the entire economy.

*The paper is based on the results of the project implemented with financial support of the Russian Ministry of Education and Science; the unique project identifier is RFMEFI60117X0014.*

## References

Ahonen T. (2016) *TomiAhonen Phone Book 2016. Statistical Review of Handset Industry*. Available at: http://www.tomiahonen.com/ebook/phonebook.html, accessed 08.10.2018.

Balabanov V., Zhelezova S., Berezovskii E., Belenkov A., Egorov V. (2013) *Navigatsionnye tekhnologii v selskom khozyaistve. Koordinatnoe zemledelie* [Navigation technologies in agriculture. Coordinate farming], Moscow: Russian Timiryazev State Agrarian University (in Russian).

Baudrillard J. (1998) *The Consumer Society. Myths & Structures,* London, Thousand Oaks, New York, Delhi: SAGE Publications. ISBN 0-7619-5691-3.

Bell D. (1973) *The coming of post-industrial society: A venture of social forecasting,* New York: Basic Books. ISBN 0-465-01281-7.

Bredikhin S., Golodnitskii A., Drozhzhin O., Istomin S., Kovalevskii V., Filippov S. (2017) *Statsionarnye energeticheskie ustanovki s toplivnymi elementami: materialy, tekhnologii, rynki* [Stationary power plants with fuel cells: materials, technologies, markets], Moscow: NTF «Energoprogress». ISBN 978-5-905918-06-3 (in Russian).

Elk K. (2016) *Embedded Software Development for the Internet of Things: The Basics, The Technologies and Best Practices*, Seatle: Create Space Independent Publishing Platform. ISBN 978-1534602533.

Filippov S., Dilman M. (2018) Sistemnye issledovaniya prioritetov tekhnologicheskogo razvitiya energetiki: metodologicheskie aspekty [Systemic studies of priorities for technological development of the energy industry: methodological aspects]. *Sistemnye issledovaniya v energetike: metodologiya i rezultaty* [System studies in the energy sector: methodology and results] (eds. A. Makarov, N. Voropai), Moscow: MPEI, pp. 63–86 (in Russian).

Filippov S.P. (2009) Small-Capacity Power Engineering in Russia. *Thermal Engineering*, vol. 56, no 8, pp. 665–672.

Filippov S.P., Dilman M.D., Ionov M.S. (2015) Demand of the Power Industry of Russia for Gas Turbines: The Current State and Prospects. *Thermal Engineering*, vol. 64, no 11, pp. 829–840. DOI: 10.1134/S0040601517110052.

Freitas R.A., Merkle R.C. (2004) *Kinematic Self-Replicating Machines*, Georgetown, TX: Landes Bioscience. ISBN: 978-1570596902.

Glazyev S. (1993) *Teoriya dolgosrochnogo tekhniko-ekonomicheskogo razvitiya* [Theory of long-term technical and economic development], Moscow: VlaDar.

Gorban A., Dunin-Barkovskii V., Kirdin A., Mirkes E., Novokhodko A., Rossiev D., Terekhov S., Senashova M., Tcaregorodtcev V. (1998) *Neiroinformatika* [Neuroinformatics], Novosibirsk: Nauka. Siberian Enterprise RAS (in Russian).

Heath S. (2003) *Embedded systems design. EDN series for design engineers* (2nd ed.), Oxford: Newnes. ISBN 978-0-7506-5546-0.

Hermann M., Tobias P., Boris O. (2015) *Design Principles for Industrie 4.0 Scenarios: A Literature Review* (Working Paper 01), Dortmund: Technische Universität Dortmund.

Kaganovich B., Filippov S., Antciferov E. (1989) *Effektivnost energeticheskikh tekhnologii: termodinamika, ekonomika, prognozy* [Efficiency of energy technologies: thermodynamics, economics, forecasts], Novosibirsk: Nauka (in Russian).

Khaitan S.K., McCally J.D. (2014) Design Techniques and Applications of Cyber Physical Systems: A Survey. *IEEE Systems Journal*, vol. 9, no 2, pp. 1–16. Available at: https://www.researchgate.net/publication/275381502_Design_Techniques_and_Applications_of_Cyberphysical_Systems_A_Survey, accessed 17.07.2017.

Koh W.T.H., Leung H.-M. (2003) *Education, Technological Progress and Economic Growth*, Singapore: Singapore Management University.

Kondratyev N. (1989) Bolshie tsikly ekonomicheskoi konyunktury [Large cycles of economic conditions]. *Problemy ekonomicheskoi dinamiki* [Problems of economic dynamics] (ed. L.I. Abalkin), Moscow: Ekonomika, pp. 172–226 (in Russian).

Kurzweil R. (2005) *The Singularity Is Near,* New York: Viking Adult.

Ladd D., Jelezko F., Laflamme R., Nakamura Y., Monroe C., O'Brien J.L. (2010) Quantum Computing. *Nature,* vol. 464, no 7285, pp. 45–53.

Lebedev P. (2018) *Prizhivetsya li v Rossii "zelenyi" TsOD?* [Will green data center take root in Russia?]. Available at: http://www.cnews.ru/reviews/infrastructure2017/articles/prizhivetsya_li_v_rossii_zelenyj_tsod, accessed 29.09.2018 (in Russian).

Lee E. (2008) *Cyber Physical Systems: Design Challenges* (Technical Report UCB/EECS-2008-8), Berkeley: University of California. Available at: https://www2.eecs.berkeley.edu/Pubs/TechRpts/2008/EECS-2008-8.pdf, accessed 17.07.2017.

McBratney A., Brett W., Tihomir A., Johan B. (2005) Future Directions of Precision Agriculture. *Precision Agriculture*, no 6, pp. 7–23.

OECD, IEA (2017) *The Future of Trucks: Implications for Energy and the Environment*, Paris: OECD, IEA.

Richardson S.M., Mitchell L.A., Stracquadanio G., Yang K., Dymond J.S., DiCarlo J.E., Lee D., Huang C.L.V., Chandrasegaran S., Cai Y., Boeke J.D., Bader J.S. (2017) Design of a synthetic yeast genome. *Science*, vol. 355, no 6329, pp. 1040–1044. Available at: http://science.sciencemag.org/content/355/6329/1040, accessed 10.03.2017.

Sadowy B. (2018) *Airbus Partners with Amsilk on Synthetic Spider Silk Technology*. Available at: http://compositesmanufacturingmagazine.com/2018/09/airbus-partners-with-amsilk-on-synthetic-spider-silk-technology/, accessed 27.09.2018.

Šmihula D. (2011) Long waves of technological innovations. *Studia Politica Slovaca*, no 2, pp. 50–69.

T-Adviser (2018a) *Noutbuki: mirovoi rynok* — 2017 [Laptops: World Market — 2017]. Available at: http://www.tadviser.ru/index.php/Статья:Ноутбуки_(мировой_рынок), accessed 19.10.2018 (in Russian).

T-Adviser (2018b) *Smartfony: rynok Rossii — 2018* [Smartphones: Russian Market — 2018]. Available at: http://www.tadviser.ru/index.php/Статья:Смартфоны_(рынок_России), accessed 19.10.2018 (in Russian).

Taleb N.N. (2007) *The Black Swan: The Impact of the Highly Improbable*, New York: Random House. ISBN 978-1-4000-6351-2.

Toffler A. (1970) *Future Shock*, New York: Bantam Books. ISBN 0-553-27737-5.

Toffler A., Toffler H. (2006) *Revolutionary Wealth,* New York: Knopf Doubleday Publishing. ISBN 0-375-40174-1.

Toyota (2017) *Environmental Report 2017: Toward the Toyota Environmental Challenge 2050*, Toyota, Aichi: Toyota Motor Corporation. Available at: http://www.toyota-global.com/sustainability/report/archive/er17/pdf/er17_full_en.pdf, accessed 06.11.2017.

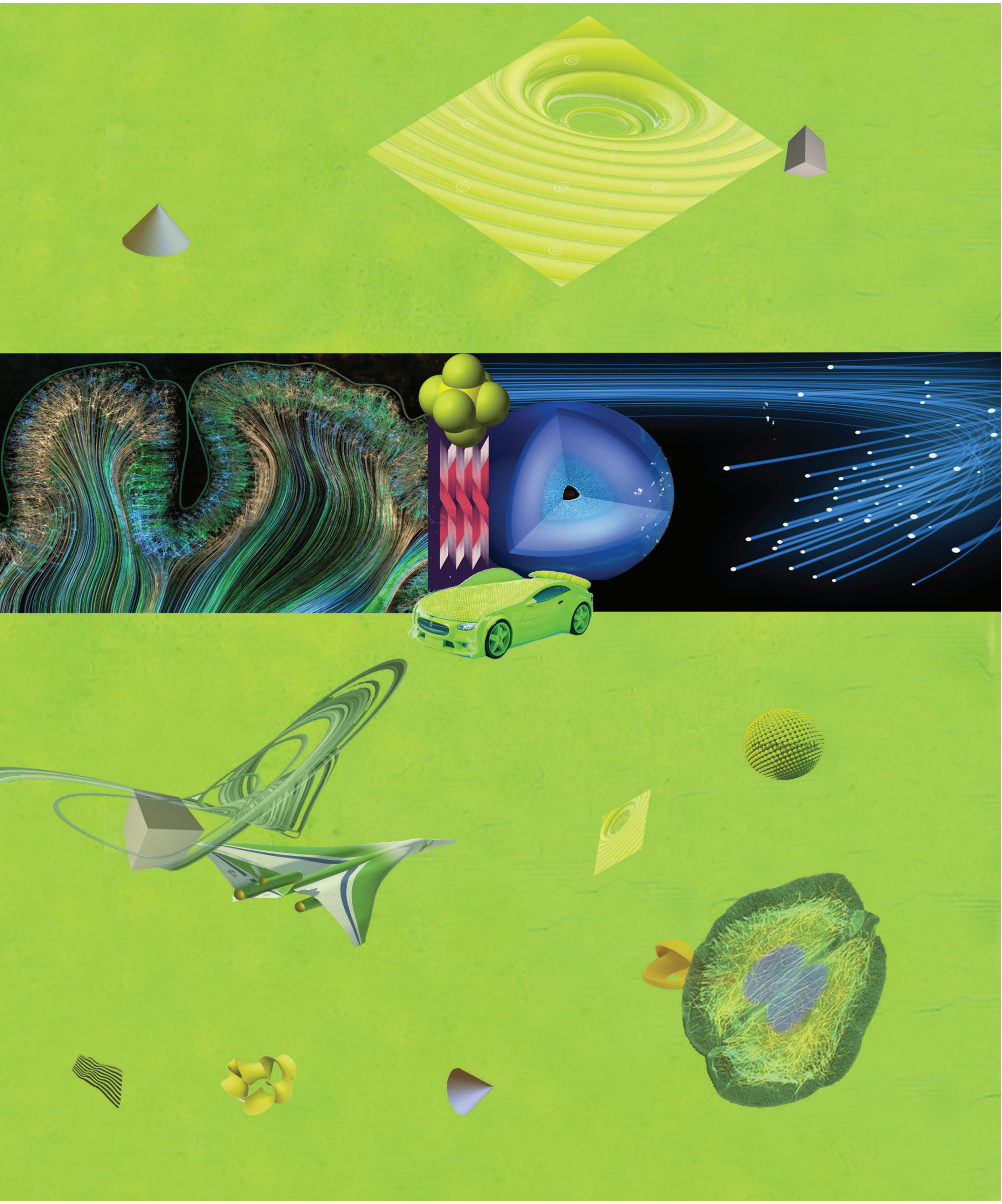
van Gelderen J. (1913) Springvloed Beschouwingen over industrielle Ontwikkelingen prijsbeweging. *De Nieuwe Tijd*, vol. 184, no 4–6, pp. 253–277; 369–384; 445–464.

Vinge V. (1993) *The Coming Technological Singularity*. Paper presented at the VISION-21 Symposium sponsored by NASA Lewis Research Center and the Ohio Aerospace Institute, March 30-31, 1993. Available at: http://www.accelerating.org/articles/comingtechsingularity.html, accessed 05.03.2017.

Yakushev V. (2016) *Tochnoe zemledelie: teoriya i praktika* [Precision Agriculture: Theory and Practice]. Saint-Petersburg: FGBNU AFI. ISBN 978-5-905200-31-1 (in Russian).

Zhang N., Wang M., Wang N. (2002) Precision Agriculture: A Worldwide Overview. *Computers and Electronics in Agriculture*, vol. 36, no 2–3, pp. 113–132.

Zvorykin A., Osmova N., Chernyshev V., Shukhardin S. (1962) *Istoriya tekhniki* [History of technology], Moscow: Izdatel'stvo sotcialno-ekonomicheskoi literatury (in Russian).



# Energy Consumption of the Russian Road Transportation Sector: Prospects for Inter-Fuel Competition in Terms of Technological Innovation


**Dmitriy Grushevenko**

Research Fellow [a]; and Leading Expert [b], grushevenkod@gmail.com

**Ekaterina Grushevenko**

Research Fellow [a]; and Expert [c], e.grushevenko@gmail.com

**Vyacheslav Kulagin**

Head of Division [a]; and Director [b], vakulagin@hse.ru

[a] Energy Research Institute of the Russian Academy of Sciences (ERI RAS), 31, bldg 2, Nagornaya str., Moscow 117186, Russian Federation

[b] Centre for Energy Studies, Institute of Pricing and Regulation of Natural Monopolies at the National Research University Higher School of Economics (HSE IPCREM), 7 Vavilova str., Moscow, 117312, Russian Federation

[c] Energy Centre, 100, Novaya str., Skolkovo village, Odintsovsky District, Moscow Region, 143025, Russian Federation


## Abstract


The development of production and consumption technologies for the road transport has led to large scale introduction of alternative energy in this sector. These alternatives to the conventional petroleum fuels include biofuels, electricity, natural gas and synthetic fuels produced from coal and natural gas. However, it is very important to point out, that inter-fuel competition is determined not only by the development of technologies, but also by such parameters as availability, fuel cost, consumer preferences and government legislations, all of which vary greatly across the globe. In other words, the very same technologies can be capable of radically altering the fuel mix in some countries while having little to none impact in the others. The topic of the inter-fuel competition development in the transportation sector holds much importance for Russia, as the country's fuels mix is almost totally dominated by the petroleum products. The diversification of energy sources for transport may positively influence energy security and domestic fuels market stability; reduce the strain on ecology, especially in major cities; all the while increasing Russian oil and petroleum products export potential.

The article presents results of the research for prospects of the developments in Russian transport sector fuel mix. The research was carried out using the tools of economic and mathematical modeling under various scenario assumptions. The analysis has shown that natural gas and, to a lesser extent, electricity hold the best prospects as petroleum products substitutes in the long-term. Their cumulative share in the total energy consumption of the road transport sector has the potential of reaching as high as 26% by 2040. Yet, the extent of substitution largely depends on the government actions for infrastructure development and tax incentives for alternative vehicle owners.



**Keywords:** inter-fuel competition; road transportation; technological innovations; alternative fuels; energy consumption; scenario planning

**Citation:** Grushevenko D., Grushevenko E., Kulagin V. (2018) Energy Consumption of the Russian Road Transportation Sector: Prospects for Inter-Fuel Competition in Terms of Technological Innovation. *Foresight and STI Governance*, vol. 12, no 4, pp. 35–44. DOI: 10.17323/2500-2597.2018.4.35.44

The diversification of the road transport sector's fuel mix is a new global trend. In 1990-2013, the global share of petroleum products (which have historically dominated this sector) decreased, from 99% to 95% [IEA, 2014], despite the significant growth of total energy consumption in the sector. This is due to the growing demand for electricity, natural gas, biofuels, and synthetic motor fuels derived from natural gas and coal. Furthermore, the sector's interest in new energy types is growing all the time, among consumers and vehicle manufacturers alike.

It should be noted that this diversification can be observed not only in developed countries that have traditionally been major oil and petroleum product importers (for them it is mainly prompted by the desire to reduce imports of these energy resources), but also for major oil producers. For example, in Iran, natural gas accounted for 14% of the total energy consumption in the road transport sector already in 2013, while in Brazil, the share of biofuels and natural gas amounted to about 19% of the sector's total energy consumption [IEA, 2014].

For oil exporters, the diversification of the fuel mix provides an opportunity to increase the exports of petroleum fuels. In addition, it serves as an environmental policy tool for all countries since all alternative transportation modes allow one to significantly reduce vehicles' direct emissions (not counting the emissions made during the production of energy resources).

So far, in terms of the diversification of the road transportation sector's fuel mix, Russia lags behind most other countries: petroleum products amount to 99% of the sector's energy balance, while the consumption of gas motor fuel and electricity remains negligible (at 1.4 million tonnes of oil equivalent). At the same time, the sector's demand for petroleum products amounts to up to 90% of total domestic consumption [IEA 2014]. Despite the road transportion sector's importance to the national economy (along with that of demand for oil as such), the number of studies forecasting the sector's fuel mix prospects remains rather small. Some works [e.g. *Bobylev et al.,* 2006; *Braginskiy,* 2012; *Milovidov et al.,* 2006] do describe certain methodological approaches to forecasting demand, but they cannot be considered detailed, integrated studies of future energy demand in the road transportion sector. The authors of this paper have developed a unique tool for forecasting demand for motor fuel. For a detailed description of the forecasting tool's theoretical and methodological basis see [*Mitrova et al.,* 2015; *Grushevenko et al.,* 2015].

The current study has the following objectives: to identify the key incentives for diversifying the fuel mix; assess the current state of inter-fuel competition in the Russian road transport sector; using the state-of-the-art economic and mathematical modeling tool, determine whether Russia has the potential for a large-scale switch to alternative energy resources in the road transportation sector; and, finally, assess the potential for the growth of demand for energy in the sector and the prospects for meeting it.

## The Structure of Energy Demand in the Transportation Sector: Incentives for Diversification

In 2015, energy consumption in the Russian transportation sector amounted to about 65 million tonnes of oil equivalent; 99% of that was accounted for by petroleum fuels (liquefied hydrocarbon gases, gasoline, and diesel). The share of gasoline amounted to 60% [IEA, 2014]. The remaining one percent of consumption came in the form of natural gas, in condensed (compressed) form.

At first glance, this structure of energy consumption in the road transportation sector of one of the world's largest exporters and producers of oil appears quite natural, especially considering that domestic retail prices of petroleum products are practically 50% lower than in Europe. However, there are several reasons to believe this structure is not optimal for the country.

The first one is that Russia regularly experiences problems with supplying the domestic market with high-quality, high-octane petrol (which dominates energy demand for personal road transportation). Particularly acute shortages were experienced in 2011, when the Omsk Refinery and the Angarsk Petrochemical Works had to conduct unplanned repair and maintenance, in 2012, after the accident at the Moscow Refinery, and in 2014, when an accident at the Achinsk Refinery coincided with the delayed completion of maintenance work at the Yaroslavl Refinery.

The reason such crises keep occurring is quite simple: the lack of petrol refining capacities. For example, as of 2016, the combined maximum technological capacity of all Russian refineries to produce high-octane Euro-5 standard petrol (the usage of fuel types with lower environmental standards has been banned in Russia since July 2016), with full utilization of all secondary production processes (i.e. no downtime, no repair, or maintenance during the year) amounts to about 40 million tonnes per year. Meanwhile demand has already reached 39 million tonnes (for more about Russian refineries' production capacities, their current state, and development prospects see [*Kapustin, Grushevenko,* 2016; *Kapustin, Grushevenko,* 2018]).

If demand for petrol keeps growing (as it does, despite the difficult economic situation in the country), the extension and modernization of required production capacities and supporting infrastructure of the oil refinery sector will require significant investments. About $20 billion will be needed [*Kapustin, Grushevenko,* 2018] in the next five to ten years, which is comparable with investments in building gas filling infrastructure (the investments required to convert Russian petrol stations for use of gas fuel are estimated at $12.6-$31.5 billion [Promexpertisa, 2016]). It is also important to keep in mind that Russian refineries are quite dependent on imported equipment and consumables (e.g., 50%-100% of catalysts applied to produce commercial petrol are imported [*Kulagin et al.,* 2015]). The weak ruble makes these costs heavier, especially combined with reduced oil export revenues. The high dependence on imported supplies also negatively affects the country's energy security. Launching the domestic production of the aforementioned catalysts would require major investments, but more importantly, it would not be possible to fully substitute imports even by 2020 [*Kapustin, Grushevenko,* 2018]. Accordingly, a valid question arises: should we invest in oil refining, almost exclusively to meet the growing domestic demand for petrol (and the sole source of these investments would be oil companies), or spread the risks between numerous market players and invest in reducing demand for petrol, among other things by diversifying the fuel mix?

The second factor that raises doubts about the structure of the Russian road transportation sector's fuel mix is that several Russian cities with over a million residents face severe environmental challenges and the petroleum products dominating the road transportation sector are relatively "dirty" energy resources. For example, on average, $CO_2$ emissions from gas-powered cars are 20%–25% lower than those of petrol cars of the same class, while the emissions of very toxic nitric oxides are 90% lower compared with diesel cars [*Curran et al.,* 2014]. Switching to electric cars can also significantly reduce the emissions of hothouse gases, if we do not take into account the emissions made over the course of electricity generation.

Third, oil and petroleum products are the key sources of the Russian Federation's currency revenues. According to the Russian State Statistics Service (Rosstat), these products' share in the exports' value structure exceeded 45% even in the crisis-hit 2015[1]. The more active use of alternative fuel types by the road transportation sector would allow Russia to export more oil and petroleum products, which would help to step up the country's export potential following Iran's example.

Note also that there is a huge surplus of previously installed gas production capacities in the European part of the country, whose output is only limited by the limited markets. Russia has significant potential to step up gas production, which could be used to generate electricity or directly in vehicle engines. This industry's development would also allow Russia to increase the exports of oil and petroleum products (which are more expensive). This is particularly relevant in a situation when the niche for domestic consumption and export of gas is limited, while the potential for stepping up production is much higher for gas than oil [*Mitrova,* 2016].

All of the above reasons can be seen as incentives for the government to encourage the substitution of petroleum products in the road transportation sector with alternative energy sources. However, the extent of such shift would largely depend upon consumer preferences, namely how much more attractive the available alternatives would look in terms of costs, convenience, and environmental characteristics.

To assess the future prospects for the emergence of a new energy mix in the road transportation sector, we will need to analyze various aspects of inter-fuel competition, taking into account consumer preferences and expected government regulatory measures.

## Inter-fuel Competition in the Russian Road Transportation Sector

Inter-fuel competition is becoming increasingly active in the present-day transport sector. Conventional oil-based fuel types (such as petrol, diesel fuel, and to a lesser extent, liquefied hydrocarbon gases (LHG)) compete with alternative energy sources which can be divided into direct and indirect substitutes (for a more detailed classification see a study previously published in *Foresight and STI Governance* [*Mitrova et al.,* 2015]):

1. Direct substitutes that do not require motorists to radically modify their car engines, such as:
    - biofuels made from plant materials: bioethanol and biodiesel [*Mussatto,* 2016];
    - coal-to-liquids and gas-to-liquids fuels [*Höök, Aleklett,* 2010; *Glebova,* 2013].
2. Indirect substitutes which do require a radical modification of vehicles and consumer infrastructure, such as:
    - Electricity to power electric or hybrid cars;
    - Fuel cells converting hydrogen energy into electricity [*Sorensen,* 2012].
    - Gas motor fuel (GMF) made from natural gas or biomethane.

Certainly not all these alternatives are finding wide application in the world. For example, due to the high production costs, synthetic GTL and CTL fuels turned out to be non-competitive in terms of price on the world market. According to [*Höök, Aleklett,* 2010], the production costs of coal- and gas-based liquefied fuels are between $48–$75 per barrel, not counting the raw material costs and the producers' tax burden. Meanwhile, the average international production cost of oil-based fuel is between $5–$15 per barrel. This ratio of oil- and non-oil-based fuel production costs is expected to remain in place in the long term.

Technologies for the large-scale application of fuel cells in transport vehicles are still seen as an issue for the future. For example, the hydrogen-powered Toyota Mirai car was sold for $55,000, which is comparable with luxury car prices. According to experts, the company makes not a profit, but a loss selling these cars, to the tune of up to $100,000 per vehicle [*Voelcker,* 2014]. For Russia, that kind of price and the lack of fuelling station infrastructure for the time being make forecasting demand for hydrogen-powered cars irrelevant.

For biofuels, the key limitation is the high cost. According to Russian legislation[2], biofuel is classified not as an energy source but as an ethyl alcohol, and is subject to an excise duty of 102 rubles ($1.6.) per liter, while

[1] Calculated by the authors using data of the Central Bank of Russia. Access mode: http://www.cbr.ru/statistics/?PrtId=svs, last accessed on 23.12.2017.

[2] Federal law No. 171-FZ of 22.11.1995 "On government regulation of the production and turnover of ethyl alcohol, alcohol- and spirits-containing products, and limiting consumption (drinking) of alcohol products"

the retail price of petroleum-based fuel as of 2016 was around 40 rubles ($0.6.) per liter, which of course makes biofuel non-competitive.

The position of electricity as an alternative energy source for the Russian road transportation sector is also quite shaky unlike, for example, on the European market where, as the authors' calculations show, electricity as a motor fuel can not only pressure conventional petroleum products, but also limit the growth of demand for compressed natural gas (CNG) [*Grushevenko et al.,* 2016]. In Russia, large-capacity public transportation vehicles (trolleybuses and trams) account for almost 100% of all electricity consumption in the road transportation sector. It should be noted that according to the Russian Ministry of Transport, the number of passengers carried by such vehicles has been declining since the early 2000s [AC, 2015]. Many large cities already display a trend toward gradually dismantling these types of transportation: for example, in St. Petersburg the fleet of trolleybuses decreased by 12% between 2005 and 2014 and the fleet of trams by 30%. The recent years' decision by the Moscow authorities to reduce the trolleybus fleet in favor of diesel buses leads to the expansion of consumption of petroleum products in this segment, however, it is worth noting that in parallel, there are significant plans to purchase electric buses. If this trend continues, demand for electricity in the large-capacity road transportation segment would be bound to a decrease in the medium term, however, there are grounds for its future growth owing to the extensive use of electric buses.

As to increasing the number of electric cars (which would lead to increased demand for electricity in that segment), there are again several limiting factors affecting the Russian market. For example, up to 90% of new car sales in Russia take place in the budget segment (up to $13,000) [Autostat, 2016], while the available electric cars (six models altogether) and even hybrid ones (seven models) belong to the medium and premium segments (with prices starting from $16,000[3]), so they remain simply unaffordable for the average consumer. Another problem is the extremely low level of service infrastructure. For example, only official dealers can service electric and hybrid cars available on the market, other service stations simply do not have the equipment and skilled personnel to repair such vehicles.

Also, Russia almost completely lacks charging infrastructure for electric cars, which significantly reduces their consumer appeal compared with petroleum-powered models, even with the lower fuel costs (on average 67%-83% cheaper than petrol). Given the almost total absence of public charging stations (about 60 altogether in the country), the only choice consumers have is to charge their cars at home, which is a very difficult task for residents of large city buildings with no parking facilities (as a rule, apartment buildings in Russia do not have a sufficiently powerful energy supply). It should be noted that Russian Grids (Rosseti) plans to build 1,000 electric car charging stations by 2018 [*Voronov et al.,* 2016], but these overly optimistic plans raise doubts: in just two years' time, the company would have to build 16 times more charging stations than their current total number (60).

Inadequate government policy to promote electric car purchases is also worthy of note. Relevant initiatives include zero customs duties for importing such vehicles into the Eurasian Economic Union (EAEU) until September 2017 [Interfax, 2016], free parking in paid parking zones in Moscow, and the free issue of parking permits for residents of such areas, and free charging until the end of 2016 [Moscow 24, 2016]. There were also plans to equip petrol stations with electric car charging outlets starting from November 1, 2016.[4]

However, the key factor limiting the widespread use of electric cars at the current stage is their high prices: on average an electric car costs 25%–50% more than a petrol- or diesel-powered one of a similar class (the world over). The same is also true for the truck segment (with practically no medium-capacity electric vehicles available at all). According to our estimates, the average annual cost of owning an electric car in 2016 was two times higher than for internal combustion vehicles. As to Russia, the situation is further aggravated by the very limited range of available electric cars: the options are either super-compact vehicles that are relatively unpopular among Russian consumers or luxury cars unaffordable to the average buyer.

In terms of combined consumer, operational, and environmental properties, gas-powered cars seem to offer the most attractive alternative in all market segments. In addition to significant savings on fuel (according to our calculations, such cars are 60% cheaper to run than petroleum-powered ones, per 100 km) and a moderate price difference (compared with similar class vehicles in various market segments), using natural gas prolongs the service life of the internal combustion engine, significantly increases the mileage between repairs, and reduces explosion and fire hazards compared with petrol and LPG (gas is lighter than air and in case of leakage, it immediately evaporates, which significantly reduces the risk of fire). Also, natural gas has a much higher self-ignition temperature and a lower explosiveness limit than, for example, petrol, which in case of a leak flows under the car and creates a pool of an explosive mixture on the ground.

In addition, installing a gas bottle and other necessary equipment does not imply a total rejection of conventional fuel types. Even mass-produced gas-powered cars have fuel tanks and can operate using gas and petrol/diesel in turn, which significantly increases their mileage and makes them much more convenient to use. Still, as of 2015, the share of gas motor fuel in Russia was just about 0.5% of the road transportation sector's total energy consumption (or less than 0.4 million tonnes of oil equivalent) [IEA, 2014].

A key reason for this low gasification rate in the sector is inadequate infrastructure. About 280 gas filling stations operate in Russia altogether [NGA, 2016], compared with 24,000 conventional filling stations. Plus, most of the existing gas stations need upgrading because they were built in the late 1980s – early 1990s. The

[3] The price of Mitsubishi i-MiEV.

[4] Russian Government Regulation No. 890 of 27.08.2015 "On amendments to certain Russian Government acts regarding the use of charging outlets for electric vehicles at filling stations".

Table 1. **Recommended use of CNG-powered vehicles for public transportation in cities**

| Population (thousand) | Share of CNG-powered vehicles (%) |
|---|---|
| 1,000+ | Up to 50 |
| 300+ | Up to 30 |
| 100+ | Up to 10 |

*Source:* composed by the authors on the basis of the Russian Government Regulation of 13.05.2013 No. 767-r "On regulating the use of gas motor fuel".

design capacity of the filling stations exceeds 2 billion square meters of CNG, but their average utilization rate is just 20% due to the small number of gas-powered vehicles in the country, only 110,000 altogether, or about 2% of the total motor vehicle fleet. In effect it is a classic infrastructure paradox: "consumers do not buy cars due to lack of filling stations, and companies do not invest in building filling stations due to low consumer demand" [*Mitrova, Galkina,* 2013].

The second reason for the slow growth of the gas-powered vehicles' fleet is problems with supply of such vehicles. As of 2016, practically no factory-made gas-powered cars and commercial minivans were available on the market, while the supply of such trucks and buses was very limited. To switch to using natural gas, most consumers have to resort to the relatively expensive custom conversion, which in most cases voids the manufacturer's warranty.

The third reason is the uncertain future prospects for CNG prices. After changes were made to Russian legislation,[5] the price of methane is no longer linked to the price of A-76 petrol (due to the absence of A-76 on the market, A-80, and then AI-92 prices were used instead). Currently no official documents regulate the upper limit of CNG prices. Accordingly, owners of gas-powered cars have no guarantees that this fuel will remain attractively priced in the future, while producers already have reservations about the economic advisability of selling gas at gas filling stations, again, due to the lack of an official price ceiling.

The government pays significant attention to promoting the use of gas motor fuel and dealing with the existing adverse situation (the infrastructural paradox). The Russian Energy Strategy Until 2030 [Ministry of Energy, 2009, and draft Energy Strategy Until 2035 [AC, 2014] mention the increased use of natural gas as motor fuel and increasing the share of gas-powered vehicles to 7% of the total motor vehicle fleet by 2035 as a promising area of developing the country's energy sector.

To promote the growth of the CNG market, the Russian government introduced norms regulating the use of this fuel type in cities (Table 1). A specialized company called Gazprom Gas Motor Fuel OJSC was established in 2012, whose mission was to promote the integrated development of the gas motor fuel market in the Russian Federation. To this end Gazprom PLC signs cooperation agreements with regional authorities, according to which the company undertakes the task of building and launching gas filling infrastructure facilities and organizing the conversion of vehicles. The regional authorities provide subsidies for creating fleets of gas-powered vehicles for public and municipal use, helping organizations put in place the necessary maintenance facilities and train staff. As of September 2016, such agreements were signed with 38 regions. Out of them, 10 were selected for priority development: St. Petersburg and the Leningrad Region, Moscow and the Moscow Region, the Krasnodar, Stavropol, Rostov, and Sverdlovsk Regions, and the Republics of Tatarstan and Bashkortostan. Already in 2016, investments were made to build 35 gas filling stations. By the end of 2018, Gazprom planned to extend the federal network of gas filling stations to 488 [Gazprom, 2016].

To promote the use of gas-powered vehicles, Gazprom Gas Motor Fuel OJSC signed cooperation agreements with numerous Russian and international vehicle manufacturers.

These steps were intended to create "guaranteed demand" for gas motor fuel by municipal motor transportation organizations, but they do not promote the use of gas-powered vehicles in the private sector: for the latter, the critical factor of switching to an alternative fuel type, in addition to infrastructural limitations, is vehicle conversion costs.

A system of subsidies for converting vehicles to run on CNG should be designed and put in place. These measures should include import duties for components and parts required to build gas-filling stations and ensure that methane-powered motor vehicles are reduced or eliminated altogether. The Russian public authorities should reduce transportation tax rates for owners of gas-powered vehicles[6].

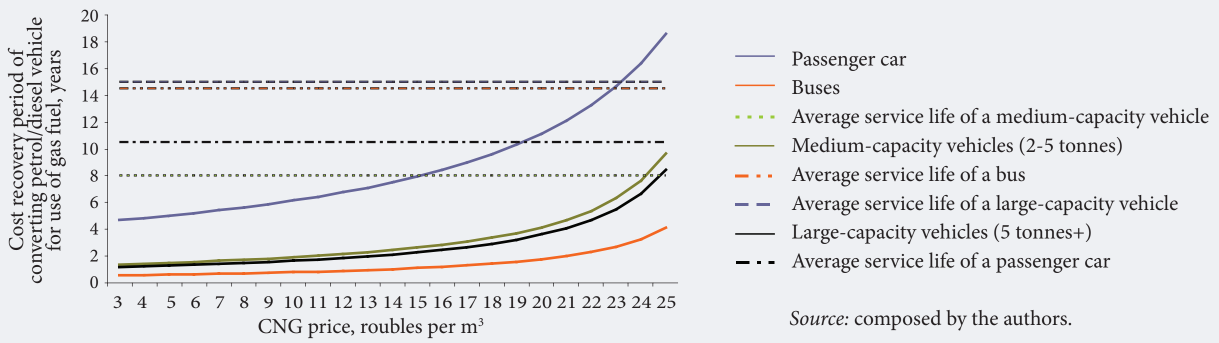
Still, even these measures to promote the use of gas motor fuel will not be enough to attract private consumers, given the uncertainty regarding the future prospects for gas prices, first of all, compressed methane.

