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*Main Article:*

# Collaborative Research in Energy Efficiency and Renewable Energy: Evidence From 5 Years of US-Russian Research Cooperation

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## Abstract

We reviewed the output of research and innovation cooperation between Russia and the US, including publications and patents, in the four prospective areas of energy efficiency and renewable energy during 2007-2011. Joint US-Russia research groups appear to focus primarily on hydrogen energy (fuel cells), followed by solar photovoltaics. The upcoming areas of smart grid and biofuels were left out entirely both from research and innovation collaboration. Russian patents in green energy technologies registered in the US are very low in comparison to those from Japan, Korea, and China.

**Index Terms:** research collaboration; science and technology; energy efficiency; renewable energy; bibliometric analysis; patent analysis

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## 1. US and Russia on the World Energy Efficiency Map

There is widespread agreement in various strategic long-term forecasts that total energy consumption in the near- to medium-term future is likely to continue rising, although at a slower pace (e.g., ERI RAS/REA, 2012; OECD/IEA, 2011). This increase will be attributable first and foremost to the fast-growing economies in Asia and will be met by fossil fuels, carbon rich coal, and, to a rising degree, by biofuels and other renewable energy resources (OECD/IEA, 2011). Owing to the commitment of many developed nations to limit their carbon emissions, attention has gradually shifted to making better use of existing energy resources and to using alternative energy sources through technological innovations. Moreover, the advancement of the oil and gas sector is characterized by the worsening composition of reserves and the quality of fossil fuels, a growing share of problematic non-conventional stocks, as well as the aspiration of many countries to decrease their dependency on energy imports.

This article analyzes the research and innovation cooperation between the US and Russia in the areas of energy efficiency and renewable energy. What these two countries have in common is an unsustainable thirst for energy. The US consumes a tremendous amount of energy and has been the largest energy consumer for more than 100 years (OECD/IEA, 2010) until China has overtaken it in 2009. On the other hand, the US also sets standards in research and production of renewables, such as biofuel production (Granade et al., 2009). Recently, the US became associated with the development of alternative deposits of energy carriers, like shale gas—with most promising potential for the US economy. Unlike the US, Russia is one of the biggest suppliers of conventional energy. Blessed with abundant traditional energy sources, two-thirds of Russia's exports comes from oil and natural gas. In 2010, Russia exported a staggering 7.5 million barrels of oil per day and 19 billion cubic meters of natural gas. These exports were primarily directed towards the European consumer markets, with an increasing share exported to the fast-growing regions of Asia (OECD/IEA, 2011).

While excessive energy consumption in the US is largely connected with individual lifestyle, Russia has inherited a very energy-intensive industrial production system. Back in the year 1980 at the times of the Soviet Union, its energy consumption reached 0.95 tons of oil equivalents per US$1,000 of GDP, while its peer nations in the OECD averaged 0.50 tons. Canada, which is situated in a similar climatic condition, used 0.74 tons. The following years saw the lowering of energy consumptions in the OECD to 0.41 tons of oil equivalents per US$1,000 of GDP, while the Soviet Union used 0.99 tons (IMF et al., 1991).

Recently Russia has directed significant efforts into increasing energy efficiency and energy saving. Although it remains one of the most energy-intensive economies in the world by any aggregate measure, it has shown the best results of all International Energy Agency member-states in lowering energy consumption over the past decade (OECD/IEA, 2009). Russia's energy saving potential has been assessed at about 45% of its total primary energy consumption, equal to the annual primary energy consumption of France (Mokveld, 2011). Russia's domestic targets are rather ambitious and aim at decreasing its GDP energy intensity by 40% in 2007-2020. Besides a focus on modernization, Russia also seeks to use its industry-specific knowledge to guide developments in this field (OECD/IEA, 2011). An important reason behind the advancement of new energy technologies is a large share of problematic hydrocarbons stocks, reaching 70%, and the growing share of nonconventional oil reserves and marginal minefields.

