Lecture Notes in Energy 16

Walter Leal Filho
Vlasios Voudouris *Editors*

Global Energy Policy and Security

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Walter Leal Filho • Vlasios Voudouris
Editors

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Editors
Walter Leal Filho
Faculty of Life Sciences
Hamburg University of Applied Sciences
Hamburg
Germany

Vlasios Voudouris
ABM Analytics Ltd
Research Centre for Energy Management
ESCP Europe Business School
London
United Kingdom

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Foreword

Energy resources, particularly fossil hydrocarbons of coal, crude oil, and natural gas, have fuelled much of human progress and economic growth since the industrial revolution. However, as supplies of relative inexpensive fossil fuels (particularly conventional oil) might have difficulties in meeting rising demand in the coming few decades, while at the same time the costs for exploiting them will become increasingly higher (because of the need to extract unconventional resources), there is a perceived need to explore novel solutions and, at the same time, examine the impacts of current pressures on energy security (both physical security and price security).

The demand for energy as a whole and electricity in particular, in areas as varied as industry or transport, means that a new paradigm in the way fuels are perceived and handled is needed. Consistent with this, the need to promote energy security and policy as key themes during the twenty-first century, particularly during periods of uncertain supply and volatile prices, is greater than ever.

Many governments and business executives around the world have ambitious plans towards changing their energy mix and investment plans to one which includes more renewables and more low-carbon energy, as a way of balancing of home-grown energy and imports. Despite these efforts to increase the share of renewables, the global energy mix is still likely to be dominated by fossil fuels in the foreseeable future, particularly gas for electricity and oil for land, air, and sea transport. The reliance on depleting conventional oil and natural gas and the geographic distribution of these reserves can have geopolitical implications for energy importers and exporters.

Against this background, this book examines the security of global and national energy supplies, as well as the sensitivity and impacts of sustainable energy policies which pay due emphasis to the various political, economic, technological, financial, and social factors that influence energy supply and security. This publication presents multidisciplinary perspectives on the interrelated topics of energy security and energy policy, within a rapidly changing sociopolitical and technological landscape.

This book has two main sets of interdisciplinary papers. One set of papers deal with technical aspects of energy efficiency, renewable energy, and the use of tariffs.

The other set of papers focus on social, economic, or political issues related to energy security and policy, also describing research, practical projects, and other concrete initiatives being performed in different parts of the world.

A unique feature of this publication is that it introduces a variety of concrete projects, initiatives, and strategies currently being undertaken and implemented across the world, showcasing concrete examples of how energy security thinking and sound energy policies can assist nations in meeting the challenges dwindling energy supplies pose to them. We hope this book will prove useful to all those interested in the connections between energy production, energy use, energy security, and the role of energy policies.

We want to thank all authors for sharing their know-how, as well as Dr. M. Sima for the support provided in producing this book.

Enjoy your reading!

Autumn 2013

Hamburg, Germany — Walter Leal Filho
London, UK — Vlasios Voudouris

Contents

Energy Policy and Security Through the Lenses of Stochastic Portfolio Theory and the ACEGES Model

Vlasios Voudouris

Abstract **Purpose** The chapter presents a new approach to address energy policy and security based upon the ACEGES (Agent-based Computational Economics of the Global Energy System) model and the SPT (stochastic portfolio theory).
Design/Methodology/Approach The ACEGES model is an agent-based model for exploratory energy policy by means of controlled computational experiments. The ACEGES model is designed to be the foundation for large custom-purpose simulations of the global energy system by modeling explicitly 216 countries.
Findings By using the ACEGES model, we can better explore the energy markets at the country level and provide assessments on export capacity (for energy producers) and import needs (for energy consumers) within a single umbrella. Based upon these country-specific assessments, the SPT framework provides a flexible framework for analyzing the energy market structure from a theoretical and practical perspective. As a theoretical methodology, the SPT framework provides insight into questions of market behavior and arbitrage and can be used to construct hedging energy portfolios with controlled behaviors. As a practical tool, the SPT framework can be applied to the analysis and optimization of energy portfolios for physical trade for energy export-oriented and import-oriented countries.
Practical Implications The integration of the ACEGES model and the SPT framework provides a way of analyzing the dynamics of the energy markets (for energy policy) and constructing energy portfolios for physical trade that can affect bilateral and multilateral energy trade agreements.

V. Voudouris (✉)
ABM Analytics Ltd., Suite 17 125 145-157 St. John Street, London EC1V 4PW, UK

Research Centre for Energy Management, ESCP Europe Business School, 527 Finchley Road, London NW3 7BG, UK
e-mail: Vlasios.voudouris@abm-analytics.com

W. Leal Filho and V. Voudouris (eds.), *Global Energy Policy and Security*, Lecture Notes in Energy 16, DOI 10.1007/978-1-4471-5286-6_1,

Originality/Value The paper provides a conceptual and a practical framework to address issues of energy policy and security by integrating for the first time the ACEGES model and the SPT framework to develop import and export portfolios for physical trade between countries.

Keywords The ACEGES model • Stochastic portfolio theory • Energy trade • Oil scenarios • Energy policy

1 Introduction

Energy (particularly oil, gas, and electricity) is an important commodity by powering and fuelling sustainable forms of economic growth and development. A sustained global economic growth is driving an enormous rise in the consumption of energy to fuel booming motorization and industrial growth. By way of an example, Asia's emerging powers have accounted for about 65 % of growth in the global oil demand over the past two decades. Moreover, according to the 2012 World Energy Outlook by the International Energy Agency, Asia's primary energy demand compound average annual growth rate is estimated to be 2.2 % over the period 2010–2035. Furthermore, nearly all projections of future world demand for primary energy assume an increase in the coming decades at a compound average annual growth rate of about 1.2 % over the period 2010–2035, despite any likely conservation measures or gains in energy efficiency.