An analysis of gas-powered vehicles' cost recovery shows that passenger cars (which dominate the private sector) are particularly sensitive to changes in CNG prices due to the low purchase prices and low mileage. The gas price ceiling (if the average price of petrol/diesel fuel remains at about 40 rubles per liter) is estimated at about 19–20 rubles per square meter; after that using a gas-powered car becomes unprofitable for the whole period of its service life (Figure 1).

[5] Russian Government Regulation of 10.04.2015 No. 338 "On invalidation of the RF Government Regulation of January 15, 1993 No.31".

[6] Russian Government Regulation of 13.05.2013 No. 767-r "On regulating the use of gas motor fuel".

Figure 1. **Cost recovery period of gas-powered motor vehicles depending on the average CNG price (with an average petrol price of 40 roubles per litre)**




*Source:* composed by the authors.

At the same time, it is important to keep in mind that there is also a price floor and selling gas motor fuel below this level becomes unprofitable for filling station owners. This floor is close to 19 rubles per square meter as well (at this level, the cost recovery period for a Russian gas filling station, given the current rate of wholesale gas prices and with full utilization, would be about two and a half years, or roughly the same as for petrol stations).

Interestingly, although gas motor fuel prices are not officially linked to the prices of petrol products, 19 rubles per litre is just about 50% of the average petrol price. We will be using this figure as a reference in our subsequent calculations and to outline the prospects for inter-fuel competition in Russia.

An integrated long-term analysis of inter-fuel competition also requires taking into account electricity as another substitute of petroleum products with good prospects in the road transportation sector in Russia.

The competitiveness estimates and subsequent calculations are based upon the following key characteristics (scenario prerequisites): fuel costs, basic car costs, the availability of infrastructure, and environmental characteristics. The current values of these parameters for various motor vehicle types are presented in Table 2.

## Scenario Building

Demand for energy in the road transportation sector was forecasted using two scenarios: "Basic" and "Promoting alternative fuel types". Both scenarios are based upon the same prerequisites and macroeconomic indicators (GDP, population, prices of oil, petroleum products, electricity, and natural gas), but differ in terms of how successful government policies promoting and supporting use of alternative motor fuels in Russia are going to be. The main macro-parameters of the study are presented in Table 3.

Both scenarios also share the same vehicle efficiency prerequisites (they assume that efficiency of vehicles powered by liquid and gas fuels would grow by 20%-25% in the next 25 years, due to the increased efficiency of the internal combustion engine among other things achieved through the application of hybrid technologies and the use of more advanced body and tire materials[7]). The efficiency of electric cars during

Table 2. **Key consumer properties of motor vehicles powered by various alternative fuel types in Russia (2015 data)**

| Parameter | Fuel type | | | |
|---|---|---|---|---|
| | **Petroleum products** | **Gas motor fuel** | **Electricity** | **Biofuels** |
| Fuel costs (*roubles per 100 km*) | 300–400 | 130–160 | 70–150 | 800–1000 |
| Price of a motor vehicle powered specific fuel type (*% of the cheapest car in the main consumer class*) | 100 | 120 | 150–350 | 100 |
| Availability of infrastructure | 24000 petrol stations | 250 gas filling stations | 40 charging stations* | 24000 petrol stations** |
| $CO_2$ emissions in the atmosphere (*g/km*) | 290–320 | 200–250 | 0*** | 95–114 |

*Notes:*
* "Fast charger" public stations without taking into account opportunities to charge cars at private homes or public parking lots
** Assuming each filling station has additional biofuel storage capacity or that biofuel is mixed with petroleum products
*** $CO_2$ emissions of electric cars do not take into account emissions made while electricity is generated
The color coding (from green to red) indicates which fuel type is better than others in terms of the relevant parameter

*Source*: composed by the authors.

[7] For more on prerequisites of increasing motor vehicles' fuel efficiency see [*Makarov et al.*, 2014].

the same period is expected to increase by 5% (only the use of better body and tire materials was taken into account, with the electric motor's efficiency factor remaining unchanged at about 90%).

Also, neither scenario envisages major changes in the conditions for inter-fuel competition between petroleum products, electricity, and natural gas on the one hand, and gas-, coal-, and biomass-based synthetic fuels on the other. In particular, such fuel types are not expected to become competitive with the alternatives in the foreseeable future in terms of production costs. That is, no large-scale production of such fuel types is expected to be launched, so there will be no supply and consumers will not have an opportunity to switch to them.

Commercialization or the large-scale use of fuel cell-powered motor vehicles is not expected either. Individual consumers can certainly buy various concept or prototype cars or luxury vehicles, but this will not significantly affect the transportation sector's energy balance during the period until 2040.

The key difference between the scenarios is the prerequisites for changing conditions for inter-fuel competition between petroleum products and their indirect substitutes, natural gas and electricity.

The basic scenario implies that key government decisions on the gasification of public transport will be carried out. The mass production of large-capacity gas-powered motor vehicles will be launched, but no subsidies will be provided for the conversion of passenger cars and medium-capacity vehicles and no mass production of gas-powered motor vehicles is expected to begin at Russian facilities. Regarding electric transport, no support will be provided for the construction of public charging stations. The existing government initiatives such as zero transport tax, permission to drive in dedicated lanes, and zero import duties will retain their current status (i.e., they will not become laws). Meanwhile electricity is gradually becoming more available, individual charging stations will appear at various parking lots and in public areas, making charging an electric car more convenient than it currently is.

The "Promoting alternative fuel types" scenario implies extending the gas filling stations' network by 2030 (following the introduction of the requirement to provide such services at all existing and new petrol stations) to a level where the infrastructure factor stops hindering people from switching to this vehicle type. Also, this scenario implies providing subsidies to convert passenger cars and medium-capacity vehicles for use of CNG (either full compensation of consumers' costs to convert their cars or launching large-scale mass production of gas-powered motor vehicles at Russian automobile factories), which would allow Russia to fully level the difference in basic prices of petrol/diesel and gas-powered vehicles by 2025.

Regarding the development of electric transport after 2025, the "Promoting alternative fuel types" scenario envisages the construction of a public "quick charging" infrastructure and creating better conditions for charging cars at home (installing charging outlets at underground parking lots and in private buildings). Generally, the charging infrastructure is expected to become comparable with the network of petrol stations by 2040. Electric car prices will be brought down by reducing import duties (from 25% of the car price to 0% after 2025) and by promoting domestic production. Cars powered by alternative fuels will be made more attractive to customers through active promotion and advertising and by allowing them to be driven in dedicated lanes in large cities.

## Modeling Results

Our calculations show that under both scenarios, the total number of cars in Russia is expected to more than double from 43 to 97 million. However, this will not double the demand for energy, due to the increased efficiency that the scenarios take into account. Total energy demand in the road transportation sector is estimated to reach 109 million tonnes of oil equivalent by 2040, compared with 64 million tonnes in 2015 (Figure 2).

Our calculations show that even if the current situation with the promotion of alternative fuel types remains unchanged, inter-fuel competition in the Russian road transportation sector is still going to increase, up to a point. Note that compressed natural gas is the key alternative to petroleum products. For example, even under the relatively pessimistic "Basic" scenario, its share of the total motor fuel consumption is going to reach 11% by 2040, or 11.5 million tonnes of oil equivalent, which is comparable to the amount of petrol consumed in 2014 in the Central and North-Western Federal Districts combined. It should also be noted

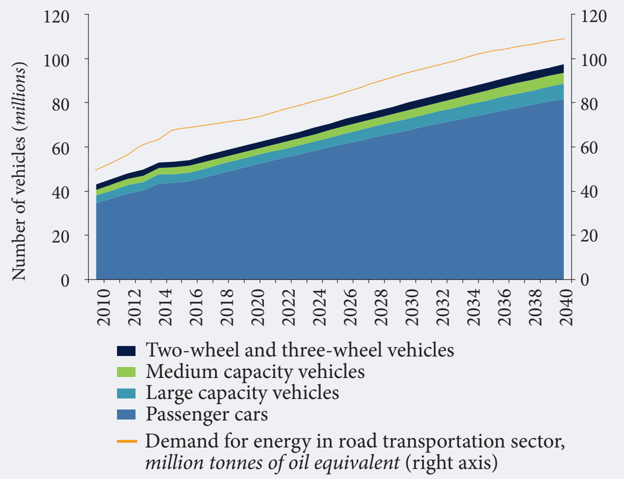
Table 3. **Dynamics of major macro-parameters between 2014-2040**

| Parameter | 2014 | 2040 |
|---|---|---|
| Average growth rate of the Russian GDP | 2.4% annual growth | |
| Russian population | 0.4% decrease, in line with the UN forecast [UN 2015]. | |
| Domestic Russian petroleum product prices (*rouble/l*)* | 40 | 60 |
| Prices of natural gas sold at filling stations (*rouble/m3*) | 20 | 40 |
| Electricity prices (*rouble/KWH*) | 4.5 | 7.7 |

* It is particularly important to measure prices in the national currency, since a majority of the population make their economic decisions (which are imitated in the course of modelling) based upon the national currency's purchasing power.

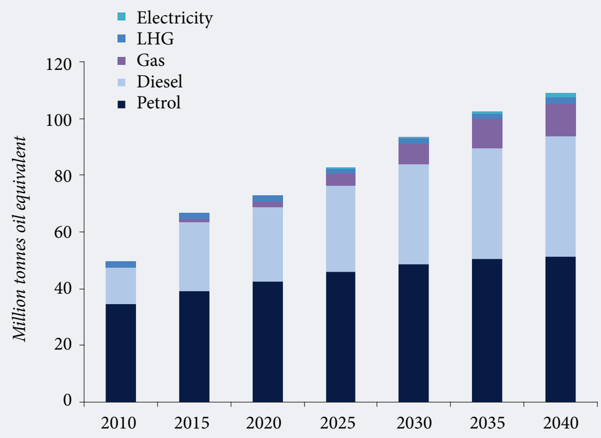
*Source*: composed by the authors.

Figure 2. **Number of motor vehicles by type, and total energy consumption in the road transport sector**




*Source*: composed by the authors.

Figure 3. **Demand for energy by fuel type under the "Basic" scenario**




*Source*: composed by the authors.

that about 35% of this amount is expected to be consumed by large-capacity vehicles which make the highest emissions, so it would lead to a significantly reduced environmental impact (compared with the situation where this substitution does not happen).

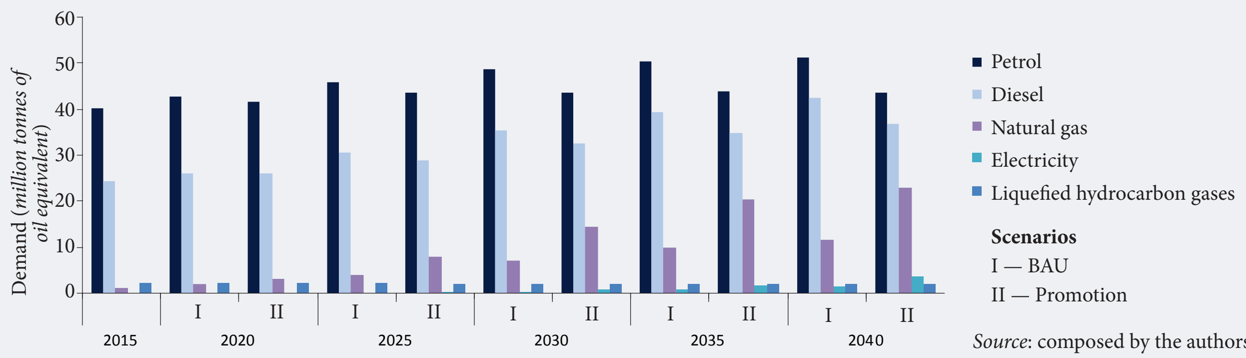
If no additional effort is made to promote the use of electric vehicles, electricity's potential to substitute petroleum-based fuels seems to be much lower. Under the "Basic" scenario, its share of the total energy consumption in the road transportation sector is not going to exceed 1% by 2040, or just over 1 million tonnes of oil equivalent. Still, it would be enough to fully meet demand for petrol in 2014 in the Far Eastern Federal District, which commonly experiences shortages of petroleum products.

If the regulatory parameters remain unchanged, petroleum products will retain their dominating position. The combined demand for such products by the road transportation sector by 2040 will reach 95.8 million tonnes of oil equivalent (Figure 3). Note that under the "Basic" scenario, demand for petrol by 2040 is expected to grow almost by 12.3 million tonnes of oil equivalent (compared with the current level), which would require the Russian oil industry to make a significant technological and investment efforts to upgrade and possibly extend its production capacities.

Additional steps to promote the use of alternative fuels described in the "Promoting alternative fuel types" scenario would lead to significant changes in the structure of energy demand by the road transportation sector. The share of gas motor fuel in total energy consumption increases by 2040 to 21% or in absolute terms to 23 million tonnes of oil equivalent, displacing petroleum products and the more expensive petrol types.

The share of electricity in total energy consumption is expected to reach 3% by 2040 or, in absolute terms, 3.5 million tonnes of oil equivalent compared with 1 million tonnes under the "Basic" scenario (Figure 4).

Figure 4. **Demand for energy by fuel type in the Russian road transport sector under the "Basic" (BAU) and "Fuel mix diversification" scenarios**




*Source*: composed by the authors.

Note that under the "Promoting alternative fuel types" scenario, demand for petrol essentially remains at the level of the Russian refineries' current production capacity due to the substitution of alternative fuel types.

## Conclusion

This study showed that Russia does have objective reasons to diversify the fuel mix of the country's road transportation sector, namely:

1. *Structural factor*: as of 2015, imports of petrol (which dominates the Russian road transportation sector's energy consumption) remained at a very low level, but Russian refineries have reached the ceiling of their production capacity. The potential to further increase the production of petrol is limited due to the lack of investment resources and domestic technologies. Stepping up production capacities would require significant investments (at about $20 billion according to [*Kapustin,* 2011]), which is comparable with the investments in, for example, developing gas motor fuel infrastructure, which, provided that all Russian petrol stations are equipped with gas motor fuel facilities, is estimated at $12.6–$31.5 billion [Promexpertisa, 2016]. If demand for this energy resource grows and no new refinery capacities are built, Russia, despite being one of the world's largest producers of oil and petroleum products, would have to import fuel.

2. *Environmental factor*: petroleum products are the least environmentally friendly fuel among the alternatives under consideration. Using CNG instead of conventional diesel and petrol would reduce harmful emissions of urban traffic into the atmosphere by 25%, while switching to electric cars would reduce vehicles' direct emissions.

3. *Export factor*: reduced demand for petroleum products on the domestic market would help Russia step up relevant exports. This has already been successfully accomplished by Iran, which has managed to convert a significant proportion of its motor vehicle fleet to the use of gas fuel by launching the domestic production of such vehicles.

4. *Gas factor*: the growth of the domestic gas market may help Russian gas producers to create an additional niche for selling their products internally, which is particularly relevant given the currently limited demand at home and on key European export markets combined with significant gas production capacities [*Kulagin, Mitrova,* 2015].

All these incentives provide good reason to consider where public support should be concentrated to promote the diversification of the fuel mix and increase the consumer appeal of specific fuel types. After all, it is the consumer preferences that ultimately determine whether customers decide to switch from petroleum products to alternatives.

The analysis shows that theoretically, on the basis of its operational characteristics, gas motor fuel can already compete with petroleum-based fuels on the Russian market. However, the degree of oil substitution would largely depend upon the regulation and promotion prospects regarding the pricing of gas motor fuel, the development of infrastructure, and subsidies for the conversion of conventional motor vehicles to use gas fuel.

Among other things, the scenario analysis indicates that electric cars, which are actively conquering the developed countries' markets, in particular in Europe, still have rather limited potential in Russia due to their very high basic prices compared with other car types. Accordingly, if gas motor fuel's success can be supported by regulatory measures, the promotion of electric cars would require further technological development in order to cut their production costs.

The Russian government has already introduced a number of measures aimed at encouraging the diversification of the fuel mix, but this is done exclusively by promoting the use of gas motor fuel by large-capacity public transportation vehicles. Plus, our calculations show that these measures will not be sufficient to achieve a significant substitution of petroleum products in the passenger car and medium-capacity vehicle segments.

Fully realizing Russia's potential to diversify the transportation sector's fuel mix and limiting the growth of demand for petroleum products requires taking an integrated approach to significantly extend consumer infrastructure (a network of gas filling stations) combined with reducing the prices of vehicles powered by alternative fuels (in the case of gas-powered ones, by launching domestic assembly line production or through the provision of tax breaks).

Implementing such measures would help save up to 13 million tonnes of oil equivalent of petroleum products by 2040 (compared with the "Basic" scenario), which can be exported. Of course, making these changes may turn out to be very expensive and require major investments which are hard to attract, especially during a recession. However, the costs are comparable with those of a major upgrading of refineries and, in the case that an integrated government policy is implemented, they would be borne not just by oil producers but shared by gas and electricity generation companies, cities, municipal authorities, consumers, and automobile manufacturers. Further, the diversification of the fuel mix would make a major contribution to improving the environmental situation in large cities and in the country as a whole.

*The study was supported by the Russian Science Foundation grant, project №14-19-01459.*

## References

Analytical Center (2014) Energeticheskaya strategiya Rossii na period do 2035 goda (osnovnye polozheniya) [Energy Strategy of Russia for the period up to 2035 (main provisions)], Moscow: Analytical Center for the Government of the Russian Federation. Available at: http://ac.gov.ru/files/content/1578/11-02-14-energostrategy-2035-pdf.pdf, accessed 15.02.2016 (in Russian).

Analytical Center (2015) *Aktivnost' naseleniya v ispol'zovanii transportnykh uslug. Byulleten' sotsial'no-ekonomicheskogo krizisa v Rossii* [Activity of the population in the use of transport services. Bulletin of the social and economic crisis in Russia]. Issue 7 (November). Moscow: Analytical Center for the Government of the Russian Federation. Available at: http://ac.gov.ru/files/publication/a/7059.pdf, accessed 25.09.2016 (in Russian).

Autostat (2016) Za 10 let srednyaya tsena legkovogo avtomobilya v Rossii vyrosla v 3 raza [For 10 years the average price of a car in Russia has grown 3 times]. *Autostat.RU*, 09.06.2016. Available at: https://www.autostat.ru/news/26250/, accessed 25.09.2016 (in Russian).

Bobylev Yu.N., Prikhod'ko S.V., Drobyshevskii S.M., Tagor S.V. (2006) Faktory formirovaniya tsen na neft' [Factors of formation of oil prices], Moscow: Institute for the Economy in Transition (in Russian).

Braginskii O.B. (2012) *Prognozirovanie rossiiskogo rynka avtomobil'nykh vidov topliva. Doklad dlya Otkrytogo seminara "Ekonomicheskie problemy energeticheskogo kompleksa" 24 aprelya 2012 g.* [Forecasting the Russian market of automotive fuels. Report for the Open Seminar "Economic Problems of the Energy Complex", April 24, 2012], Moscow: RANEPA. Rezhim dostupa: http://ecfor.ru/wp-content/uploads/seminar/energo/z129.pdf, data obrashcheniya 18.04.2016 (in Russian).

Curran S.J., Wagner R.M., Graves R.L., Keller M., Green J.B. Jr. (2014) Well-to-wheel analysis of direct and indirect use of natural gas in passenger vehicles. *Energy*, no 75, pp. 194–203.

ERI RAS, Analytical Center (2014) Prognoz razvitiya energetiki mira i Rossii do 2040 goda [Forecast of the development of energy in the world and Russia until 2040] (eds. A. Makarov, L. Grigoryev, T. Mitrova, Moscow: The Energy Research Institute of the Russian Academy of Sciences, Analytical Center for the Government of the Russian Federation (in Russian).

Gazprom (2016) V tekushchem godu «Gazprom» postroit 35 novykh AGNKS [This year Gazprom will build 35 new CNG stations]. *Gazprom official website*. Available at: http://www.gazprom.ru/press/news/2016/august/article280185/, accessed 17.01.2017 (in Russian).

Glebova O. (2013) *Gas to Liquids: Historical Development and Future Prospects*, Oxford: Oxford Institute for Energy Studies.

Grushevenko E., Grushevenko D., Kulagin V. (2016) *Long-term impact of technological development on European road transportation sector's fuel mix: Focus on electric vehicles*. Paper presented at the 10th International Conference on Electric Power Quality and Supply Reliability. Available at: http://ieeexplore.ieee.org/stamp/stamp.jsp?arnumber=7724107, accessed 20.07.2017.

Höök M., Aleklett K. (2010) A review on coal to liquid fuels and its coal consumption. *International Journal of Energy Research*, vol. 34, no 10, pp. 848–864.

IEA (2014) *World Energy Outlook 2014*, Paris: International Energy Agency.

Interfax (2016) EEK prodlila snizhennye poshliny na elektromobili do sentyabrya 2017 goda [ECE has extended reduced duties on electric vehicles until September 2017]. Available at: http://www.interfax.ru/business/518259, accessed 24.05.2017 (in Russian).

Kapustin N., Grushevenko D. (2016) Russia refines on. *Energy Focus*, no 26 (Spring), pp. 89–94.

Kapustin N.O., Osipova E.D. (2015) Sistemnyi analiz meropriyatii chetyrekhstoronnego soglasheniya [System analysis of the activities of the quadrilateral agreement]. Neft', gaz i biznes [Oil, Gas, and Business], no 6, pp. 13–18 (in Russian).

Kapustin V. (2011) Renessans v neftepererabotke otmenyaetsya? [Renaissance in oil refining is canceled?]. *Neftegazovaya vertikal'* [Oil and Gas Vertical], no 21. Available at: http://www.ngv.ru/magazines/article/renessans-v-neftepererabotke-otmenyaetsya/, accessed 17.01.2017.

Kulagin V.A., Grushevenko D.A., Kozina E.O. (2015) Effektivnoe importozameshchenie [Effective import substitution]. *Energetika i geopolitika* [Energy and Geopolitics], no 1 (49), pp. 49–57 (in Russian).

Kulagin V.A., Mitrova T.A. (2015) *Gazovyi rynok Evropy: utrachennye illyuzii i robkie nadezhdy* [Europe's gas market: Lost illusions and timid hopes], Moscow: ERI RAS, NRU HSE (in Russian).

Milovidov K.N., Korzhubaev A.G., Eder L.V. (2006) Neftegazoobespechenie global'noi ekonomiki [Oil and Gas Supply of the Global Economy]. M.: Centrlitneftegaz (in Russian).

Minenergo (2009) Energeticheskaya strategiya Rossii na period do 2030 goda (utverzhdena rasporyazheniem Pravitel'stva Rossiiskoi Federatsii ot 13.11.2009 g. No. 1715-r) [Energy Strategy of Russia for the period up to 2030 (approved by Order of the Government of the Russian Federation of November 13, 2009 no 1715-r)], Moscow: Ministry of Energy of the Russian Federation. Available at: https://minenergo.gov.ru/node/1026, accessed 15.02.2016 (in Russian).

Mitrova T. (2016) Shifting Political Economy of Russian Oil and Gas. A Report of the CSIS Energy and National Security Program. Lanham; Boulder; New York; London: Rowman & Littlefield.

Mitrova T., Kulagin V., Grushevenko D., Grushevenko E., Galkina A. (2015a) Integrated method of petroleum products demand forecasting considering economic, demographic and technological factors. *Economics and Business Letters*, vol. 4, no 3, pp. 98–107.

Mitrova T.A., Galkina A.A. (2013) Mezhtoplivnaya konkurentsiya [Interfuel competition]. *Ekonomicheskii zhurnal VShE* [*The HSE Economic Journal*], no 3, pp. 394–413 (in Russian).

Mitrova T., Kulagin V., Grushevenko D., Grushevenko E. (2015b) Technology Innovation as a Factor of Demand for Energy Sources in Automotive Industry. *Foresight and STI Governance*, vol. 9, no 4, pp. 18–31. DOI: 10.17323/1995-459X.2015.4.18.31.

Moskva 24 (2016) Dve besplatnye stantsii zaryadki elektromobilei otkrylis' v Moskve [Two free charging stations for electric vehicles opened in Moscow]. *Moscow 24*, 22.04.2016. Available at: goo.gl/whb639, accessed 05.11.2016 (in Russian).

Mussatto S.I. (2016) A closer look at the developments and impact of biofuels in transport and environment; what are the next steps? *Biofuel Research Journal*, vol. 3, no 1, p. 331. DOI: 10.18331/BRJ2016.3.1.2.

NGV (2015) Mirovoi rynok KPG po sostoyaniyu na noyabr' 2015 g. [The world market of CNG as of November 2015]. *National Gas Vehicle Association website*. Available at: http://www.ngvrus.ru/statistics.html, accessed 17.01.2017 (in Russian).

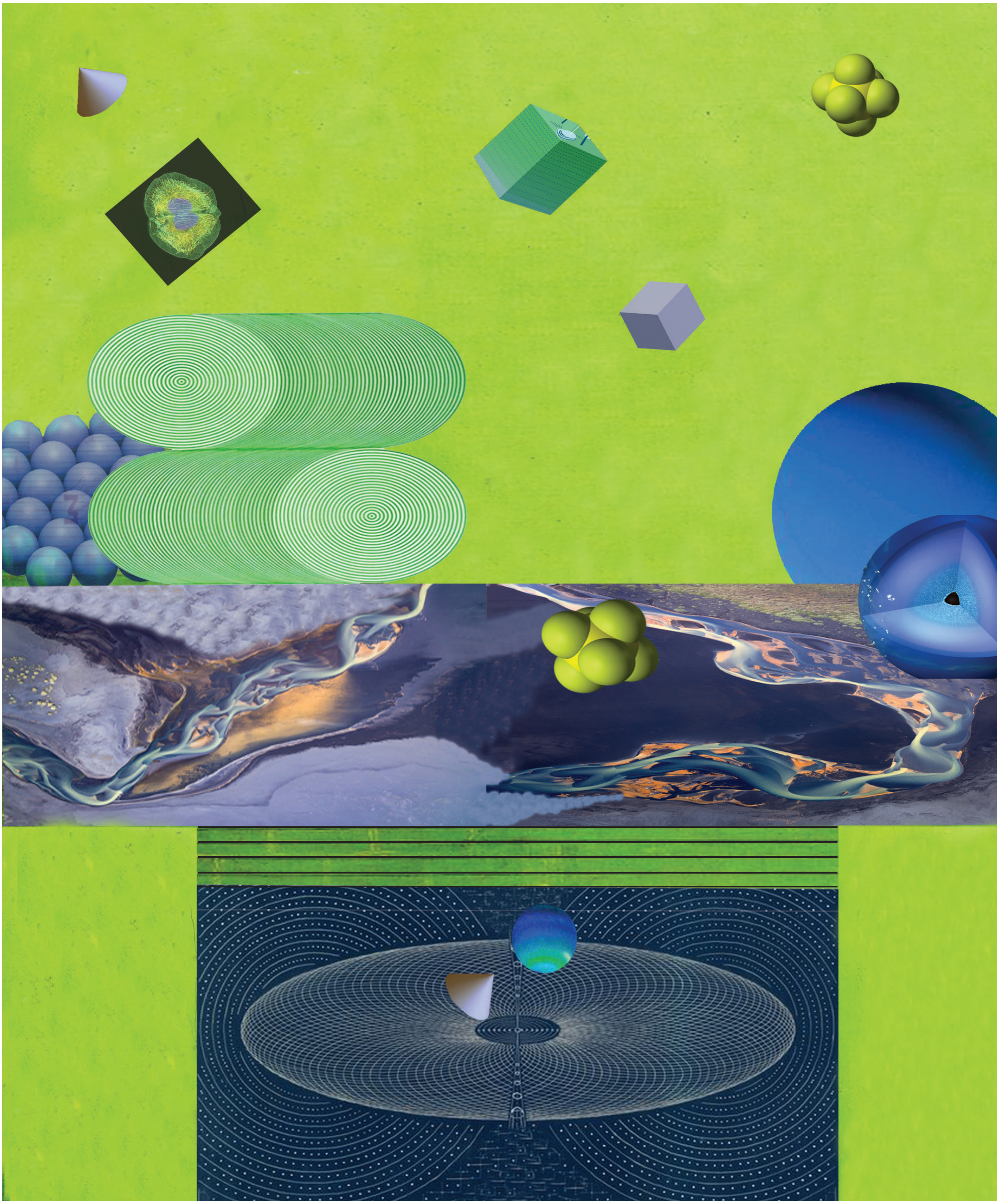
Promekspertiza (2016) Pravitel'stvo RF obyazalo AZS prodavat' gazomotornoe toplivo [The government of the Russian Federation ordered the gas station to sell gas engine fuel]. Available at: http://promexpertiza.ru/pravitelstvo_rf_obyazalo_azs_prodavat_gazomotornoe_toplivo/, accessed 17.01.2017 (in Russian).

Sørensen B. (2012) *Hydrogen and Fuel Cells. Emerging Technologies and Applications* (2nd ed.), Amsterdam; Boston; Heidelberg; London; New York; Oxford; Paris; San Diego; San Francisco; Singapore; Sydney; Tokyo: Elsevier.

UN (2015) *World Population Prospects: 2015 Revision. UN Population Division Report*, Geneva: United Nations.

Voelcker J. (2014) *How Much Money Does The 2016 Toyota Mirai Lose? A Lot, Perhaps. Green Car Reports*. Available at: http://www.greencarreports.com/news/1095773_how-much-money-does-the-2016-toyota-mirai-lose-a-lot-perhaps, accessed 20.09.2017.

Voronov A., Tsinoeva Ya., Dyatel T. (2016) Elektromobili podzaryazhayut l'gotami [Electric cars are recharged with benefits]. *Kommersant*, issue 123 of 12.07.2016. Available at: https://www.kommersant.ru/doc/3036078, accessed 21.09.2017 (in Russian).



# Applying Global Databases to Foresight for Energy and Land Use: The GCDB Method

**Gilbert Ahamer**

Senior Scientist, gilbert.ahamer@chello.at

Wegener Centre for Climate and Global Change, Graz University, Macherstrasse 15, 8047 Graz, Austria

## Abstract

Any economy strongly depends on energy trends, which, as practice shows, are non-linear. This paper proposes an efficient method for predicting these trends. It is based upon a geo-referenced approach and combines a biosphere-energy model with a Global Change Data Base (GCDB). The advantage of the considered method over "pure modelling" lies in its heuristics, dealing with the real historical dynamics of techno-socio-economic systems. Newly emerging qualities and saturation effects will be better portrayed by the proposed method, which includes first and second derivatives. The novelty of the GCDB method is in that it uses correlations of data series rather than data points. This allows for insights when contemplating swarms of data series and a heuristic examination of whether or not the widely-used hypothesis of path dependency in energy economics – and, more generally, in economic development – is applicable.

The author believes that the application of the GCDB method will increase the credibility of conclusions based on the collected data, enrich the knowledge in the field of «growth theory», expand the knowledge base, and increase the efficiency of public policy related to climate change.

**Keywords:** energy foresight; global modelling; Global Change Data Base; scenarios; trends extrapolation; dynamics-as-usual scenario; biomass energy; land use change; saturation

**Citation:** Ahamer G. (2018) Applying Global Databases to Foresight for Energy and Land Use: The GCDB Method. *Foresight and STI Governance*, vol. 12, no 4, pp. 46–61. DOI: 10.17323/2500-2597.2018.4.46.61

## Introduction: mapping energy trends from the system dynamics perspective

Any economy puts a strong emphasis on the production of energy, and Kazakhstan (picked out as only one representative of an ex-Soviet country) might be a striking illustration of this (albeit transitory) state of development that all-too-often still includes nuclear energy with its unresolved safety issues [WNA, 2018], including polluting radioactive fallout [*Ahamer,* 2012]. Presently, mostly fossil fuels are produced on Kazakh territory, but limitations of availability and global climate protection treaties might well change the traditionally high increase in fossil fuel demand and hence could profoundly affect Kazakhstan's economic structure, which underlines its political influence in the Central Asian region [*Gürgen et al.,* 1999, IMF, 2009].

In order to early identify and respond to such changes, attempts to "map" energy trends are undertaken (e.g., [IPCC, 2002; IIASA, WEC, 1998; *Foster, Rosenzweig,* 2003; *Barro,* 1991]). Traditional *trend extrapolation* follows the structure shown in Figure 1a at the left – be it linear, exponential or through other mathematical methods. For shorter periods, such an algorithm might be appropriate. However, if we want to extend projection periods to several decades, *saturation effects* and *new qualities* should be detectable, as shown in Figure 1b.

From the systems dynamics perspective of this article [*Sterman,* 2000], both these types of development are understood as principally foreseeable, because they may be predicted by increasingly stronger change rates, even if these are of initially minimal level ("weak signals" [*Steinmüller,* 2012; *Hiltunen,* 2006]. Hence, they often remain unperceived when principally understanding that reality is describable as a huge system of interconnected differential equations.

In future research terminology, other types of unexpected and more unlikely events are called "wildcards" [*Nikolova,* 2017; *Walsh et al.,* 2015; *Mehrabanfar,* 2014], while a "tipping point" [*Steinmüller,* 2012] can principally be foreseen and explained from a systems dynamics viewpoint.

