Ratner, Svetlana; Gomonov, Konstantin; Revinova, Svetlana

Article

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International Journal of Energy Economics and Policy

ISSN: 2146-4553

available at http: www.econjournals.com

International Journal of Energy Economics and Policy, 2023, 13(4), 40-45.

Public Funding for Energy Innovation and Decarbonization Goals: A Coherence Challenge

Svetlana Ratner[1,2], Konstantin Gomonov[1]*, Svetlana Revinova[1]

[1]Department of Economic and Mathematical Modelling, Peoples' Friendship University of Russia (RUDN University), 6 Miklukho-Maklaya Street, Moscow, 117198, Russian Federation, [2]Economic Dynamics and Innovation Management Laboratory, V. A. Trapeznikov Institute of Control Sciences, Russian Academy of Sciences, 65 Profsoyuznaya Street, Moscow, 117997, Russian Federation. *Email: gomonov-kg@rudn.ru

Received: 10 March 2023 **Accepted:** 13 June 2023 **DOI:** https://doi.org/10.32479/ijeep.14329

ABSTRACT

This study is devoted to assessing the impact of public spending on research and development in the field of energy efficient technologies on achieving the goals of decarbonization and improving the energy efficiency of the economy. Using the two-stage Data Envelopment model, the study identifies countries with the highest and lowest efficiency of the national energy efficiency innovation support system. It was revealed that the most noticeable reduction in the carbon intensity and energy intensity of the economy in the medium term is demonstrated by countries that pay more attention to the introduction of organizational and social innovations related to changing consumer behavior (Brazil, Spain). Countries that are accumulating knowledge in radically new technological areas demonstrate the low efficiency of the innovation system at the implementation stage in the medium term (Japan, South Korea, US).

Keywords: Energy Innovations, Decarbonization, Energy Efficiency, Data Envelopment Analysis, Public Funding
JEL Classifications: O32, Q4, Q55

1. INTRODUCTION

The ambitious goals of decarbonizing the global economy by 2050 can only be achieved if a wide range of energy efficient technologies are developed and implemented in various industries, agriculture, transport and construction sectors (IEA 2021a, 2021b). The governments of almost all developed countries currently support research and development in the field of energy efficiency and create conditions for stimulating investment in the development of energy efficient and renewable energy technologies by private companies (Lerman et al., 2021). However, the introduction of energy efficient technologies (hereinafter, energy efficient technologies will also mean renewable energy technologies that also contribute to decarbonization) in practice is quite difficult due to the presence of a large number of barriers to energy efficiency, including infrastructure, economic, organizational and behavioral ones (IPCC, 2001; Sorrell et al., 2000). This situation is well known in the scientific literature on the topic of energy economics and has been called the "energy efficiency gap": it's a situation in socio-technical system when the introduction of technically mature and economically viable technologies is hampered by the presence of a large number of different barriers (Hirst and Brown, 1990; Koopmans and Te Velde, 2001; Jaffe and Stavins, 1994).

Comparing the effectiveness of government policies to support energy efficient technologies is an interesting scientific task, as it helps to assess the real prospects for achieving national decarbonization goals, as well as to determine the most effective ways and means to overcome energy efficiency barriers in different countries (Bagaini et al., 2020; Ebrahimigharehbaghi et al., 2019; Ratner et al., 2022). Much attention has been paid to this problem in modern literature. For example, study

(Guzowska et al., 2021) shows that there were significant differences in the level of environmental efficiency of R&D expenditures in the energy sector between European countries, and changes in environmental efficiency in most of the countries studied were not satisfactory. Paper (Danish, 2022) proves that public budget on energy research, development and demonstration have the significant role in decreasing environmental pollution, including CO_2 emissions. Hailemariam with co-authors (Hailemariam et al., 2022) using historical data from a panel of 27 developed and emerging economies also prove that R&D investment in renewable energy technologies significantly reduces major greenhouse gas emissions. Using panel data analysis for the European Union countries from 1991 to 2021, Voumik et al. (Voumik et al., 2022) demonstrate that spending on R&D lessen environmental deterioration levels in the long term. Kocak and Alnour (Kocak and Alnour, 2022) examine greenhouse gas emissions, government energy R&D expenditures, and biofuel consumption for the 1981-2020 period in USA and find that a positive shock in energy R&D expenditure reduces greenhouse gas emissions in the long run. They also prove that a negative shock increases greenhouse gas emissions.

