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Competitive dynamics of energy, environment, and economy in the U.S.

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A B S T R A C T

This paper applies the Lotka–Volterra model to investigate the competitive interactions among energy, environment, and economy (3*Es*) in the U.S. The proposed LV-COMSUD (Lotka–Volterra COmpetition Model for SUstainable Development) has satisfactory performance for model fitting and provides a useful multivariate framework to predict outcomes concerning these interactions. Our key findings include a pure competition between emissions and GDP (Gross Domestic Product), neutralisms between renewable and fossil/nuclear energy, and commensalisms between GDP and renewable/fossil energy and between nuclear energy and fossil energy/emissions. These results indicate that renewable/fossil energy use contributes to GDP and interacts indirectly with emissions, that an environmental Kuznets curve exists, and that the amount of produced nuclear energy correlates with emission. The U.S. is dependent on non-clean energy sources and its energy efficiency has room for improvement. The results provide unique insights for policy makers to craft up sustainable economic development plans. Overall, it is suggested that for developed markets such as the U.S., to enhance energy security and mitigate climate changes, improving energy efficiency and developing low-carbon clean energy should be top priorities.

1. Introduction

Climate change and global warming have been ongoing environmental issues. In recent decades, the quantity of GHGs (greenhouse gases) in the atmosphere has increased dramatically, leading to an increase of overall temperature in the atmosphere. The most common GHG is carbon dioxide (CO_2), and 96.5% of all CO_2 emissions are accounted for by the burning of fossil fuels (coal, natural gas, and petroleum) associated with economic and other human activities. How to balance the environmental protection, energy security, and economic development to achieve sustainable development has proven to be one of the greatest challenges of the 21st century. Referred to as the 3*Es* (Environment-Energy-Economy) issues, they often involve simultaneous consideration of CO_2 emissions, energy consumption, and GDP (Gross Domestic Product).

The linkage among different types of energy resources (renewable, nuclear, and fossil), environment, and economic development (3*Es*) is apparently complicated and may even be market-specific. To systematically investigate the 3*Es* issues, the current research focuses on the competitive interactions among energy consumption, emissions and real GDP, and among different types of energy (e.g., renewable, nuclear, and fossil fuel), using the U.S., as an exemplar of the developed market.

The U.S. is the world's largest and the top-performing national economy, with abundant natural resources, a well-developed infrastructure, and high productivity. It is the world's largest producer of oil and natural gas [1–3]. The reports of the Annual Energy Outlook 2014 (AEO2014) reference case [4] indicate that between 2012 and 2040 (a) the U.S. total primary energy consumption is projected to grow at a 0.4% CAGR (compound-annual-growth-rate) from 95 quadrillion Btu (British thermal units) to 106 quadrillion Btu; (b) the consumption of natural gas, coal, renewable, and nuclear energy are projected to grow at 0.8%, 0.3%, 1.6%, and 0.2% CAGR, respectively; (c) the consumption of petroleum and other liquids remains relatively flat at −0.1% CAGR; and (d) its electricity demand growth is projected to remain relatively low at 0.9% CAGR, as the rising demand is offset by efficiency gains from new appliance standards and investments in energy-efficient equipment. Low electricity demand will result in a greater decline in fossil-fueled generation and CO_2 emissions [4]. In terms of the composition of energy sources, it is projected that the U.S. fossil fuel share

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of total energy use will fall from 82% to 80%; the natural gas share will grow from 27% to 30%; petroleum and other liquids will decline from 36% to 31%; the coal share will remain flat; renewable will grow from 9% to 12%; and nuclear will remain roughly constant at 8%, from 2012 to 2040 [4]. Clearly, the U.S. energy consumption exhibits interactions among different energy sources.

Additionally, the reports of the AEO2014 reference case also indicate that the U.S. real GDP is projected to grow by 2.6%, 2.5%, and 2.4% CAGR for years 2012–2015, 2012–2025, and 2012–2040, respectively, and U.S. energy-related CO_2 emissions are projected to decline by 0.2% CAGR from 2012 to 2040. Reasons for the decline include lower economic growth, increased use of renewable technologies and fuels; automobile efficiency improvements; slower growth in electricity demand; and increased use of natural gas, which is less carbon-intensive than other fossil fuels [4]. Furthermore, a major factor in the CO_2 emissions reduction is shale gas, which will lead to continued displacement/retirement of coal plants and has the potential to provide even more CO_2 reduction in the future [5]. Accordingly, there are strong interactions among emissions, different types of energy consumption, and sustainable GDP growth with limited resources in the U.S.