## Diverse understanding of foresight in literature

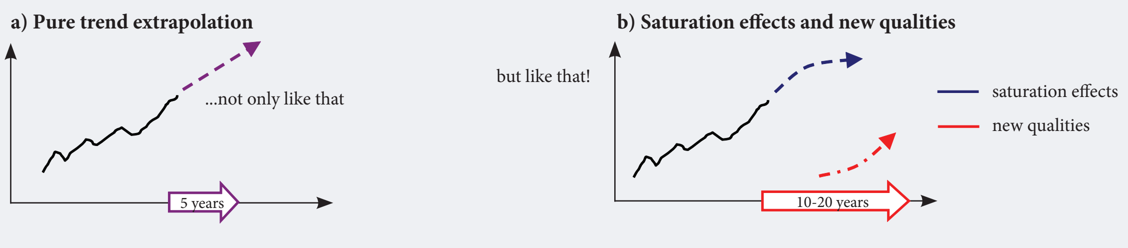
While the term foresight is often used by companies for their immediate individual business prospects and for guidance on optimal investment strategies [Foresight Group, 2018] or for specific technological developments such as molecular nanotechnology [Foresight Institute, 2018; *Drexler,* 1986] or transport [Foresight Automotive, 2018], some scientists place more emphasis on the political consultation aspect of assessing multiple expert assessments on possible futures [Futurezone, 2013] or states' own procedures for planning their technology policies through technology foresight [BMBF, 2012; Austrian Parliament, 2018]. Numerous foresight companies [*Horx,* 2018; Z_Punkt, 2018] populate a dynamic market that suggests, discusses and assesses several diverse futures, rather than merely "judging correctly what is going to happen in the future and planning actions based on this knowledge", as suggested by mainstream dictionaries [Cambridge, 2018].

While for "pure" trend extrapolation we need values (let us call them x), we will compute and contemplate the first and second derivatives ($\partial x$ and $\partial^2 x$) for facilitating the detection of saturation effects and new qualities. We consider all the cases (x, $\partial x$ and $\partial^2 x$) in details.

Until now, the basic foresight approaches for energy and land-use change (i.e. the "mapping" and "tracing" of energy issues into the future) have taken many forms. On the forthcoming pages, two such approaches are proposed: (1) classical maps of energy demand and potential energy supply and (2) plots of energy-related structural variables against GNP/cap. We map the *spatial* and *temporal* patterns of supply and demand (and their driving forces). The combination of both approaches facilitates the "mapping" and "tracing" of dynamic structures [*Ahamer,* 2019] – in other words, foresight on a per-country level.

*Geography* as a spatial discipline (as distinct from e.g. physics, history or economics which rely more on temporal paradigms) proposes different views on reality from an idealised standpoint that no human being ever takes in practice (generalised bird's-eye view [*Ahamer,* 2019]). But this "borderline case"

Figure 1. **A long-term analysis may as well unfold along wave-like steps of evolution: nonlinear futurology**




*Source:* the author.

of a bird's-eye view permits the existing differences in perception among individuals to be overcome. Principally speaking, such a bridging of standpoints is needed in any civil society [*Schmitz*, 2009, p. 9; *Schmitz*, 2003, p. 21] in order to find – rather create – consensus solutions [*Knizhnikov*, 2018].

Using spatial and temporal maps, this article investigates the following issue: how much energy do we need globally and how can we cover that demand globally?

## Mapping spatial patterns of energy demand

In the following, a simple formula shall be applied that has often been called "Kaya identity" [*Kaya,* 1990; *Kaya et al.,* 1997; *Rosa, Dietz,* 2012], has largely been used in energy economics, climate protection and projections of $CO_2$ emissions [IPCC, 2002; IIASA, 1998; WEC 2003]:

$CO_2 = (CO_2 / E) \times (E / GNP) \times (GNP/capita) \times P$ , (1)

where: $CO_2$ — level of $CO_2$ emissions
E — demand for energy (for a specific energy carrier)
GNP — gross national product (for a specific economic sector)
P — population.

Generally speaking and using terms of system analysis [*Sterman,* 2000; *Bentley et al.,* 2004; *Vester, von Hesler,* 1980; *Meadows et al.,* 1972] any complex (economic or other living) system tends to grow as a result of its inner structure [*Heylighen,* 1996; *Chan,* 2001]. Consequently, the growth rate of any (economic or other) system is closely determined by its inner (political, technological, social etc.) structure. We may hypothesise: if the system's structure remains the same, the growth rates are likely to be constant[1]. But in reality, each system changes during growth and alters its structure. This is the reason why each of the formula's quotients changes: it "walks along a *path of development*", and hence characterises the "emission scenarios".

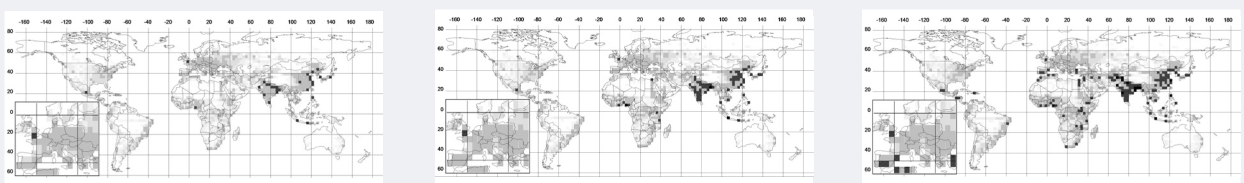
This section shows gridded maps for each of the four magnitudes of which quotients appear in the formula (1) for the years 1990, 2025 and 2100: Population (Figure 2), Gross National Product GNP (Figure 3), demand of primary energy (Figure 4), shares of the fuels indexed by f (Figure 5). Additionally, the formula includes at the left end the respective emission factor to compute resulting $CO_2$ emissions (Figure 6 and Figure 7). This 2.5° × 2.5° grid for driving factors was designed for the "Combined Energy and Biosphere Model" CEBM, which projects IEA data[2].

The maps in this section show the *extensive* magnitudes Pop, GNP, E, $CO_2$. Quite visibly, these magnitudes are very suitable for classical geographic maps which focus on *spatial* structures. Among others, a shift in emphasis may be observed away from former centres such as Western Europe, Northern America, and Eastern Europe including CIS countries towards countries such as China and India, also partly Africa. This shift in components of $CO_2$ emissions is in line with political and strategic shift, and generally in line with plausible evolutionary processes.

As already mentioned, the above maps in Figure 2 to Figure 7 show quantities that are measurable in numbers, monetary units, physical energy units – hence quantities pertaining to the material, physical world, often called extensive magnitudes because of their physical extension.

Figure 2. **Population in 1990, 2025, 2100 according to the CEBM scenario (*1000 inhab.*)**

**a) 1990** **b) 2025** **c) 2100**



0–100 | 100–300 | 300–1000 | 1000–3000 | 3000–10000 | 10000–30000 | 30000–100000 | >100000

*Note*: All figures in this article are based on the author's own elaborations that are described in details at [*Ahamer*, 2019].

[1] In analogy to the well-known basic law in mechanics, attributed inter alia to Sir Isaac Newton: if no acceleration occurs, the velocity of a material body remains constant – this could thus be called the "Newtonian foresight paradigm".

[2] The CEBM methodology was developed by the author during the year of his affiliation to IIASA [*Ahamer,* 1994].

Figure 3. **Gross National Product GNP in 1990, 2025, 2100 according to the CEBM scenario (*millions USD / year*)**

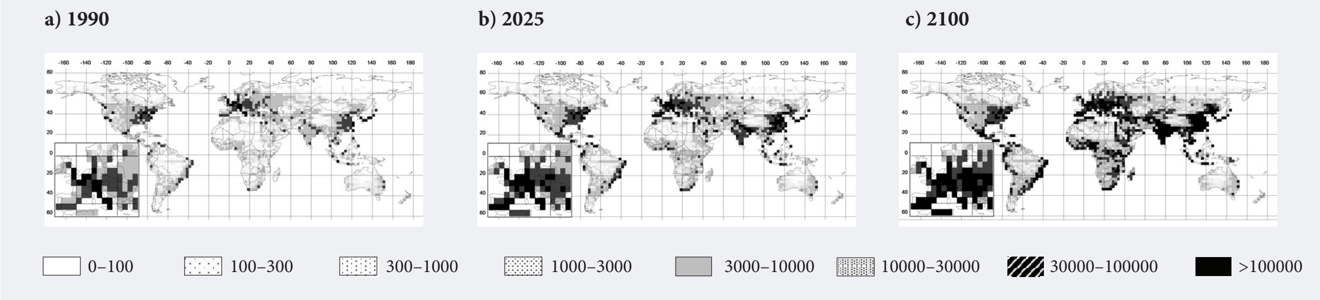



Figure 4. **Energy demand in 1990, 2025, 2100 according to the CEBM scenario (*PJ / year*)**

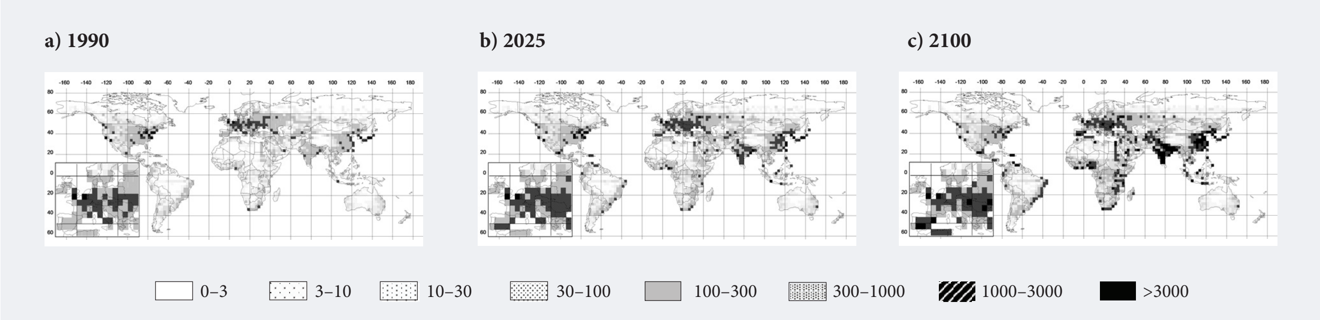



Figure 5. **Various fuel shares in primary energy mix in 1990 according to the CEBM (*% / 100*)**

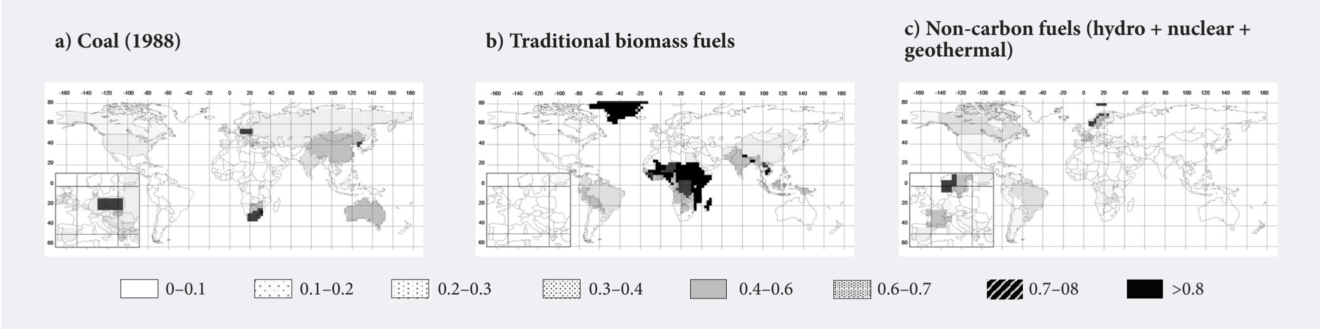



Figure 6. **$CO_2$ emissions from various sources in 1990 according to the CEBM data (*kt C / year*)**

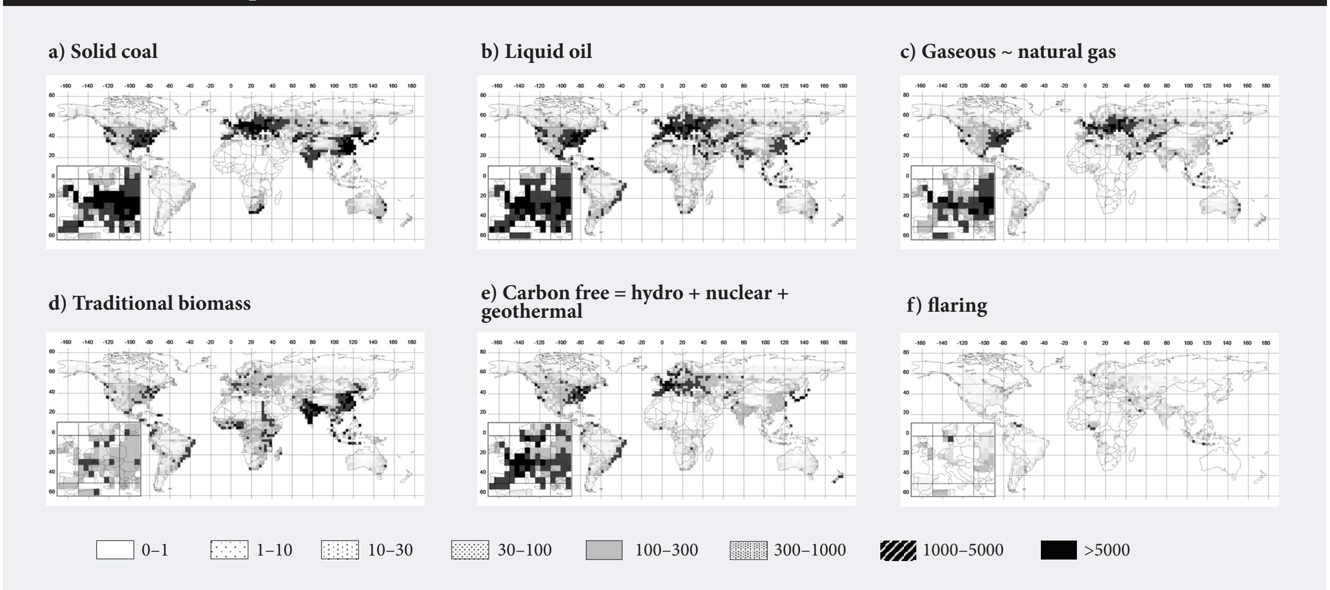
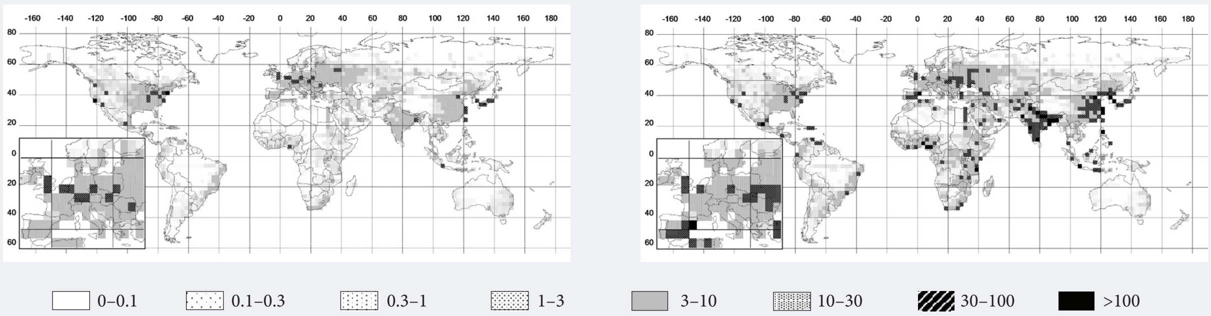


Figure 7. **$CO_2$ emissions from fossil fuels in 1990 and 2100 according to the CEBM scenario** (*Mt / year*)

**a) 1990**

**b) 2100 (valid for the biomass scenario and approximately for the base case scenario)**




The modelling experience of the author [*Ahamer*, 2013, 2019] shows that extensive magnitudes are not likely to follow smooth paths (as has been suggested by the hypothesis of path dependency advocated by some branches of economics). Smooth paths and sizeable trends are more likely to be observed in systemic variables that are considered to describe a system's (here an energy system's) internal structure, inner interdependences and hence temporal dynamics. Based on this experience, the decision was made to shift the act of trend analysis from the realm of extensive magnitudes to the realm of intensive magnitudes. This decision is motivated both by pragmatic evidence (trends in intensive variables were visibly more stable) and by systemic deliberations (the software, culture, and organisational structure of a system is more stable than its imminent behaviour under annually changing outside pressures).

Therefore, the above formula and the methodology of projection does focus on the quotients of adjacent extensive factors, namely GNP/cap, E/GNP and $CO_2$/E, the so-called "drivers of $CO_2$ emissions". Such quotients are called *intensive* magnitudes and describe systems and structures: the economic system, the

Figure 8. **CEnergy demand per capita in 1990 and 2100** (***GJ/cap. per year***)

**a) 1990**

**b) 2100 (according to the estimation of the CEBM)**

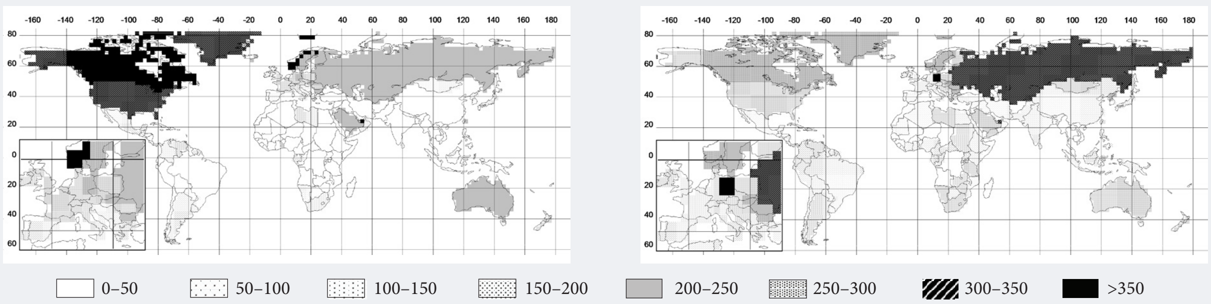



Figure 9. **Fossil $CO_2$ emissions per capita $CO_2$/cap for 1990 and 2100** (***t C/cap per year***)

**a) 1990**

**b) 2100 (according to the estimation of the CEBM)**

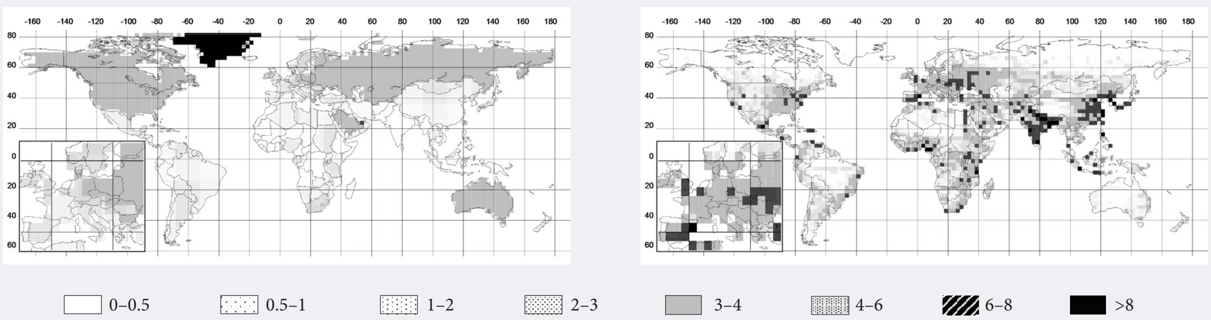


Figure 10. **Energy intensity (energy needed per economic output) E/GNP for 1990 and 2100** (*MJ per USD*)

**a) 1990** **b) 2100 (according to the estimation of the CEBM)**

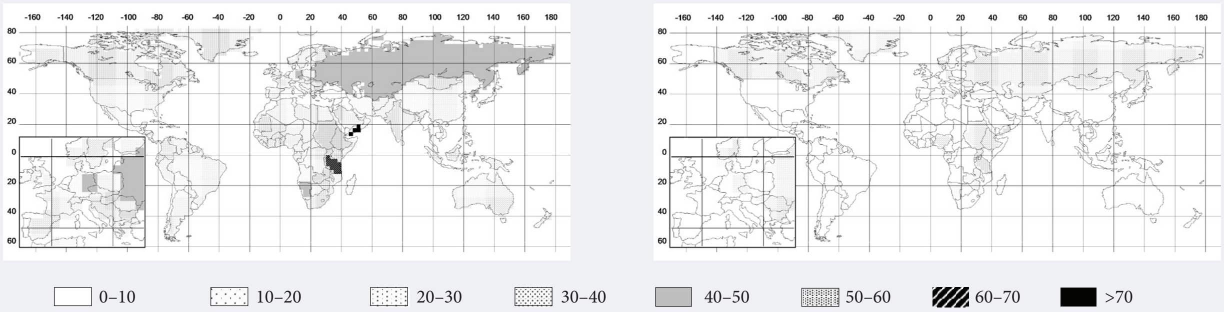
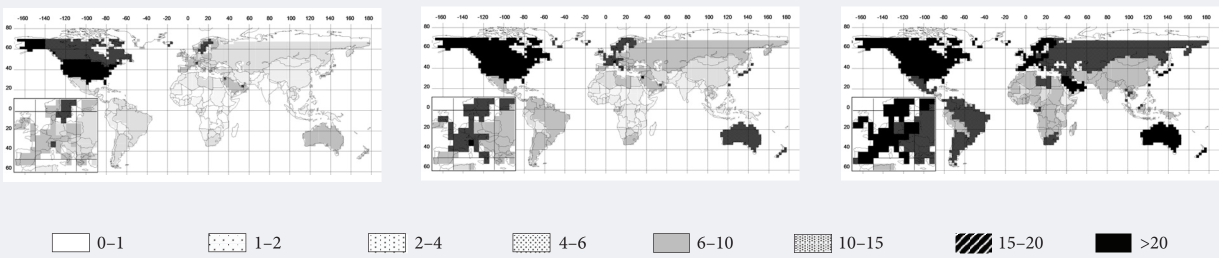



Figure 11. **The economic level of a country (Gross National Product per capita) GNP/cap according to the CEBM for 1990, 2025 & 2100 (under tight assumption of world-wide economic saturation)** (***1000 USD / cap.***)

**a) 1990** **b) 2025** **c) 2100**




energy system, the fuel structure – which are mostly characteristic of an entire country. Below we will display these maps that consequently have a per-country structure in the model used.

In addition to the *absolute* magnitudes ($CO_2$, E, GNP, Pop), the following figures show the *relative* magnitudes made up of the quotients of the neighbouring (and the subsequent) variables for the years 1990 and 2100: E/cap (Figure 8), $CO_2$/cap (Figure 9), E/GNP (Figure 10), GNP/cap (Figure 11).

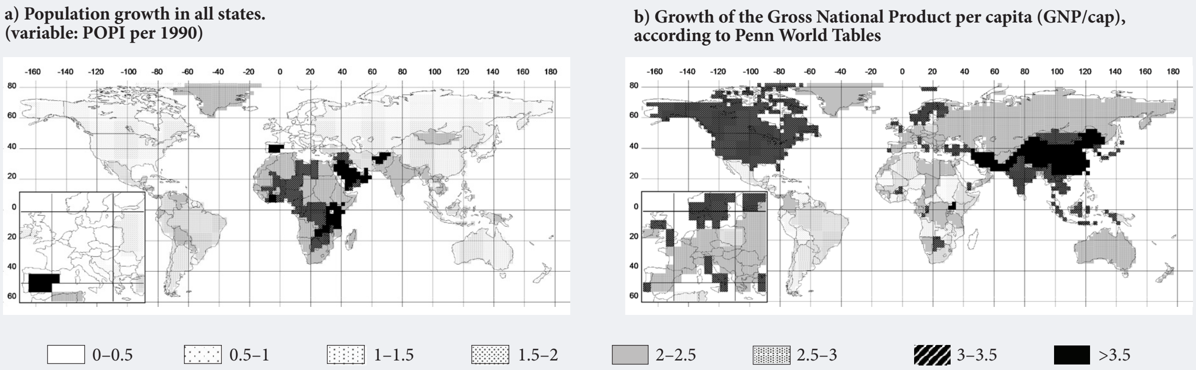
It becomes visible from the uniform distribution of data within a country that the assumption of a homogenous energy system and economic system within a country was held to be reasonable. Therefore, the "granularity" of mapping changes from 2433 grid elements to 200 countries. An additional "degree of freedom" for mapping emerges from this systemic structure – this will be made use of in next sections.

All components of the formula have been mapped in the above figures. The reader might have noticed that each of these parameters develops with a different dynamic and geographic pattern, might run into saturation or even reverse the direction of change from + to – or vice versa.

Geographic patterns of growth may show parallel growth in all countries or widening gaps between countries – this is a highly disputed question among economists [*Basu, Weil,* 1998] – regarding "growth theory"; regarding this question, a person may prefer to take a *Neo-classical* or *Keynesian* view [*Barro,* 1999]. Findings offered by literature include: political stability and democracy also promote economic growth [*Barro,* 1991, p. 432], not only technology [*De Long, Summers,* 1991], research & development [*Jones, Williams,* 1998] and stable economic integration [*Rivera, Romer,* 1991, 1994; *Devereux, Lapham,* 1994]. Regression methods were widely used to analyse growth patterns in China and the USSR throughout the previous century [*Ofer,* 1987; *Chow,* 1993]. "*Evolutionary economics*" views developing economic structures [*Bergh, Stagl,* 2003, p. 290] and links them to institution building. In a sense, this recent scientific discipline can be seen as an application of Schumpeter's ideas [*Hanusch,* 1988].

In some studies [*Grossman, Krueger,* 1995, p. 370], environmental damage is reported to increase with GNP growth until a level of 9000$/cap and then it decreases: this behaviour is referred to as the Environmental Kuznets Curve (EKC) [*Foster, Rosenzweig,* 2003]. According to the IMF [IMF, 2009], Kazakhstan's GDP/cap amounts to 6868$/a for 2007 – a good indication of upcoming improvement of fossil fuel-induced environmental damage…

Figure 12. **The population growth rate (at left) and the economic growth rate (at right) for 1990 (*% per year*)**




From the above deliberations, we can deduce that growth rates play a central role in describing the dynamics of a system, and thus in its future development. Consequently, we should concentrate on how to "map" them in a suitable manner.

As two examples, the growth rates for population (at left in Figure 12) and for GNP/cap (at right in Figure 12) are displayed as a traditional map, again serving to discern typical geographical patterns. However, interpretation will largely follow the lines of complex historic, economic and political "world wisdom" and does not easily open itself to simple dependencies on latitude, longitude or climate[3].

At this point, our perspective opens from "patterns" to "the *dynamics of patterns*" – such as will be dealt with in later chapters.

## Mapping Spatial Patterns of Potential Energy Supply by Biomass

One of the targets of the CEBM was to try to match global energy demand (series of figures after Figure 4 above) with the potential from biomass energy, because biomass energy is seen as a ready-to-use energy source that causes no net $CO_2$ emissions. The following Figure 13 shows such spatial patterns of the maximum theoretical biomass potential, namely the annual growth of woody or herbaceous biomass on the natural or agricultural area of a grid cell [*Ahamer,* 1994; *Ahamer,* 2019]. By using only annual biomass growth (and not the entire biomass stocks), one basic criterion for sustainability appeared to be fulfilled.

The global megatrend of agricultural efficiency improvement is likely to release pressure on arable land and to free up a certain amount of arable land for other targets such as energy production[4]. Therefore, an increased availability of land for biomass growth might be hypothesised in industrialised countries under favourable conditions.

The computation of the global potential of biomass for energy in Figure 13 uses five different principal strategies for land-use and plant growth (from above):

- as = energy use of agricultural biomass
- av = energy plantations on former natural areas
- nv = energy use of natural biomass at a plant age of 5 years (~ short rotation plants)
- nvn = energy use of natural biomass (= forestry)
- ap = energy plantation on former agricultural areas.

As Figure 13 shows, the global potential of biomass energy is unevenly distributed across the world and – more strikingly – the centres of biomass production do not coincide with the centres of energy demand. The result when comparing the geographic patterns of Figure 13 with Figure 4 is the huge need for transportation arising from such an extensive biomass-based energy strategy!

Figure 14 compares the global totals of energy supply (above three bars) with energy demand (below two bars): the main message is that the theoretical biomass potential equals the magnitude of the actual demand. In practice and after all necessary reductions from a theoretical potential, biomass alone as a fuel could never satisfy the needs of a global energy system — this is the second message of the CEBM results.

[3] Even if several authors have tried to deliver explanations that may seem overly simplistic to many readers [*Landes,* 2000].

[4] Similarly, a rise in forests with GDP/cap is reported by Foster & Rosenzweig [*Foster, Rosenzweig,* 2003, p. 601].

Figure 13. **Geographic distribution of the biomass fuel potentials for five biomass growth strategies: as, av, nv, nvn, ap** (*g C / m² per year*)

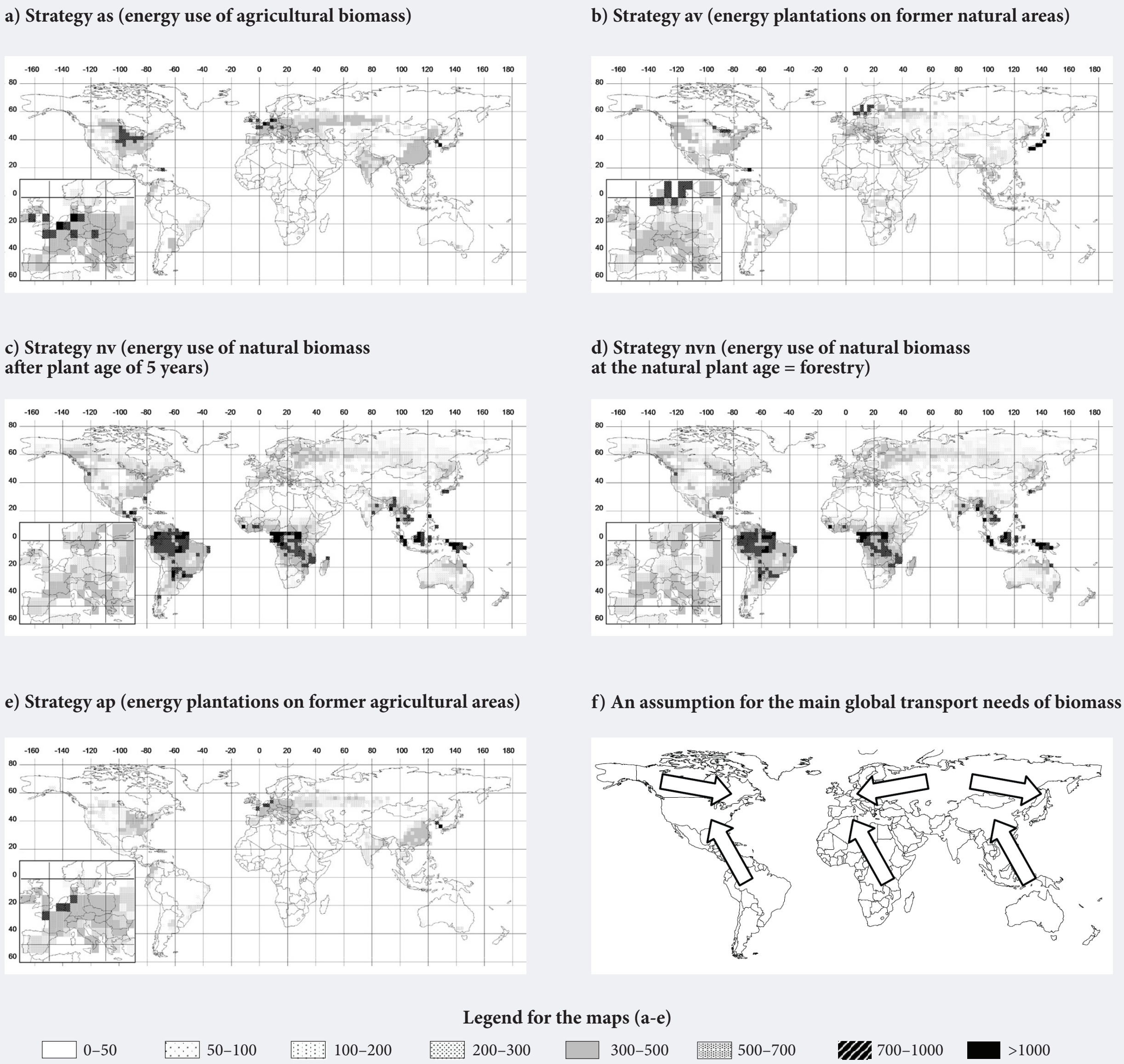
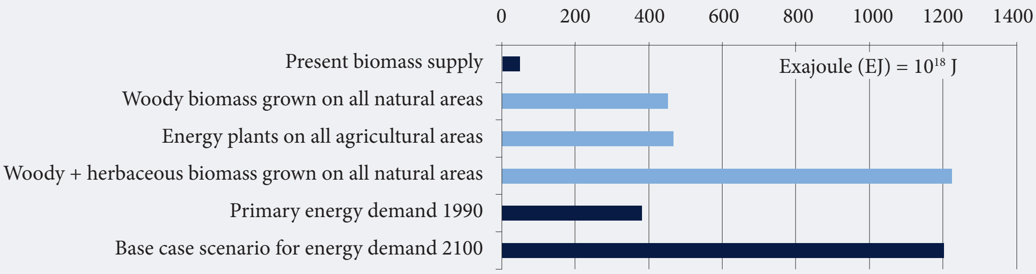



Figure 14. **The global biomass potential compared to the global primary energy demand**




*Source*: simplified after [*Ahamer*, 2019] based on CEBM calculations (no conversion losses considered)..

## Growth of energy demand: mapping temporal dynamics

As mentioned, the aim of this article and the entire endeavour of creating the GCDB (Global Change Data Base) is to portray future development, i.e. develop a concrete quantitative foresight method. Further we will focus on explaining this "GCDB method".

Regarding a suitable strategy for visualising data and their dynamic development, one well-known option is to use the horizontal axis of a trend visualisation to illustrate the trend over time. Another, possibly less known option (e.g. also used for [Gapminder, 2018] or [IPCC, 2002, p. 125]) is to replace time with "economic level" (GNP/cap) because such a transformation of coordinates creates easily visible graphic structures – and because the economic path (even from some theoretical viewpoints) depends on the economic structure, which in turn depends on economic levels. Figure 15 gives an example of such a "mapping strategy".

What seems useful as a quantitative diagnostic tool is a sufficiently large, harmonised and geo-referenced database together with the means for producing a sufficient number of correlations between these data sets (not simply within the individual data). Then, the most stable and meaningful correlations shall be used as landmarks in a sufficiently plausible "*map* of techno-socio-economic evolution" (see the following figures with swarms of red lines). A subset of such "*robust paths of development*" will be interpreted based upon its potential to *lead towards targets of sustainability vs. lead away from targets* of sustainability. The most common example is engendered $CO_2$ emissions, and therefore this will be focused on in this approach.