Many of the fast growing economies have relatively few "cheap" fossil fuel (e.g., crude oil and natural gas) resources of their own, while most of the remaining resources are geographically concentrated in a few countries around the world. Moreover, because of the critical importance of crude oil and natural gas to modern economic activity, it is important to try to estimate plausible trajectories of future country-specific crude oil and natural production and export capacities while accounting for below- and aboveground uncertainties that might limit the export capacity of the major world crude oil and natural gas players.

Here, we use the ACEGES (Agent-based Computational Economics of the Global Energy System) model [first proposed by Voudouris (2011) and demonstrated by Voudouris et al. (2011)] to explore the future export and production potential of crude oil for selected countries (Saudi Arabia, Russia, and Iraq). The key advantage of the ACEGES model is the high degree of heterogeneity that can be incorporated in the energy scenarios in order to quantify the uncertainties within each scenario (in addition to the wide range of uncertainties that can be explored by developing fundamentally different scenarios—internally coherent and plausible narratives about the future). Effectively, ACEGES-based scenarios are evidence-based tools for long-term energy policies by demarcating, for example, plausible narratives of future oil and natural gas production for 216 countries based upon policy assumptions such as oil and gas upstream investment incentives (e.g., price signals, mineral taxes, and subsidies) and energy efficiency measures.

In other chapters in the book, Flaherty and Leal (2013), Skindilias and Lo (2013), and Leung et al. (2013) discuss complementary aspects of energy security. Here, the stochastic portfolio theory (SPT) [first proposed by Fernholz and Shay (1982) and elaborated by Fernholz (2002)] provides an additional framework in conceptualizing and addressing concerns about energy security, particularly diversification of physical energy trade both for energy-importing and energy-exporting countries. SPT is a flexible framework for analyzing portfolio behavior. As a theoretical framework, SPT provides insight into questions of market behavior and can be used to construct portfolios with controlled behavior. As a practical tool, SPT has been applied to the analysis and optimization of portfolio performance.

This chapter demonstrates how energy policy and security can be explored by integrating the ACEGES model with the SPT framework. In particular, the chapter presents a conceptual framework to address energy security and drive energy policy in terms of diversifying energy imports (for net energy consumer) and energy exports (for net energy producers). Therefore, the output of the ACEGES model feeds into the SPT framework to suggest plausible energy trades between countries.

Section 2 outlines the key features of the ACEGES model and the SPT framework. Section 3 presents the results of an ACEGES-based scenario and discusses how SPT framework can be used to suggest energy trade arrangement between countries. Section 4 concludes.

2 The ACEGES Model and the SPT Framework

2.1 The ACEGES Model

The ACEGES model is an agent-based model (ABM) for exploratory energy policy. The ABM paradigm is a novel and flexible modeling framework for the computational study of socioeconomic and natural processes. The ABM paradigm conceptualizes, in this instance, the global energy market as a complex adaptive system of interacting agents (countries) who do not necessarily possess perfect rationality and information.

Currently, the ACEGES model explores the supply side of the primary energy system, while the demand side is a deterministic function:

$$\text{demand}_{(a_{(t)})} = (1 + g_a) * \text{demand}_{(a_{(t-1)})}, \tag{1}$$

where $\text{demand}_{(a_{(t)})}$ is the demand of agent a at time t. The specification of g_a (country-specific demand growth rate) is used to capture a range of factors (e.g., prices, energy efficiency measures, technological innovation) that affect the growth rate of the country-specific demand for crude oil and natural gas. Therefore, g_a can be a (parametric or nonparametric) regression function with explanatory variables (including time).

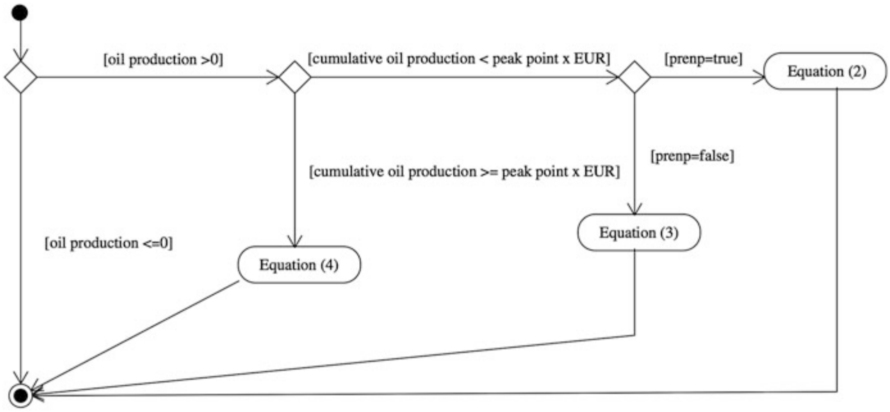

Fig. 1 Simplified behavioral rule for crude oil and natural gas production (*Source*: Voudouris et al. (2011) with permission)

By way of an example, Fig. 1 displays the decision rule for crude oil and natural gas production of the agents in the ACEGES model. The ACEGES model models 216 countries. Therefore, the equations shown in Fig. 1 are country specific.