To systematically investigate these interactions among the different energy resources and among the 3*E*s in the U.S., we propose a tripartite Lotka-Volterra [6,7] Competition Model for Sustainable Development (LV-COMSUD). Originated from studies of predator–prey relationships, the LV-COMSUD model treats energy consumption, emissions, and real GDP as components of a dynamic system and studies their interactions using a set of ordinary differential equations in a general form of competing species. The model provides a novel angle and basis to examining sustainable development policies. In particular, LV-COMSUD seeks to identify necessary actions to enable and facilitate sustainable economic development with a secure and affordable supply of energy in a clean and healthy environment.

The remainder of this paper is organized as follows: Section 2 introduces the literature of 3*E*s causality and the applications of the Lotka–Volterra (LV) model. Section 3 briefly presents the ARIMA (autoregressive integrated moving average), ARIMAX, and tripartite LV-COMSUD models. Section 4 reports empirical findings on competitive interactions and forecasts of the 3*E*s. Section 5 draws conclusions and discusses policy implications of our findings.

2. Literature review

The relationships among the *3E*s seem rather complex. On the one hand, economic development is hard to achieve without energy consumption, which may increase emissions of greenhouse gas and lead to damages to the environment. On the other hand, economic development may spur technological advances which may improve energy efficiency and curb or even reduce emissions. Indeed, one may argue that technological break-through enabling energy efficiency improvement and emission reduction, as well as the implementation of such new technologies, may not be plausible without heavy investment fueled by economic growth. Given the existence of these countervailing forces, the dynamic relationships among economic development, energy consumption, and environment protection have obvious policy implications and thus have attracted significant research interest.

One stream of research has used different methodologies to investigate the relationships among the 3*Es* for the design and implementation of green economy (e.g., MOLP (multi-objective linear programming), [8,9]; vector ECM (error correction model), [10–20]; TY (Toda-Yamamoto procedure), [21–23]). With respect to the interaction relationships among emissions, energy consumption, and economic growth, the analysis through the MOLP model by Refs. [8,9] for Portugal has explored the role of technology in carbon mitigation and energy system planning settings, and the effects of distinct polices on the total system costs, the fuel and technology mix, and emissions. With respect to the causal relationships among emissions, energy consumption, and economic growth, the empirical results through an ECM analysis by Refs. [10–20] vary, due in part to the difference in country/market characteristics, time periods analyzed, and model specifications. The different results of causality have different policy implications. The U.S. is not included in Refs. [10–20], but articles [21–23] investigated 3*E*s causalities using the TY procedure in the U.S.

Another stream of research investigates the nexus of both emissions-economy and economy-energy. For the emissions-economy nexus, following the EKC (Environmental Kuznets Curve) hypothesis, the results have shown that the relationship between economic development and the environment may not be linear. That is, emissions may not increase monotonically as a country's economy develops [24–26]. For the economy-energy nexus, the issues of a nation's energy independency and security are examined. The results are especially vital to the design and implementation of energy conversion policies [27–32]. Other research has focused on substitutions between clean (e.g., renewable and nuclear) and non-clean (e.g., fossil fuel) energy resources [33–36].

For the 3*E*s issues in the U.S, a set of literature is shown in Table 1. The first three papers used the TY model. Soytas et al. [21] found no causalities between GDP and energy consumption/emissions and a long-run unidirectional causality from energy consumption to emissions for the period 1960–2004, implying that the U.S. economic growth is independent and does not pose environmental problems, and the U.S. may consider improving energy efficiency and reducing energy consumption as environmental policies without having to worry about hurting its economic growth. Menyah and Wolde-Rufael [22] found bidirectional causality between GDP and emissions, unidirectional causalities from GDP to renewable energy consumption and from nuclear energy consumption to emissions, but no causality from renewable energy consumption to emissions in the long-run for the period 1960–2007, implying that nuclear power can help mitigate CO_2 emissions but renewable does not, and that it may not be possible to reduce emissions without sacrificing economic growth. Payne [23] found an absence of causalities among renewable energy consumption, GDP, and emissions, and unidirectional causalities from real oil prices to GDP/emissions in the long-run for the period 1949–2009, implying that an increase in energy costs had a statistically negative effect on both economic growth and petroleum-based fuels use.

For the emissions-economy nexus in the U.S., Burnett et al. [24] found a long-run causality among emissions, energy production, and income for the period 1981–2003, implying that economic growth drives emissions intensities but not absolute emissions. For the economy-energy nexus in the U.S., there are four papers included in Table 1. Payne [27] found no causalities between renewable/non-renewable energy consumption and GDP in the long-run over the period of 1949–2006. Extending the work of [27] to specific sectors, Bowden and Payne [28] found unidirectional causality from non-renewable energy consumption to real GDP in industrial sector with bidirectional causality in commercial and residential sectors, and unidirectional causality from renewable energy consumption to real GDP in residential sector with no causality in industrial and commercial sectors in the long-run. Extending the work of [27] to specific energy resources, Payne [29] found unidirectional causalities from real GDP to natural gas consumption and from petroleum to real GDP; and no causality