Empirical findings of (Caglar et al., 2022) show that the energy efficiency R&D budgets in major economies in the world are not at a level to enhance environmental quality. Paper (Meckling et al., 2022) investigates the evolution of public energy R&D funding and institutions across eight major economies in the period of last 18 year and finds that governments have very little success in creating new effective forms of bridging science and market for acceleration of commercialization. A study in US (Wang and Wang, 2019) found that the intensity of R&D in energy efficiency technologies is an important positive factor in reducing carbon intensity while maintaining economic growth. However, investments in R&D have different performances in different sectors of the economy and their distribution can be optimized.

Thus, while energy technology R&D spending helps achieve decarbonization goals in theory, many factors can increase or decrease the positive effects of R&D. Therefore, policymakers need reliable methods that help them evaluate the effectiveness of certain areas of investment in R&D.

The purpose of this work is to develop an approach to assessing the effectiveness of the state policy of various countries in the field of supporting energy efficient technologies. As the main result of government policy, we consider changes in the energy intensity and carbon intensity of national economies in recent years. To evaluate the effectiveness, we apply the classical approach based on the calculation of the ratio of the result to the resources expended. Since a noticeable reduction in the energy intensity and carbon intensity of the economy in modern conditions can be achieved only through the introduction of cardinal energy innovations, by the spent resources we mean the government investments on research, development and demonstration projects in the field of energy technologies.

The calculation of effectiveness is carried out using the Data Envelopment Analysis methodology, which allows one to expand the traditional understanding of efficiency in the case when several types of resources are used and as a result, several different useful outputs are achieved (Emrouznejad and Yang, 2018). As an information base we used IEA Energy Technology RD&D Budgets database and World Bank data for 23 countries - Australia, Austria, Belgium, Brazil, Canada, Czech Republic, Denmark, Finland, France, Germany, Hungary, Ireland, Italy, Japan, South Korea, Netherlands, Norway, Poland, Spain, Sweden, Switzerland, UK and USA.

The rest of the paper is purposefully structured as follows: Section 2 describes methodology and data. Section 3 portrays the results, provides discussion, and policy implication. Section 4 presents the conclusion.

2. METHODOLOGY AND DATA

In this study, the government support system for the development of energy efficient technologies in each country is considered as a “black box” system, and described by a set of inputs and outputs. As inputs, we use the volume of government spending on research, development, and demonstration projects (RD&D) for various energy technologies (% of GDP). As outputs, we consider reductions in the energy intensity and carbon intensity of the country’s economy.

Considering that developing energy innovations is a long process, we take the average numbers for RD&D budgets for period 2010-2012, while consider changes in carbon intensity and energy intensity as the difference between the averages for 2010-2012 and the averages for 2016-2018. The use of 3-year mean allows smoothing out declines and peaks in both financing, energy consumption, and emissions associated with short-term fluctuations and random events.

In contrast to the traditional DEA model (Ratner et al., 2022), this study introduces a two-stage model in which the process of developing and implementing energy efficient technologies is divided into two natural stages - the development of energy related innovations and their practical implementation. It should be mentioned, that multi-stage and network DEA models are an important development of the methodology for comparative assessment of the effectiveness of economic agents, proposed initially (Kao, 2014). In the traditional DEA model, the transformation of inputs into outputs is unknown, which causes intermediate indicators to be lost. In practice, it leads to the inability to distinguish and identify which part of the DMU is responsible for its overall inefficiency (Arteaga et al., 2019; Chodakowska and Nazarko, 2017). If the researcher a priori knows any additional information about the structure of the DMU or the process of its operation, then the logical development of the traditional model will be to divide the DMU into two or more subsystems. They are interconnected by the so-called intermediate outputs, i.e. such outputs of one subsystem that are simultaneously inputs to another subsystem. With the introduction of such a complicated DMU structure in the model, the quality of managerial information that can be driven from results of solving the problem increase significantly. It gives the possibility for optimizing the strategy of the modeled economic agents and increases the quality of decision-making process (Xionghe et al., 2019; Ajirlo et al., 2019).