## 2. Research Collaboration on Energy Efficiency

Through the recent years, the interest in evaluating research activities has grown exponentially. On the one hand, researchers found the science of science a very interesting and lucrative field of study. On the other hand, stakeholders, like public administration, have recently increased their interest in the performance of the science system to ensure efficiency and effectiveness of spending taxpayer's money and comply with the principle of thrift. The development of new energy-related technologies, including technologies in the sphere of energy efficiency and renewables, demand the direction of resources into research and development (R&D) (see contributions to the new growth theory, e.g., Nordhaus, 2002). As the R&D expenditure slowed down remarkably during the 2009 financial crisis, advancing the technology capable of reducing carbon footprint has fallen behind expectations (OECD/IEA, 2011).

International science and technology (S&T) collaboration is a viable tool to improve the efficiency of R&D expenditure. In fact, the benefits of international research collaboration go much further than sheer economies of scale. Well-connected science fosters the exchange of new ideas, allowing all partners to access newly created knowledge. This knowledge—in the best case—trickles down to different users seeking opportunities for commercial activity (Gault, 2010).

Research cooperation as a functional aspect of Technology Innovation Systems is mostly used among the developed (OECD, EU, and G8) countries. Probably the most prominent examples in today's research landscape is the collaboration between the US and China, which started back in 1978. Before 1980, France, Italy, the UK, Sweden, and Japan had signed bilateral intergovernmental agreements (S&T agreements), and from 2000 onwards, energy-related R&D activities are prominent in R&D collaboration. Studying these collaborations is rather challenging. Insights are generally rather limited (e.g., Liping, 2011; Yuan & Lyon, 2012) and the Russia-US cooperation is no different. As both countries depend on a smarter use of their energy resources in the future at national and micro levels, advancing renewable energy and energy efficiency issues hold prominent positions in the countries' research agenda. However, little is known about the effectiveness of the Russia-US joint activities in this sphere.

## 3. Focus and Approach of Our Study

We have applied bibliometric and patent analysis to study the outcomes of this cooperation and to analyze topics researched and patents received. This is in line with previous studies (e.g., Bergek, Jacobsson, Carlsson, Lindmark, & Rickne, 2008), which suggest using bibliometrics to analyze structural components of the Technology Innovation Systems. The number of scientific publications and citations are the most frequently used indicators to evaluate research activity of a variety of actors, ranging from universities to design bureaus. Furthermore, it is very difficult to evaluate the goodness or badness of a particular structural element without referring to its effects on the innovation process (Bergek et al., 2008; Klein Woolthuis, Lankhuizen, & Gilsing, 2005), and patents serve as a reference point here. The output of research activities is two-dimensional: quantitative and qualitative. Traditionally, quality is assessed through peer review, with very subjective outcome (Kruytbosch, 1989; Nederhoff, 1988; Roeder, Baumert, Naumann, & Trommer, 1988; Travis & Collins, 1991). Alternatively, bibliometric studies use publication and citation indicators as proxies for quality (Aksnes & Taxt, 2004; Korevaar & Moed, 1996; Rinia, Van Leeuwen, Van Vuren, & Van Raan, 1998). Citation factors can also be approximated though databases like the SCI, SSCI, A&HCI, and Scopus, as only those journals are included which have a sufficiently high impact factor (Schmoch & Schubert, 2008). Although co-publication cannot act as a proxy for quality (Schmoch & Schubert, 2008), it does function as a measure of integration of different R&D areas. See, for example, Glänzel and Schubert's (2004) study on the integration between Europe and the US in the years 1980-2000. Also, internationally co-authored articles are more frequently cited (Glänzel & De Lange, 2002; Glänzel & Schubert, 2004). To guide our bibliometric and patent analysis, we used keywords: the list of technologies and products identified by experts in the field, which are also in line with priorities of the Energy Working Group of the US-Russia Bilateral Presidential Commission (issued in May 2010):

(a) Advancing smart grid implementation
(b) Conversion of algae biomass to liquid fuels
(c) Development of hydrogen and fuel cell technologies for stationary use
(d) Converting solar energy to other usable forms of energy
(e) Mine methane drainage technologies, drilling practices, and best practices for mining methane recovery/utilization
(f) New materials for high temperature and radiation resistant materials for eventual use in reactors and accelerators (US-Russia Bilateral Presidential Commission, 2010)