The mathematical description of the supply side of the ACEGES model is given by

$$\text{production}_{(a_{(t)})} = \text{production}_{(a_{(t-1)})} + g_a * \text{demand}_{(a_{(t-1)})} + \text{wd}_{(a_{(t)})}, \tag{2}$$

$$\text{production}_{(a_{(t)})} = \text{production}_{(a_{(t-1)})} + g_a * \text{demand}_{(a_{(t-1)})}, \tag{3}$$

$$\text{production}_{(a_{(t)})} = \text{production}_{(a_{(t-1)})} - \left(\text{production}_{(a_{(t-1)})} * \left(\frac{\text{production}_{(a_{(t-1)})}}{y_{(a_{(t-1)})}}\right)\right), \tag{4}$$

where $\text{production}_{(a_{(t)})}$ denotes the annual oil production of a_t, $y_{(a_{(t)})}$ denotes the oil yet to produce a_t before $\text{production}_{(a_{(t)})}$, $\text{prenp}_{(a_{(t)})}$ is a Boolean attribute that denotes if a_t is a pre-peak net producer, $\text{wd}_{(a_{(t)})}$ is the share of world demand to be satisfied by a_t if it is a net producer, $\text{nwd}_{(t_{(1)})}$ is the net world demand at time $t-1$, nppnp_{tl} is the total number of pre-peak net producers at $t-1$, $\text{mp}_{(t_{(1)})}$ is the mean production from the pre-peak net producers, $\text{wd}_{(a_{(t)})} = (\text{nwd}_{t-1}/\text{nppnp}_{t-1}) * (\text{production}_{(a_{(t-1)})}/\text{mp}_{t-1})$ assumes that agents with larger production would be able to increase production more to meet net unmet world demand, $\text{production}_{(a_{(t-1)})}/y_{(a_{(t-1)})}$ corresponds to the reserve to production ratio (R/P) being constant post-peak for each agent a.

Effectively, Eq. (2) assumes that pre-peak net-producing countries will produce crude oil and natural gas in order to fulfill the net unmet world demand for crude oil and natural gas (world demand—world production). We think that this assumption

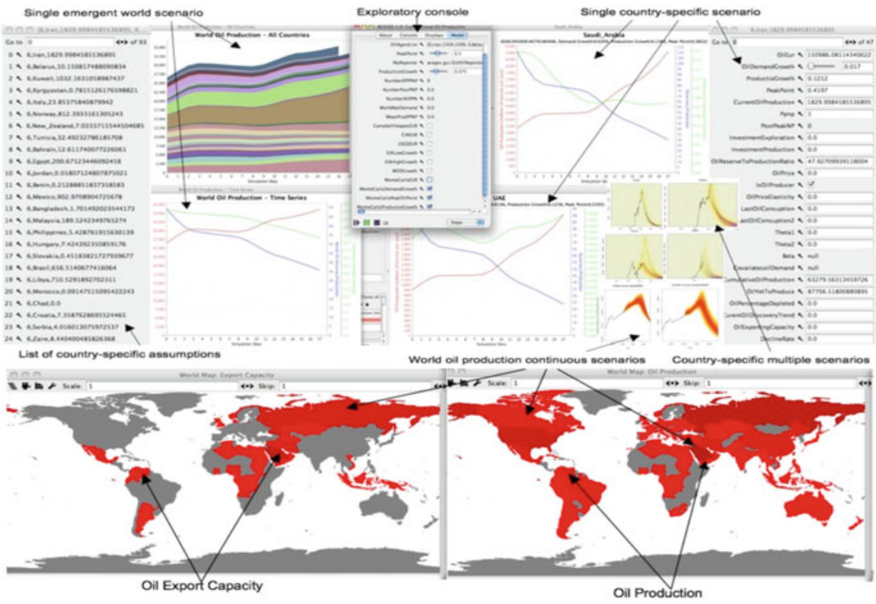

Fig. 2 The GUI of the ACEGES model

is realistic given that (1) the key crude oil and natural gas exporters will not like to cause a permanent damage in the world demand for crude oil and natural gas and (2) the key crude oil and natural gas exporters still complete to enhance their market shares. This is an approximation of the “consumers logic” first developed by Royal Dutch Shell in the 1970s.

Although the process of developing scenarios is primarily a nonmechanistic mental process, the ACEGES model can facilitate the exploration of plausible developments in the future by means of computational experiments using a graphical user interface (GUI), which is shown in Fig. 2. The “model” tab enables the scenario team to set up the key driving forces of crude oil and natural gas scenarios such as production growth, demand growth, peak/decline point, and estimated volumes of crude oil and natural gas originally present before any extraction. The graphic representations show the simulated scenarios of a single run (each run can simulate, e.g., 100 years). The GUI gives access to model data, plays, stops, pauses, and steps the simulation. Once the user runs a large number of simulations, say 10,000 simulations, the scenario narrative can be developed based upon the simulated outputs.

It is important to clarify that here we are proposing a way of developing continuous scenarios of the crude oil and natural gas markets using the ACEGES model. Scenarios are not forecasts or predictions. Scenarios are coherent and credible alternative stories about the future based upon the identified driving forces.

As discussed by Jefferson and Voudouris (2011), the ACEGES model supports the development of scenarios by means of computational experiments in order to portray plausible futures. The key advantage of the ACEGES model is the explicit modeling of 216 countries and the high degree of complexity (but not complication) that can be introduced to explore the uncertainties of the crude oil and natural gas market outlooks. This high degree of complexity is very difficult to be introduced with conventional models (see also Tesfatsion 2001).