In order to discriminate two main processes in operation of the system for supporting the development of energy efficient technologies, we introduce two intermediate outputs: (1) the number of patents for "clean" energy and (2) the number of patents for hydrocarbon energy received in each country in the period 2013-2015 (per 10,000 residents). These indicators present the results of research and development process and simultaneously present outputs for implementation process (Figure 1).

Descriptive statistics for inputs, intermediate outputs, and system outputs is presented in Tables 1 and 2.

The efficiency score of each separated stage (sub-DMU I and sub-DMU 2) is calculated according to the CCR model. The system efficiency score is calculated as the product of the efficiency score of the first and second stages (multiplicative form). This approach to the calculation of the system efficiency score is the simplest and is possible in the case when the first and second stages are of equal importance for the final result. This study assumes that the importance of the development phase and the implementation phase are the same.

Let's mark the efficiency of *k-th* DMU on the first stage as E_k^1, and on the second stage as E_k^2. Then optimization problem for the first stage will be formulated as following:

$$\max E_k^1 = \frac{\sum_{d=1}^{2} z_{dk}\omega_{dk}}{\sum_{i=1}^{5} x_{ik}u_{ik}} \quad (1)$$

s.t.

$$\frac{\sum_{d=1}^{2} z_{dk}\omega_{dk}}{\sum_{i=1}^{m5} x_{ik}u_{ik}} \leq 1; \quad (2)$$

Where
x_{ik}, i=1, 2……5 are inputs,
z_{dk}, d=1, 2 - are intermediate outputs
y_{rk}, $r = 1, 2$ - are system outputs
$u_{ik} \geq \varepsilon \ \forall_i$, $\omega_{dk} \geq \varepsilon \ \forall_p$, $\varepsilon > 0$ - are nonnegative weighs.

Optimization problem for the second stage will be formulated as following:

$$\max E_k^2 = \frac{\sum_{r=1}^{2} y_{rk}v_{rk}}{\sum_{d=1}^{2} z_{dk}\omega_{dk}} \quad (3)$$

s.t.

$$\frac{\sum_{r=1}^{2} y_{rj}v_{rk}}{\sum_{d=1}^{2} z_{di}\omega_{dk}} \leq 1; \quad (4)$$

$$v_{rk} \geq \varepsilon\forall_r, \ \omega_{dk} \geq \varepsilon\forall_p, \varepsilon > 0.$$

Then system efficiency score for $k - th$ DMU is calculated as a product:

$$E_k = E_k^1 \times E_k^2 \quad (5)$$

Given the fact that not all of the countries under consideration achieved positive results in the dynamics of energy efficiency and carbon intensity over the studied period, some outputs in the data sample turned out to be negative (Table 2). This required the use of special methods for dealing with negative outputs. In the study, the method of shifting the scale of measuring negative outputs, developed by one of the authors in earlier works, was applied (Ratner et al., 2021). The application of this procedure is possible only for a model with constant returns to scale (CCR). Therefore, at the first stage, an input-oriented CCR model was used; at the second stage, an output-oriented CCR model was used.

3. RESULTS AND DISCUSSION

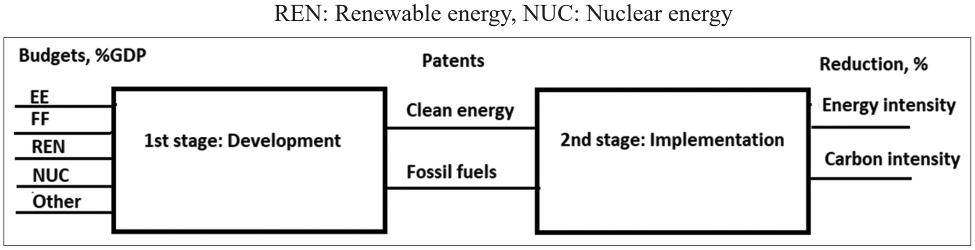
The results of calculating the efficiency scores of the first and second stages, as well as the overall (systemic) efficiency scores are shown in Table 3.