A vast pool of Russian and international experts, who agreed to express their views on the condition of anonymity, were questioned in the course of a foresight study undertaken by the Higher School of Economics (National Research University, Russia) in 2012-2013. Based on the judgments of these experts, we identify four strategic thematic priority areas: (1) hydrogen energy, (2) solar energy, (3) smart grid, and (4) biofuel production. The first area is divided into two subareas: (1a) fuel cells and (1b) hydrogen production and storage. Each of the four thematic areas was further broken down into a more detailed list of technologies and products that served as keywords for our analysis (the complete list of keywords is included in Appendix A).

First we searched the Thomson Reuters' Web of Science database to identify Russian and US publications (and citations) in these priority areas, filtering for US-Russian co-authorship. Based on these data we calculated the following indicators: total volume of publications, citation ratio, and the level of co-authorship. We considered a publication as Russian or US if these countries were mentioned in the working address of at least one of the (co-)authors. For the analysis of average citation indicators of publications we made use of the Citation Report function of the Web of Knowledge portal. The documents analyzed in this study are scientific articles, reviews, and proceedings. In order to identify the most researched and actively developing areas, we compared the main bibliometric indicators with total worldwide publication indicators.

To put the outcome of the US-Russian research cooperation in a context, we studied entries into the US Patent and Trademark Office (USPTO) and the World Intellectual Property Organization's databases to identify emerging technology areas. The patent search was based on the Questel QPAT database, which contains the information on patents and trademarks registered with the USPTO. First, we created a database of all patents on energy efficiency worldwide. Then, we refined the patent search by groups of the International Patent Classification (IPC), pre-selected by energy efficiency experts in the four previously identified areas. All areas except smart grid were detailed further by experts though selection of corresponding IPC groups. The patent search for the last group—smart grid—was made using keywords (see Appendix A, item 3) as it was impossible to correctly reflect this domain through certain IPC codes. This is the case because the smart grids domain covers not only certain technologies, but also specific processes which are not presently covered by IPC groups. We therefore relied on a number of keywords and took into account the latest reports and methodological developments of the World Intellectual Property Organization (WIPO) and Eurostat in energy and alternative energy. The patent search was made during April 2012.

We acknowledge that the Web of Science is biased towards publications in English and does not cover the majority of periodicals in other languages. In fact, the database contains not more than 10% of all papers published by the Russian researchers (which may vary from 20,000 to 24,000 papers per year). Moreover, areas such as mathematics or computer science are under-represented. To compensate for this limitation, we resorted to the Russia Scientific Citation Index, RSCI (available from eLIBRARY.ru). Launched in 2005, it includes over 2.3 million publications of Russian authors, patents, as well as citation data from over 3,500 Russian journals. For reasons of comparability we limited our search to articles in journals and conference proceedings.

## 4. Findings: US and Russia Publications

In order to identify the most researched and discussed areas and technologies, we started by comparing the main bibliometric indicators (total number of publications in the world, average number of citations, average growth rate) in the four selected areas. The biggest share of publications in the Web of Science focused on "converting solar energy into electrical and chemical energy" (a total of 35,620 publications in 2007-2011) and "hydrogen energy" (34,084 publications during the same period) (Figure 1). The high activity in these two areas corresponds with relatively high average citation levels (10.09 and 8.55 per paper respectively). Both of these areas have been actively and consistently developing in the course of the last five years, showing moderate advancement. 'Biofuel production' was developing at a comparable pace, demonstrating high average citation levels and publication growth rate. The highest growth happened in 'smart grids', outpacing the growth rate of peer areas (Figure 2). The average level of citation which remained at a lower level could well be an outcome of generally lower citation levels in engineering and computer sciences than in natural sciences (Figure 3). Average growth pace of the number of publications in this area in 2007-2011 amounted to 2.8, while in absolute terms the number of publications grew during the same period from 9 to 585.