In order to give an example of the graphical appearance of the global data used by the GCDB method, trends for the driving forces of global change demonstrate the relative importance of effects on the climate caused by different aspects of the human impact on $CO_2$ concentration (compare Figure 16 and [*Altmann et al.,* 2013; *Öttl et al.,* 2014]).

## The GCDB method: architecture and analytical tools

The *Global Change Data Base* GCDB comprises over 2000 country-oriented variable sets (primary variables) for 100-200 countries ranging over several decades (mostly 1960-1991, depending on data availability) taken from the internationally accepted data stocks from international institutions such as the International Energy Agency IEA, the United Nations UN and its Statistical Office, the Food and Agriculture Organisation FAO, The World Bank WB, Human Development Indicators HDI, and World Development Indicators WDI (at left in Figure 17).

From these primary variables (mostly "extensive variables" according to the above definition), the GCDB is able to derive several thousand secondary variables such as indicators, intensities or rates (as examples of the above-defined "intensive variables"). The *analytical tool* of the GCDB (AT) is able to produce both quantitatively and graphically several thousand correlations between the abovementioned variable types (compare Figure 18), as explained in [*Ahamer,* 2013].

Diagrams are provided on a per-country basis, per continent, and for eleven world regions common to most global modelling, as used in energy economics [IPCC, 2002; GEA, 2012].

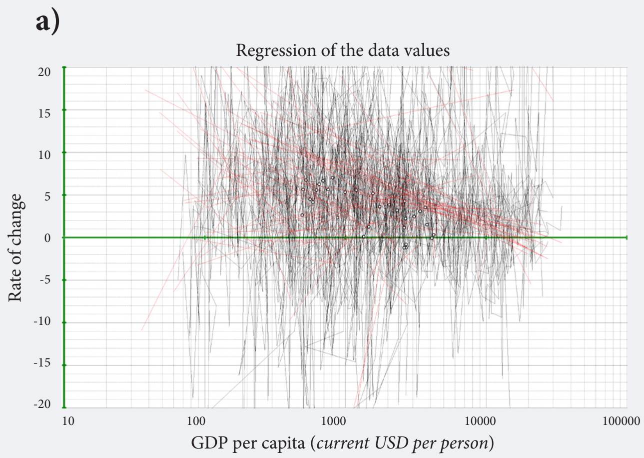
With the specific GCDB analytical tool, computations of country data and regional aggregates of sums, differences, products, quotients and derivatives of any GCDB variables are calculated along with correlation coefficients and plotted correlations of time series for several decades. For primarily graphical analysis, it *combines* the perspectives of *time series analysis* [*Jones,* 1995, p. 502; *Islam et al.,* 2003, p. 151] and *cross-correlation analysis* (e.g. [*Barro,* 1991, 2001]) for explaining the levels, rates of change, and saturation effects in the field of economy, energy use and land use.

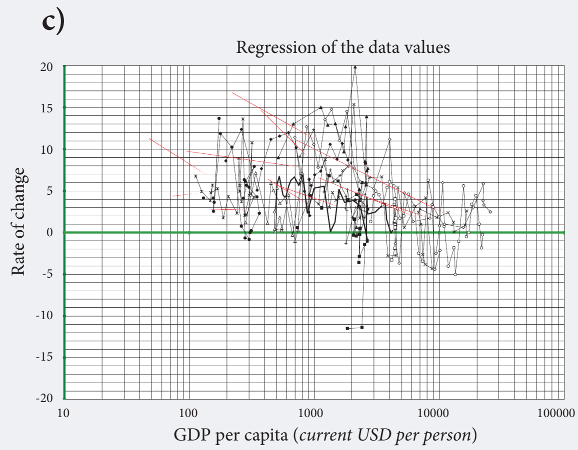
A considerable advantage of the proposed methodology – if combined with the concept of "path of development" (e.g. along rising GDP/cap.) – consists of the ability of the methodology to overcome the principal restriction of the reliability of projections to (following a rule of thumb) half of the period for which data exist. If ever the arrays of data for all countries were positioned near to a common path (which is the very criterion to be checked), then the basis of expansion into a likely future path stretches over "states from very poor to very rich" which is a substantially larger information basis than "states during some decades". Another advantage is that the 1st and 2nd derivatives of data series can be expected to exclude a number of flaws negatively affecting statistical analysability.

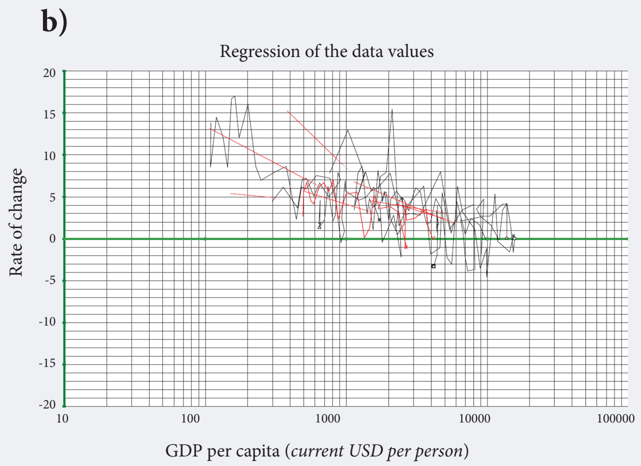
Until a recent literature check, *no such methodology had been found* until recently in scientific journals with the 15 highest impact factors[5] in the fields of economy and energy. Furthermore, stable trends representing "paths of development" are identified and used to build a more complete picture of evolutionary patterns.

[5] Among which are: *Journal of Economic Literature, Quarterly Journal of Economics, American Economic Review, Ecological Economics, Econometrica, Economic Policy, Economic Geography, Economy and Society, Energy, Energy Economics, Journal of Financial Economics, Journal of Political Economy, NBER Macroeconomic Annals, Social Indicators Research*. For the explanation of the 'ISI impact factor', see http://isiwebofknowledge.com/.

Figure 15. **The growth rate of the final energy demand as a function of GNP/cap** (%)




**Legend to diagram (b)**

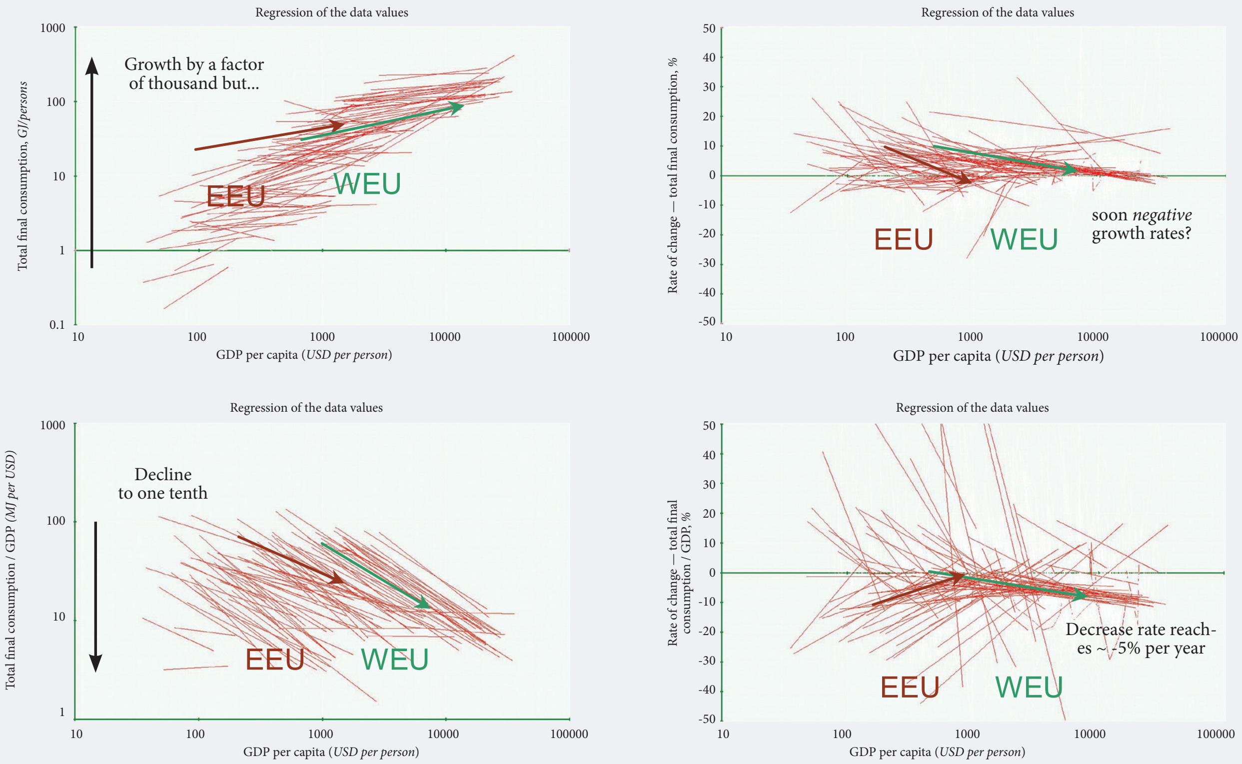
- Soviet Union
- Africa
- Asia
- Europe
- Northern and Central America
- Oceania
- South America
- World
- Logarithmic (Soviet Union)
- Logarithmic (Africa)
- Logarithmic (Asia)
- Logarithmic (Europe)
- Logarithmic (Northern and Central America)
- Logarithmic (Oceania)
- Logarithmic (South America)
- Logarithmic (World)

**Legend to diagram (c)**

- World
- North America
- Latin America and Caribbean
- Western Europe
- Central and East Europe
- Former Soviet Union
- Middle East and North Africa
- Sub-Saharan Africa
- Centrally Planned Asia
- South Asia
- Other Pacific Asia
- Pacific OECD
- Logarithmic (World)
- Logarithmic (North America)
- Logarithmic (Latin America and Caribbean)
- Logarithmic (Western Europe)
- Logarithmic (Central and East Europe)
- Logarithmic (Former Soviet Union)
- Logarithmic (Middle East and North Africa)
- Logarithmic (Sub-Saharan Africa)
- Logarithmic (Centrally Planned Asia)
- Logarithmic (South Asia)
- Logarithmic (Other Pacific Asia)
- Logarithmic (Pacific OECD)

*Note*: Each black graph represents one country for duration of some three decades. For reducing the volatility of information visualized, a trend line is computed (in red). One red line thus means the trend of one single state (at left), of one continent (centre) and of one region (at right).

## Figure 16. **Dynamics of energy demand per capita**

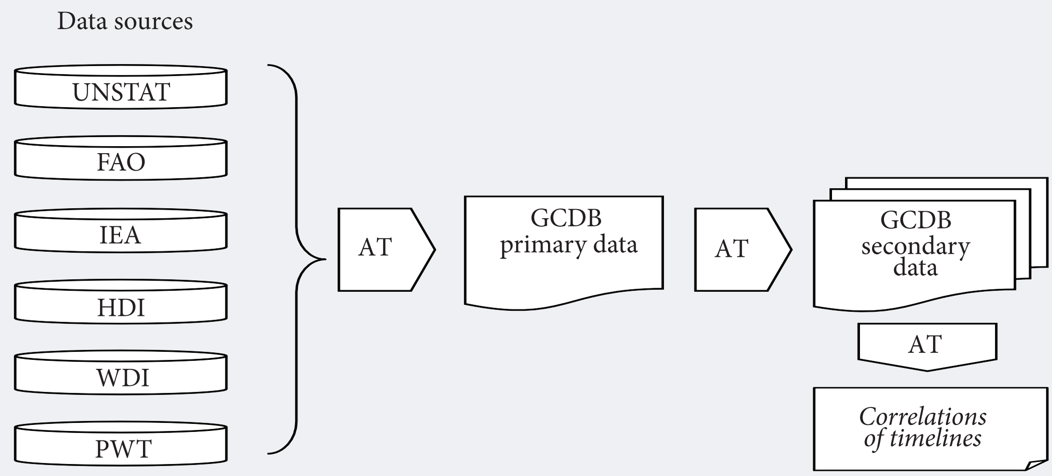



*Note*: Energy demand per capita is still rising worldwide (above left), but its already decreasing growth rate is starting to touch zero (above right) when plotted for all single countries as a function of economic level (Gross Domestic Product per capita = GDP/cap). This trend suggests a transition in the global energy system. Similarly, energy demand per GDP (= energy intensity) is strongly declining worldwide (below left) and additionally its growth rate is starting to decrease strongly (below right). .

*Legend*: WEU = Western Europe; EEU = Central & Eastern Europe without Russia.

*Source*: [*Ahamer*, 2015].

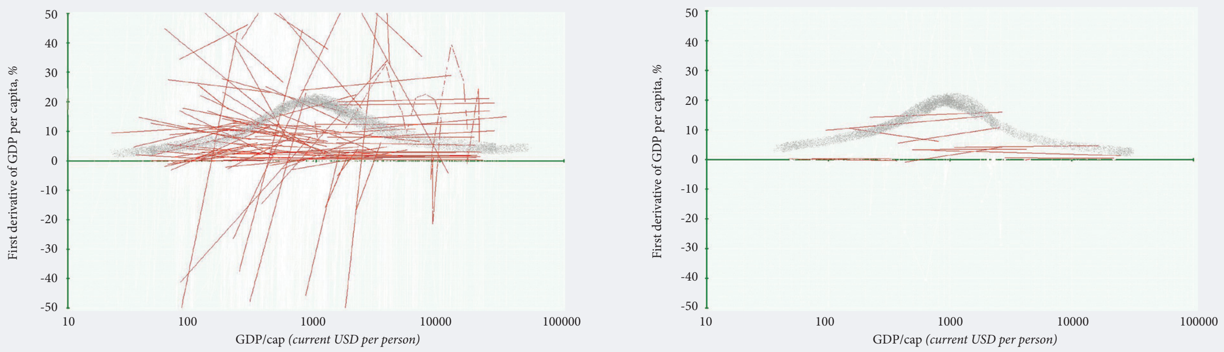
## Figure 17. **Data flow scheme for the "Global Change Data Base" GCDB**




*Note*: For the details on abbreviation see text. At left — internationally compatible data sources. These data are topographically harmonised by the analytical tool (AT). By their mathematical combination, the AT computes a greater multitude of secondary data that are able to be correlated and then displayed graphically in order to detect so-called "paths of development" as hypothesised by some growth theories.

*Source*: [*Ahamer*, 2013].

Figure 18. **First attempts for spatio-temporal maps**




*Note*: Relative growth of GDP per capita is plotted against GDP/cap for an average of three decades for all countries (at left), and aggregated into 11 regions [*Ahamer*, 2019]. Grey sprayed-on colour hypothesises elevated growth rates of middle-income countries as compared to countries with high or low income; readily compatible with saturation growth curves (compatible in principle with [*Korotayev, Zinkina,* 2014]).

Global Climate Change is mainly driven by $CO_2$ emissions [IPCC, 2001, 2014] which in turn are driven by economic, industrial and energy supply structures. The underlying evolutionary changes in these structures act as decisive driving forces for Global Change – and these driving forces are quantified.

Until now, the method of projecting the present condition of the socio-economic state has been widely used [*Ang, Liu,* 2000, p. 538]. However, the parameter "**changes in rates of change**" has not yet been sufficiently studied in order to yield well-founded information on likely deviations from a "business-as-usual" path of development. Such deviations are likely to occur as crucial results from the internal system structure of the global techno-socio-economic system.

In this approach, the primary source of knowledge is the (intersubjectively re-examinable) "**reality**" (in the form of data describing reality) and not "*model results*" (or even prescriptions derived from preconceived models of reality as it is supposed to be, from whatever scientific school they might stem)[6]. Therefore, information on correlations or changes in directions of development are based on data (from past decades), *not on pre-conceived convictions* laid down in world models. Interpretation (after having analysed using the GCDB tools) is up to the reader.

The *methodology* itself consists of analysing the "path locus" of all countries' time series and the texture, slope and twist of this array of curves including state-of-the-art statistical analysis.

The **"main formula"** of the GCDB approach for *energy-related* $CO_2$ emissions is based on the above-mentioned IPAT or Kaya identity [*Kaya,* 1990; *Kaya et al.,* 1997; *Rosa, Dietz,* 2012], which in here enlarged by one quotient distinguishing primary and final energy[7]. It reads:

$$CO_2 = (CO_2 / E_p) \times (E_p / E_f) \times (E_f / GDP) \times (GDP / capita) \times Population$$

where: $CO_2$ — level of $CO_2$ emissions (for a specific fuel and sector)
$E_p$ — demand for primary energy (for a specific fuel and sector)
$E_f$ — demand for final energy (for a specific fuel and sector)
GDP — gross national product (in a specific economic sector)
P — population.

Please note: for *land use change-related* $CO_2$ emissions, a similar system structure is developed where the area takes the place of energy and the crop type takes the place of the fuel.

Types of variables describing the dynamics of the global evolutionary system (mostly as a function of GDP/cap), are depicted in Table 1, while hierarchy of indicators for the considered methodology presented in Table 2.

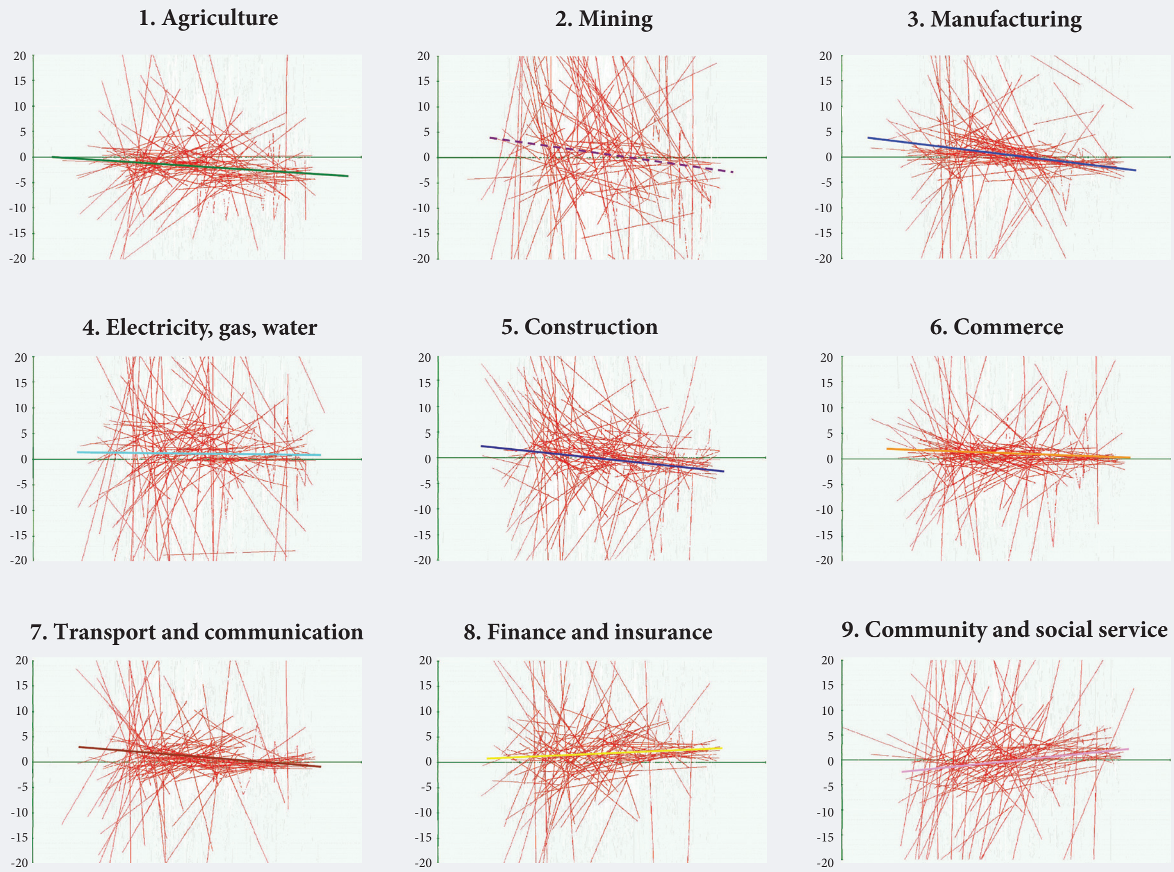
The IT methodology consists of (i) computing, (ii) statistically analysing and (iii) graphically depicting *all* forms of *all* types of variables of the GCDB, mostly following the "main formula".

When implementing the abovementioned main formula, harmonisation of different sectoral catalogues (e.g. between IEA and SNA statistics) must be performed; all remaining amounts must be interpreted with sufficient caution based on earlier experiences in national environmental accounting, especially

[6] Just as in the tradition of Galileo Galilei; who, for instance, urged contemporary cardinals *to look through his telescope* onto the astronomic reality supporting his worldview [*Galilei,* 2002].

[7] For yet more detailed notation see [*Ahamer,* 2013, p. 373].

Figure 19. **Preliminary analyses by the GCDB on the various growth rates within nine single economic sectors (%)**




*Legend*: see Figure 18; vertical axis ranges from -20%/a to +20%/a. Values above the green (zero) line mean growth; below mean decline.

regarding transportation and household [*Schipper et al.,* 2000]. For this endeavour, the meaning of "sectoral intensity" will sometimes need to be handled cautiously as a *proxy variable* for relative shifts in "attention" or "attribution of values". The proposed method takes into account the "decomposition method" approaches [*Schipper et al.,* 2000, p. 22] as having high merit in attributing percentages of driving forces to the "decarbonisation effect", "intensity effect", "rebound effect" and other partial movements of the interconnected socio-economic meta-structures.

## Conclusion

Applying the GCDB method for forecasting presumes a number of implications for science and society. Further strengthening of understanding and corroborating the various, often contradictory *developmental theories* will contribute to multicultural understanding among economic ideologies, including related university curricula such as "Global Studies" [*Bader et al.,* 2013, 2014]. It will provide further background information for studies that are designing, assessing and monitoring national and global *climate protection measures.* Economic "*growth literature*" will be widened by the approach of

Table 1. **Variables describing the dynamics of the global evolutionary system**

| Variable | Description |
|---|---|
| Levels | Denoted by the "state vector" x in this text, per each country, as times series |
| Rates of change | First derivative of a state vector : $\partial$x, compare Figure 19), including saturation levels (cases where first derivatives tend towards zero) |
| Changes in the rates of change | Second derivative of a state vector: $\partial^2$x, aimed at better detecting saturation and other non-linear behaviour, including variability of all the above types (inter-country, inter-region, inter-temporal. |
| *Source:* compiled by the author. | |

Table 2. **Hierarchy of indicators**

| Category | Described parameter | Examples | Graphical representation |
|---|---|---|---|
| Extensive entities | Stocks, flows | Energy, population, area | Figure 2 to 7 |
| Intensive entities | Structures | Quotients, indicators, energy intensities | Figure 8 to 11 |
| Shares | Compositions | Sectoral GDP, fuel mix | Figure 19 |
| *Source*: author. | | | |

phase-dependent relative impact of "growth factors" on GDP growth. The GCDB toolkit will contribute to the to-date tool boxes in *scenario writing,* as well as concrete interdisciplinary application of concepts of *systems science* and game theory.

Awareness of background picture of global trends, when comparing to the trajectory of the respective nation. Systems analysis approach becomes more concrete towards "Global Change". This underpins a clearer link between the *practicability* of declared climate protection targets and the realistic room for *action,* thus allowing a more profound assessment of the directions of action for *national climate policy.* This leads to increasing public awareness of the necessity to *steer technological development* for ecology and $CO_2$ abatement.

From the above calculations, at first glance, we see that growth rates of global energy demand will decline. This result is stable with regard to all fuels: the peak of coal, oil and gas seems to be over soon – in this sequence of fuels. A suitable counterstrategy against this megatrend which threatens the economic basis of any countries, but especially of post-Soviet states such as Kazakhstan (also Russia and others), is to diversify – into biomass, solar and wind (compare [*Ermolenko et al.,* 2017; *Proskuryakova, Kovalev,* 2015]) – and to explore such potentials by global information systems.

Summing up, the Global Change Data Base (GCDB) method is a suitable tool for **detecting trends and changes in trends in the global energy system**, thus for better understanding its global dynamic behaviour.

## References

Ahamer G. (1994) Influence of an Enhanced Use of Biomass for Energy on the $CO_2$ Concentration in the Atmosphere. *International Journal of Global Energy Issues*, vol. 6, no 1/2, pp. 112–131.

Ahamer G. (2012) Geo-Referenceable Model for the Transfer of Radioactive Fallout from Sediments to Plants. *Water, Air, and Soil Pollution*, vol. 223, no 5, pp. 2511–2524, DOI: 10.1007/s11270-011-1044-x.

Ahamer G. (2013) A Planet-Wide Information System. *Campus-Wide Information Systems*, vol. 30, no 5, pp. 369–378. DOI 10.1108/CWIS-08-2013-0032.

Ahamer G. (2015) Applying student-generated theories about global change and energy demand. *International Journal of Information and Learning Technology*, vol. 32, no 5, pp. 258–271. DOI 10.1108/IJILT-01-2015-0002.

Ahamer G. (2019) *Mapping Global Dynamics. From Local Pollution to Global Evolution*, Heidelberg, New York, Dordrecht, London: Springer.

Altmann M., Eisenreich S., Lehner D., Moser S., Neidl T., Rüscher V., Vogeler T. (2013) Global inequality and poverty in perspectives of geography. *Multicultural Education & Technology Journal*, vol. 7, no 2/3, pp. 127–150.

Ang B.W., Liu F.L. (2000) A new energy decomposition method: Perfect in decomposition and consistent in aggregation. *Energy*, vol. 26, no 6, pp. 537–548.

Austrian Parliament (2018) *Foresight and Technology Assessment: Monitoring of future themes for the Austrian Parliament*, Vienna: Austrian Parliament. Available at: https://www.parlament.gv.at/SERV/FTA/, accessed 04.12.2018.

Bader L., Bereuther T., Deutsch E., Edlinger J., Füreder S., Kaspar E., Köttstorfer M., Mautner C., Rossegger C., Samonig A., Samonig S., Schuster C., Witz G., Zotter V., Ahamer G. (2013) Quality Improvements in Curricula for Global Studies. *Multicultural Education and Technologies Journal*, vol. 7, no 2/3, pp. 113–126. DOI 10.1108/17504971311328035.

Bader L., Bereuther T., Deutsch E., Edlinger J., Füreder S., Kaspar E., Köttstorfer M., Mautner C., Rossegger C., Samonig A., Samonig S., Schuster C., Witz G., Zotter V., Rozanov A., Ilyin V., Ahamer G. (2014) Multiparadigmatic Humanities: Curricula for Global Studies. *International Journal of Humanities and Social Science*, vol. 4, no 6, part 1, pp. 314–337.

Barro R.J. (1991) Economic Growth in a Cross Section of Countries. *Quarterly Journal of Economics*, vol. 106, no 2, pp. 407–443.

Barro R.J. (1999) Ramsey Meets Laibson in the Neoclassical Growth Model. *Quarterly Journal of Economics*, vol. 114, no 4, pp. 1125–1152.

Barro R.J. (2001) Human Capital and Growth. *American Economic Review*, vol. 91, no 5, pp. 12–17.

Basu S., Weil D.N. (1998) Appropriate Technology and Growth. *Quarterly Journal of Economics*, vol. 113, no 4, pp. 1025–1054.

Bentley L.D., Dittman K.C., Whitten J.L. (2004) System analysis and design methods. Boston, MA: McGraw-Hill, Irwin.

Bergh J.C.J.M., Stagl S. (2003), Coevolution of economic behaviour and institutions — towards a theory of institutional change. *Journal of Evolutionary Economics*, vol. 13, no 3, pp. 289–317.

BMBF (2012) *Mit Foresight in die Zukunft schauen*, Berlin: BMBF. Available at https://www.bmbf.de/de/mit-foresight-in-die-zukunft-schauen-930.html, accessed 04.12.2018.

Cambridge (2018) Foresight in the Cambridge Dictionary. Available at https://dictionary.cambridge.org/dictionary/english/foresight, accessed 04.12.2018.

Chan S. (2001) *Complex Adaptive Systems*. Paper presented at the ESD.83 R Research Seminar in Engineering Systems, October 31 – November 6, 2001. Available at: http://web.mit.edu/esd.83/www/notebook/Complex%20Adaptive%20Systems.pdf, accessed 04.12.2018.

Chow G.C. (1993) Capital Formation and Economic Growth in China. *Quarterly Journal of Economics*, vol. 108, no 3, pp. 809–842.

De Long J.B., Summers L.H. (1991) Equipment Investment and Economic Growth. *Quarterly Journal of Economics*, vol. 106, no 2, pp. 445–502.

Devereux M.B., Lapham B.J. (1994) The Stability of Economic Integration and Endogenous Growth. *Quarterly Journal of Economics*, vol. 109, no 1, pp. 299–305.

Drexler E. (1986) *Engines of Creation: The Coming Era of Nanotechnology*, New York: Anchor Books.

Ermolenko G.V., Ermolenko B.V., Proskuryakova L., Fetisova Y. (2017) Wind and solar PV technical potentials: Measurement methodology and assessments for Russia. *Energy*, vol. 137, pp. 1001–1012.

Foresight Automotive (2018) *Implementing innovations & adding economic value: Interdisciplinary exchange and fruitful networking*. Available at: https://foresight-automotive.com/ziele/?lang=en.

Foresight Group (2018) *Vision & Values*. Available at https://www.foresightgroup.eu/, accessed 04.12.2018.

Foresight Institute (2018) Advancing beneficial technology. Available at https://foresight.org/#, accessed 04.12.2018.

Foster A.D., Rosenzweig M.R. (2003) Economic Growth and Rise of Forests. *Quarterly Journal of Economics*, vol. 118, no 1, pp. 601–637.

Futurezone (2013) *Foresight: Den Zukünften auf der Spur*. Available at: https://futurezone.at/science/foresight-den-zukuenften-auf-der-spur/24.590.988, accessed 04.12.2018.

Galilei G. (2002) *Sidereus Nuncius (News about new stars)* (reprinted by H. Blumenberg), Frankfurt: Suhrkamp.

Gapminder (2018) *Statistical tools*. Available at: https://www.gapminder.org/tools/, accessed 04.12.2018.

GEA (2012) *Global Energy Assessment — Toward a Sustainable Future*, Cambridge (UK) and New York: Cambridge University Press; Laxenburg (AT): International Institute for Applied Systems Analysis.

Grossman G.M., Krueger A.B. (1995) Economic Growth and the Environment. *Quarterly Journal of Economics*, vol. 110, no 2, pp. 353–377.

Gürgen E., Snoek H., Craig J., McHugh J., Izvorski I., van Rooden J. (2009) Economic Reforms in Kazakhstan, Kyrgyz Republic, Tajikistan, Turkmenistan, and Uzbekistan (Occasional Paper 183), Washington, D.C. International Monetary Fund. Available at: http://www.imf.org/external/pubs/nft/op/183/index.htm, accessed 11.06.2018.

Hanusch H. (ed.) (1988) *Evolutionary Economics: Applications of Schumpeter's Ideas*, Cambridge, New York, Melbourne: Cambridge University Press.

Heylighen F. (1996) The Growth of Structural and Functional Complexity during Evolution. *The Evolution of Complexity* (eds. F. Heylighen, D. Aerts), Dordrecht: Kluwer Academic Publishers. Available at http://pespmc1.vub.ac.be/Papers/ComplexityGrowth.html, accessed 04.12.2018.

Hiltunen E. (2006) Was It a Wild Card or Just Our Blindness to Gradual Change? *Journal of Futures Studies*, vol. 11, no 2, pp. 61–74.

Horx M. (2018) *Zukunftsinstitut and Publications*. Available at https://www.horx.com/, accessed 04.12.2018.

IIASA, WEC (1998) *Global Energy Perspectives in 1998*, London: World Energy Council; Laxenburg (AT): International Institute for Applied Systems Analysis.

IMF (2009) *Republic of Kazakhstan — Concluding Statement of the IMF Mission, January 16, 2009,* Washington, D.C. International Monetary Fund. Available at: http://www.imf.org/external/np/ms/2009/011609.htm, accessed 11.06.2018.

IPCC (2001) *Climate Change 2001* (Synthesis Report. A Contribution of Working Groups I, II, and III to the Third Assessment Report of the Intergovernmental Panel on Climate), Cambridge (UK), New York: Cambridge University Press.

IPCC (2002) *Special Report on Emissions Scenarios (SRES)*, Geneva: Intergovernmental Panel on Climate Change. Available at: www.ipcc.ch/pdf/special-reports/spm/sres-en.pdf, accessed 11.06.2018.

IPCC (2014) *The Fifth Assessment Report*, Geneva: Intergovernmental Panel on Climate Change.

Islam S.M.N., Munasinghe M., Clarke M. (2003) Making long-term economic growth more sustainable: Evaluating the costs and benefits. *Ecological Economics*, vol. 47, no 2-3, pp. 150–166.

Jones C.I. (1995) Time Series Tests of Endogenous Growth Models. *Quarterly Journal of Economics*, vol. 110, no 2, pp. 495–525.

Jones C.I., Williams J.C. (1998) Measuring the Social Return to R&D. *Quarterly Journal of Economics*, vol. 113, no 4, pp. 1119–1135.

Knizhnikov A. (2018) *WWF Rating 2018: Results, Progresses, Challenges regarding environmental responsibility in the Russian oil & gas industry*. Paper presented at the Ecological Responsibility in Russia's Energy Sector Workshop, 5th December 2018, Berlin.

Korotayev A., Zinkina J. (2014) On the structure of the present-day convergence. *Campus-Wide Information Systems*, vol. 31, no 2/3, pp. 139–152.

Landes D.S. (2000) *The Wealth and Poverty of Nations: Why Some Are So Rich and Some So Poor*, New York: W.W. Norton.

Lovelock J. (1988*) The Ages of Gaia. A Biography of Our Living Earth*, New York, London: W. W. Norton & Co.

Meadows D.H., Randers J.; Meadows D.L., Behrens W.W. (1972) *The Limits to Growth: A Report for the Club of Rome's Project on the Predicament of Mankind*, New York: Universe Books.

Mehrabanfar E. (2014) Wild Cards Applications in Futures Studies. *International Journal of Modern Management & Foresight*, vol. 1, no 8, pp. 212–218.

Nikolova B. (2017) The wild card event: Discursive, epistemic and practical aspects of uncertainty being 'tamed'. *Time & Society*, vol. 26, no 1, pp. 52–69. DOI: 10.1177/0961463X15577283.