Table 1: Descriptive statistics for inputs (public spending on energy related development and demonstration projects projects, percentage GDP, mean in 2010-2012)

Descriptive statistics	EE	FF	REN	NUC	Other
Mean	0.018	0.007	0.022	0.008	0.013
Median	0.009	0.003	0.010	0.005	0.009
SD	0.026	0.013	0.053	0.010	0.024
Kurtosis	4.008	12.296	22.270	2.038	19.847
Asymmetry	2.307	3.340	4.689	1.640	4.338
Variance	0.092	0.060	0.261	0.034	0.122
Minimum	0.001	0.000	0.003	0.000	0.000
Maximum	0.093	0.060	0.264	0.034	0.122

Source: Compiled by the authors. EE: Energy efficiency, FF: Fossil fuels, REN: Renewable energy, NUC: Nuclear energy, SD: Standard deviation

Figure 1: The model of the system of government support for energy efficient technologies. Note: EE: Energy efficiency, FF: Fossil fuels, REN: Renewable energy, NUC: Nuclear energy



Source: Compiled by the authors

Table 2: Descriptive statistics for intermediate and system outputs (number of energy related patents [/10,000 residents] in 2013-2016; differences in carbon intensity and energy intensity [mean in 2010-2012 and 2016-2018])

	Patents (FF)	Patents (clean)	Difference (carbon)	Difference (energy)
Mean	0.896	4.967	0.252	0.041
Median	0.627	2.700	0.015	0.038
SD	1.155	4.764	1.120	0.053
Kurtosis	6.366	0.000	22.949	−0.383
Asymmetry	2.425	1.059	4.788	−0.187
Variance	4.871	15.720	5.445	0.207
Minimum	0.048	0.069	−0.057	−0.072
Maximum	4.919	15.789	5.388	0.135

Source: Compiled by the authors. FF: Fossil fuels, SD: Standard deviation

Table 3: Efficiency scores of DMUs

DMU	Score 1	Score 2	Score-total
Australia	0.220061	0.488151	0.327754
Austria	1	0.084375	0.290474
Belgium	1	0.224387	0.473695
Brazil	0.726724	1	0.852481
Canada	0.494208	0.050956	0.158691
Czech Republic	0.17511	0.609854	0.32679
Denmark	1	0.074278	0.27254
Finland	0.885891	0.030909	0.165475
France	0.600736	0.104984	0.251133
Germany	1	0.060084	0.24512
Hungary	1	0.263434	0.513258
Ireland	1	0.191068	0.437113
Italy	0.203025	0.694839	0.375592
Japan	1	0.159087	0.398857
Korea	1	0.004546	0.067424
Netherlands	0.791532	0.17833	0.375705
Norway	1	0.03326	0.182373
Poland	0.133279	0.212801	0.16841
Spain	0.018861	1	0.137335
Sweden	1	0.09433	0.307132
Switzerland	0.564345	0.254013	0.378617
UK	0.896854	0.155249	0.373143
USA	1	0.032723	0.180895

Source: Calculated by the authors using MaxDEA software

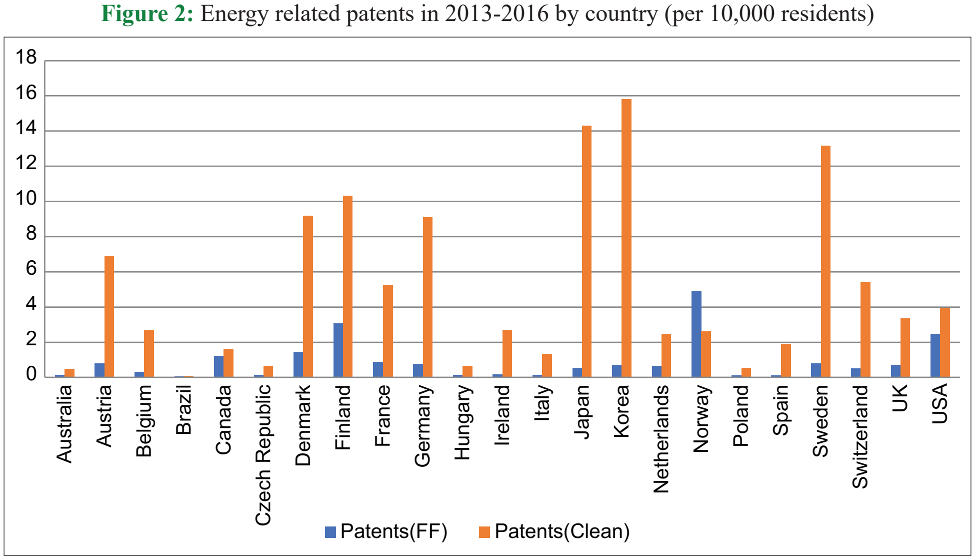
The most effective DMUs at the first stage were Austria, Belgium, Denmark, Germany, Hungary, Ireland, Japan, Korea, Norway, Sweden and the USA (Score 1 = 1). These countries are the most efficient in developing energy innovations and registering energy related patents. In the second stage, there are only two effective DMUs: they are Brazil and Spain. Quite high coefficients of efficiency of the stage of implementation of innovations also have Italy and the Czech Republic (Score 2 >0.6). We can conclude that these countries are making the best use of energy technology patents in practice and are rapidly implementing energy innovations that reduce the energy and carbon intensity of their national economies. Brazil, Hungary and Belgium have the highest system efficiency scores (Score_Total). The lowest values of the scores of system efficiency are observed in South Korea, Canada, Finland, and the United States. For South Korea and USA, it is precisely because of the low efficiency of the implementation stage.