2.2 The Stochastic Portfolio Theory

Here, stochastic portfolio theory (SPT) is introduced as a mathematical framework for analyzing energy trade behavior and market structure. SPT framework is consistent with observable characteristics of energy trade portfolios. In other words, given the characteristics of the global energy market, say oil and gas markets, SPT framework can be used to construct energy import and energy export portfolios with controlled behaviors. Therefore, based upon the ACEGES-based scenarios, SPT framework guides the creation of portfolios of energy trades of net energy import and net energy export countries. Collectively, the ACEGES model and SPT framework address issues of energy policy (primarily through the ACEGES model) and security (primarily through the SPT framework).

Given the production and demand scenarios of the 216 countries represented by the ACEGES model, the SPT framework suggests the import (export) portfolio of the importing (exporting) countries by determining the portfolio weight—the proportion of the portfolio's total import (export) that is "invested" to a particular country. By way of an example, Greece's optimal oil import portfolio weight for Iranian oil might be 0.4. A zero weight for Iranian oil means no imports from Iran. The weights can be rebalanced over time to accommodate changing market conditions such as increased discovering in Southeast Mediterranean or East Africa. However, the rebalancing of portfolio weights needs to be accommodated by diplomatic initiatives. ACEGES-based scenarios with the SPT framework provide a way of initiating forward-looking diplomatic initiatives to support portfolios of energy imports or portfolios of energy exports. The benchmark portfolio is the one that the benchmark weights are based on countries' market share. This means that if Saudi Arabia has the highest export capacity, the benchmark weight for Saudi Arabia is equal to Saudi Arabia's export capacity divided by the sum of the export capacity from all oil-producing countries (including Saudi Arabia). By default, the ACEGES model uses the benchmark portfolio to decide how the world unmet demand is met by the countries with available export capacity.

It should be clear from above that the key step is to set target weights that represent an optimal (or better compared with the benchmark) combination of countries from where to import (for energy-importing countries) or export (for energy-exporting countries). The mathematics of SPT determines these weights based only on the volatility and correlation characteristics of the energy production/export capacity of the countries for energy-importing countries or the volatility and correlation characteristics of the energy demand for energy-exporting countries.

To determine the portfolio weights π_i, the energy (import or export) portfolio optimization is accomplished by maximizing the portfolio growth rate Y_π (the subscript t has been dropped to simplify the notation):

$$\Upsilon_{(\pi)} = \sum_{i=1}^{n} \pi_i \Upsilon_i + \frac{1}{2}\left[\sum_{i=1}^{n} \pi_i \sigma_i^2 - \sum_{i,j=1}^{n} \pi_i \pi_j \sigma_{ij}\right], \tag{5}$$

under the constraints

$$\sum_{i=1}^{n} \pi_i = 1, \tag{6}$$

and

$$\pi_1, \ldots, \pi_n \geq 0, \tag{7}$$

By way of an example, the portfolio growth rate Y_π of an oil import portfolio is equal to the weighted average oil export capacity growth rate + the excess growth rate. The excess growth rate is half the weighted average of oil export capacity variance (denoted by σ_i^2)—the portfolio variance which is based on the covariance (denoted by σ_{ij}) of oil export capacities. While a country j constructs its portfolio, if trade between a country i is not desirable for political or any other aboveground or belowground factors, then π_i can be set to 0 or restricted to a very small number.

For more details, Fernholz (2002) provides a detailed mathematical discussion of the stochastic portfolio theory with reference to stock markets.

3 Example: Constructing Oil Import Portfolios

Here, we will present a hypothetical example of how the integration of the ACEGES model and the SPT framework can be integrated to construct oil import portfolios based upon projected export capacity for Saudi Arabia, Russia, and Iraq.

The process of constructing oil import portfolios using the SPT starts by generating plausible scenarios using the ACEGES model. One option is to develop the "Collective View" scenario. This is a scenario where all the values of the key and more important uncertainties (e.g., oil originally present before any extraction, upstream investment, demand growth) are selected through a Monte Carlo process [see Voudouris et al. (2011) and Matsumoto et al. (2012) for details]. Once the oil scenarios have been created, the characteristics of the oil market can be explored. Because the ACEGES model models explicitly 216 countries, data on forward-looking country-specific oil production and demand is readily available.

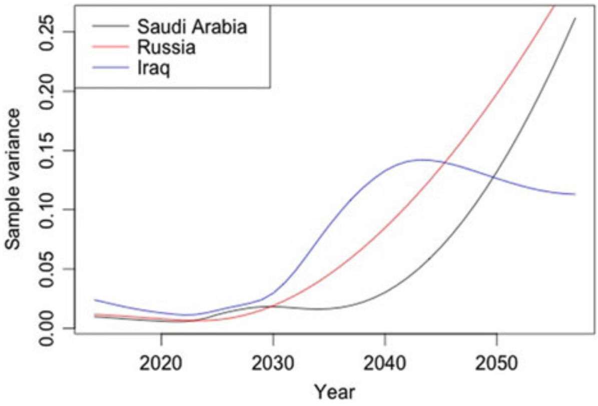

Fig. 3 Time-varying sample variance of oil export capacity for selected countries

To construct the oil import portfolio based upon country-specific export capacity, we need to estimate measures of variance, covariance, and growth rates of individual countries. It should be noted that each ACEGES-based scenario is made up of many simulations, say 10,000. Therefore, when calculating the building blocks to maximize Eq. (5), the first decision that needs to be taken is whether to select a particular simulation or the average of the simulations. As shown by Voudouris et al. (2011) and Matsumoto et al. (2012), one way is to use centiles to summarize the simulations and write the scenario narrative. For example, the media centile can be selected to estimate measures of variance, covariance, and growth rates of individual countries.