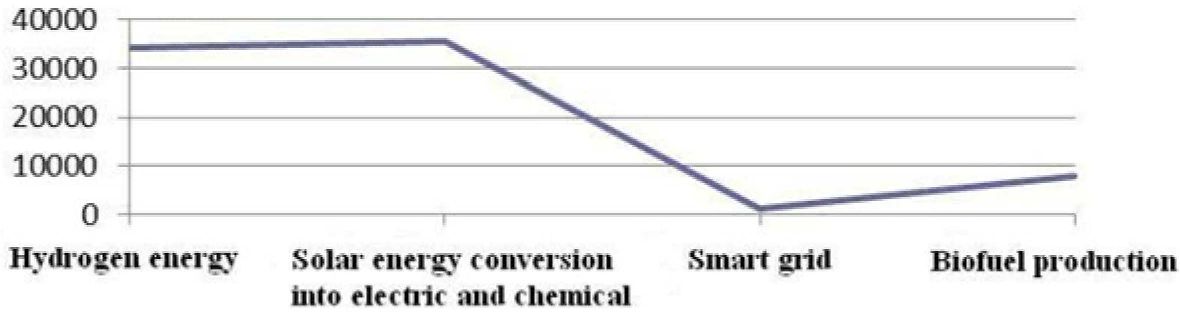


*Figure 1.* Number of publications in the four energy efficiency research areas (Source of data: Web of Science, 2007-2011).

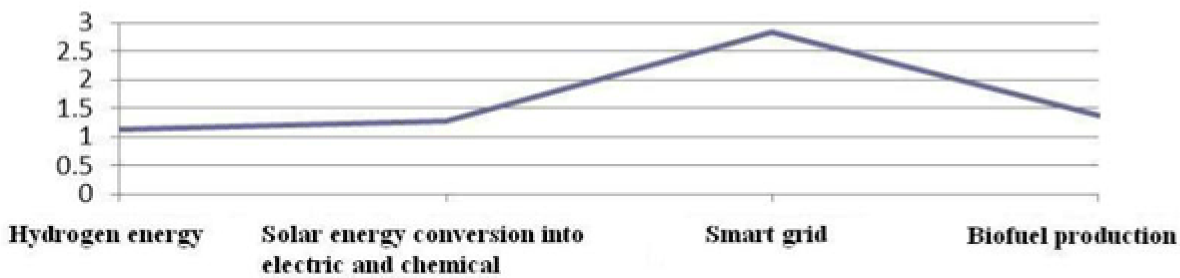


*Figure 2.* Average growth rate of publications in the four energy efficiency research areas (Source of data: Web of Science, 2007-2011).

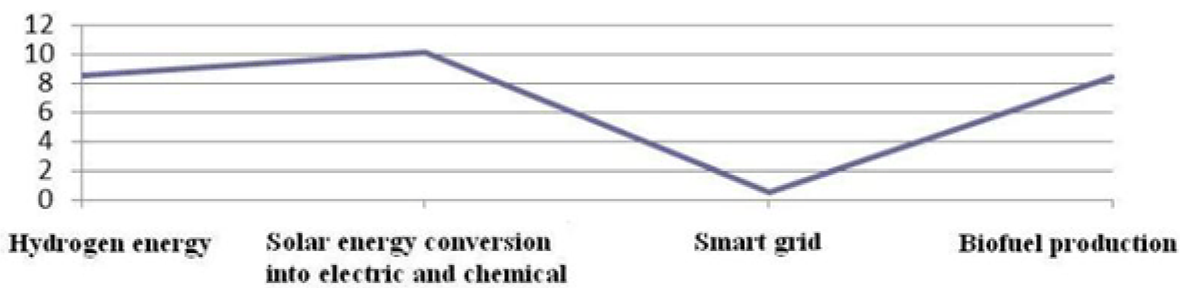


*Figure 3.* Average citation level of publications in the four energy efficiency research areas (Source of data: Web of Science, 2007-2011).