Analyzing the number of patents by country (Figure 2), it can be noted that in the period from 2013 to 2016, almost all countries registered more patents in the field of clean energy (including energy-efficient technologies in industry and construction) than in the field of fossil fuels. Norway is the only country where the number of patents in the field of fossil fuels technologies is higher than in the field of clean energy. A significant share of patents in the field of fossil fuels is also held by the USA, Canada and Finland.

Therefore, the low efficiency of the second stage of the innovation process can be explained by the fact that hydrocarbon energy is still a significant priority in the innovative development of the economies of these countries. Despite significant attention to clean energy innovation, these technologies have not yet become dominant in the economic system, which so far does not allow achieving the goals of decarbonization and improving the energy efficiency of the economies of these countries. These findings are in line with (Meckling et al., 2022).

Low score of implementation stage in Japan also aligns with the commonly reported findings of Japan's significant decline in

Figure 2: Energy related patents in 2013-2016 by country (per 10,000 residents)



Source: Compiled by the authors

research performance by international comparisons (Yamashita, 2021, Kwon et al., 2017). On another hand, the weak impact of a large number of patents in Japan and South Korea on reducing the energy and carbon intensity can be explained by the fact that they are accumulating knowledge in radically new areas of technological development that have not yet reached the stage of industrial development. Thus, for instance, papers (Yuan and Yuan, 2023, Khan et al., 2021, Hardman et al., 2013) show, that in last decades U.S., Japan, Germany, China, and South Korea are the core technology sources in the field of fuel cell electric vehicles.

Countries with a small number of patents can achieve high results through the introduction of organizational eco-innovations (standards, energy management systems, etc.), changes in consumer behavior, as well as the growth of non-energy-intensive sectors of the economy. For example, in Brazil, the successful implementation of a national system of energy efficiency standards for residential buildings can be noted (Fossati et al., 2016), as well as improvements in load energy management and its acceptance by society (Hans et al., 2017). In Spain, last decades there is a lot of attention from policymakers to residential heating sector. Improved building insulation and renovation of thermal heating systems based on heat pumps and biomass cause significant reductions in energy consumption on heating (López-Bernabé et al., 2022). Introduction of energy efficiency certificates programs in residential building sector helps to improve consumer behavior by getting benefits from cashing in the gains from increasing energy efficiency (Bian and Fabra, 2020). Another example can be introduction of EU energy-efficiency rating system for cars, which has been quite successful in Spain and got significant support from the population (Galarraga et al., 2014).

4. CONCLUSION

The proposed method for identifying the most effective and least effective systems of state support for the development of the introduction of energy efficient technologies helps to highlight countries whose experience deserves more detailed study in order to highlight the best practices for reducing barriers to energy efficiency. The results obtained in this study may be of interest to policymakers in the field of energy efficiency and decarbonization of the world and national economy. However, it should be noted that the developed model is the simplest and can be improved in several directions.