By way of an example, Fig. 3 shows the estimated sample time-varying variances of Saudi Arabia, Russia, and Iraq. The estimates are based upon a randomly selected simulation out of the many simulations of the "Collective View" scenario rather than estimating and selecting the media centile. This is because the idea here is to demonstrate the process of constructing import portfolios. Based upon (5), an oil import portfolio should put higher weight on Iraq until about 2045 and then more weight should be placed on Russia. However, variance is not the only key building block. We should also consider the covariance matrix while an import portfolio is constructed.

Figure 4 shows the estimated sample covariance of "Saudi Arabia–Russia," "Saudi Arabia–Iraq," and "Iraq–Russia." Based upon (5), an oil import portfolio should put higher weight on countries with higher negative covariance. Therefore, Fig. 4 suggests that an import portfolio with high weights on Saudi Arabia and Russia is at risk from 2035 onwards. Finally, Fig. 5 shows the export capacity growth rate for selected countries. Thus, Fig. 5 shows the last building block in calculating the oil import portfolio growth rate Y_π. Given the estimated measures presented in Figs. 3, 4, and 5, an optimization algorithm can be employed to estimate the oil import portfolio weights π_i that maximize Y_π.

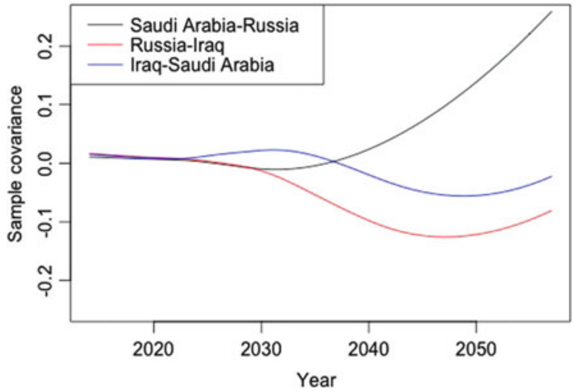

Fig. 4 Time-varying sample covariance of oil export capacity for selected countries

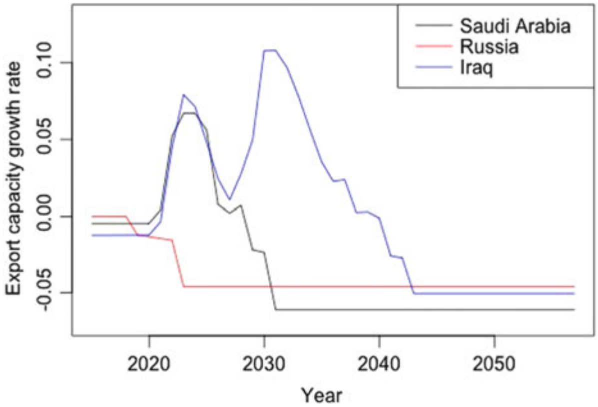

Fig. 5 Time-varying export capacity growth rate for selected countries

4 Conclusion

We recognize that it is nearly impossible to predict the exact future evolution of country-specific energy export capacities and to construct long-term energy portfolios for physical trade. However, the ACEGES model is a computational laboratory that enables us to explore plausible futures of export and production of energy sources. The key advantage of the ACEGES model is the high degree of heterogeneity that can be incorporated in the scenarios in order to quantify the uncertainties within each scenario.

The stochastic portfolio theory (SPT) is a mathematical framework for generating portfolios, including energy portfolios. The SPT framework is consistent with observable characteristics of markets. In other words, given the characteristics of the global energy market as generated by the ACEGES model, say oil and gas markets, the SPT framework can be used to construct energy import and energy export portfolios with controlled behaviors as demonstrated in Sect. 3.

In particular, based upon the ACEGES-based scenarios, the SPT framework guides the creation of portfolios of energy trades of net energy import and net energy export countries. Collectively, the ACEGES model and SPT framework address issues of energy policy (primarily through the ACEGES model and the creation of plausible scenarios) and security (primarily through the SPT framework for the generation of energy portfolios with controlled behaviors).

Our longer run goal for the integration of the ACEGES model and the STP framework is a complete computational laboratory that rings true to industry participants and policymakers and that can be used as a tool for long-term planning and investment processes as well as the construction of active energy portfolios for physical trade.

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Prof. Dr. Vlasios Voudouris is the CEO of ABM Analytics Ltd and Affiliate Professor at the triple-crown accredited ESCP Europe Business School (Paris, London, Berlin, Madrid, Torino). Vlasios is also the Editor of the 'Oil and Gas Perspectives' SI at the Energy Policy journal. Vlasios has a wealth of experience in evidence-based energy policy, quantitative analysis and risk-adjusted investment processes.

Energy Security as a Subset of National Security

Chris Flaherty and Walter Leal Filho

Abstract Purpose The notion of energy security can be defined in one of two ways. It can be viewed as an economic concept or as a subset of national security. Viewed as a subset of national security, it allows for processes such as 3D vulnerability analysis to be used, which identifies areas of vulnerability in the physical infrastructure carrying energy from place to place. Some of these vulnerabilities can have national and international implications for a country's energy security.