Ofer G. (1987) Soviet Economic Growth. *Journal of Economic Literature*, vol. 25, no 4, pp. 1767–1833.

Öttl U.F.J., Pichler B., Schultze-Naumburg J., Wadispointner S. (2014) Integration policies in Europe – a web-based search for consensus**.** *Campus-Wide Information Systems*, vol. 31, no 2/3, pp. 121–138.

Proskuryakova L., Kovalev A. (2015) Measuring energy efficiency: Is energy intensity a good evidence base? *Applied Energy*, no 138, pp. 450–459. DOI: 10.1016/j.apenergy.2014.10.060.

Rivera L.A., Romer P.M. (1991) Economic Integration and Endogenous Growth. *Quarterly Journal of Economics*, vol. 106, no 2, pp. 531–555.

Rivera L.A., Romer P.M. (1994) Economic Integration and Endogenous Growth – An Addendum. *Quarterly Journal of Economics*, vol. 109, no 1, pp. 307–308.

Rosa E.A., Dietz T. (2012) Human drivers of national greenhouse-gas emissions. *Nature Climate Change*, vol. 2, pp. 581–586. DOI:10.1038/nclimate1506.

Schipper L., Unander F., Marie-Lilliu C. (2000) *The IEA Energy Indicators: Understanding the Energy-Emissions Link*, Paris: International Energy Agency. Available at: http://s3.amazonaws.com/zanran_storage/www.iea.org/ContentPages/26167538.pdf, accessed 06.07.2018.

Schmitz A. (2003) *Elitenwandel und politische Dynamik in Kasachstan* (SWP-Studie 39/2003), Berlin: Die Stiftung Wissenschaft und Politik (SWP). Available at: http://www.swp-berlin.org/common/get_document.php?asset_id=179, accessed 06.07.2018.

Schmitz A. (2009) *Kasachstan: neue Führungsmacht im postsowjetischen Raum?* (SWP-Studie 2009/S07), Berlin: Deutsches Institut für Internationale Politik und Sicherheit. Available at: https://www.swp-berlin.org/fileadmin/contents/products/studien/2009_S07_smz_ks.pdf, accessed 06.07.2018.

Steinmüller K. (2012) Wild Cards, Schwache Signale und Web-Seismographen. *Focus Jahrbuch 2012* (ed. W.J. Koschnick), pp. 1–26. ISBN 9783981088793.

Sterman J. (2000) *Business Dynamics: Systems Thinking and Modeling for a Complex World*, New York: McGraw Hill.

Vester F. (1980) *Sensitivitätsmodell*, Frankfurt-am-Main: Regionale Planungsgemeinschaft Untermain.

Walsh C.L., Glendinning S., Castán-Broto V., Dewberry E., Powell M. (2015) Are wildcard events on infrastructure systems opportunities for transformational change? *Futures*, vol. 67, pp. 1–10. Available at: https://doi.org/10.1016/j.futures.2015.01.005, accessed 04.12.2018.

WEC (2003) *Drivers of the Energy Scene*, London: World Energy Council. Available at: http://www.worldenergy.org/publications/315.asp, accessed 06.07.2018.

WNA (2018) *Uranium and Nuclear Power in Kazakhstan*, London: World Nuclear Association. Available at: http://www.world-nuclear.org/information-library/country-profiles/countries-g-n/kazakhstan.aspx, accessed 06.11.2018

Z_Punkt (1986) *Was wir für Sie tun können*. Available at http://www.z-punkt.de/de/profil, accessed 04.12.2018.

# Assessing the Future of Renewable Energy Consumption for United Kingdom, Turkey and Nigeria

**Nurcan Kilinc Ata**
Postdoctoral Researcher and Project Analyst, nurcankilinc@yahoo.com

University of Stirling, Stirling FK9 4LA, UK

## Abstract

The relationship between economic growth and renewable energy (RE) consumption has received enormous attention in the literature. However, there are diverse views about the causality and nature of this relationship. The paper investigates how RE consumption during power generation is affected by economic growth and electricity prices using data from 1990 to 2012. This is conducted by using three case study countries (United Kingdom, Turkey, and Nigeria). Then, a prediction model is developed for the year 2030. The findings in this paper show that RE consumption, for the period under consideration, is significantly determined by income and electricity prices in the long run. These findings support the advantages of government policies encouraging the use of RE by implementing RE markets and RE portfolio standards to not only enhance the security and environmental concerns, but also from a macroeconomic point of view (stable economic growth).

**Keywords:** renewable energy; energy consumption; economic growth; forecasting; vector auto-regression; international comparisons; United Kingdom; Turkey; Nigeria

**Citation:** Kilinc-Ata N. (2018) Assessing the Future of Renewable Energy Consumption for United Kingdom, Turkey and Nigeria. *Foresight and STI Governance*, vol. 12, no 4, pp. 62–77. DOI: 10.17323/2500-2597.2018.4.62.77

The relationship between energy consumption and economic growth is well established. Securing abundant, affordable energy is critical to manufacturing, infrastructure expansion, transportation, and increasing standards of living. However, less is known about the relationship between renewable energy (RE) consumption and economic growth. Countries of varying economic positions encourage interest in RE for a variety of reasons related to improving the standard of living for their citizens. Developed countries want to encourage the expansion of RE sources to strengthen the energy security of supply and address climate change [*Edenhofer et al.,* 2013; *Hocaoglu, Karanfil,* 2013; *Johnstone et al.,* 2010], while developing and underdeveloped countries' interest in RE is based upon facilitating the modernization of the energy sector, fostering energy sustainability, and supporting economic development goals [*Kaygusuz et al.,* 2007; REN21, 2018]. For example, the use of RE is a solution to the challenges of African rural electrification [*Inglesi-Lotz,* 2013]. Addressing this need with RE has important implications for raising Africa's standard of living but would also act as a driver for increased economic development.

With countries having disparate motivation and goals with respect to RE development, a fair question to ask is whether the interplay between RE and economic development is consistent across countries despite these differences. One way to shed light on this question is to select a case study set of countries with vast differences in economic development, energy resources, and policies with regard to RE. The countries of the United Kingdom (UK), Turkey, and Nigeria represent such a set. These countries were selected because they are diverse and unlike many countries, the required data is available. Their main characteristics are provided at the Table 1.

Numerous studies have explored the relationship between economic growth and total energy consumption and found a positive correlation [*Payne,* 2010; *Halicioglu,* 2009; *Bowden, Payne,* 2010; *Huang et al.,* 2008]. For the case study countries, this finding has been replicated in the UK [*Humphrey, Stanislaw,* 1979; *Lee, Chien,* 2010], Turkey [*Ocal, Aslan,* 2013], and Nigeria [*Ighodaro,* 2010; *Akinlo,* 2009]. Less research has been conducted on the more specific relationship between economic growth and RE development [*Apergis, Payne,* 2010, 2014; *Menyah, Wolde-Rufael,* 2010; *Sadorsky,* 2009a], and to date, no empirical study has been conducted on this relationship in the UK, Turkey, and Nigeria.

The goal of this study was to take a unique approach, compared to previous studies, in order to scrutinize the link between RE consumption (electricity from renewables) and economic development within the case study countries. The present study describes the electricity market in the case study countries with an analysis of power generation using a range of different renewable energy sources. This study will use a standard VAR model to focus on RE consumption, income, and electricity prices and how they may interact with one another. Moreover, this VAR model will reveal any dynamic interactions between these variables and allow for the construction of forecasts that will predict the future of the relationship between RE and economic development through 2030. A finding that a change in economic growth has a significant impact upon RE consumption is consistent with the work of others [*Apergis, Payne,* 2010; 2014; *Menegaki,* 2011; *Sadorsky,* 2009a, 2011]. However, this study is different because these previous studies used panel VAR techniques and only did so to argue that there is a relationship between RE consumption and other variables such as carbon dioxide (CO2) emissions, oil prices, and gross domestic product (GDP). This study's use of a diverse group of countries, a longer time span of data than used previously [*Menegaki,* 2011; *Ohler, Fetters,* 2014], and a more recently collected data set offers an opportunity to discover new and important insights into the interplay between RE consumption and economic development. To my knowledge, this approach, using this kind of analysis, with these particular variables, over such a long period of time, and on this unique set of countries has never been attempted.

## Review of the Existing Literature

The Vector Autoregression (VAR) model approach has been used with success to examine the relationship between RE consumption and variables related to economic development [*Apergis, Payne,* 2010, 2014; *Menegaki,* 2011; *Sadorsky,* 2009a, 2011; *Ohler, Fetters,* 2014]. Sadorsky [*Sadorsky,* 2011] used the VAR model to analyze the relationship among RE consumption, income, oil prices, and oil consumption over the period from 1980 to 2008. He suggested that positive shocks to income increase RE consumption. Sadorsky [*Sadorsky,* 2009a] employs a VAR approach to analyze the relationships among RE consumption, income, oil prices, and CO2 emissions in the G7 countries over the period 1980-2005 by performing panel unit root and cointegration tests. He pointed out that increases in income and CO2 emissions are the major drivers for increases in RE consumption in the long run. Silva et al. [*Silva et al.,* 2012] analyzed how an increasing share of RE sources in power generation affects economic growth and carbon emissions using structural VAR approach over the period 1960 to 2004 for Denmark, Portugal, Spain, and the United States. Their findings show that economic costs emerged with the increase of RE in terms of GDP per capita and the decrease of CO2 emissions per capita was ensured.

Several studies have looked at the relationship between RE consumption and different macroeconomic variables (e.g., income, oil prices, capital, labor) at the country or regional level [*Sadorsky,* 2009b, 2011; *Salim, Rafiq,* 2012; *Vaona,* 2012]. The consensus from these studies is that increases in income are positively related to increased RE consumption. This makes sense given that RE prices may be higher

Table 1. **Basic Characteristics of the Case Study Countries**

| Parameters | UK | Turkey | Nigeria |
|---|---|---|---|
| State of economy | Developed | Developing | Underdeveloped |
| Geographic position (global region) | Europe | Asia | Africa |
| Territory (km$^2$) | 242,495 | 783,562 | 923,768 |
| Climate | Temperate maritime (it is mild with temperatures not much lower than 0ºC in winter and not much higher than 32ºC in summer) | Hot summer Mediterranean (It is hot with dry summers and mild to cool, wet winters) | Tropical |
| GDP growth in 2013 (%) | 1.9 | 3.6 | 7.7 |
| Rise of RE consumption (%)* | 19 | 19.3 | 1.97 |
| Target share of RE in energy production | 20% by 2020 | 30% by 2030 | 10% by 2025 |

*Note*: * For the UK, data from 2011 are provided; for Turkey and Nigeria, data from 2012. By comparison, the global growth rate of RE sources was 4.4% in the first decade of the 21st century worldwide.

*Source*: compiled by the author based on [IRENA, 2018a; World Bank, 2013; *Pao, Fu,* 2013; *Ward, Inderwildi,* 2013; *Melikoglu,* 2013; *Yusuf,* 2014].

than energy derived from fossil fuels in some circumstances and people need to be able to afford RE to use it. Sadorsky [*Sadorsky,* 2009b] presented two empirical models of RE consumption and income for 18 emerging countries with panel VAR over the period 1994 to 2003. First empirical model assessed the relationship between RE consumption and income, and the results show that increases in income have a positive impact upon RE consumption. The second model examined the relationships among RE consumption, income, and electricity prices. This result suggested that RE consumption is more sensitive to RE price changes than overall electricity demand.

Apergis and Payne [*Apergis, Payne,* 2010] used panel VAR techniques to analyze the relationship between RE consumption and economic growth for a panel of 20 OECD countries over the period 1985-2005. The theoretical framework uses an aggregate production function relating output to labor, capital, and RE. They found evidence of bidirectional causality between RE consumption and economic growth in both the short and long run. Salim and Rafiq [*Salim, Rafiq,* 2012] analyzed the determinants (income, pollutant emission, and oil prices) on RE consumption for six developing countries (Brazil, China, India, Indonesia, Philippines, and Turkey) by using both panel data and time series analyses covering the period 1980 to 2006. Their results suggest that there are bidirectional causal links between RE and income and between RE and pollutant emission. These outcomes indicate that in the long run, RE consumption is significantly determined by income, while oil prices seem to have less of a negative impact upon RE consumption in these countries. More recently, Ohler and Fetters [*Ohler, Fetters,* 2014] studied the causal relationship between economic growth and electricity generation from renewable sources across 20 OECD countries over the period of 1990 to 2008. They found evidence of a bidirectional short-run relationship between aggregate renewable electricity generation and GDP. Apergis and Payne [*Apergis, Payne,* 2014] observed Central American countries from 1980 to 2006 using the panel VAR approach.[1] Their results suggest evidence of bidirectional causality between RE consumption and economic growth in the long run.

In contrast to bidirectional results, some papers reported a unidirectional relationship between RE consumption and economic growth. Vaona [*Vaona,* 2012] by using Granger non-causality tests [*Granger,* 1980] found unidirectional Granger causality from RE consumption to real GDP for Italy.[2] Payne [*Payne,* 2011] investigated the relationship between biomass consumption and GDP in the US and found a positive unidirectional relationship from biomass to GDP. Menyah and Wolde-Rufael [*Menyah, Wolde-Rufael,* 2010] studied the relationships between RE consumption, CO2 emissions, nuclear consumption, and real GDP for the United States over the period 1960-2007 using the VAR model. They reported that there are unidirectional causality relations from nuclear energy consumption to CO2 emissions and from GDP to RE but no causality from RE consumption to CO2 emissions. Menegaki [*Menegaki,* 2011] studied the causal relationship between economic growth and RE for 27 European countries in a VAR panel context over the period 1997–2007. His outcomes did not confirm causality between RE consumption and GDP.

To summarize the literature review, there have been a great number of studies on the relationship between RE consumption and economic growth, but the current research lacks clear evidence on the direction of causality between these three variables in general and within case countries. Furthermore, existing research does not include data from the past three years, a period of notable RE growth that merits inclusion in forecasting models.

---

[1] They define RE consumption as total renewable electricity consumption in millions of kilowatt-hours.

[2] The author investigated RE consumption and income relationship with an annual frequency from 1861 to 2000.

Table 2. **Data sources**

| Organization | Reference |
|---|---|
| World Bank | [World Bank, 2013] |
| International Energy Agency (IEA) | https://www.iea.org/energyaccess/database/ |
| Turkish Statistical Institute (TUIK) | http://www.turkstat.gov.tr/ |
| United Kingdom Energy Research Centre (UKERC) | http://www.ukerc.ac.uk/ |
| International Renewable Energy Agency (IRENA) | [IRENA, 2018b] |
| US International Energy Statistics (EIA) | https://www.eia.gov/outlooks/ieo/ |
| *Source*: compiled by the author. | |

## Data and Methodology

### Data

Annual data for the UK, Turkey, and Nigeria from 1990 through 2012 was collected on RE consumption (ren), electricity price (ep), and income (gdp). Data sources are summarized in Table 2.

Data on *RE consumption* was derived from the IEA database and measured in billion kilowatt-hours. RE is the electricity generated from wind, solar, geothermal, biomass, hydropower, tidal, and wave sources. This paper uses electricity price, as opposed to oil price (the most pervasive energy source), because of the strong penetration of the RE sources and the fact that the electricity price has added significance in the energy balances of most countries [*Silva et al.,* 2012].

*GDP per* capita comes from the World Bank database and is measured in current US dollars. It is an indicator of economic well being in a country. GDP is also taken as per capita due to the fact per capita variables ensure a better and less biased comparison among countries with differing population characteristics [*Aqeel, Butt,* 2001]. A key economic growth indicator, GDP was used as a proxy of income in the studies detailed above [*Marques, Fuinhas,* 2011; *Sadorsky,* 2009a]. In the literature, economic growth measured in terms of GDP (real or per capita), or growth rate of GDP, uses different econometric methodologies, countries, and time periods [*Apergis, Payne,* 2010; *Bretschenger,* 2010; *Bruns, Gross,* 2013; *Chiou-Wei et al.,* 2008; *Gross,* 2012; *Payne, Taylor,* 2010]. For instance, Payne and Taylor [*Payne, Taylor,* 2010] found no Granger causality between energy consumption and real GDP. This is consistent with the findings of [*Menyah, Wolde-Rufael,* 2010; *Chiou-Wei et al.,* 2008]. There is a long-run equilibrium relationship between real GDP and energy consumption [*Apergis, Payne,* 2010; *Belke et al.,* 2011; *Mohammadi, Parvaresh,* 2014].

*The electricity price* variable was taken from the Turkish Statistical Institute (TUIK), United Kingdom Energy Research Centre (UKERC), and World Bank databases and it is reflected in the current fuel price index numbers 2005=100 for this paper. This study analyzes an additional channel of causality by presenting electricity prices. Although electricity prices have been neglected in many previous studies (e.g., [*Yildirim et al.,* 2012]), I examine electricity price as a proxy because of its effects on both energy consumption and economic growth. Furthermore, an increase in prices is anticipated to indicate a decline in energy demand, which leads to a decline in energy consumption [*Odhiambo,* 2010]. In other words, while energy demand represents the rate at which electricity is consumed, energy consumption represents the amount of electricity that has been consumed over a certain time.

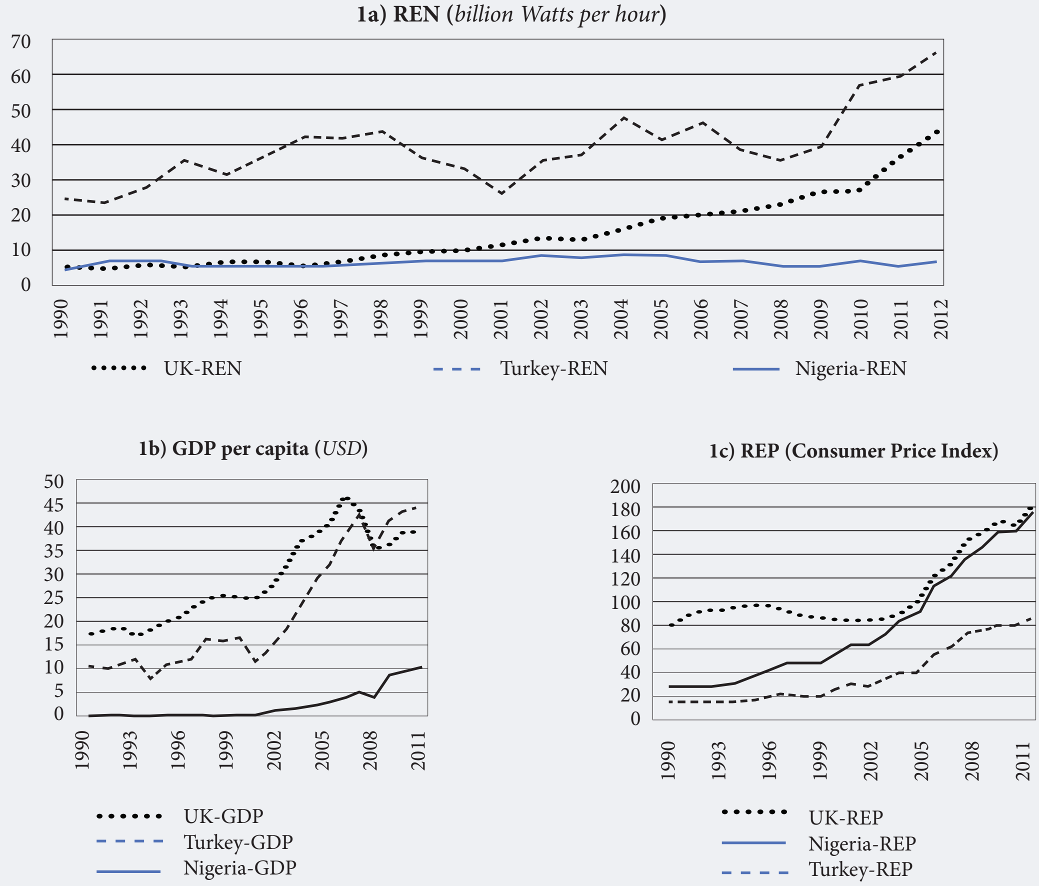
RE consumption has been growing for the UK and Turkey but it is stable for Nigeria over the period (Figure 1a). GDP per capita has been growing along a linear trend line for all countries (1b). Electricity prices in all case study countries tend to move upward over time (1c). Figure 1 shows the heterogeneity of the historical data of the three countries. For instance, in Figure 1b, the trends are more like quadratic functions than linear. In Figure 1c, there is even an obvious drop in the UK in terms of electricity prices for a certain time period.

The selection of the variables for this study is based on comparability with the variables collected in previous research, so that the data collected on these variables in the more recent timeframe of this study can easily be compared with data collected earlier.

### Methodology

The standard VAR technique was developed for the model estimation of the relationship between RE consumption and economic growth. The present study uses a standard VAR model to focus on RE consumption, income, and electricity prices and how they interact with one another. Moreover, this VAR model reveals any dynamic interactions between these variables and allows for the construction of forecasts that will predict the future of the relationship between RE and economic development through 2030. This approach is used because there is no need to made assumptions of exogeneity concerning which variables are response variables or explanatory variables since all variables in VAR are treated as endogenous, thus reflecting the realities of interdependence. This model ensures a much richer data structure that can capture complex dynamic properties of the data [*Sadorsky,* 2011; *Taylor,* 2010].

Figure 1. **Data Plots**




*Source*: author's calculations.

Moreover, the model is well suited to forecast the effects of specific policy actions or of significant changes in the economy [*Tiwari,* 2011]. For the Granger causality test, a VAR model was selected rather than a VECM model as the VECM model is only defined when the time-series are cointegrated. Finally, when this is the case, the series need to be integrated in the same order. Furthermore, a VAR model is preferred rather than using a VECM model for causality testing [*Giles,* 2011].

These features make VAR the ideal choice for analyzing the macroeconomic responses in the case countries to RE consumption. The standard VAR model is specified as:

$$Y_t = \Gamma(L)Y_{t-1} + \varepsilon_t \qquad (1)$$

where $Y_t$ is a vector of stationary variables {ΔREN, ΔEP, ΔGDP} with ΔREN = the first difference in renewable consumption; ΔGDP = economic growth as per capita; ΔEP = the change in electricity prices, and $\varepsilon_t$ = the vector of error terms. $\Gamma(L)$ is the lag operator which is calculated below.

$$\Gamma(L) = \Gamma_1 L^1 + \Gamma_2 L^2 + \cdots + \Gamma_p L^p \qquad (2)$$

The model also makes provisions for error terms and shocks to calculate the impulse response functions (IRF) and the forecast error variance decompositions (FEVD). IRF and FEVD show the dynamic responses and size of the total effect, respectively. The estimation of interaction between RE consumption, economic growth, and electricity price are based on the IRFs and the FEVDs after estimating the VAR model. The IRFs usually show the effects of shocks on the adjustment path of the variables. The FEVDs measure the contribution of each type of shock to forecast error variance. Both computations are effective in determining how shocks to economic variables reverberate through a system [*Phillips,* 1998].

The IRFs are based on the Cholesky decomposition approach. The Cholesky decomposition strategy entails a contemporaneous relationship among the variables. The first variable in the VAR system influences the other variables contemporaneously, while the following variables in the VAR impact the variables listed earlier only in their lag form [*Aziz, Dahalan,* 2015]. Considering that the variables correspond to the Cholesky decomposition, the order (*ren; gdp; ep)* is then imposed from the most to the least exogenous.

Table 3. **Summary Statistics over 1990-2012 for Variables**

| | uk_ren | uk_gdp | uk_ep | t_ren | t_gdp | t_ep | n_ren | n_gdp | n_ep |
|---|---|---|---|---|---|---|---|---|---|
| Mean | 15.45759 | 29293.26 | 108.8696 | 37.72006 | 5532.397 | 97.61371 | 6.039212 | 781.5134 | 71.96087 |
| Median | 12.02800 | 25870.99 | 92.80000 | 35.49400 | 4219.544 | 74.11461 | 5.850000 | 377.5003 | 57.30000 |
| Maximum | 43.82253 | 46610.53 | 181.4000 | 64.37187 | 10666.06 | 206.0910 | 8.152000 | 2722.298 | 178.9000 |
| Minimum | 5.321000 | 17270.12 | 80.20000 | 22.57500 | 2268.397 | 46.70890 | 4.343000 | 153.0762 | 3.930000 |
| Std. Dev. | 10.47715 | 9311.265 | 31.56791 | 10.63177 | 3028.173 | 55.77279 | 0.965901 | 766.0461 | 55.36502 |
| Skewness | 1.180469 | 0.284903 | 1.104866 | 0.840289 | 0.650318 | 0.793446 | 0.746967 | 1.519842 | 0.506311 |
| Kurtosis | 3.690039 | 1.695320 | 2.676368 | 3.428594 | 1.795478 | 2.034864 | 3.321090 | 4.071345 | 2.035646 |
| Jarque-Bera | 5.798087 | 1.942417 | 4.779835 | 2.882703 | 3.011588 | 3.305975 | 2.237647 | 9.954652 | 1.873909 |
| Probability | 0.055076 | 0.378625 | 0.091637 | 0.236608 | 0.221841 | 0.191477 | 0.326664 | 0.006892 | 0.391819 |
| Sum | 355.5245 | 673745.1 | 2504.000 | 867.5614 | 127245.1 | 2245.115 | 138.9019 | 17974.81 | 1655.100 |
| Sum Sq. Dev. | 2414.957 | 1.91e+09 | 21923.73 | 2486.758 | 2.02e+08 | 68433.29 | 20.52523 | 12910187 | 67436.28 |
| Observations | 23 | 23 | 23 | 23 | 23 | 23 | 23 | 23 | 23 |

*Source*: author's calculations.

The lag-length for the model is selected using the Akaike Information Criteria (AIC) [*Akaike,* 1974] because of its better performance in small samples [*Ozturk, Acaravci,* 2013]. This study carried out the stationarity and cointegration tests, as well as the Granger causality tests, for all variables. Finally, this paper also implemented the prediction model which was developed by using a time series forecasting system and evaluated using the VAR method to construct a dynamic forecast over the period 2013-2030 for the UK, Turkey, and Nigeria. E-views and Stata were used in this study to analyze these variables.

### Summary Statistics

Table 3 below shows the summary statistics for the variables in the case study countries.

The following diagnostic tests were carried out to analyze and understand the characteristics of the variables. First, the lag selection was carried out. Second, the test for stationarity was conducted by applying several diagnostic tests to check if the series contained unit roots (non-stationary series) or not (stationary series). Third, the cointegration properties of the variables were checked. Then, the study indicates the nature of causality for the variables of interest.

### Lag Selection

To reliably check for co-integration, it is crucial to determine the suitable lag length. According to [*Kireyev,* 2000], excessively short lags may fail to capture the system's dynamics leading to the omission of

Table 4. **Lag Selection - Information Criteria**

| Lag | LL | LR | p | AIC | HQIC | SBC |
|---|---|---|---|---|---|---|
| ***UK*** | | | | | | |
| 0 | 47.048 | | | –5.18211 | –5.1675 | –5.03507 |
| 1 | 52.5228 | 10.95 | 0.279 | –4.76739 | –4.70893 | –4.17924 |
| 2 | 76.3458 | 47.646 | 0.000 | –6.51127 | –6.40896 | –5.482 |
| 3 | 86.8965 | 21.102 | 0.012 | –6.69371 | –6.54755 | –5.22333 |
| 4 | 134.313 | 94.834* | 0.000 | –11.2133* | –11.0233* | –9.30186* |
| ***Turkey*** | | | | | | |
| 0 | 10.3676 | | | –0.86678 | –0.852164 | –0.719743* |
| 1 | 22.5791 | 24.423 | 0.004 | –1.2446 | –1.18614 | –0.65645 |
| 2 | 29.6669 | 14.176 | 0.116 | –1.01964 | –0.917328 | 0.009625 |
| 3 | 38.4023 | 17.471 | 0.042 | –0.988507 | –0.842349 | 0.48187 |
| 4 | 59.7156 | 42.627* | 0.000 | –2.43712* | –2.24712* | –0.525635 |
| ***Nigeria*** | | | | | | |
| 0 | 16.466 | | | –1.58424 | –1.56962 | –1.4372 |
| 1 | 29.7209 | 26.51 | 0.002 | –2.08481 | –2.02634 | –1.49666 |
| 2 | 39.5511 | 19.66 | 0.020 | –2.18248 | –2.08017 | –1.15322 |
| 3 | 53.3843 | 27.666 | 0.001 | –2.75109 | –2.60494 | –1.28072 |
| 4 | 89.2336 | 71.699* | 0.000 | –5.90983* | –5.71983* | –3.99834* |

*Notes*: Endogenous – RE consumption, GDP; Electricity price; Exogenous – constant

*Source*: author's calculations.

Table 5. **Unit Root Test for the Series in Levels**

| Data | ADF-test | | | | | | Data | PP-test | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Intercept and no trend | | | Intercept and trend | | | | Intercept and no trend | | | Intercept and trend | | |
| | lags | t-stat | %5 level* | lags | t-stat | %5 level* | | lags | t-stat | %5 level* | lags | t-stat | %5 level* |
| ren_uk | 2 | 1.82 | –3.02 | 3 | –1.38 | –3.67 | ren_uk | 21 | 4.71 | –3.00 | 6 | –2.56 | –3.63 |
| ren_t | 3 | –0.74 | –3.02 | 2 | –3.64 | –3.65 | ren_t | 2 | –1.40 | –3.00 | 2 | –2.34 | –3.63 |
| ren_n | 3 | –2.29 | –3.02 | 3 | –2.77 | –3.67 | ren_n | 2 | –3.22 | –3.00 | 2 | –3.06 | –3.63 |
| Gdp_uk | 4 | –0.76 | –3.04 | 3 | –2.86 | –3.67 | Gdp_uk | 1 | –1.00 | –3.00 | 0 | –1.46 | –3.63 |
| Gdp_t | 0 | –0.34 | –3.00 | 0 | –2.55 | –3.63 | Gdp_t | 0 | –0.34 | –3.00 | 0 | –2.55 | –3.63 |
| Gdp_n | 3 | 1.34 | –3.02 | 4 | –0.90 | –3.69 | Gdp_n | 3 | 1.07 | –3.00 | 10 | –2.96 | –3.63 |
| Ep_uk | 1 | 0.32 | –3.01 | 1 | –1.30 | –3.64 | Ep_uk | 2 | 0.44 | –3.00 | 2 | –0.71 | –3.63 |
| Ep_t | 0 | 0.75 | –3.00 | 0 | –2.39 | –3.63 | Ep_t | 2 | 0.88 | –3.00 | 4 | –2.42 | –3.63 |
| Ep_n | 4 | –2.91 | –3.04 | 1 | –4.97 | –3.64 | Ep_n | 1 | –3.59 | –3.00 | 1 | –1.62 | –3.63 |

*Note*: * — indicates the level of significance at 5% (5% level of critical value) and Lag length selected using Akaike's information criterion which is given in the first column.

*Source*: author's calculations.

variables, coefficients' bias, and serial correlation-based errors, whilst lag lengths that are excessively long cause a rapid loss of the degree of freedom and over-parameterization. In other words, the estimation of the appropriate lag prevents the over-parameterization of the model. The Akaike Information Criterion (AIC), the Hannan Quinn Information Criterion (HQIC) [*Hannan, Quinn,* 1979], and the Schwarz Bayesian Criterion (SBC) [*Schwarz,* 1978] were used for this purpose. The information criteria suggest that the appropriate lag length that should be used to test for co-integration is VAR=4, which was used for the evaluation of VAR. The lag-length selection table is presented in Table 4 below.

### Stationary Properties

The autocorrelation function (ACF) and partial autocorrelation function (PACF) demonstrate that the variables (RE consumption, economic growth, and electricity price) are non-stationary. For this study, formal stationarity tests were carried out through unit root tests. The unit root tests included a constant, time trend, and four lags in line with the general and specific stationarity analysis. At the level of dynamic series, the null hypotheses that the variables are non-stationary are not rejected, indicating non-stationarity for all the variables.

To identify the order of the integration of the series, a unit root test [*Ng, Perron,* 2001] was employed with Augmented Dickey Fuller (ADF) [*Dickey, Fuller,* 1981] and Phillips and Perron (PP) [*Phillips, Perron,* 1988] tests. Then, a cointegration analysis was conducted in order to identify the nature of the cointegration [*Abbott, De Vita,* 2003]. Diagnostic tests for the existence of stationarity are crucial as the two categories of the series are treated in different ways [*Brooks,* 2008] and the non-stationary does not have a constant mean and there is the emergence of heteroscedasticity [*Enders,* 1995]. The ADF and PP unit root tests imply that all series are stationary, in other words, they are all integrated by order 0, that

Table 6. **Unit Root Test for the Series in the First Difference (1st difference of the values)**

| Data | ADF-test | | | | | | Data | Тест PP-test | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Intercept and no trend | | | Intercept and trend | | | | Intercept and no trend | | | Intercept and trend | | |
| | lags | t-stat | %5 level* | lags | t-stat | %5 level* | | lags | t-stat | %5 level* | lags | t-stat | %5 level* |
| ren_uk | 1 | –3.94 | –3.02 | 1 | –4.81 | –3.65 | ren_uk | 10 | –6.62 | –3.01 | 20 | –14.94 | –3.64 |
| ren_t | 2 | –3.62 | –3.02 | 2 | –3.49 | –3.67 | ren_t | 1 | –4.83 | –3.01 | 1 | –4.71 | –3.64 |
| ren_n | 3 | –2.19 | –3.04 | 0 | –6.25 | –3.64 | ren_n | 0 | –6.48 | –3.01 | 0 | –6.25 | –3.64 |
| Gdp_uk | 3 | –2.60 | –3.04 | 3 | –2.55 | –3.69 | Gdp_uk | 5 | –3.18 | –3.01 | 6 | –3.08 | –3.63 |
| Gdp_t | 0 | –5.31 | –3.01 | 0 | –5.23 | –3.64 | Gdp_t | 0 | –5.31 | –3.01 | 0 | –5.23 | –3.64 |
| Gdp_n | 0 | –5.00 | –3.01 | 3 | –4.96 | –3.69 | Gdp_n | 3 | –5.15 | –3.01 | 14 | –9.74 | –3.64 |
| Ep_uk | 0 | –2.28 | –3.01 | 3 | –2.60 | –3.64 | Ep_uk | 1 | –2.26 | –3.01 | 1 | –2.84 | –3.64 |
| Ep_t | 0 | –4.49 | –3.01 | 0 | –4.76 | –3.64 | Ep_t | 1 | –4.49 | –3.01 | 3 | –4.80 | –3.64 |
| Ep_n | 0 | –1.64 | –3.01 | 1 | –2.45 | –3.65 | Ep_n | 1 | –1.80 | –3.01 | 2 | –3.00 | –3.64 |

*Note*: * — indicates the level of significance at 5% (5% level of critical value) and Lag length selected using Akaike's information criterion which is given in the first column.