Overall, US authors publish the most contributions in the four areas, although China is following closely. The cumulative input of the US authors in the publication activity in the four selected areas constitutes nearly one quarter of all publications worldwide. This input is most noticeable in the areas of smart grid and biofuel production, which demonstrated the highest average publication growth rate in the last 5 years (Table 1). This is in stark contrast to the number of Russian publications, which remains at very low levels. Of all the four energy efficiency areas under consideration, joint Russia-US publications are most widely present in the category "hydrogen energy." The leading research organization in Russia, which has the highest number of highly cited publications in the technology areas under consideration is the Institute of Katalysis by G. K. Boreskov of the Siberian Branch of the Russian Academy of Sciences (in Novissibirsk). More specifically the highest number of joint Russia-US publications is in "Solid-oxide fuel cells" (6), "Steam reforming" (4), and "Hydrogen Storage in nanostructure carbon" (5). Table 2 features those thematic areas (from the list of areas presented in Appendix A), to which the input of US researchers was most significant (accounted to more than 30% of the world publications in a given thematic area).

Table 1. *Growth Rate of US and Russia Publications in Energy Efficiency Technology Areas* (Source of Data: Web of Science, 2007-2011)

| | **Hydrogen Energy** | **Solar Energy** | **Smart Grid** | **Biofuel Production** | **Total** |
|---|---|---|---|---|---|
| US (%) | 22.30 | 21.24 | 37.91 | 36.86 | 23.45 |
| Russia (%) | 1.33 | 0.97 | 0 | 0.65 | 1.07 |

Table 2. *Share of US Publications in Energy Efficiency Technology Areas* (Source of Data: Web of Science, 2007-2011)

| **Technology Area** | **Share of US Publications (%)** |
|---|---|
| **1. Hydrogen Energy** | |
| Proton-exchange membrane fuel cell | 31.8 |
| Phosphoric-acid fuel cells | 33.3 |
| Microbial fuel cell | 36.3 |
| Water thermolysis | 33.3 |
| Compressed hydrogen storage | 35.3 |
| Liquid hydrogen storage | 36.0 |
| Cryo-compressed hydrogen storage | 100 |
| Carbohydrates | 40 |
| Hydrogen storage in glass capillary arrays or hollow glass microspheres | 33.3 |
| Hydrogen storage in metal-organic frameworks | 31.2 |

| | |
|---|---|
| **2. Solar Energy** | |
| Artificial photosynthesis | 32.4 |
| **3. Smart Grid** | |
| Smart metering, demand response (or dynamic demand) | 39.5 |
| **4. Biofuel Production** | |
| Lignocellulosic biomass conversion | 50.0 |
| Algae fuel | 35.8 |
| Dimethylfuran (DMF) production from biomass | 50.0 |
| Algaculture | 40.0 |

It is remarkable to note that the share of Russian publications in the worldwide publication count, as captured in the Web of Science, is as low as 1.07%, lower than the share of Russian publications in all scientific disciplines in the overall number of world publications (which is about 1.7%).

It would seem as if Russia's researchers are yet to build competencies in these emerging fields. For instance, no Russian researcher has published papers in the area of smart grid in journals indexed by Web of Science, although this field shows a most promising outlook. To understand the true Russian publication output, we searched the Russian Scientific Citation Index (RSCI) —the largest of its kind in Russia and analogous to the Web of Science. The database confirms the low number of publications, including limited citations in the selected technology areas.

Hydrogen energy that was previously identified as the most significant area of the Russia-US research cooperation and the most significant area of publications by the Russian researchers in the Web of Science, has been the most significant area of publication output in Russian language over the last 5 years. However, looking into the numbers of publications in specific topics, we noted that according to the RSCI the topics most researched by Russian scholars domestically and internationally differ. More specifically, the greatest number of publications and citations in Russian is on hydrogen energy (193 publications/132 citations) and storage (82/8), gasification or thermal partial oxidation and catalytic partial oxidation (553), bioethanol (72/8) and biodiesel (56/26) production, smart metering (141/87). Finally, the limited number of Russian publications and citations both in RSCI and Web of Science may also be attributable to the Russian preference for books and other types of publications.

Judging by the number of joint publications, Russia-US cooperation in the selected thematic areas remains rather limited with not a single joint publication on smart grid. Table 3 features those selected technologies on which there is at least one joint US-Russia publication.