Design/Methodology/Approach A conceptual framework for using 3D vulnerability analysis is presented as a methodology for collecting physical infrastructure vulnerability information. This can be used identifying areas of vulnerability—such as a particular section of transcontinental oil pipeline that if it was to fail would seriously weaken the energy security and ultimately national security of the country (or set of countries) reliant on it.

Findings The economic approach to energy security tends to be descriptive and frequently concerned with the price and supply measures of energy security. Approaches such as these, however, are not connected with the much broader national security and foreign relations policy realms. As well, the national security approach to energy security allows incorporation with Critical National Infrastructure Protection (CNIP) concepts, such as 3D vulnerability analysis. This method can be used to collect physical infrastructure vulnerability information, which can be used to identify potential threats to energy security (as a subset of national security).

C. Flaherty (✉)
Optimal Risk, London, UK

Soane Point, 6-8 Market Place, Reading, UK
e-mail: chris.flaherty@optimalrisk.com

W.L. Filho
Research and Transfer Centre, Applications of Life Sciences, Hamburg University of Applied Sciences, Lohbrügger Kirchstr. 65, Hamburg 21033, Germany

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Practical Implications The conclusions illustrate how concepts, such as 3D vulnerability analysis, can be used to achieve energy security. The 3D vulnerability analysis approach described collects physical infrastructure vulnerability information, which can be used to identify potential threats to energy security (as a subset of national security).
Originality/Value The paper provides a conceptual framework for looking at 3D vulnerability analysis and the relationship of this methodology to a wider understanding of energy security and ultimately national security.

Keywords Energy security • National security • Critical national infrastructure protection (CNIP) • 3D vulnerability analysis • Geographical information systems (GIS)

1 Introduction

The exact definition of national security, from a US perspective, and its relationship to concepts such as "energy security" is spread between two core US government documents. The US Department of Defense's Dictionary of Military and Associated Terms defines "national security" as a "collective term encompassing both national defense and foreign relations of the United States" (Director for Joint Force Development 2012). The US defense dictionary also lists concepts such as "national security interests," which includes in its listed definition the necessity "for fostering economic well-being" (Director for Joint Force Development 2012). Finally, there is the US President's statement on his National Security Strategy, which illustrates that energy security finds its way into the strategic approach to building the core foundations—economically and politically, as a component of national security (President of the United States 2010). From this perspective, energy security becomes a subset of national security concepts. An overview of this typology identifies three linked notions:

National security
Energy security
Vulnerability analysis

Looking at energy security from a purely economic view tends to focus on the association between national security and the availability of natural resources for energy consumption. As well, access to cheap energy is a given as being essential to the functioning of modern economies. It is also a given that the uneven distribution of energy supplies among countries can lead to significant vulnerabilities. However, there is also a much wider spectrum of energy security concepts. Various countries employ different strategies to achieve the same basic goal of energy security and ultimately national security.

Added to this typology is the concept of 3D vulnerability analysis (which will be discussed later). This is a "ground-level-and-view-up" approach, looking at the actual physical infrastructure which is carrying the energy. This process can be used to develop detailed information about the large-scale national and international vulnerabilities of the energy systems. This can be used as a road map to help achieve energy security. This is used to provide a security risk analysis of the built and fixed infrastructure environments as well as populate the analysis of potential threats to a country's (or group of countries) energy security.

The first part of this paper will look at energy security in an economic sense and then the broader national security approach to energy security. This examines how various countries have sought to achieve energy security. Finally, the concept of 3D vulnerability analysis is discussed.

2 Energy Security in an Economic Sense

As outlined by Winzer (2011) there are several competing definitions of supply security. They all include the idea of avoiding sudden changes in the availability of energy relative to demand. A common feature of current definitions is that they all warn against the risks of discontinuity in energy supply, which characterizes a scenario where energy provision is insecure.

The notion of energy security, in a purely economic sense, can be defined in many ways. For instance, it can be the capacity of a country to meet all its energy needs with the energy it produces itself or energy which it can reliably obtain from partners. But regardless of the definition one is inclined to use, energy security tends to be assessed along price and supply measures. This can be detailed, examining a "multipolar axis of physical, price, and geopolitical security." Typically, the concept of energy security entails understanding the risks inherent in the use of fossil fuels, particularly oil for transport and gas for electricity generation and heating. Each of these elements entails specific risks and potentials.

Energy consumption worldwide has steadily increased over the past three decades and has presently reached substantial levels, as is illustrated in Table 1, which provides an overview of energy consumption from selected countries. This state of affairs means that energy issues not only are central to economic development but have also evolved to be matters of national security.

Table 1 shows that for countries such as the UK, Germany, Russian Federation, China, and the USA over the next 20 years, energy consumption will continue to increase. From an economic view the classical problems, which affect national security, will be the availability of natural resources for energy consumption and access to cheap energy. As well, it can be anticipated that the uneven distribution of energy supplies among countries will and can lead to significant vulnerabilities, such fuel shortages causing economic and political instability. For instance, in respect of energy, it is known that the EU meets about 50 % of its energy needs through imports. This is likely to increase to 70 % by 2030. Such dependence leads to various economic, social, ecological, and physical risks for the EU since a suspension of supply from one of the sources would have severe consequences to the economy of member countries.