*Source*: author's calculations.

Table 7. **Unit Root Test for the Series in the Second Difference (2st difference of the values)**

| Data | ADF-test | | | | | | Data | Тест PP-test | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Intercept and no trend | | | Intercept and trend | | | | Intercept and no trend | | | Intercept and trend | | |
| | lags | t-stat | %5 level* | lags | t-stat | %5 level* | | lags | t-stat | %5 level* | lags | t-stat | %5 level* |
| ren_uk | 2 | -5.06 | -3.85 | 2 | -4.94 | -3.69 | ren_uk | 8 | -14.95 | -3.02 | 8 | -14.82 | -3.65 |
| ren_t | 0 | -8.83 | -3.02 | 4 | -3.47 | -3.73 | ren_t | 3 | -10.35 | -3.02 | 3 | -10.24 | -3.65 |
| ren_n | 1 | -6.90 | -3.02 | 1 | -6.73 | -3.67 | ren_n | 19 | -22.69 | -3.02 | 19 | -26.01 | -3.65 |
| Gdp_uk | 1 | -6.09 | -3.02 | 1 | -6.01 | -3.67 | Gdp_uk | 14 | -9.02 | -3.02 | 14 | -9.08 | -3.65 |
| Gdp_t | 0 | -8.53 | -3.02 | 0 | -8.30 | -3.65 | Gdp_t | 9 | -16.80 | -3.02 | 10 | 17.68 | -3.65 |
| Gdp_n | 4 | -4.25 | -3.06 | 3 | -4.49 | -3.71 | Gdp_n | 17 | -19.87 | -3.02 | 15 | 23.37 | -3.65 |
| Ep_uk | 0 | -5.59 | -3.02 | 0 | -5.53 | -3.65 | Ep_uk | 1 | -5.63 | -3.02 | 0 | -5.53 | -3.65 |
| Ep_t | 2 | -4.50 | -3.04 | 2 | -4.86 | -3.69 | Ep_t | 11 | -14.40 | -3.02 | 9 | 15.99 | -3.65 |
| Ep_n | 0 | -4.46 | -3.02 | 0 | -4.20 | -3.65 | Ep_n | 3 | -4.66 | -3.02 | 5 | -5.01 | -3.65 |

*Note*: * — indicates the level of significance at 5% (5% level of critical value) and Lag length selected using Akaike's information criterion which is given in the first column.

*Source*: author's calculations.

is I(0). The characteristics of the dynamic series (levels) and the first difference were evaluated with the help of two different unit root tests, namely ADF and PP. This present study provides some results that depend upon the test used (ADF or PP) and upon the trend specification.

The unit root tests included the constant, time trend, and four lags in line with the general and specific stationarity analysis methodology. As Perron [*Perron,* 1988] notes, the hypothesis of a unit root with a trend are usually precluded a priori, for instance, if the series is in logarithmic form, it implies an ever increasing (or decreasing) rate of change. Regarding the dynamic series (levels), the null hypotheses that the variables are non-stationary are not rejected. It can be seen that the test statistic is less negative than the critical values at a 5% level of significance for each series and as a result, do not reject H0 since all the variables are non-stationary. The results are displayed in Table 5. After taking first differences, each of the time series appears to contain a unit root in their levels but almost all series are stationary in their first difference indicating that they are integrated at order one, i.e., I(1). The results are displayed in Table 6 which indicates that the second ADF test of the first difference shows that most series are stationary having more negative test statistics than the applicable critical values. RE price in the UK and Nigeria are not stationary after the first differences. The series became stationary by taking the second difference of the values indicating that they are integrated at I(2). Table 7 displays the results from the ADF and PP test and it can be seen that the critical values of a 5% level of significance is less negative than the test statistic for each series and as a result, H(0) is rejected because all the variables are stationary.

### Cointegration Analysis

This study applied the necessary cointegration analysis after the stationarity tests above. The outcome of the trace test (λmax) along with that of the eigenvalue test indicates the long-run relationship between RE consumption and the two other variables (economic growth and electricity price) for each country. The present study rejects the null hypothesis of no cointegration on behalf of the alternative hypothesis that there is at least one cointegration relationship at the five percent (5%) significance level for Nigeria. The result of the cointegration tests meets the a priori assumption of the stationarity of the variables. The present study enables all the variables to be included in the VAR model in their level forms with the introduction of the lags where necessary. This approach avoids the loss of significant information from the time-series co-movements of the variables [*Kireyev,* 2000]. The outcome of the cointegration test is presented in Table 8 below.

It is widely known that cointegration tests depending on the individual time series have low statistical power, especially when the time series is short [*Belke et al.,* 2011]. Cointegration between the variables can be examined by employing time series tests such as the Johansen's maximum likelihood approach. The hypotheses for this test are the following: the null hypothesis ($H_0$) states that there are r cointegrating vectors, whereas the alternative hypothesis ($H_1$) illustrates that there are r+1 or more [*Brooks,* 2008]. Given that the unit root test showed that the variables are non-stationary in their levels and differenced forms, the result of the cointegration tests satisfies the a priori assumptions of the stationarity of the variables.

## Empirical Results and Discussions

All variables were expressed in natural logarithms for estimating the VAR [*Ewing et al.,* 2007; *Narayan, Prasad,* 2008; *Sadorsky,* 2009a] and logarithmical differences were used because this guarantees all

Table 8. **Johansen Tests for Cointegration (Trend: constant, Lags=4)**

| Max rank | Parms | LL | Eigenvalue | trace statistic (λmax) | 5% critical value | 1% critical value |
|---|---|---|---|---|---|---|
| ***UK*** | | | | | | |
| 0 | 30 | 76.281248 | | 116.0644 | 29.68 | 35.65 |
| 1 | 35 | 112.98909 | 0.98668 | 42.6487 | 15.41 | 20.04 |
| 2 | 38 | 130.95271 | 0.87917 | 6.7215 | 3.76 | 6.65 |
| 3 | 39 | 134.31347 | 0.32658 | | | |
| ***Turkey*** | | | | | | |
| 0 | 30 | 30.406466 | | 58.6182 | 29.68 | 35.65 |
| 1 | 35 | 45.425247 | 0.82914 | 28.5806 | 15.41 | 20.04 |
| 2 | 38 | 56.132362 | 0.71625 | 7.1664 | 3.76 | 6.65 |
| 3 | 39 | 59.715562 | 0.34397 | | | |
| ***Nigeria*** | | | | | | |
| 0 | 30 | 51.050487 | | 76.3662 | 29.68 | 35.65 |
| 1 | 35 | 83.416096 | 0.97780 | 11.6350*,** | 15.41 | 20.04 |
| 2 | 38 | 87.338587 | 0.36964 | 3.7900 | 3.76 | 6.65 |
| 3 | 39 | 89.233586 | 0.19984 | | | |

*Note:* Presence of cointegration relationship: * — significant at 1% level; ** — significant at 5% level.

*Source*: author's calculations.

variables are stationary. VAR estimation strategies, which require the model identification by using the stationarity test, lag selection, causal ordering, and restrictions for measuring the impulse response functions and forecast error variance decomposition are presented below. Finally, a prediction model was developed for the years 2013-2030 for each country. Therefore, this section includes the impulse response function, variance decomposition from the VAR, and the prediction model.

### Impulse Response Function Analysis

The analyses examined the relationship between RE consumption, economic growth, and electricity price using the IRF methodology. Impulse response functions are only valid if the VAR is stable. Therefore, some steps must be taken to ensure that the VAR is stable while the IRFs are used to interpret the results [*Sadorsky,* 2011]. The IRF indicates how a residual shock to one of the innovations in the model influences the contemporaneous and future values of all endogenous variables [*Silva et al.,* 2012]. Significance was determined at the 95% confidence intervals. The error bands were gained by using a Monte Carlo simulation approach with 1,000 replications. According to the confidence intervals of the hypothesis, which were selected for the evaluation of the importance of the impulse response, standard errors were calculated. The IRF indicates how long, and to what extent, RE consumption reacts to an unanticipated change in income or electricity price [*Lee, Chiu,* 2011].

The IRF table presented in Table 9 shows that RE consumption in the case study countries responded negatively and significantly to a 10% deviation in economic growth by 0.2% (negatively) in the short run and, 0.06% (positively) in the long run. This indicates that income shocks among other variables affect the case study countries' RE consumption within the period under consideration. This means that economic growth in the sample countries respond positively and significantly to RE consumption shocks. Furthermore, RE consumption in the case study countries responded positively and significantly to a 10% change in prices by 0.09% in the short run and 0.05% (negatively) in the long run. The graphical representation of the predicted cointegrated plots for the sample countries are displayed in Figures 2, 3, and 4.

This study's findings regarding RE consumption and economic growth are consistent with the empirical results of [*Apergis, Payne,* 2014, 2010; *Tugcu et al.,* 2012] who found a relationship between RE consumption and income, and they concluded that the Granger causality function was more effective in explaining this relationship in the long run. In contrast, Menegaki's [*Menegaki,* 2011] empirical results attained using an identical approach did not confirm Granger causality between RE consumption and income.

### Variance Decomposition

This study's analyses applied the advanced generalized forecast error variance decomposition to investigate the relationships between RE consumption, income, and electricity price, as well as to gauge the influences of the variables upon one another in the short and long run.

The variance decomposition reports are presented below in Table 10. The variance decomposition indicates that in the short run, approximately 1.3% of the fluctuations in case study countries' economic growth are explained by a 39% deviation in RE consumption shock. In the long run, in this case, ten years, a

Table 9. **Impulse Response Function Table**

| Lag | RE consumption response to GDP impulse | | | GDP response to RE consumption impulse | | |
|---|---|---|---|---|---|---|
| | IRF | Lower* | Upper* | IRF | Lower* | Upper* |
| 0 | 0 | 0 | 0 | 0.129837 | 0.041622 | 0.218052 |
| 1 | -0.021632 | -0.063027 | 0.019763 | -0.155564 | -0.270597 | -0.040532 |
| 2 | 0.040584 | -0.014034 | 0.095201 | 0.013535 | -0.107074 | 0.134145 |
| 3 | -0.025187 | -0.078152 | 0.027778 | 0.070993 | -0.063262 | 0.205248 |
| 4 | 0.00415 | -0.042702 | 0.051002 | -0.056148 | -0.180937 | 0.06864 |
| 5 | 0.009342 | -0.03387 | 0.052554 | 0.025267 | -0.059429 | 0.109963 |
| 6 | -0.016782 | -0.053222 | 0.019658 | 0.00568 | -0.082561 | 0.093922 |
| 7 | 0.012847 | -0.018325 | 0.044018 | -0.026774 | -0.10865 | 0.055103 |
| 8 | -0.001571 | -0.028398 | 0.025256 | 0.020374 | -0.037378 | 0.078126 |
| 9 | -0.006052 | -0.029513 | 0.017408 | -0.002498 | -0.044919 | 0.039924 |
| 10 | 0.00697 | -0.012225 | 0.026164 | -0.00701 | -0.053275 | 0.039256 |
| **Lag** | **RE consumption response to price impulse** | | | **Price response to RE consumption impulse** | | |
| | **IRF** | **Lower*** | **Upper*** | **IRF** | **Lower*** | **Upper*** |
| 0 | 0 | 0 | 0 | 0.000646 | -0.030654 | 0.031946 |
| 1 | 0.00973 | -0.041043 | 0.060504 | -0.034834 | -0.064462 | -0.005206 |
| 2 | -0.03622 | -0.106353 | 0.033914 | 0.011393 | -0.018633 | 0.041418 |
| 3 | 0.024402 | -0.027108 | 0.075913 | 0.017364 | -0.013523 | 0.048251 |
| 4 | 0.004931 | -0.030296 | 0.040159 | -0.009334 | -0.033847 | 0.01518 |
| 5 | -0.016644 | -0.051474 | 0.018186 | 0.000057 | -0.020569 | 0.020683 |
| 6 | 0.014873 | -0.021251 | 0.050998 | 0.000853 | -0.016769 | 0.018474 |
| 7 | -0.006975 | -0.034516 | 0.020566 | -0.003537 | -0.01881 | 0.011736 |
| 8 | -0.003459 | -0.02586 | 0.018943 | 0.003204 | -0.007783 | 0.014191 |
| 9 | 0.008274 | -0.013356 | 0.029905 | 0.000627 | -0.007485 | 0.008739 |
| 10 | -0.00557 | -0.022887 | 0.011747 | -0.001856 | -0.009575 | 0.005863 |

*Note*: * — 95% lower and upper bounds.

*Source*: author's calculations.

100% deviation in RE consumption shocks accounts for about 7% of the fluctuations in economic growth in the case study countries. Furthermore, 0.2% of the fluctuations in electricity prices are explained by a 2% deviation in RE consumption shock in the short run and a 100% deviation for about 5.6% of the fluctuations in electricity prices in the long run.

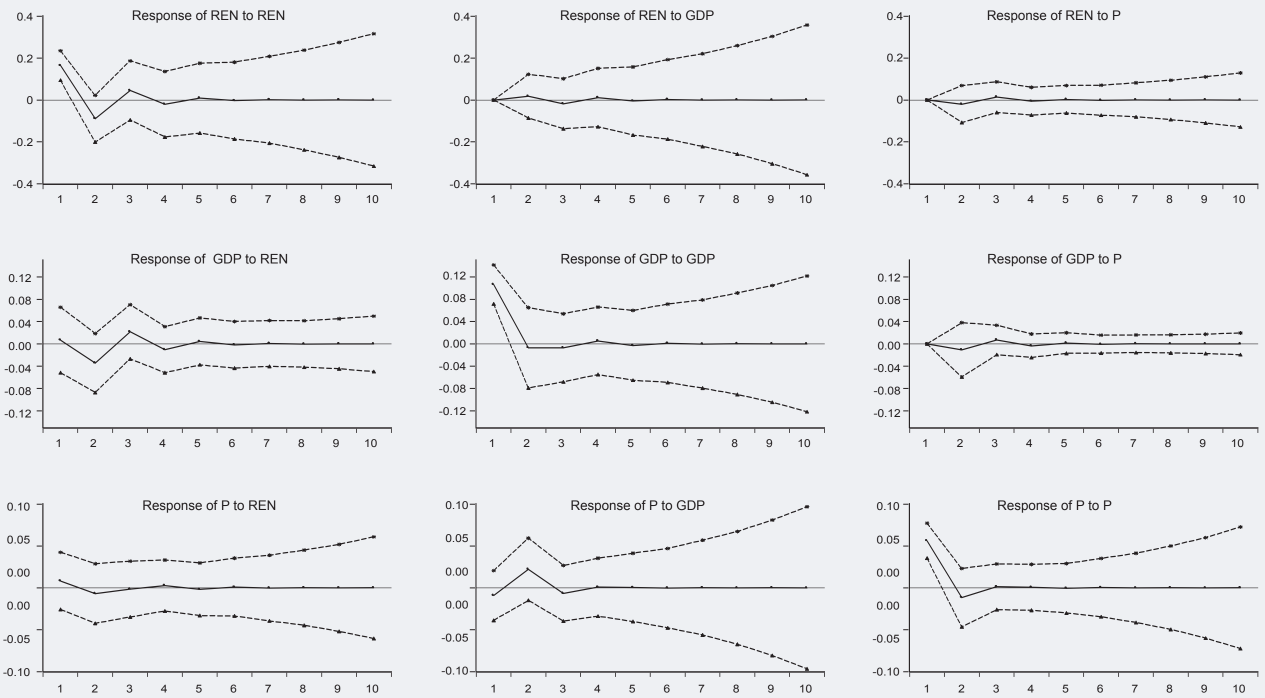
As a result, economic growth significantly affects RE consumption in the sample countries both in the short and long run. Likewise, electricity prices in the countries are found to have significant effects upon RE consumption during the period under consideration. This result is in line with a priori expectations. This outcome is also consistent with the literature on the relationship between economic growth and RE consumption [*Apergis, Payne,* 2014, 2010; *Silva et al.,* 2012; *Sadorsky,* 2011].

Generally, the present study shows that, barring any country level response, changes in RE consumption are transmitted to the sample countries' economies. The claim that macroeconomic activities respond to RE consumption is further confirmed by the VAR Granger causality test in Table 11, which suggests that RE consumption causes economic growth in the sample countries. The table further shows there was a bidirectional Granger causality running from RE consumption to income and from income to RE consumption for all countries. There are positive relationships between RE consumption and economic growth. These findings are consistent with the previous studies' findings for the relationship between RE consumption and income shocks [*Apergis, Payne,* 2010; 2014; *Ohler, Fetters,* 2014; *Sadorsky,* 2009b; *Salim, Rafiq,* 2012]. In contrast, while Akinlo [*Akinlo,* 2008] found no Granger causality in either direction between economic growth and energy consumption for Nigeria, some empirical studies such as [*Payne,* 2011; *Menegaki,* 2011; *Menyah, Wolde-Rufael,* 2010] found unidirectional Granger causality between RE consumption and income.

The results further demonstrate that economic welfare enhancement translates to more renewables deployment for the sample countries. The level of these impacts in various countries is also different as these countries respond differently to changes in RE consumption.

Although there is no causality from RE consumption to electricity price, there is causality running from electricity price to RE consumption for Turkey. This study found a unidirectional relationship between RE consumption and electricity prices. Likewise, there is unidirectional causality link between RE consumption and electricity prices for Nigeria. While there is causality for the correlation between

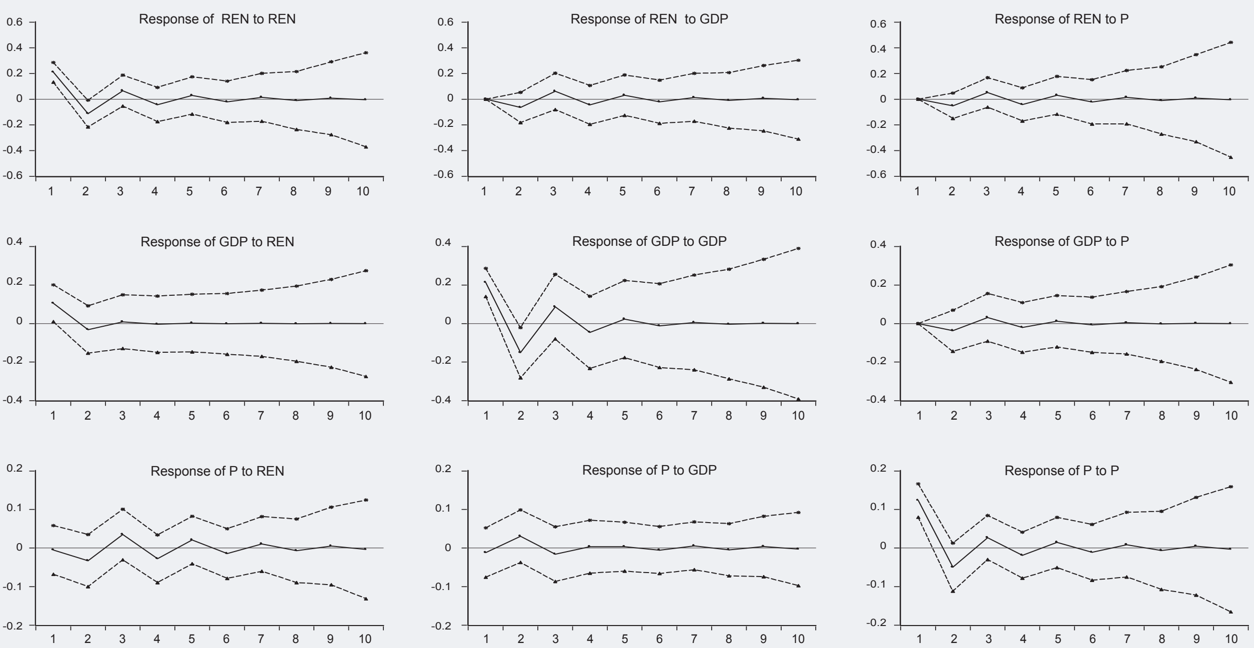
## Figure 2. **Impulse Response Functions for the UK**




*Note*: During the period from 3 to 10, the impulse response of RE consumption to a shock in income and price is zero and insignificant, because zero is included in the confidence interval. Diagram 4 represents the impulse response of income to a shock in RE consumption so that in the period from 1 to 3 the response of income to RE shocks is negative and significant, because the confidence interval does not include zero. The impulse response of price to a shock in RE consumption is positive and significant for the period from 1 to 3 and is constant and insignificant.

*Source*: author's calculations.

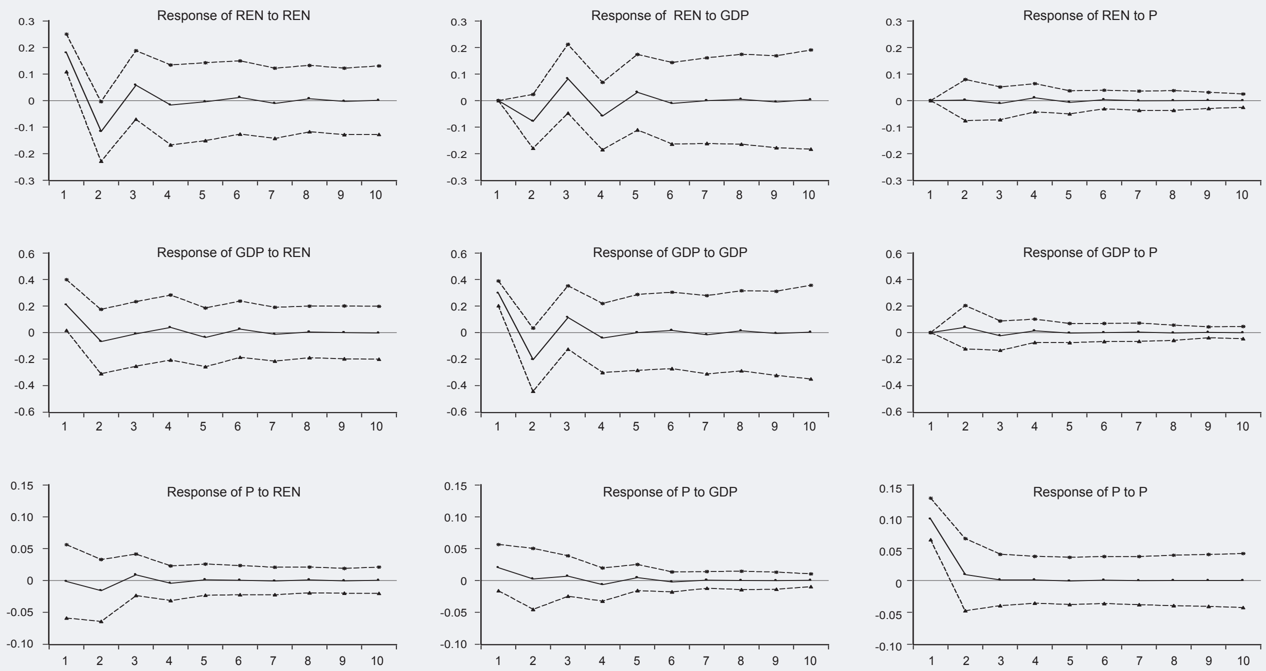
## Figure 3. **Impulse Response Functions for Turkey**




*Note*: The response of RE consumption to a shock in income and price are positive and statistically significant for 3 years because the confidence interval does not include zero. The response of income to a shock in RE consumption is statistically significant for 1 and 2 years, and then it is zero. The response of price to a shock in RE consumption is positive and statistically significant for 3 to 5 years.

*Source*: author's calculations.

Figure 4. **Impulse Response Functions for Nigeria**




*Note*: The response of RE consumption to a shock in income is positive for 3 and 4 years and significant at 5% level, as zero is not included in the confidence interval. The response of RE consumption to a shock in price is zero and statistically insignificant at 5% level, as the confidence interval contains the value of zero. The response of income to a shock in RE consumption is statistically significant. The response of price to a shock in RE consumption is negative and statistically significant for the period of 3 years, then it is zero.

*Source*: author's calculations.

Table 10. **Variance Decomposition**

| Step | RE consumption response to GDP impulse | | | GDP response to RE consumption impulse | | |
|---|---|---|---|---|---|---|
| | FEVD | Lower* | Upper* | FEVD | Lower* | Upper* |
| 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 1 | 0 | 0 | 0 | 0.359297 | 0.013927 | 0.704667 |
| 2 | 0.013606 | -0.039131 | 0.066342 | 0.454295 | 0.081983 | 0.826606 |
| 3 | 0.05345 | -0.094369 | 0.20127 | 0.453227 | 0.081536 | 0.824917 |
| 4 | 0.066252 | -0.111242 | 0.243745 | 0.475294 | 0.099743 | 0.850845 |
| 5 | 0.062214 | -0.106638 | 0.231066 | 0.491207 | 0.089595 | 0.892818 |
| 6 | 0.06205 | -0.111837 | 0.235937 | 0.489189 | 0.081451 | 0.896927 |
| 7 | 0.067427 | -0.123816 | 0.258671 | 0.486876 | 0.081447 | 0.892306 |
| 8 | 0.070319 | -0.126972 | 0.267609 | 0.490213 | 0.077361 | 0.903064 |
| 9 | 0.069973 | -0.126466 | 0.266411 | 0.491456 | 0.073618 | 0.909293 |
| 10 | 0.070507 | -0.128206 | 0.26922 | 0.491059 | 0.07384 | 0.908278 |
| **Step** | **RE consumption response to ptrice impulse** | | | **Price response to RE consumption impulse** | | |
| | **FEVD** | **Lower*** | **Upper*** | **FEVD** | **Lower*** | **Upper*** |
| 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 1 | 0 | 0 | 0 | 0.000086 | -0.008263 | 0.008436 |
| 2 | 0.002753 | -0.02596 | 0.031465 | 0.193485 | -0.090817 | 0.477787 |
| 3 | 0.035547 | -0.109357 | 0.180451 | 0.190556 | -0.076611 | 0.457722 |
| 4 | 0.048243 | -0.13047 | 0.226955 | 0.213567 | -0.075414 | 0.502547 |
| 5 | 0.045567 | -0.119104 | 0.210239 | 0.21828 | -0.080995 | 0.517554 |
| 6 | 0.05008 | -0.125819 | 0.225979 | 0.216683 | -0.082071 | 0.515436 |
| 7 | 0.054289 | -0.13638 | 0.244959 | 0.216089 | -0.081811 | 0.513988 |
| 8 | 0.054823 | -0.137006 | 0.246652 | 0.217155 | -0.085225 | 0.519534 |
| 9 | 0.054766 | -0.136561 | 0.246093 | 0.218058 | -0.086876 | 0.522992 |
| 10 | 0.056024 | -0.13899 | 0.251038 | 0.218054 | -0.087023 | 0.523131 |

*Note*: * — 95% lower and upper bounds.

*Source*: author's calculations.

### Table 11. **Granger Causality Test**

Granger Causality Wald tests

| Equation | Excluded | Chi2 | Prob>Chi2 |
|---|---|---|---|
| | ***UK*** | | |
| RE consumption | GDP | 25.396 | 0.000 |
| | Electricity price | 80.805 | 0.000 |
| | All | 112.68 | 0.000 |
| GDP | RE consumption | 109 | 0.000 |
| | Electricity price | 113.39 | 0.000 |
| | All | 180.89 | 0.000 |
| Electricity price | RE consumption | 10.759 | 0.029 |
| | GDP | 15.19 | 0.004 |
| | All | 25.758 | 0.001 |
| | ***Turkey*** | | |
| RE consumption | GDP | 11.435 | 0.022 |
| | Electricity price | 3.8749 | 0.423 |
| | All | 12.801 | 0.119 |
| GDP | RE consumption | 19.495 | 0.001 |
| | Electricity price | 17.067 | 0.002 |
| | All | 27.886 | 0.000 |
| Electricity price | RE consumption | 93.067 | 0.000 |
| | GDP | 34.292 | 0.000 |
| | All | 109.51 | 0.000 |
| | ***Nigeria*** | | |
| RE consumption | GDP | 47.803 | 0.000 |
| | Electricity price | 14.694 | 0.005 |
| | All | 49.931 | 0.000 |
| GDP | RE consumption | 24.957 | 0.000 |
| | Electricity price | 20.436 | 0.000 |
| | All | 39.161 | 0.000 |
| Electricity price | RE consumption | 3.5722 | 0.467 |
| | GDP | 5.0131 | 0.286 |
| | All | 12.546 | 0.128 |

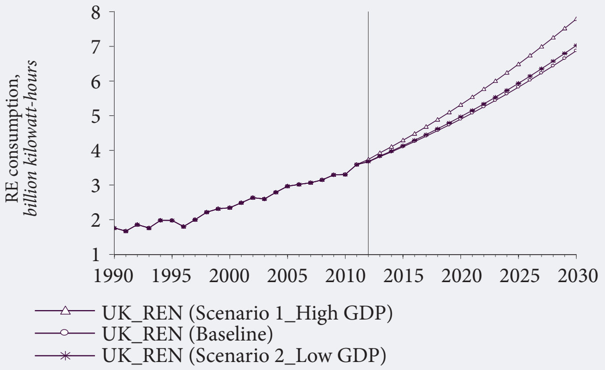
*Source*: author's calculations.

### Table 12. **Baseline Forecast of RE Consumption for Three Countries**

| Years | UK | Turkey | Nigeria |
|---|---|---|---|
| 2015 | 4.10 | 4.00 | 1.80 |
| 2020 | 4.90 | 4.18 | 1.80 |
| 2025 | 5.82 | 4.32 | 1.79 |
| 2030 | 6.87 | 4.48 | 1.77 |

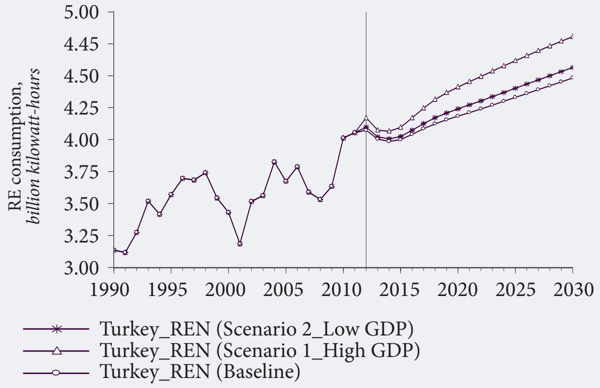
*Source*: author's calculations.

### Figure 5. **RE Consumption Forecast for the UK**



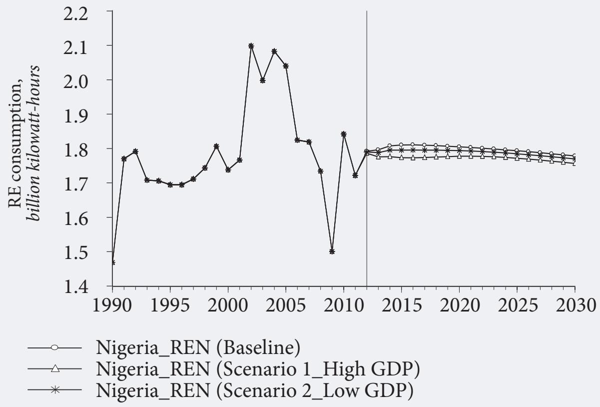

*Source*: author's calculations.

### Figure 6. **RE Consumption Forecast for Turkey**




*Source*: author's calculations.

### Figure 7. **RE Consumption Forecast for Nigeria**




*Source*: author's calculations.

RE consumption and electricity prices, there is no causality from electricity price to RE consumption. The result for Nigeria is also consistent with the study of Ebohon [*Ebohon,* 1996], which showed that price shock does not affect economic activity and energy consumption in Nigeria. For the United Kingdom, there is bidirectional causality in the relationship between RE consumption and electricity prices. Sadorsky (2009a) suggests that in the UK, RE consumption is more responsive to electricity price changes and that a drop in electricity prices encourages RE consumption.

## RE Forecasts

The forecasts for RE energy demand over the period 2013-2030 were based on two VAR model scenarios. Scenario 1 assumes a high level of economic growth, while Scenario 2 assumes a low level of economic growth. Growth estimates were based on the World Bank database of annual GDP growth ratio for the countries. These scenarios assume some level of economic growth because many scholars and institutions (such as the IEA, World Bank) anticipate positive growth rates for these countries. This paper used GDP and electricity prices as predictors for the forecast because they play a role in RE consumption.

For RE consumption in the UK, Figure 5 indicates an obvious trend of rising renewable consumption. In 2030, RE consumption is forecast at 6.87 billion kilowatt-hours and for a high and low level of economic growth 7.78 and 7.02 billion kilowatt-hours are forecasted, respectively.

Figure 6 shows the forecasting for RE consumption in Turkey. The forecasting trend graph in Figure 3 shows a steady upward slope for the coming years. In 2030, RE consumption is forecast at 4.48 billion kilowatt-hours while with a high and low level of economic growth 4.81 and 4.56 billion kilowatt-hours are forecasted, respectively. Furthermore, the obvious RE consumption drop in 2001 addressed Turkey's 2000-2001 financial crisis since it may have affected the forecast results.

In Figure 7, the total renewable consumption fluctuated over the period. RE consumption is expected to stabilize in future years. The forecast of RE consumption for Nigeria is basically the historical average. The forecast did not reflect the recent peak in 2003-2005 and the drop in 2009. In 2030, RE consumption is forecast at 1.77 billion kilowatt-hours, while with a high and low level of economic growth 1.75 and 1.76 billion kilowatt-hours are forecasted, respectively.

Based on the vector autoregressive model of the three case study countries, the estimated RE consumption for the years 2015, 2020, 2025, and 2030 are presented in Table 12. The forecast illustrates the apparent growth of consumption of RE in the UK and Turkey, but not in Nigeria.

## Conclusions and Policy Implications

This study investigated the dynamic interaction between RE consumption, income, and electricity prices for the three case study countries employing a standard VAR approach. The study was conducted using the data of the United Kingdom, Turkey, and Nigeria from 1990 to 2012. In this regard, the aim of this paper was to analyze how an increasing share of renewable sources in power generation affects income and price while the forecasts for the case study countries were essential for the completion of this research. The results from IRF indicate that positive shocks to income increase RE consumption. This means that effective economic policies favoring economic growth and development should also lead to increases in RE consumption. The study's results also show that economic growth in the sample countries has a positive relationship with RE consumption.