First, demonstration projects, at least some of them, can be referred to the implementation stage, that is, their budgets are more appropriately considered in the model as additional inputs of the second stage. However, the data available on research and demonstration project budgets do not allow separate allocation of budgets spent on demonstration projects. Nevertheless, in the constructed model, it is possible to consider the division of budgets by introducing a certain coefficient α in range from 0 to 1. The exact value of α can be set either by an expert or by solving an additional optimization problem.

Secondly, when selecting data for a numerical example, it was assumed that a patent (as output of research and development stage) can be obtained approximately 3 years after the start of R&D funding, and the result of implementation of technology can be obtained in practice approximately 3 years after getting a patent. These assumptions correspond to the logic of the innovation process; however, they do not consider many features of the implementation of various types of energy innovations, such as the timing of the construction of large energy facilities, the time required for the certification of certain technologies, etc. Therefore, the calculated values of the efficiency coefficients can be corrected by shifting the time interval for data collection.

The elimination of these two noted limitations is the subject of further research by the authors.

5. FUNDING

This publication has been supported by the RUDN University Scientific Projects Grant System, project № 061608-2-000.

REFERENCES

Ajirlo, S.F., Amirteimoori, A., Kordrostami, S. (2019), Two-stage additive integer-valued data envelopment analysis models: A case of Iranian power industry. Journal of Modelling in Management, 14(1), 199-213.

Arteaga, F.J.S., Tavana, M., Caprio, D.D. (2019), A dynamic multi-stage slacks-based measure data envelopment analysis model with knowledge accumulation and technological evolution. European Journal of Operational Research, 278(2), 448-462.

Bagaini, A., Colelli, F., Croci, E., Molteni T. (2020), Assessing the relevance of barriers to energy efficiency implementation in the building and transport sectors in eight European countries. The Electricity Journal, 33(8), 106820.

Bian, X., Fabra, N. (2020), Incentives for information provision: Energy efficiency in the Spanish rental market, Energy Economics, 90, 104813.

Caglar, A.E., Ulug, M. (2022) The role of government spending on energy efficiency R&D budgets in the green transformation process: Insight from the top-five countries. Environmental Science and Pollution Research, 29, 76472-76484.

Chodakowska, E., Nazarko, J. (2017), Network DEA models for evaluating couriers and messengers. Procedia Engineering, 182, 106-111.

Danish, Ulucak, R. (2022) Analyzing energy innovation-emissions nexus in China: A novel dynamic simulation method. Energy, 244, 123010.

Ebrahimigharehbaghi, S., Qian, Q., Meijer, F., Visscher, H. (2019), Unravelling Dutch homeowners' behaviour towards energy efficiency renovations: What drives and hinders their decision-making? Energy Policy, 129, 546-561.

Emrouznejad, A., Yang, G.l. (2018), A survey and analysis of the first 40 years of scholarly literature in DEA: 1978-2016. Socio-Economic Planning Sciences, 61, 4-8.

Fossati, M., Scalco, V. A., Linczuk, V. C. C., Lamberts, R. (2016), Building energy efficiency: An overview of the Brazilian residential labeling scheme. Renewable and Sustainable Energy Reviews, 65, 1216-1231.

Galarraga, I., Ramo, A., Lucas, J., Labandeira, X. (2014), The price of energy efficiency in the Spanish car market. Transport Policy, 36, 272-282.

Guzowska, M.K., Kryk, B., Michalak, D., Szyja, P. (2021), R&D spending in the energy sector and achieving the goal of climate neutrality. Energies, 14, 7875.