Table 1 An overview of energy consumption in selected countries

Energy consumption in million tonnes of oil equivalent (MTOE)			
Region	Current (MTOE)	Projection (MTOE)	Difference (%)
UK	137.50 (2009)	148.065–167.037 (2030)	108–122
Germany	213.28 (2009)	199.255–194.976 (2030)	93–91
Russian Federation	991.0 (2008)	1,375.0–1,565.0 (2030)	139–158
	422.834 (2009)		325–370
China	1,432.986 (2009)	3,280.8 (2030)	224
	2,275.00 (2010)		144
US	2,380.02 (2009)	2,653.26–2,797.90 (2030)	111–118
	1,462.524 (2009)		181–191

International Energy Agency (2011)

In geopolitical terms, 45 % of oil imports come from the Middle East, and 40 % of natural gas imports come from Russia. The EU does not yet have all the necessary means to influence the international market and is at the mercy of suppliers. This weakness was highlighted by the sharp rise in oil prices at the end of 2000. As a means to steer against this trend, it prepared a Green Paper on the security of energy supplies (CEC 2000), which is still being implemented today. One solution recommended by the Green Paper is to draw up a strategy for security of energy supply aimed at reducing the risks in terms of supply, quantities, and price, linked to this external dependence. However, this is just one way of understanding “energy security” as a concept; in the next part, a much wider spectrum of energy security concepts is overviewed. Various countries employ different strategies to achieve the same basic goal of energy security, and these different approaches provide a much broader characterization of the concept of energy security, as a subset of national security.

3 How Various Countries Achieve Energy Security

As was introduced in the introduction, the concept of national security can be defined “to include, not only defence, but also state craft, foreign relations, and economic policy” (Kaufmann 1988; Flaherty 2003). National security is also “a central component of public policy” (Edwards and Walker 1988). The concept of national security changed significantly in the last decade of the twentieth century. The most notable change has been an extension beyond international relations concepts to incorporate domestic individual security as well as the earlier ideas of national defense. In short, many countries adopt strategies, policies, and military action under the mantel of energy security, which provides a much broader characterization of the concept, as a definition in its own right. The broad spectrum of coverage has significance especially when the various strategies used by countries that seek to achieve a notional concept of energy/national security are examined.

The core concept of national and energy security has also of late been extended and somewhat redefined by the more encompassing notions of National Power and Homeland Security, which have all developed into partly interchangeable concepts; and these ideas over span the more conventional concepts such as that of the economy or national defense (President of the United States 2010). Under this approach, specific concepts such as "energy security" very much represent building blocks for the direct operation of supra-concepts such as Critical National Infrastructure Protection (CNIP—which most countries now use some variation[1]), which is largely concerned with the problem—as to how to best structure a methodology for developing a vulnerability—based on security risk assessment that can show how various threats can impact on the infrastructure systems that a country, or group of countries, relies vulnerability -based security risk assessment.

The passing of the US Homeland Security Act of 2002 represents a radical transition between an extraterritorial notion of national security and expansion of the concept into the civil domain (Flaherty 2003). The US Homeland Security Act merged a large number of US Government agencies into one entity. This entity was not only intended to deal with the traditional defense-related areas of national security but also nontraditional areas such as internal US security, its law enforcement, borders, as well as trade, investment, and energy security (however that may be defined, in the context of future US President's policy initiatives).

The notion of energy security takes on many manifestations; it becomes linked to foreign policy, defense, or various trade and investment strategies. For instance, China since the period of economic reform in the 1980s in order to achieve energy security has developed overseas corporations engaged in foreign investment and reliant as well on nationalist Chinese overseas business networks to facilitate these trusted relationships (Flaherty 2002). This strategy was intended to ensure that China in the twenty-first century will have access to important energy stocks and the transport of these into China securely. The Chinese government in the 1990s, in response to the rise in energy consumption (Yang 2011), as well as the political perception that China's domestic petroleum resources are far from sufficient to sustain its economic growth (Webber et al. 2002), decided to let its state-owned petroleum companies seek access to overseas supplies of oil and gas through investment. The focus of which has largely been a continental-based strategy. The most significant areas are Russia (Siberia gas fields) and the central Asian

[1] The US Presidential directive PDD-63 of May 1998 set up a national program for "Critical Infrastructure Protection." In Europe the equivalent "European Programme for Critical Infrastructure Protection" (EPCIP) refers to the doctrine or specific programs created as a result of the European Commission's directive EU COM (2006) 786 which designates European critical infrastructure that in case of fault, incident or attack could impact both the country where it is hosted and at least one other European member state. Member states are obliged to adopt the 2006 directive into their national statutes. In the UK, the same concept developed as CPNI, or the governmental authority—"Centre for the Protection of National Infrastructure"—that mandates critical infrastructure protection strategies for the UK.

republics especially of Kazakhstan (where China has two oil fields) and Turkmenistan (gas resources).

Maritime countries such as Australia have fundamentally focused on energy security as a justification for key foreign policy decisions, such as to ally with the USA, in regard to the war on terror in Iraq and Afghanistan (post-2001), seeing instability in these regions as a fundamental national threat to vital sea trade routes that carry their energy needs (Nelson 2007).

The Russian Federation, in particular, has long acknowledged the links between energy and security (Ministry of Energy of the Russian Federation 2010). As well, the Russian Federation has linked energy security to its military policies, adopting a continental strategy. The post-2000 revival of Russian Federation military capability has been aimed at ensuring capacity to project conventional forces efficiently within the Eurasian land mass and possibly beyond (House of Commons 2009). This seems to now be linked with energy security, as this has been recently identified as an area of common interest under the US reset policy agenda and the NATO-Russia Council Joint Review of Common Security Challenges, underpinning renewed US and NATO cooperation with Russia (Johnson 2011). In the case of Russian foreign policy, it has been suggested that energy security and military capability are used interchangeably in order to build capacity to dominate vital energy routes (carrying oil and natural gas) throughout Eastern Europe (Paillard 2010).