The policy implications of this study's findings are potentially important for the case study countries because they highlight the importance of increasing RE consumption within the relevant energy portfolios. Thus, it seems that there is a new market emerging in the energy industry with the potential to create major changes in the current traditional energy markets, if not in the short run then certainly in the medium or long run. In this regard, it seems from the review that the gradual growth rates experienced on the RE market in the past are strong indicators about the trends that those markets would also follow in the future with effective policies. One of the more important policy implications of these results is that income variables have a powerful influence upon the development of renewable sources. For instance, government monetary and fiscal policies can increase income and wealth generation by focusing on increasing innovation and productivity. Specifically, case study countries' energy and economic policies should focus on developing or increasing RE investments for future development purposes.

This study has shown that the income effect is positive and it has policy implications economically and politically for the countries. These findings support the advantages of government policies encouraging the use of RE by implementing RE markets and RE portfolio standards to not only improve security and address environmental concerns, but also from a macroeconomic point of view (stable economic growth). Furthermore, RE consumption is determined by the electricity (RE) price in the long run. Given that renewable energy infrastructure is very expensive, countries produce higher priced electricity from RE sources, but most consumers are not prepared to pay such a price.

It is also worth noting the limitations of this study, which include mainly the period 1990 to 2012. The application of the model with a reduced number of observations, despite its limitations, was in line with previous studies [*Silva et al.,* 2012; *Soytas, Sari,* 2009]. Furthermore, there are weaknesses in the data on Nigeria as it was very difficult to find robust data for Nigeria. However, the present paper has strong implications for the two other countries with its depth of analysis. The above limitations should be considered in future studies.

## References

Abbott A.J., De Vita G. (2003) Another Piece in the Feldstein – Horioka Puzzle. *Scottish Journal of Political Economy,* vol. 50, no 1, pp. 68–89.

Akaike H. *(1974)* A new look at the statistical model identification. *IEEE Transactions on Automatic Control, v*ol. 19, no 6, pp. 716–723. DOI:10.1109/TAC.1974.1100705.

Akinlo A.E. (2008) Energy consumption and economic growth: Evidence from 11 Sub-Sahara African countries. *Energy Economics,* vol. 30, no 5, pp. 2391–2400.
Akinlo A.E. (2009) Electricity consumption and economic growth in Nigeria: Evidence from cointegration and co-feature analysis. *Journal of Policy Modelling,* vol. 31, no 5, pp. 681–693.
Apergis N., Payne J.E. (2010) Renewable energy consumption and economic growth: Evidence from a panel of OECD countries. *Energy Policy,* vol. 38, pp. 656–660.
Apergis N., Payne J.E. (2014) Renewable energy, output, CO2 emissions, and fossil fuel prices in Central America: Evidence from a nonlinear panel smooth transition vector error correction model. *Energy Economics,* vol. 42, pp. 226–232.
Aqeel A., Butt M.S. (2001) The relationship between energy consumption and economic growth in Pakistan. *Asia-Pacific Development Journal,* vol. 8, no 2, pp. 101–110.
Aziz M.I.A., Dahalan J. (2015) Oil Price Shocks and Macroeconomic Activities in Asean-5 Countries: A Panel VAR Approach. *Eurasian Journal of Business and Economics*, vol. 8, no 16, pp. 101–120.
Belke A. Dobnik F., Dreger C. (2011) Energy consumption and economic growth: New insights into the cointegration relationship. *Energy Economics,* vol. 33, no 5, pp. 782–789.
Bowden N., Payne J.E. (2010) Sectoral analysis of the causal relationship between renewable and non-renewable energy consumption and real output in the US. *Energy Sources Part B: Economics, Planning, and Policy*, vol. 5, no 4, pp. 400–408.
Bretschenger L. (2010) *Energy Prices, Growth, and the Channels in Between: Theory and Evidence* (Economics Working Paper Series), Zurich: ETH Zurich.
Brooks C. (2008) *Introductory econometrics for finance* (2nd ed.), Cambridge: Cambridge University Press.
Bruns S.B., Gross C. (2013) What if energy time series are not independent? Implications for energy-GDP causality analysis. *Energy Economics,* vol. 40, pp. 753–759.
Chiou-Wei S.Z., Chen C.F., Zhu Z. (2008) Economic growth and energy consumption: Evidence from linear and nonlinear granger causality. *Energy Economics,* vol. 30, no 6, pp. 3063–3076.
Dickey D.A., Fuller W.A. (1981) Likelihood ratio statistics for autoregressive time series with a unit root. *Econometrica,* vol. 49, no 4, pp. 1057–1072.
Ebohon O.J. (1996) Energy, economic growth and causality in developing countries. *Energy Policy,* vol. 24, no 5, pp. 447–453.
Edenhofer O., Hirth L., Knopf B., Pahle M., Schlömer S., Schmid E., Ueckerdt F. (2013) On the economics of renewable energy sources. *Energy Economics,* vol. 40, no S1, pp. S12–S23.
Enders W. (1995) *Applied econometric time series* (2nd ed.), London: John Wiley&Sons Inc.
Ewing B.T., Sari R., Soytas U. (2007) Disaggregate energy consumption and industrial output in the United States. *Energy Policy,* vol. 35, no 2, pp. 1274–1281.
Giles D. (2011) *VAR or VECM When Testing for Granger Causality?* Available at: http://davegiles.blogspot.com.tr/2011/10/var-or-vecm-when-testing-for-granger.html, accessed 25.05.2015.
Granger C.W.J. (1980) Testing for causality: A personal viewpoint. *Journal of Economic Dynamics and Control*, vol. 2, pp. 329–352. DOI:10.1016/0165-1889(80)90069-X.
Gross C. (2012) Explaining the (non-) causality between energy and economic growth in the U.S. — A multivariate sectoral analysis. *Energy Economics,* vol. 34, no 2, pp. 489–499.
Halicioglu F. (2009) An econometric study of CO-2-emissions, energy consumption, income and foreign trade in Turkey. *Energy Policy,* vol. 37, no 3, pp. 1156–1164.
Hannan E.J., Quinn B.G. (1979) The Determination of the order of an autoregression. *Journal of the Royal Statistical Society, Series B*, vol. 41, pp. 190–195.
Hocaoglu F.O., Karanfil F. (2013) A time series-based approach for renewable energy modelling. *Renewable and Sustainable Energy Reviews,* vol. 28, pp. 204–214.
Huang B.N. Hwang M.J., Yang C.W. (2008) Causal relationship between energy consumption and GDP growth revisited: A dynamic panel data approach. *Ecological Economics,* vol. 67, no 1, pp. 41–54.
Humphrey W.S., Stanislaw J. (1979) Economic growth and energy consumption in the UK, 1700-1975. *Energy Policy,* vol. 7, no 1, pp. 29–42.
Ighodaro C.A. (2010) Co-integration and causality relationship between energy consumption and economic growth: Further empirical evidence for Nigeria. *Journal of Business Economics and Management,* vol. 11, no 1, pp. 97–111.
Inglesi-Lotz R. (2013) *The Impact of Renewable Energy Consumption to Economic Welfare: A Panel Data Application* (Department of Economics Working Paper Series 15, March), Pretoria: University of Pretoria.
IRENA (2018a) *Renewable energy auctions: Cases from sub-Saharan Africa,* Abu Dhabi: International Renewable Energy Agency.
IRENA (2018b) *Renewable capacity statistics 2018,* Abu Dhabi: International Renewable Energy Agency.
Johnstone N., Haščič I., Popp D. (2010) Renewable energy policies and technological innovation: Evidence based on patent counts. *Environmental and Resource Economics,* vol. 45, no 1, pp. 133–155.
Kaygusuz K., Yuksek O., Sari A. (2007) Renewable energy sources in the European Union: Markets and capacity. *Energy Sources, Part B: Economics, Planning, and Policy*, vol. 2, no 1, pp. 19–29.
Kireyev A. (2000) *Comparative Macroeconomic Dynamics in the Arab World: A Panel VAR Approach* (IMF Working Paper, Middle Eastern Department, WP/00/54), Washington, D.C.: International Monetary Fund.
Lee C.C., Chien M.S. (2010) Dynamic modelling of energy consumption, capital stock, and real income in G7 countries. *Energy Economics,* vol. 32, no 3, pp. 564–581.
Lee C.C., Chiu Y.B. (2011) Nuclear energy consumption, oil prices, and economic growth: Evidence from highly industrialized countries. *Energy Economics,* vol. 33, no 2, pp. 236–248.
Marques C.A., Fuinhas J.A. (2011) Do energy efficiency measures promote the use of renewable sources? *Environmental Science & Policy,* vol. 15, no 3, pp. 471–481.
Melikoglu M. (2013) Vision 2023: Feasibility analysis of Turkey's renewable energy projection. *Renewable Energy,* vol. 50, issue C, pp. 570–575.
Menegaki A.N. (2011) Growth and renewable energy in Europe: A random effect model with evidence for neutrality hypothesis. *Energy Economics,* vol. 33, no 2, pp. 257–263.
Menyah K., Wolde-Rufael Y. (2010) CO2 emissions, nuclear energy, renewable energy and economic growth in the US. *Energy Policy,* vol. 38, no 6, pp. 2911–2915.
Mohammadi H., Parvaresh S. (2014) Energy consumption and output: Evidence from a panel of 14 oil-exporting countries. *Energy Economics,* vol. 41, pp. 41–46.
Narayan P.K., Prasad A. (2008) Electricity consumption-real GDP causality nexus: Evidence from a bootstrapped causality test for 30 OECD countries. *Energy Policy,* vol. 36, no 2, pp. 910–918.

Ng S., Perron P. (2001) Lag length selection and the construction of unit root tests with good size and power. *Econometrica,* vol. 69, no 6, pp. 1519–1554.
Ocal O., Aslan A. (2013) Renewable energy consumption-economic growth nexus in Turkey. *Renewable and Sustainable Energy Reviews,* vol. 28, pp. 494–499.
Odhiambo N.M. (2010) Energy consumption, prices and economic growth in three SSA countries: A comparative study. *Energy Policy,* vol. 38, no 5, pp. 2463–2469.
Ohler A., Fetters I. (2014) The causal relationship between renewable electricity generation and GDP growth: A study of energy sources. *Energy Economics,* vol. 43, issue C, pp. 125–139.
Ozturk I., Acaravci A. (2013) The long run and causal analysis of energy, growth, openness and financial development on carbon emissions in Turkey. *Energy Economics,* vol. 36, issue C, pp. 262–267.
Pao H.T., Fu H.C. (2013) Renewable energy, non-renewable energy and economic growth in Brazil. *Renewable and Sustainable Energy Reviews,* vol. 25, pp. 381–392.
Payne J.E., Taylor J.P. (2010) Nuclear energy consumption and economic growth in the US: An empirical note. *Energy Sources, Part B: Economics, Planning, and Policy,* vol. 5, no 3, pp. 301–307.
Payne J.E. (2011) On biomass energy consumption and real output in the US. *Energy Sources, Part B: Economics, Planning, and Policy,* vol. 6, no 1, pp. 47–52.
Payne J.E. (2010) Survey of the international evidence on the causal relationship between energy consumption and growth. *Journal of Economic Studies,* vol. 37, no 1, pp. 53–95.
Perron P. (1988) Trends and random walks in macroeconomic time series: Further evidence from a new approach. *Journal of Economic Dynamics and Control,* vol. 12, no 2, pp. 297–332.
Phillips P.C., Perron P. (1988) Testing for a unit root in time series regression. *Biometrika,* vol. 75, no 2, pp. 335–346.
Phillips P.C.B. (1998) Impulse response and forecast error variance asymptotic in nonstationary VARs. *Journal of Econometrics,* vol. 83, pp. 21–56.
REN21 (2018) *Renewables 2018 Global Status Report,* Paris: REN21 Secretariat. ISBN 978-3-9818911-3-3.
Sadorsky P. (2009a) Renewable energy consumption, CO2 emissions and oil prices in the G7 countries. *Energy Economics,* vol. 31, no 3, pp. 456–462.
Sadorsky P. (2009b) Renewable energy consumption and income in emerging economies. *Energy Policy,* vol. 37, no 10, pp. 4021–4028.
Sadorsky P. (2011) Modelling renewable energy consumption for a greener global economy. *Planet Earth 2011 — Global Warming Challenges and Opportunities for Policy and Practice* (ed. E. Carayannis), Rijeka, Shanghai: InTech, pp. 507–524.
Salim R.A., Rafiq S. (2012) Why do some emerging economies proactively accelerate the adoption of renewable energy? *Energy Economics,* vol. 34, no 4, pp. 1051–1057.
Schwarz G.E. (1978) Estimating the dimension of a model. *Annals of Statistics,* vol. 6, no 2, pp. 461–464. DOI:10.1214/aos/1176344136, MR 0468014.
Silva S., Soares I., Pinho C. (2012) The impact of renewable energy sources on economic growth and CO2 emissions — a SVAR approach. *European Research Studies,* vol. 15 (Special Issue on Energy), pp. 132–144.
Soytas U., Sari R. (2009) Energy consumption, economic growth, and carbon emissions: Challenges faced by an EU candidate member. *Ecological Economics,* vol. 68, no 6, pp. 1667–1675.
Taylor J.W. (2010) Triple seasonal methods for short-term electricity demand forecasting. *European Journal of Operational Research,* vol. 204, pp. 139–152.
Tiwari A.K. (2011) A structural VAR analysis of renewable energy consumption, real GDP and CO2 emissions: Evidence from India. *Economics Bulletin,* vol. 31, no 2, pp. 1793–1806.
Tugcu C.T., Ozturk I., Aslan A. (2012) Renewable and non-renewable energy consumption and economic growth relationship revisited: Evidence from G7 countries. *Energy Economics,* vol. 34, no 6, pp. 1942–1950.
Vaona A. (2012) Granger non-causality tests between (non) renewable energy consumption and output in Italy since 1861: The (ir) relevance of structural breaks. *Energy Policy*, vol. 45, pp. 226–236.
Ward D.J., Inderwildi O.R. (2013) Global and local impacts of UK renewable energy policy. *Energy Environment Science,* vol. 6, pp. 18–24.
World Bank (2013) *World Development Indicators 2013.* Available at: http://data.worldbank.org/, accessed 10.10.2014.
Yildirim E., Sarac S., Aslan A. (2012) Energy consumption and economic growth in the USA: Evidence from renewable energy. *Renewable and Sustainable Energy Reviews,* vol. 16, no 9, pp. 6770–6774.
Yusuf S.A. (2014) *Impact of energy consumption and environmental degradation on economic growth in Nigeria* (MPRA Paper 55529), Munchen: University of Munchen.

# Limits of Technological Efficiency of Shale Oil Production in the USA

**Alexander Malanichev**
Visiting Professor, a_malanichev@list.ru

New Economic School, Skolkovskoe str. 45, Moscow, 121353, Russian Federation

## Abstract

The development of the shale oil extracting technology revolution in the United States led to the rapid growth of its production and reduced the related costs to an acceptable level. The shale oil revolution dramatically influenced the global oil market and was a key factor in the reduction of oil prices in 2014-2016. This paper investigates the problems of long-term forecasting of shale oil production and the productivity of drilling rigs. This research applies an asymmetric bell-shaped function using the OLS approach. This function is derived as an analytical solution of the differential equation of oil production. Another contribution of this study is the asymmetric function, which correlates better with the data on the extraction of traditional and non-traditional oil resources.

An analysis of the empirical data with the derived asymmetrical bell-shaped curve shows that the productivity of drilling rigs would peak by 2026 at 1,200 bbl per day, which is two times higher than the current level. The peak of production would correspond to the maximum oil production of 11.3 mln bbl per day and to technically recoverable resources of 96 bln bbl. This could mean that starting from 2023, the volume of oil shale oil production in the US may not be enough to meet growing global demand for oil and other resources with even higher production costs. The theoretically grounded and practically tested asymmetrical bell-shaped curve can serve as one of the tools for assessing the long-term impact of technological innovation over the course of Foresight studies for the oil and gas complex.

**Keywords:** shale oil production; technological efficiency; institutional factors; bell-shaped curve fitting; rig productivity.

**Citation:** Malanichev A. (2018) Limits of Technological Efficiency of Shale Oil Production in the USA. *Foresight and STI Governance*, vol. 12, no 4, pp. 78–89.
DOI: 10.17323/2500-2597.2018.4.78.89

Increased shale oil production in the United States was one of the major factors behind the dramatic decline in oil prices in 2014-2016. Shale oil is light with a low sulphur content contained in tight reservoirs [*Mănescu, Nuño,* 2015]. The short investment cycle allowed the US shale oil industry to push OPEC out of its position as the price regulator on the global oil market [*Baffes,* 2015].

Oil production is affected by several groups of factors (geological, technological, economic, and political), including specific features of the industry's regulation. In the long term, geological and technological factors become decisive [*Benes et al.,* 2012]: the more rapidly exploration and production technologies improve, the more hydrocarbons can be extracted and marketed under comparable economic conditions, and the higher the revenues will be.

Several engineering- and geology-based approaches were applied to model the geological and technological factors affecting oil production [*Brandt,* 2010]. We mean a set of hypotheses concerning production profiles throughout the oil field's life, usually presented in the form of bell-shaped curves. The most popular is the symmetric bell-shaped Hubbert curve which allowed researchers to predict the peak of oil production in the United States between 1965 and 1970 [*Hubbert,* 1956].

The main advantage of the geological engineering approach is its taking into account the non-linear nature of production growth over time, plus there is no need to predict oil price behavior in the long term. The flaws of this approach include its insufficient consideration of major oil production limitations (such as the need to maintain material balance and natural production decline). Production profiles are set a priori, while the quality of empirical data approximations is verified using mathematical procedures [*Semenychev et al.,* 2014].

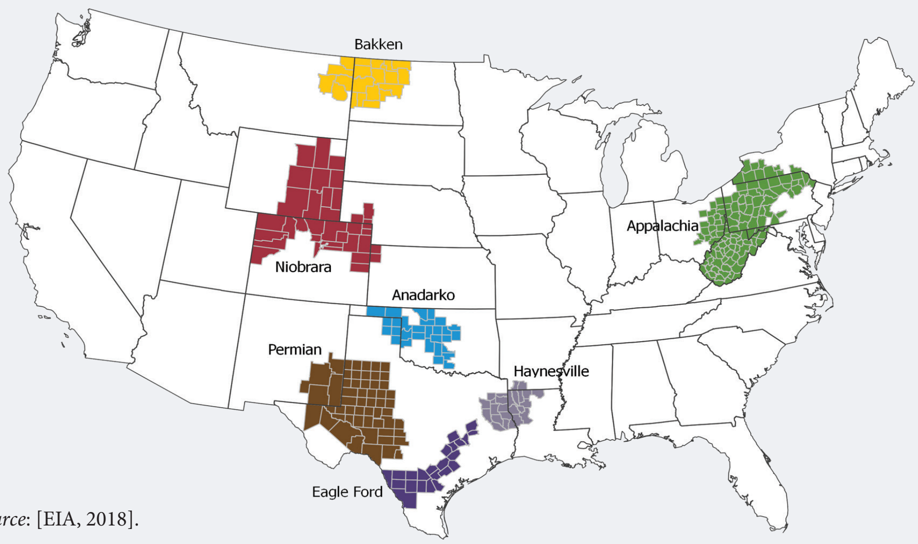
To deal with these shortcomings, [*Malanichev*, 2017a] proposed an ordinary differential equation that describes oil production growth taking into account the need to maintain material balance in oil reservoirs and the natural production decline. The Hubbert symmetric bell-shaped curve is a particular solution of this equation. However, since long-term oil production dynamics mostly remain asymmetrical (*Sorrel et al.*, 2009), the proposed method required certain adjustments.

The first objective of this paper is to find an analytical solution for the oil production differential equation precisely in the form of an asymmetric bell-shaped curve. This will allow one to take into account physical conditions, clearly interpret the curve's coefficients, and ensure better compliance with observational data. The practical result of empirical data analysis based on the above curve will be a long-term production forecast and an estimate of technically recoverable reserves in US shale oil fields.

The second objective is to review key technologies, and other prerequisites that made the "shale revolution" possible in the United States by identifying a key technological efficiency indicator for oil production and preparing a long-term forecast of its growth. It is assumed that the technological curve is less variable than production volume, as it is less dependent upon the price factor.

This study was based on shale oil production data at seven key US fields for 2007-2017 (Fig. 1), presented in the Drilling Productivity Report of the US Energy Information Administration (EIA) [EIA, 2018]. Total oil production is measured using a set of indicators for individual formations, while drilling rig' productivity is calculated as a weighted average.

Figure 1. **Location of US shale oil fields under consideration**




*Source*: [EIA, 2018].

## Technological and Institutional Factors of the "Shale Revolution"

The rapid growth of hydrocarbon production from tight reservoirs in the United States is due to a number of favorable technological and institutional factors. The first group includes the development of horizontal drilling and multiple fracturing technologies, new tools and capabilities for the development of complex wells, an extended range of chemical and physical methods of affecting the reservoir to increase the flow of hydrocarbons to the bottom of the well, and so on. Institutional factors include ownership guarantees, a transparent mechanism for getting access to oil-bearing areas, a developed service market, small and medium oil and gas businesses, good transport infrastructure, and a large financial market [*Shafrannik*, *Kryukov*, 2016].

The increased share of hydrocarbons produced from non-conventional fields by the US oil and gas sector was achieved after a long period of developing and improving relevant production technologies (Table 1).

Due to the lack of breakthrough inventions, the existing approaches to combining horizontal drilling, hydraulic fracturing, and 3D seismic surveying have been improved over the past 10-15 years [*Ivanov*, 2017a]:

- *Repeated hydraulic fracturing*. According to Halliburton, this technology increases recoverable reserves by 80% and cuts costs by 66%. In 2015, the number of fracturing stages reached 50 and their density was reduced to 3 meters. Proppant concentration increased to 3 t/m. Length of horizontal trunk exceeded 3 kilometers. Production via carbon dioxide injection after fracturing is now being promoted.
- *Cluster drilling*, which is applied at 58% of wells, amounts to drilling vertical wells in a section of the grid and then connecting them with horizontal wells. This reduces well costs by 15–30% and significantly reduces drilling time.
- *Analytical methods for processing 3D seismic data, "big data", and computer modeling* are being developed by oil and gas companies and by technology services providers. For example, the FracFit™ Baker Hughes technology allows one to collect and analyze data to quickly and efficiently complete and stimulate shale wells, resulting in a 45% increase in production.

Along with improved production technologies, a key prerequisite of the "shale revolution" in the US was the development of financial technologies. While oil prices remained high (in 2005-2014), the tight oil sector has managed to attract significant financial resources from leading world markets, among other things because money was readily available due to the Federal Reserve's low interest policy [*Zhukov, Zolina*, 2017]. When the market situation deteriorated in 2015-2017, the hedging of price-related risks prevented US crude oil production from dropping below the June 2014 level (when prices exceeded $100 per barrel). Guaranteed sales at a relatively high price in a falling market helped to maintain the financial stability of oil-producing companies in the US and provided them with a steady flow of liquidity.

In contrast, on a growing market hedging turns out to be a constraining factor. According to Bloomberg, in 2018 63% of expected revenues were hedged at the average price of $48.2 per barrel, while the actual price of a barrel of WTI oil at the beginning of the year was $64 [Denning, 2017]. Thus, hedging on the oil market turns out to be ineffective with an upward price trend, but ensures companies' stability with a downward one.

Hedging was a financial driver of the US "shale revolution" and remains an essential element of the developed institutional business environment in the United States. Other components of this environment include the following tools and characteristics [*Shafrannik, Kryukov*, 2016]:

- The *established institution of private land and subsoil ownership*. In the US, the landowner owns the subsoil and has the right to geological exploration, development, and mining by default, while the advanced rules and mechanisms make obtaining relevant authorizations simple and straightforward.
- The *largest fleet of drilling rigs* (in 2011 the number of simultaneously operating rigs exceeded 1,800); most of them allow one to drill long horizontal wells. This is more than the combined fleet of the former Soviet republics, Saudi Arabia, and Canada. It should be noted that after the rig fleet stabilized at 800, the growth of drilling volumes was mainly due to increased productivity, as the equipment was upgraded.
- *Investment and tax incentives* to keep marginal wells operational. The resulting huge number of drilled wells, combined with the newly acquired and systematized knowledge, facilitated the US oil and gas sector's taking a new development path.
- *Developed transport infrastructure*, including road and special-purpose networks (such as pipelines and terminals), with free and non-discriminatory access.
- *Numerous independent small and medium oil companies* that are more flexible and willing to take on the risk of working with small fields and hard-to-reach resources. Such players' share is almost 60%

of hydrocarbon production in the United States, which was the reason why the oil recovery rate in the US over the past 20-30 years grew from 25-28% to 40%.

- *Less strict environmental requirements for hydraulic fracturing*. Influenced by the US Vice President (formerly Executive Director and Chairman of the Board of Directors of Halliburton) Dick Cheney, in 2005 the US Congress took fracturing technology out of the Environmental Protection Agency's (EPA) supervision and removed it from the coverage of the federal water laws [*Glushenkova*, 2015]. Shale oil production in the country is mainly concentrated in sparsely populated areas of non-agricultural states such as Oklahoma, Texas, Nevada, etc. However, even there the development of shale deposits may pose a threat to the environment. Firstly, if technologies are applied carelessly, drinking water extracted from underground reservoirs can be polluted. Secondly, oil production exacerbates seismic instability, even in relatively safe areas. Thirdly, it may be accompanied by emissions of methane and other greenhouse gases. Fourthly, there is a risk of contamination and subsidence of soil in production areas and the associated problem of cleaning and disposing of drilling mud and water used for hydraulic fracturing.

The favorable institutional environment for the development of production technologies in the US contributed to the development of unconventional hydrocarbon deposits, while the "learning curve" has led to increased oil recovery from the drilled wells (Fig. 2).

At the key Permian formation reviewed above, the average well oil recovery was steadily growing over the observation period (from 2007) and by 2017, the new flow rates have exceeded 450 bbl./d. The average well output is a representative indicator for describing the quality of hydrocarbon reserves and productivity, but not the drilling efficiency. The oil production per drilling rig is a more comprehensive indicator. This data is readily available due to the monthly monitoring of the seven key formations published in the Drilling Performance Report [EIA, 2018].

## Growth of Drilling Rig Productivity

The productivity of drilling rigs is directly reflected in the level of oil production in the US shale deposits and technically recoverable reserves. The higher the productivity, the higher the output given the same number of active rigs.

Since 2007, the productivity of the average drilling rig grew by 15 times reaching 625 bbl./d by the end of 2017 and it continues to increase (Fig. 3). In the context of high oil prices in 2010-2014, this indicator grew due to the technological factor, i.e., the classic proliferation of innovations [EIA, 2016]. Since the end of 2014, productivity growth was also influenced by low oil prices.

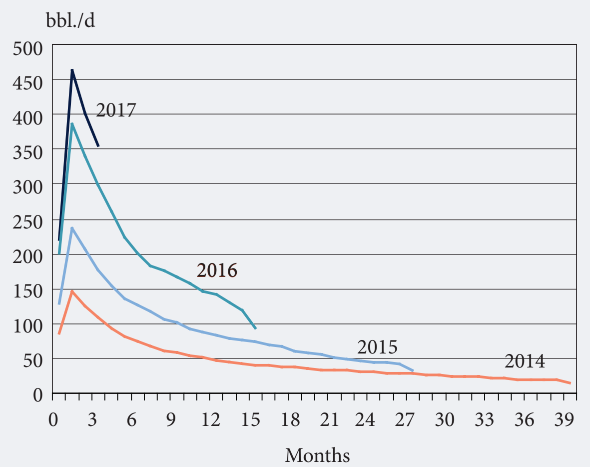
As a result of the falling oil prices in 2014-2016, the number of active drilling rigs dropped from 1,549 in October 2014 to 317 in May 2016. Such a rapid decrease resulted in an equally fast increase in productivity, which by August 2016 peaked at 711 bbl./d, mainly due to cyclical rather than technological factors [Rystad Energy, 2016]. While the volume of drilling and the fleet of rigs were being reduced, only the

Table 1. **The main stages of developing key tight oil production technologies in the US**

| Year | Technology, application |
|---|---|
| 1929 | Drilling of the first horizontal well in Texas |
| 1947 | First hydraulic fracturing in Kansas |
| 1949 | First cost-effective hydraulic fracturing in Oklahoma |
| 1979 | Development of the Barnett Formation begins: the first shale formation fracture |
| 1986 | The first multistage hydraulic fracturing of a shale formation (seven stages) |
| 1992 | The first 3D seismic survey in Texas |
| 1997 | The first application of a water-based reagent for fracturing the Barnett formation |
| 2000 | Drilling of the first horizontal well in the Barnett formation |
| 2002 | Horizontal drilling combined with hydraulic fracturing in the Barnett formation |

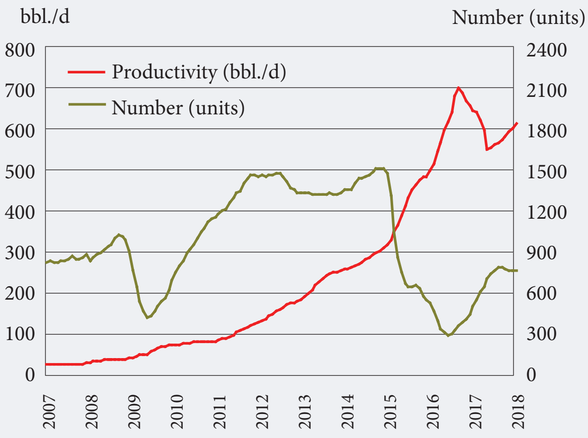
*Source:* [*Zolina*, 2014].

Figure 2. **Oil production from the average well in the Permian formation in 2014-2017**



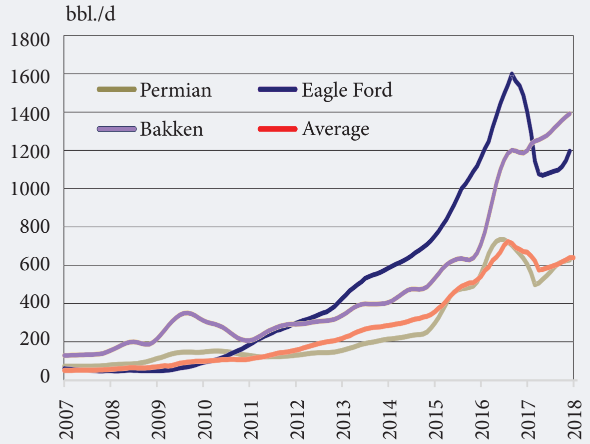

*Source:* composed by the author based on [EIA, 2017].

Figure 3. **Weighted average productivity of drilling rigs in seven fields, and the number of drilling rigs**




*Source:* composed by the author based on [EIA, 2018].

Figure 4. **Drilling rigs' productivity in the largest US fields, and the weighted average for seven fields**




*Source:* composed by the author based on [EIA, 2018].

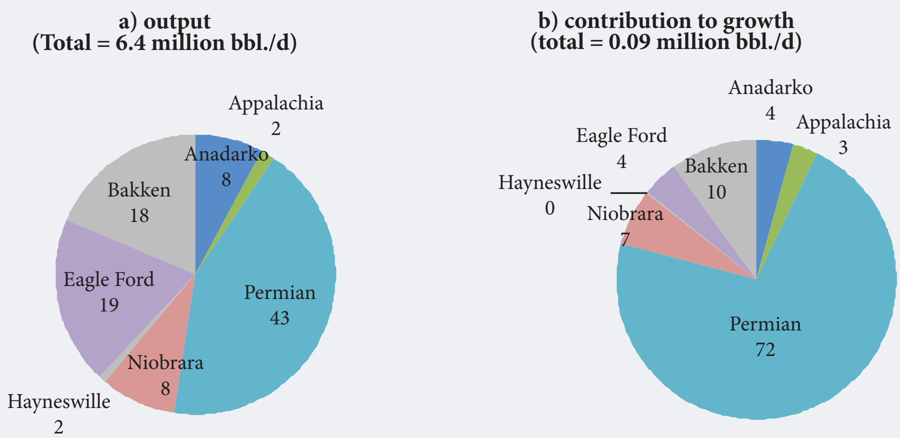
most promising areas were developed and only the most efficient (high grade) rigs remained in operation [*Hoza*, 2015]

The upward price trend of 2016 led to an increase in drilling activity beginning in June. However, the growing fleet of operating drilling rigs, increased drilling volumes, and the development of less rich areas resulted in a cyclical decrease in productivity, from 711 bbl./d in August 2016 to 586 bbl./d in August 2017. The stagnation of drilling, in its turn, "suspended" the cyclic factor, so productivity began to grow again due to the long-term technological trend associated with increased production efficiency. Accordingly, by the end of 2017 it reached 625 bbl./d.

Thus, in the short term, drilling rigs' productivity is significantly affected by production volume and the level of drilling (the cyclical factor), while the geological (gradual depletion of deposits) and technological factors act as long-term ones [*Hughes*, 2016]. Along with them, the average drilling productivity for all fields (Fig. 4) is also affected by the fourth factor, namely the spatial one. It amounts to the fact that drilling rig productivity and output vary between different fields, depending, among other things, on the rate of their reserves' change.

At the end of 2017, the largest Permian oil field in the US produced 2.8 million barrels per day, or 43% of total shale oil production in the country (Fig. 5). Furthermore, the production at this field is growing at

Figure 5. **Structure of production at US fields (as of December 2017)** (%)




*Source*: composed by the author based on [EIA, 2018].

the most rapid rate, while Permian's contribution to the growth of shale oil production reached 72%. This is followed by the Eagle Ford and Bakken fields (20% and 18%, respectively), with a much more modest contribution to production growth (at 4% and 10%, respectively). This is due to the reduced number of operating drilling rigs, so production only grows due to increased per rig output.

The geological features of the fields and the degree of their depletion are quite different, leading to significant variations in drilling rig productivity levels. For example, at the most valuable Permian field at the end of 2017, productivity was close to the average value (614 bbl./d), while the maximum of 1,383 bbl./d was recorded at Bakken and almost 1,185 bbl./d at Eagle Ford. However, the contribution of such high indicators is offset by the low drilling activity at the last two fields (Fig. 5b), so the average productivity for all fields is close to that of the Permian field (see Fig. 4).