Hailemariam, A., Ivanovski, K., Dzhumashev, R. (2022), Does R&D investment in renewable energy technologies reduce greenhouse gas emissions? Applied Energy, 327, 120056.
Hardman, S., Steinberger-Wilckens, R., van der Horst, D. (2013) Disruptive innovations: The case for hydrogen fuel cells and battery electric vehicles. International Journal of Hydrogen Energy, 38(35), 15438-15451.
Hans, H.Z., Daniel, T., Jacqueline, G.R., André, R., Ines, H. (2017), Electrical energy demand efficiency efforts in Brazil, past, lessons learned, present and future: A critical review. Renewable and Sustainable Energy Reviews, 67, 1081-1086.
Hirst, E., Brown, M. (1990), Closing the efficiency gap: Barriers to the efficient use of energy. Resources, Conservation and Recycling, 3(4), 267-281.
IEA. (2021a), Net Zero by 2050, Paris: IEA. Available from: https://www.iea.org/reports/net-zero-by-2050
International Energy Agency. (2021b), Power Systems in Transition. France: International Energy Agency.
IPCC. (2001), Chapter 5: Intergovernmental Panel for Climate Change, Barriers, Opportunities, and Market Potential of Technologies and Practices in Climate Change Mitigation Contribution of Working Group III to the Third Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge: UK. Available from: https://www.ipcc.ch/site/assets/uploads/2018/03/5.pdf [Last accessed on 2022 Oct 29].
Jaffe, A.B., Stavins, R.N. (1994), The energy-efficiency gap: What does it mean? Energy Policy, 22(10), 804-810.
Kao, C. (2014), Network data envelopment analysis: A review. European Journal of Operational Research, 239(1), 1-16.
Khan, U., Yamamoto, T., Sato, H. (2021), An insight into potential early adopters of hydrogen fuel-cell vehicles in Japan. International Journal of Hydrogen Energy, 46(18), 10589-10607.
Kocak, E., Alnour, M. (2022), Energy R&D expenditure, bioethanol consumption, and greenhouse gas emissions in the United States: Non-linear analysis and political implications. Journal of Cleaner Production, 374, 133887.
Koopmans, C.C., Te Velde, D.W. (2001), Bridging the energy efficiency gap: Using bottom-up information in a top-down energy demand model. Energy Economics, 23(1), 57-75.
Kwon, S., Lee, J., Lee, S. (2017), International trends in technological progress: Evidence from patent citations, 1980-2011. The Economic Journal, 127(605), 50-70.
Lerman, L.V., Gerstlberger, W., Lima, M.F., Frank, A.G. (2021), How governments, universities, and companies contribute to renewable energy development? A municipal innovation policy perspective of the Triple Helix. Energy Research and Social Science, 71, 101854.
López-Bernabé, E., Linares, P., Galarraga, I. (2022), Energy-efficiency policies for decarbonising residential heating in Spain: A fuzzy cognitive mapping approach. Energy Policy, 171, 113211.
Meckling, J., Galeazzi, C., Shears, E., Xu, T., Anadon, L.D. (2022), Energy innovation funding and institutions in major economies. Nature Energy, 7, 876-885.
Ratner, S., Berezin, A., Gomonov, K., Serletis, A., Sergi, B.S. (2022), What is stopping energy efficiency in Russia? Exploring the confluence of knowledge, negligence, and other social barriers in the Krasnodar Region. Energy Research and Social Science, 85, 102412.
Ratner, S., Lychev, A., Rozhnov, A., Lobanov, I. (2021), Efficiency evaluation of regional environmental management systems in Russia using data envelopment analysis. Mathematics, 9(18), 2210.
Ratner, S.V., Balashova, S.A., Lychev, A.V. (2022), The efficiency of national innovation systems in post-soviet countries: DEA-based approach. Mathematics, 10(19), 3615.
Sorrell, S., Schleich, J., Scott, S., O'Malley, E., Trace, F., Boede, U., Ostertag, K. and Radgen, P. (2000), Reducing Barriers to Energy Efficiency in Public and Private Organizations. Brighton: Energy Research Center-Science and Technology Policy Research (SPRU), University of Sussex.
Voumik, L.C., Rahman, M., Akter, S. (2022), Investigating the EKC hypothesis with renewable energy, nuclear energy, and R&D for EU: Fresh panel evidence. Heliyon, 8(12), 12447.
Wang, Q., Wang, S. (2019), Decoupling economic growth from carbon emissions growth in the United States: The role of research and development. Journal of Cleaner Production, 234, 702-713.
Xionghe, Q., Debin, D, Mei-Po, K. (2019), Spatial spillovers and value chain spillovers: Evaluating regional R&D efficiency and its spillover effects in China. Scientometrics, 119(2), 721-747.
Yamashita, N. (2021), Economic crisis and innovation capacity of Japan: Evidence from cross-country patent citations. Technovation, 101, 102208.
Yuan, Y., Yuan, X. (2023), Does the development of fuel cell electric vehicles be reviving or recessional? Based on the patent analysis. Energy, 272, 127104.