Table 3. *Joint US-Russia Publications in Selected Technology Areas*
(Source of Data: Web of Science, 2007-2011)

| **Technology Area** | **No. of Publications** |
|---|---|
| **Hydrogen Energy** | |
| Solid-oxide fuel cells | 6 |
| Direct methanol fuel cell | 1 |
| Water electrolysis | 1 |
| Steam reforming | 4 |
| Thermochemical process of hydrogen production | 1 |
| Fermentative hydrogen production | 1 |
| Metal hydrides | 2 |
| Hydrogen storage in metal-organic frameworks | 1 |
| Hydrogen storage in nanostructured carbon (carbon buckyballs and nanotubes) | 5 |
| **Solar Energy** | |
| Amorphous silicon solar cell | 1 |
| Dye-sensitized solar cell | 1 |
| Artificial photosynthesis | 1 |
| **Biofuel Production** | |
| Dimethyl ether production from biomass | 1 |

## 5. Findings: US and Russia Patents

At the second stage of our research we applied patent analysis to scan for emerging technologies resulting from the research cooperation between US and Russia. In the course of the US Patent and Trademark Office (USPTO) patent search, we used groups of the International Patent Classification (IPC), pre-selected by energy-efficiency experts. Each of these areas was further detailed though corresponding IPC groups that cover the first three areas. We analyzed the volume of USPTO patents (number of patents, registered in the USPTO in a given area), studied the patent activity dynamics, and identified the most rapidly developing categories in each of the four technology areas.

We note increased activity in fuel cells starting from 2010. As the data for 2011 were incomplete, lower values should not be interpreted as lower interest in the area of research. Among the USPTO patents in the area of fuel cells, the most frequently patented were technologies in the category “non-active parts (fuel cells, manufacturing).” This group has been actively developing since 2009, and in 2010 contained 480 patents—surpassing the number in any other subgroup of fuel cells. Among the categories, which have been actively patented, are “hybrid cells” and “pyrolysis or gasification of biomass.”

The majority of patents in this area were registered by the US, Korea, Japan, Taiwan, and Germany.

The largest share of patents in biofuels was registered in the category "genetically engineered organisms," while we noticed a declining trend in "biodiesel" and "bioethanol" groups and consistent patenting patterns in the group "integrated gasification combined cycle." The majority of patents registered in USPTO in the group biofuel came from US applicants, followed by Canada, Japan, Korea, Denmark, Taiwan, and Italy. There were no applicants from Russia in this area in 2010-2011.

The largest and fastest developing category in the field of solar energy is "assemblies of a plurality of solar cells," which gathers hundreds of patents annually. Much smaller, but fast growing are the fields of "silicon; single-crystal growth", "electric lighting devices with, or rechargeable with, solar cells." At the same time, the category "devices adapted for the conversion of radiation energy into electrical energy" has shown a gradual decrease. The highest number of patent applications in solar energy was filed by Japan, Korea, China, and US; much smaller numbers from Singapore, Taiwan, and Germany. Again, no patents were registered by Russian applicants in 2010-2011.

We note an actively growing trend for smart grid, and the most consistent patenting activity in this category for "energy demand management/demand side management." Also strong interest was diverted to patenting in "distributed generation," and "flexible alternating current transmission system". The most noticeable activity in patenting at USPTO was registered in the solar energy and fuel cells areas, the applicants being primarily from the US, Korea, Japan, and China (Table 4).

Table 4. *Patenting in the Sphere of Energy Efficiency in USPTO (No. of Applicants)*

| | **IPC Group** | **2007** | **2008** | **2009** | **2010** | **2011** |
|---|---|---|---|---|---|---|
| 1 | Fuel cells | 870 | 967 | 913 | 996 | 24 |
| 2 | Solar energy | 928 | 1114 | 1338 | 984 | 13 |
| 3 | Smart grid | 22 | 8 | 35 | 31 | 5 |
| 4 | Biofuels | 366 | 702 | 674 | 529 | 114 |

## 6. Conclusions

In this study we reviewed the output of research cooperation between Russia and the US, including publications and patents, in the sphere of energy efficiency and renewable energy during 2007-2011. The bibilometric analysis allowed for the selection of priority research categories within the wider technological areas that are actively developing in Russia and the US, as well as those categories which are characterized by close interaction of Russian and US researchers.