The fifth factor affecting drilling rigs' efficiency is the share of wells drilled at the completion stage: the installation of casing, cementing, perforating, hydraulic fracturing, and so on, i.e., the operations that allow one to begin production. Part of the drilled wells go straight into the so-called backlog of drilled but uncompleted (DUC) wells. Well completion is often delayed due to the lack of available equipment and consumables, insufficient economic efficiency of production, or for speculative reasons [Rystad Energy, 2016]. The latter include rising oil prices or accelerated commissioning of wells if there is a downward price trend.

The number of DUC wells by the end of 2017 exceeded 7,000 [EIA, 2018], raising legitimate concerns about a significant increase in production when these wells are commissioned (completed) during an upward trend in oil prices [*Ivanov*, 2017b]. However, such expectations are subject to high uncertainty. For example, at the moment it is impossible to estimate the share of "dry" DUC wells, i.e., those unsuitable for commercial production, or their production costs, the rate of fleet deployment for hydraulic fracturing, the prospects for overcoming the shortage of proppant, and various other logistical constraints [IHS, 2015].

The dynamics of reserve wells' numbers display a growing trend when drilling and output grow amid rising oil prices. The reverse was observed only from February to November 2016, when, due to the insufficient volume of drilling, the queues to rent hydraulic fracturing equipment got shorter: in 10 months' time the number of reserve wells decreased by 925, i.e., on average at the rate of 9.25 wells per month. Given the average per well output of 400 bbl./d, the added capacity provided an increase of 0.0037 million barrels per day, or just 1.5% of the new flow rates for the period under consideration.

As we see, out of the five drilling rig efficiency factors, only the technological (the development of production technologies) and geological ones (the depletion of hydrocarbon fields) are worthy of attention in the long term. The spatial factor and production from reserve wells along with output variations seem to have a significantly smaller impact. In the next section, a hypothesis is presented regarding the shape of the curve describing drilling rig productivity following the application of technological innovations and geological changes.

## Growth of Drilling Rig Productivity throughout the Field's Life Cycle

The classic approach to studying the proliferation of innovations is based upon the technology life cycle concept [*Mansfield*, 1968]. In the course of numerous studies, it was found that the process of innovative products' penetration (diffusion) is best described by a logistic function whose graph can be presented as an S-shaped non-linear curve that reaches a certain saturation level [*Little*, 1981; *Rogers*, 2002]. Productivity growth at the early stages of technology implementation is slow, since the lack of experience requires a considerable amount of time to master it. The accumulation of experience by researchers, engineers, managers, and businessmen triggers a positive feedback loop that accelerates the diffusion of innovations and productivity growth.

Technology developers make significant efforts to maximize their returns but after a while the diminishing marginal utility law triggers negative feedback. When the technological limits of growth are reached, the cost of each unit of change increases exponentially and the S-shaped curve smooths over. Such dynamics are typical for most industries including the production of automobiles, ships, internal and external combustion engines, semiconductors, vacuum tubes, disk drives, etc. [*Foster*, 1986].

However, there are many limitations to using S-curves as prognostic tools [*Schilling, Esmundo*, 2009]. Firstly, the actual limits of a technology's efficiency are rarely known in advance and experts from different companies may have different opinions about this issue. Secondly, unexpected changes on the market, complementary (replacement) technologies, or individual components can both speed up and slow down a technology's life cycle. Thirdly, S-curves do not describe the proliferation of innovations in all industries equally well. For example, for fossil fuels (coal, gas, oil), energy generation technologies have the form of not S-shaped, but rather bell-shaped curves (Fig. 6).

The bell-shaped curve describing the productivity of technologies for the extraction and use of fossil fuels can be explained as follows. After reaching its peak, productivity begins to decline due to two factors. The first is a significant slowdown or stabilization of the innovation's effect. The second is the exhaustion of the learning curve combined with the depletion of deposits and exhaustion of attractive sites ("sweet spots"), which forces companies to drill deeper and deeper and develop increasingly less rich deposits with lower extraction rates [*Montgomery, O'Sullivan*, 2017].

Industry experts also point out that a decline in drilling productivity is inevitable.

How long productivity will be growing is, of course, highly uncertain. However, the cyclical component will sooner or later lead to a growing trend changing to a downward one. The growth of productivity based on choosing the "sweetest spots" for development will soon come to an end [IHS, 2016].

In addition to the depletion of promising areas, a pressing problem with shale deposits is the reduced distance between wells.

A site can be drilled only once. In addition, productivity growth is limited by the distance between adjacent wells. An excessively dense grid of wells leads to reduced productivity. Empirical evidence suggests that adjacent wells may adversely affect one another. Though oil can be extracted more efficiently when wells are located close to each other, the per well recovery rate will drop and the overall output in the area will not increase [*Hughes*, 2016].

Thus, a hypothesis was suggested, and illustrated, that drilling rigs' productivity within the life cycle of a field can be described by a bell-shaped curve. Next, a mathematical formula will be derived for an asymmetric bell-shaped curve suitable for describing shale oil production and the growth of drilling rig productivity.

## The Asymmetrical Bell-Shaped Function

The mathematical description of oil production technologies' efficiency can be found in literature that analyzes and forecasts hydrocarbon supply. Table 2 presents a classification of the various approaches to modeling this supply and references to sources with typical examples. A more complete review of the most common approaches can be found in [*Brandt*, 2010].

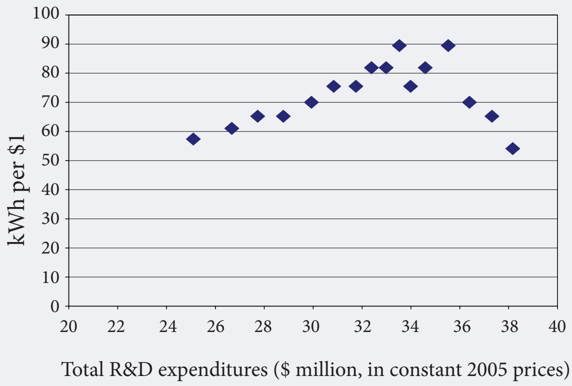
For the purposes of this paper we are primarily interested in the fourth approach, namely predicting production by fitting a bell-shaped curve. In our previous study [*Malanichev*, 2017a] we considered a set of assumptions for describing a theoretical oil production and drilling rigs productivity model using a symmetric bell-shaped curve proposed in 1838 for modeling population size [*Verhulst*, 1838] and then for predicting oil production volume in the United States [*Hubbert*, 1956].

Table 2. **Main approaches to forecasting oil production growth**

| No. | Approach | Description | Sources |
|---|---|---|---|
| 1 | Fitting natural production decline curve | Short-term production forecast for individual wells. Geological and technological factors are taken into account. | [*Arps*, 1944; *Clark*, 2011; *Malanichev*, 2017c] |
| 2 | Superposition of natural production decline curves | Geological, technological, and economic factors are taken into account. | [*Sorrel et al.*, 2009; *Malanichev*, 2017b] |
| 3 | "Bottom up" | Based on plans for the development of new sites or fields and their empirical production profiles. | [*Sorrel et al.*, 2009] |
| 4 | Fitting bell-shaped curve | Long-term production forecast for the field. Geological and technical factors are taken into account. | [*Hubbert*, 1956; *Semenychev et. al.*, 2014; *Malanichev*, 2017a; *Kozlov*, 2018] |
| 5 | Solving a differential equation with a lagging argument | Analysis of conditions leading to economic fluctuations. Forecast based on analytical solution of a differential equation. Geological and economic factors are taken into account. | [*Malanichev*, 2018] |
| 6 | Econometric | Forecast based on economic factors. | [*Kaufmann, Cleveland*, 2001; *Afanasiev*, 2016; *Ermolina*, 2017] |
| 7 | Optimal planning | Solving the problem of optimal production planning, taking into account the time value of money. | [*Hotelling*, 1931; *Okullo et al.*, 2014] |
| 8 | Combined | Combines fitting of bell-shaped curve with economic factors such as oil prices. | [*Benes et al.*, 2012; *Zolina*, 2014; *Ermolina*, 2017] |
| 9 | System imitation | Takes into account numerous interconnected factors and models the process of oil producers' making investment decisions. | [*Davidsen*, 1990; *Makarov et al.*, 2011] |

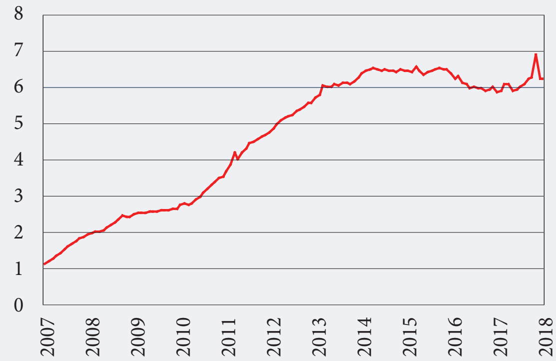
*Source:* composed by the author.

Figure 6. **Technological curves for the extraction and use of fossil fuels: technology performance (kWh per $1) vs R&D costs, 1990–2005**




*Source*: [*Schilling, Esmundo*, 2009].

Figure 7. **Production decline rate *b* (%)**




*Source*: composed by the author based on [EIA, 2018].

However, empirical evidence indicates that the production curve is asymmetrical. Rapidly increasing at the beginning of the development of a field, it reaches a peak and then slowly decreases. This asymmetrical bell-shaped profile with a flatter right side is typical of both conventional [*Bierman, Biryukov*, 2017] and unconventional [*Coyne*, 2017] hydrocarbon deposits.

In order to obtain an asymmetric bell-shaped curve, we will find an analytical solution of the differential production equation, making a number of simplifying assumptions [*Malanichev*, 2017a]. In the shale oil production case, the changes include the development of new wells drilled in the current month and reduced production from existing wells (drilled before the month in question). This balance can be described using an ordinary differential equation of the first order:

$$\frac{dq}{dt} = e{\cdot}N - b{\cdot}q, \tag{1}$$

where:

*Q* is oil production volume (million bbl./d);

$e{\cdot}N$ is oil production from new wells (million bbl./d). The well is considered new for one month after it was completed and commissioned;

*e* is drilling rig productivity (bbl./d). Calculated as the number of barrels of oil extracted during the month from the wells drilled by one rig during the same period;

*N* is the number of active rigs that drilled new wells during the same month;

$b{\cdot}q$ is the rate of natural production decline in line with the exponential decline law. [*Malanichev*, 2017c] also considers other laws that affect the dynamics of production decline (the harmonic and hyperbolic ones).;

*b* is the empirical production decline rate.

A distinctive feature of shale oil is the high rate of production decline from the well, often by 60%-70% during the first year of operation. This is reflected in higher natural production decline rates compared with conventional oil, where this value varies between 2%-14% depending on the field, with the average of 6.2% [*Fustier et al.*, 2016].

Another specific feature of shale oil is the insufficient accuracy of the exponential natural production decline law when applied to it, compared with the harmonic or hyperbolic laws [*Clark*, 2011; *Malanichev*, 2017c]. Nevertheless, the use of these non-linear laws in expression (1) complicates the integration of the equation and requires further research.

To find an analytical solution for equation (1) in the form of an asymmetric bell-shaped function, two simplifying assumptions were made regarding its coefficients. First, in line with [*Saussay*, 2018; *Kozlov*, 2018], we take production decline rate *b* as a variable, which is consistent with the observational data (Fig. 7). We shall use the following specification:

$$b = k \cdot (\gamma + 1) \cdot \left(\frac{Q}{EUR}\right)^{\gamma}, \quad (2)$$

where:

$k$ and $\gamma$ are positive empirical coefficients;

$Q$ is the accumulated production volume, $q = dQ/dt$;

EUR (estimated ultimate recovery) is the initial amount of recoverable resources (the sum of already extracted oil and technically recoverable resources).

The Q/EUR ratio serves as the resource depletion rate whose value ranges between 0-1. As the field's reserves deplete, the natural production decline rate gradually increases (Fig. 7).

Next, we assume the new flow rates $e{\cdot}N$ are proportional to production volume $q$:

$$e \cdot N = k \cdot q. \quad (3)$$

Regression analysis shows a significant correlation by the $t$-statistic criterion between new flow rates and production (Fig. 8). The regression constant is close to zero and statistically indistinguishable from it.

Substituting expressions (2) and (3) in equation (1) and integrating it over time results in an ordinary differential equation describing cumulative production dynamics:

$$\frac{dQ}{dt} = k \cdot Q \cdot \left(1 - \left(\frac{Q}{EUR}\right)^{\gamma}\right). \quad (4)$$

In form, this is the Bernoulli equation whose analytical solution is an S-shaped Richards function [*Richards*, 1959]:

$$Q(t) = \frac{EUR}{\left(c \cdot e^{-k \cdot \gamma t} + 1\right)^{\frac{1}{\gamma}}}. \quad (5)$$

The differentiation of this expression over time produces an asymmetrical bell-shaped function:

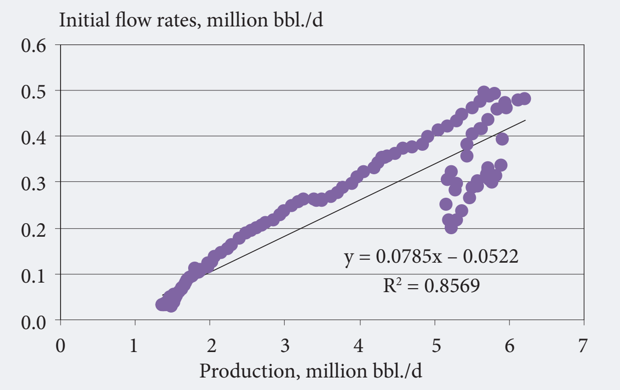
$$q(t) = Q'(t) = \frac{c \cdot k \cdot EUR}{e^{-k \cdot \gamma t} \cdot \left(c \cdot e^{-k \cdot \gamma t} + 1\right)^{\frac{1}{\gamma}+1}}, \quad (6)$$

where the constants $c$, $k$, $EUR$ and $\gamma$ can be found by fitting the production curve to the actual data, for example, by the least-squares method. The inflection point of the logistic curve $Qinf$ which corresponds to the peak of production is calculated using the following formula:

$$Q_{inf} = \left(\frac{1}{1+\gamma}\right)^{\frac{1}{\gamma}} \cdot EUR. \quad (7)$$

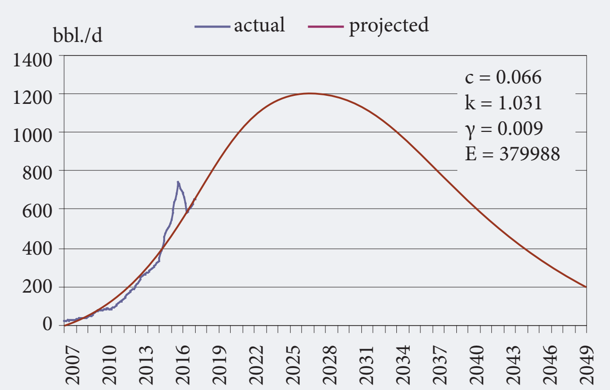
According to assumption (3), the bell-shaped function (6) is used to approximate drilling rig productivity $e(t)$. The curve constants $c$, $k$, $\gamma$, and $E$ (cumulative performance, an analogue of $EUR$) were found using

Figure 8. **Correlation between new flow rates and production in 2007-2017**




*Source*: composed by the author based on [EIA, 2018].

Figure 9. **Average drilling rigs' productivity**




*Source*: composed by the author based on [EIA, 2018].

Figure 10. **Main models based on the differential oil production balance equation**

Economic fluctuations of oil production [*Malanichev*, 2018]

$$\frac{dq}{dt} = e \cdot N\,(t - \tau) - \varphi\,(q)$$

t – time
τ – time lag between the investment solution and its implementation

Differential oil production balance equation

$$\frac{dq}{dt} = e \cdot N - \varphi\,(q)$$

Natural production decline rate laws [*Malanichev*, 2017c]:

$\varphi\,(q) = b \cdot q$ — exponential
$\varphi\,(q) = b \cdot q^2$ — parabolic
$\varphi\,(q) = b \cdot q^a$ — hyperbolic

Symmetrical bell-shaped curve [*Verhulst*, 1838; *Hubbert*, 1956; *Malanichev*, 2017a]

$$\frac{dQ}{dt} = b \cdot Q \cdot \left(1 - \frac{Q}{EUR}\right)$$

$eN = qQ2b/EUR$

Richards asymmetrical bell-shaped curve [*Richards*, 1959]

$$\frac{dQ}{dt} = k \cdot Q \cdot \left(1 - \left(\frac{Q}{EUR}\right)^{\gamma}\right)$$

$$b = k\,(\gamma + 1) \cdot \left(\frac{Q}{EUR}\right)^{\gamma} \qquad eN = kq$$

*Source*: composed by the author.

the least-squares method over the course of approximating the empirical data on drilling rig productivity averaged for the seven shale formations in the US for the period between 2007-2017 [EIA, 2018]. The optimization procedure was carried out using Excel Solver. The calculations show that productivity will peak by 2026 at $e$ = 1,200 bbl./d (Fig. 9)

The calculations show that the development of oil production technologies will allow one to double drilling rig productivity compared with the current level. The relevant indicators of the Bakken, Eagle Ford (Fig. 4), and Permian formations confirm that it is physically possible. The latter field also has good growth prospects [*Malanichev*, 2017c].

If the current level ($N$ = 800 units) is taken as the number of active rigs, then according to equation (3) their productivity will peak at the maximum oil production at 11.3 million bbl./d and technically recoverable reserves at 96 billion barrels. Similar values are presented in the literature: for example, the amount of technically recoverable reserves is estimated at 92 billion barrels [EIA, 2015].

The above estimate of the potential shale oil production matches the results obtained using a bell-shaped curve [*Malanichev*, 2017a], which confirms the validity of the calculations. Under the conservative scenario for the growth of global demand (1 million bbl./d), the potential for increasing production at shale deposits in the United States will be exhausted in five years' time. This may mean that by 2023 they would no longer be able to meet global demand for oil, so other resources, even those with higher production costs, would have to be developed.

## Discussion and Conclusion

At the end of 2017 oil production at shale fields in the United States exceeded 6.3 million bbl./d (6% of the global oil sales), turning it into a key factor of the emergence of a new market balance. The "shale revolution" became possible due to sufficiently large explored hydrocarbon reserves in tight reservoirs, improved production technologies, and a number of institutional factors. The latter include developed competitive oilfield services markets, the largest drilling rig fleet, an established institution of private land and subsoil ownership, investment and tax incentives for developing low-yield wells, advanced transport infrastructure, environmental requirements favorable for hydraulic fracturing, efficient financial markets including stock exchange insurance tools, and so on.

The main shale oil production technologies (horizontal drilling and hydraulic fracturing) were developed as early as in the first half of the 20th century. Their continuous improvement, the introduction of multicore drilling and multi-stage fracturing, establishing the optimal length of horizontal well sections, and the amount of proppant led to significantly reduced shale oil production costs and made it commercially viable.

A key factor for reducing shale oil production costs was increased well productivity. For example, at the largest formation in the United States, the Permian field, the average new well production rate steadily grew, from 150 bbl./d in 2014 to 450 bbl./d in 2017. The entire production cycle is more comprehensively measured by drilling rig productivity, which by the end of 2017 had reached an average of 625 bbl./d.

Oil rig productivity in the US is affected by five main factors: the development of production technologies, the depletion of deposits, uneven productivity at different fields, the commissioning of reserve wells, and production volume. In the long run, the development of technologies and the amount of technically recoverable reserves turn out to be the most important ones.

In conventional industries, the proliferation of technological innovations that result in productivity growth is typically described by S-shaped curves. However, in the mining industries where technology development has natural limits (i.e., the depletion of natural resources) the situation is different. Technological development initially leads to increased production, but when the reserves in the area being developed are depleted, it decreases. No matter how powerful drilling rigs' drives and injection pumps for hydraulic fracturing are, the laws of natural production decline and depletion of reserves will ultimately lead to reduced oil production and drilling rig productivity.

This paper presents an attempt to develop an analytical tool for the long-term forecasting of shale oil production and the estimation of drilling rig productivity, which would allow one to assess the limits for these indicators' growth. In particular, an asymmetric bell-shaped function was proposed as an analytical solution of the differential production equation (Fig. 10), which describes long-term oil production and drilling rig productivity growth.

An analysis of empirical data based on using the suggested asymmetrical bell-shaped curve shows that the average drilling rig productivity at US shale oil fields may peak by 2026 at 1,200 bbl./d or two times the current level. Production volume will reach 11.3 million bbl./d and technically recoverable reserves will be 96 billion barrels. If that is how things will develop, as early as by 2023, US shale oil producers may be unable to meet the growing global demand for oil, so they would have to start developing other resources with even higher production costs.

The asymmetrical bell-shaped curve, theoretically substantiated and tested on empirical data, can be recommended as a practical and effective tool for conducting Foresight studies of the global oil and gas sector taking into account prospective technological developments.

## References


Afanasiev A.A. (2017) *Prognozirovanie dobychi nefti i gazovogo kondensata v vychislimoi modeli denezhnogo obrashcheniya rossiiskoi ekonomiki* [Forecasting the production of oil and gas condensate in the computable model of the monetary circulation of the Russian economy]. *Ekonomika i matematicheskie metody* [Economics and Mathematical Methods], vol. 53, no 2, pp. 50–65 (in Russian).

Arps J.J. (1944) Analysis of decline curves. *AIME*, no 160, pp. 228–247.

Baffes J., Kose, M.A., Ohnsorge F., Stocker M. (2015) *The Great Plunge in Oil Prices: Causes, Consequences, and Policy Responses* (PRN 15/01), Washington, D.C.: World Bank Group.

Benes J., Chauvet M., Kamenik O., Kumhof M., Laxton D., Mursula S., Selody J. (2012) *The Future of Oil: Geology versus Technology* (WP/12/109), Washington, D.C.: International Monetary Fund.

Bierman S., Biryukov A. (2017) *Russia's Largest Oilfield May Be About to Gush Cash Once Again*. Available at: https://www.bloomberg.com/news/articles/2017-02-15/siberian-oil-giant-that-bankrolled-soviets-may-gush-cash-again, accessed 05.09.2018.

Brandt A.R. (2010) Review of mathematical models of future oil supply: Historical overview and synthesizing critique. *Energy*, vol. 35, no 9, pp. 3958–3974.

Clark A.J. (2011) *Decline Curve Analysis in Unconventional Resource Plays Using Logistic Growth Models*, Austin, TX: The University of Texas in Austin.

Coyne D. (2017) *Future US Light Tight Oil (LTO) Update*. Available at: http://peakoilbarrel.com/future-us-light-tight-oil-lto-update/, accessed 05.09.2018.

Davidsen P.I., Sterman J.D., Richardson G.P. (1990) A petroleum life cycle model for the United States with endogenous technology, exploration, recovery, and demand. *System Dynamics Review*, vol. 6, no 1, pp. 66–93.

Denning L. (2017) *Will Oil Producers Do as They Say or Do as They Sell in 2018*? Available at: https://www.bloomberg.com/gadfly/articles/2017-12-13/oil-producer-hedging-data-a-worry-for-opec), accessed 05.09.2018.

EIA (2015) *World Shale Resource Assessments*, Washington, D.C.: U.S. Energy Information Administration (EIA).

EIA (2016) *Expected decrease in Lower 48 oil production is partially offset by rising GOM output*. Available at: https://www.eia.gov/todayinenergy/detail.php?id=25892#, accessed 05.09.2018.

EIA (2017) *U.S. crude oil production forecast expected to reach record high in 2018*. Available at: https://www.eia.gov/todayinenergy/detail.php?id=32192, accessed 05.09.2018.

EIA (2018) *Drilling Productivity Report* (March), Washington, D.C.: U.S. Energy Information Administration (EIA).

Ermolina A. (2017) *Modelirovanie predlozheniya traditsionnoi nefti na osnove fizicheskikh i ekonomicheskikh faktorov* (magisterskaya dissertatsiya) [Conventional oil supply modelling based on physical and economic factors (Master thesis)], Moscow: NES (in Russian).

Foster R. (1986) *Innovation. The Attacker's Advantage*, New York: Summit Books.

Fustier K., Gray G., Gundersen C., Hilboldt T. (2016) *Global oil supply*, London: HSBC Global Research.

Glushenkova E.I. (2015) Ekologicheskiye posledstviya slantsevoy revolyutsii [Ecological consequences of the shale revolution]. *Zapad – Vostok – Rossiya* [West – East – Russia], pp. 184–189 (in Russian).

Hotelling H. (1931) The economics of exhaustible resources. *Journal of Political Economy*, vol. 39, no 2, pp. 137–175.

Hoza M. (2015) *The limits of high grading*. Available at: https://btuanalytics.com/the-limits-of-high-grading/, accessed 05.09.2018.

Hubbert M.K. (1956) Nuclear Energy and the Fossil Fuels Drilling and Production Practice. *Proceedings of the Spring Meeting of the Southern District, Division of Production, American Petroleum Institute*, San Antonio, TX: Shell Development Company, pp. 22–27.

Hughes J.D. (2016) *Drilling Deeper. A Reality Check on U.S. Government Forecast for a Lasting Tight Oil & Shale Gas Boom*, Santa Rosa, CA: Post Carbon Institute.

IHS (2015) *Still an Adolescent, Permian's Wolfcamp Delaware Offers Promising Adulthood as E&P Operators Expand Development, IHS Says*. Available at: https://news.ihsmarkit.com/press-release/energy-power-media/still-adolescent-permians-wolfcamp-delaware-offers-promising-adulth, accessed 05.09.2018.

Ivanov N. (2017a) Slantsy 3.0 [Shale 3.0]. *Neftegazovaya vertical,* no 17, pp. 12–20 (in Russian).

Ivanov N. (2017b) *Slantsevaya neft' na mirovom rynke: novye tendentsii. Doklad dlya Pyatoi mezhdunarodnoi konferentsii «Global'naya energeticheskaya transformatsiya: ekonomika i politika», Moskva, 15 dekabrya* [Shale oil in the world market: New trends. Paper for the Fifth International Conference "Global Energy Transformation: Economics and Politics". Moscow, December 15]. Available at: https://www.imemo.ru/files/File/ru/conf/2017/15122017/01_Ivanov.pdf, accessed 05.09.2018 (in Russian).

Kaufmann R.K., Cleveland C.J. (2001) Oil production in the lower 48 states: Economic, geological, and institutional determinants. *Energy,* vol. 22, no 1, pp. 27–49.

Kozlov A. (2018) *Modelirovanie dobychi slantsevoi nefti na osnove nesimmetrichnoi kolokoloobraznoi krivoi* (magisterskaya dissertatsiya) [Modeling the extraction of shale oil on the basis of an asymmetrical bell-shaped curve (Master thesis)], Moscow: NES (in Russian).

Little A.D. (1981) *The Strategic Management of Technology,* Cambridge, MA: Massachusetts Institute of Technology.

Makarov A., Veselov F., Eliseeva O., Kulagin V., Malakhov V., Mitrova T., Filippov S., Plakitkina L. (2011) *Model'no-informatsionnyi kompleks SCANER* [Modeling and information complex SCANER], Moscow: ERI RAS (in Russian).

Malanichev A.G. (2017a) Differentsial'noe uravnenie dobychi slantsevoi nefti [Differential equation of shale oil production]. *Neft', gaz i biznes* [Oil, Gas and Business], no 2, pp. 44–49 (in Russian).

Malanichev A.G. (2017b) Modeli dobychi slantsevoi nefti v SSHA dlya razlichnykh gorizontov prognozirovaniya [The models of shale oil production in the USA for different forecast horizons]. *Neft', gaz i biznes* [Oil, Gas and Business], no 3, pp. 13–17 (in Russian).

Malanichev A.G. (2017c) Prognoz dobychi nefti na zalezhi Permian na osnove raznostnogo uravneniya [Forecast of oil production at Permian play based on the difference equation]. *Problemy ekonomiki i upravleniya neftegazovym kompleksom* [Problems of Economics and Management of the Oil and Gas Complex], no 12, pp. 40–45 (in Russian).

Malanichev A.G. (2018) Prognoz dobychi nefti na slantsevykh mestorozhdeniyakh SSHA na osnove analiticheskikh reshenii differentsial'nogo uravneniya s zapazdyvayushchim argumentom [Modelling of economic oscillations of shale oil production]. *Zhurnal Novoi ekonomicheskoi assotsiatsii* [Journal of New Economic Association], no 2 (38) (in Russian).

Mănescu C.B., Nuño G. (2015) Quantitative effects of the shale oil revolution. *Energy Policy,* no 86, pp. 855–866.

Mansfield E. (1968) *The Economics of Technological Change*, New York: W.W. Norton & Company Inc.

Montgomery J.B., O'Sullivan F.M. (2017) Spatial variability of tight oil well productivity and the impact of technology. *Applied Energy,* no 195, pp. 344–355.

Okullo S.J., Reynes F., Hofkes M.W. (2014) *Modeling Peak Oil and the Geological Constraints on Oil Production* (CentER Discussion Paper 2014–036), Tilburg: Tilburg University.

Richards F.J. (1959) A Flexible Growth Function for Empirical Use. *Journal of Experimental Botany*, no 10 (29), pp. 290–300.

Rogers E. (2002) *Diffusion of Innovations* (5th ed.), New York: Free Press.

Rystad Energy (2016) *North American Shale Report*, Oslo: Rystad Energy.

Saussay A. (2018) Can the US shale revolution be duplicated in continental Europe? An economic analysis of European shale gas resources. *Energy Economics*, no 69, pp. 295–306.

Schilling M.A., Esmundo M.( 2009) Technology S-curves in renewable energy alternatives: Analysis and implications for industry and government. *Energy Policy,* vol. 37, no 5, pp. 1767–1781.

Semenychev V.K., Kurkin E.I., Semenychev E.V. (2014) Modelling and forecasting the trends of life cycle curves in the production of non-renewable resources. *Energy,* vol. 75, issue C, pp. 244–251.

Shafrannik Yu.K., Kryukov V.A. (2016) *Neftegazovyi sektor Rossii: trudnyi put' k mnogoobraziyu* [Russia's oil and gas sector: A difficult path to diversity], Moscow – Novosibirsk – Tyumen: "Pero" (in Russian).

Sorrel S., Speirs J., Bentley R., Brandt A., Miler R. (2009) *Global oil depletion. An assessment of the evidence for a near-term peak in global oil production*, London: UK Energy Research Centre.

Verhulst P.F. (1838) Notice sur la loi que la population suit dans son accroissement. *Correspondance mathématique et physique*, vol. 10, pp. 113–121.

Zhukov S.V., Zolina S.A. (2017) Finansovyi rynok — draiver rosta neftedobychi v SSHA [Financial Market as a Driver of US Oil Production Growth]. *Ekonomika i organizatsiya promyshlennogo proizvodstva* [Economics and industrial production organization], no 10, pp. 85–96 (in Russian).

Zolina S.A. (2014) Prognozirovanie dobychi trudnoizvlekaemoi nefti v SSHA [Forecasting the extraction of hard-to-recover oil in the US], Moscow: IMEMO RAS (in Russian).

# FORESIGHT AND STI GOVERNANCE

National Research University
**Higher School of Economics**

Institute for Statistical Studies
and Economics of Knowledge



**Address:**
National Research University Higher School of Economics
20, Myasnitskaya str., Moscow, 101000, Russia
**Tel: +7 (495) 621-40-38**
**E-mail: foresight-journal@hse.ru**

http://foresight-journal.hse.ru/en/

**Periodicity — quarterly**

**ISSN 2500-2597**
**ISSN 2312-9972 (online)**
**ISSN 1995-459X (Russian print version)**

**Publisher:**
National Research University
Higher School of Economics

# NOTES FOR AUTHORS

Before submitting your article, please prepare your manuscript using the following guidelines:

Articles should be topical and original, should outline tasks (issues), describe the key results of the author's research and his/her conclusions;

Manuscripts are to be submitted via e-mail: foresight-journal@hse.ru

### Format

All files should be submitted as a Word document.

The text should be in Times New Roman 14 pt, 1.5 spaced and fit to the width, all margins should be 20 mm.

### Article Length

Articles should be between 20000 and 60000 characters (incl. spaces). Optimal size is 40 000 characters.

### Article Title

To be submitted in native language and English. A title of not more than eight words should be provided.

### Author Details (in English and native language)

Details should be supplied on the Article Title Page, including:

- Full name of each author
- Position, rank, academic degree
- Affiliation of each author, at the time the research was completed
- Full postal address of the affiliation
- E-mail address of each author

### Abstract

An abstract should be: informative (no general words), original, relevant (reflects your paper's key content and research findings); structured (follows the logics of the results presented in the paper), concise (between 250 and 300 words).

- Purpose (mandatory)
- Design/methodology/approach (mandatory)
- Findings (mandatory)
- Research limitations/implications (if applicable)
- Practical implications (if applicable)
- Social implications (if applicable)
- Originality/value (mandatory)

It is appropriate to describe the research methods/methodology if they are original or of interest for this particular research. For papers concerned with experimental work describe your data sources and data processing techniques.

Describe your results as precisely and informatively as possible. Include your key theoretical and experimental results, factual information, and any interconnections and patterns shown. Give special priority in your abstract to new results and data with long-term impact, important discoveries and verified findings that contradict previous theories as well as data that you think have practical value.

Conclusions could be associated with recommendations, estimates, suggestions, and hypotheses described in the paper.

Information contained in the title should not be dublicated in the abstract . Try to avoid unnecessary introductory phrases (e.g. 'the author of the paper considers…').

Use language typical of research and technical documents to compile your abstract and avoid complex grammatical constructions.

The text of the abstract should include the key words of the paper.

### Keywords

Please provide up to 10 keywords on the Article Title Page, which encapsulate the principal topics of the paper.

### Headings

Headings must be concise, with a clear indication of the distinction between the hierarchy of headings.

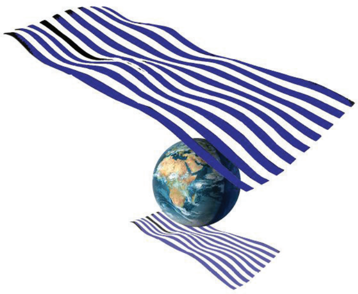
### Figures

All figures should be of high quality, legible, and numbered consecutively with arabic numerals. All figures (charts, diagrams, line drawings, web pages/screenshots, and photographic images) should be submitted in electronic form preferably in color as separate files, that match the following parameters:

Photo images — JPEG or TIFF format. Minimum resolution 300 dpi, image size not less than 1000x1000 pix

Charts, diagrams, line drawings- EXCEL or EPS format

ISSN 1995-459X
9 771995 459777



Website

Download on the App Store

GET IT ON Google Play