US research organizations are widely represented in all thematic areas, while the number of Russian publications remains rather low. In a worldwide comparison, English-language publications of Russian researchers in the journals indexed by the Web of Science in the four prospective areas account for only 1.07%, which means that research in the area of energy efficiency and renewables is not part of Russia's research and technological specialization. The analysis of the Russian database showed somewhat differing priorities of Russian researchers that publish in Russian as compared to those that produce English language publications. For instance a lot is published in Russian language on smart grid and biofuel production. We found that "solar photovoltaics" and the broad area of hydrogen energy are the technology areas that attract the most attention of joint US-Russia research groups. Of the four energy efficiency areas under study, smart grid has advanced the most in terms of publication activity within the 5-year period. Still, for the years 2007-2011 there were almost no joint US-Russia publications in the area of smart grid and biofuel production.

Our analysis of publications and patents in the selected technology areas confirms that the US is the leading country in energy efficiency research and development. The cumulative share of the US in the four areas amounts to nearly one quarter of the world total. The output from the Russia-US research cooperation in the prospective areas of energy efficiency and renewable energy is rather low. Hydrogen energy remains the one area where Russia-US research partnership has advanced the most—an area that is also rather developed in Russia. There is very little Russian publication in the emerging field of smart grid which is also an actively growing area in patenting.

Given that no patents were registered by Russian applicants in the USPTO in the majority of selected technology groups, we find no proof that Russian green energy innovations in these prospective areas find their way to the US market. At the same time, Japan, Korea and China have advanced quite well in this regard benefiting from the growing US and world demand for the new clean energy technologies.

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*Appendix A:*

## List of Keywords Characterizing the Selected Priority Areas for Bibliometric Analysis

### 1. Hydrogen Energy

*1a. Fuel Cells*

Proton-exchange membrane fuel cell
Phosphoric-acid fuel cell

Molten-carbonate fuel cell
Alkaline fuel cell
Solid-oxide fuel cell
Reversible fuel Cell
Direct methanol fuel cell
Direct coal fuel cell
Microbial fuel cell or biological fuel cell or Enzyme based fuel cell

*1b. Hydrogen Production and Storage*

Hydrogen energy
Water electrolysis
Plasma gasification
Steam reforming
Gasification or thermal partial oxidation and catalytic partial oxidation
Thermochemical process of hydrogen production
Water thermolysis
Fermentative hydrogen production or Enzymatic hydrogen generation or Biocatalysed electrolysis
Hydrogen storage
Compressed hydrogen storage
Liquid hydrogen storage
Cryo-compressed hydrogen storage
Metal hydrides
Carbohydrates
Underground hydrogen storage
Hydrogen Storage in Glass capillary arrays or Hollow glass microspheres
Hydrogen Storage in Metal-organic frameworks
Hydrogen Storage in nanostructured carbon (carbon buckyballs and nanotubs)

**2. Solar Energy**

Monocrystalline silicon solar cell
Polycrystalline silicon solar cell
Amorphous silicon solar cell
Thin-film solar cell
Heterojunction solar cell
Multijunction solar cell
Organic semiconductor solar cell or polymer solar cell
Organic heterojunction solar cell
Dye-sensitized solar cell
Magnetic solar cell
Building-integrated photovoltaics
Photoelectrochemical cell; photocatalytic water splitting
Artificial photosynthesis

**3. Smart Grid**

Smart grid
Smart metering
Energy demand management or Demand side management
Distributed generation
Substation automation
Supervisory control and data acquisition
Phasor measurement unit
Demand response or Dynamic demand
Flexible alternating current transmission system

**4. Biofuel Production**

Lignocellulosic biomass conversion
Algae fuel
Biomass-to-Liquids process
Second generation biofuels
Biomethanol production
Bioethanol production
Biobutanol production
Biodiesel production
Biodiesel production
Dimethyl ether production from biomass
Dimethylfuran production from biomass
Algaculture
Photobioreactor for microalgae production
Catalytic combustion
Oxyfuel combustion
Chemical looping combustion

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