In the military context, there has been a focusing on the capability that can destroy or disable national energy systems as a means to compel a nation. Known as graphite bombs, these were first used against Iraq in the Gulf War (1990–1991) to knock out 85 % of the electrical supply. Similarly, later versions of these were used by NATO against Serbia (in May 1999), disabling 70 % of that country's power grid. In the later stage of Operation ALLIED FORCE, the NATO air force used conventional bombs and rockets to target power high lines and transformer stations (Lambeth 2001). Saudi Arabia and Iraq have similarly seen insurgency and terrorist constantly attack and destroy oil facilities, as a strategy to overwhelm the government (Al-Rodhan 2006; IAGS 2012). The Islamic Republic of Iran Navy (IRIN) and the Iranian Revolutionary Guard Corps Navy, which is now primarily tasked with securing Iran's interests in the Persian Gulf region, have both clearly developed capability intended to compromise shipping. The IRIN has developed a flotilla of domestically produced Ghadir-class midget submarines, while the Revolutionary Guard has some 1,500 boats and fast attack boats, armed with a variety of antiship missiles intended to harass shipping. These capabilities, combined with minelayers, allow for a repeat of the 1984–1987 phase of the Iraq–Iran war dubbed the "Tanker War."

These later examples of the various military campaigns and weapon systems aimed at energy transport are more than just threats; these form part of a well-defined military strategy, aimed at the destruction of a country's national capacity. Examples such as these show a multitude of ways that countries employ to achieve the same basic goal of energy security, and these different approaches provide a much broader characterization of the concept of energy security. The notion of energy security takes on many manifestations linked to foreign policy, defense, or various trade and investment strategies. The question becomes how can we identify national security threats relating to the supply of energy staples oil and gas. This could, for instance, be the risks associated with critical transport nodes, such as the Straits of Hormuz, Malacca Straits, and the Suez Canal. However, in order to identify those risks, one approach is a "ground-level-and-view-up" one, looking from a physical vulnerabilities perspective, which helps identify security risks, threats as well as mitigation strategies. However, in order to have truly national security implications, this process for vulnerability analysis has to be conducted on a sufficient national/international scale.

4 Vulnerability Analysis

Identifying some of the key physical built-environment risks involved along various paths for transporting energy such as oil and gas can be problematic. For instance, "on the path" of energy in transit from the supplier to the consumer country:

> "An ideal way of capturing this kind of risk would be to account for the exact path of each energy import flow into each consuming country, e.g., whether the energy is exported through vulnerable areas, whether alternative transport routes are available, and so on. However, to our knowledge such data are not available." (Le Coq and Paltseva 2009)

However, supra-concepts such as CNIP were specifically created to deal with this exact problem. This is where 3D vulnerability analysis comes into play—as it is supposed to be creating the data needed to do this. The problem is how to overcome the complexity such as that found across Europe and globally as there are multiple regulatory and technologically disparate subsystems—all involved in the transport of energy. The failure of the weaker ones can threaten any country's national and international "horizontal" linkages that work across its energy supply system. In many cases over which, it may exert little or no control.

5 The European Union Concept of "Horizontal Convergence" for Infrastructure Protection

The EU concept of "horizontal convergence" (CEC 2006) for infrastructure protection justifies the use of 3D vulnerability analysis. The original 2006 Commission of the European Communities "proposed council directive" outlined the need for:

- The "identification and designation of European critical infrastructure"
- The assessment of the need to improve their protection
- Further identified that these needed a "horizontal framework," for this identification (CEC 2006)

The phrase "horizontal convergence" is a borrowing from economic geography, identifying in addition to the vertical integration of European supply systems; there was also a need to understand the "horizontal" linkages which reside within individual member countries and which crisscross these. This is intended as a means to identify multiple regulatory and technologically disparate EU member states and the aspiration to collect uniformly and ultimately share similar levels of critical infrastructure protection, via the technology convergence currently being experienced.

The same "horizontal convergence" analogy provides a starting point for developing a 3D vulnerability analysis for energy security focused on identifying the weaknesses and threat points embedded within national and extraterritorial linked infrastructure. The argument is there can be uneven development of various lengths of infrastructure identified across Europe. These contribute to vulnerabilities that can substantial raise the security risk index for other member countries relying on the successful transportation of energy staples via these less reliable paths. Adaptation of methodologies, such as the "3D analysis box" (Flaherty 2010), for use in the analysis of these vulnerabilities, can contribute to solving this very problem.

6 3D Vulnerability Analysis: Micro- Versus Macroanalysis

A macrolevel economic view of energy security argues:

> "The composition of energy imports also matters for security. If energy imports are well diversified, the consuming country faces a smaller risk of supply disruption than if all its energy imports come from a single supplier, other things equal. Therefore, one needs to account not only for the overall contribution of imported energy into the consuming country's energy portfolio, but also for the diversity of the energy suppliers that contribute to these imports."

Typically it is argued that "other things equal, suppliers that constitute a larger share of country's energy imports potentially may cause more problems for energy security." Another way of looking at this argument is that a further level of inquiry could be added overlaying the macrolevel economic view, with a microlevel vulnerability survey of the system that is actually being used. In some cases, it may well be found that the potential vulnerabilities actually reverse the proposition—"suppliers that constitute a larger share of a country's energy imports potentially may cause more problems for energy security"—as it could be found that this particular supplier is functioning and that other potentials (the diversified pool of suppliers) actually represent a source of higher security risk, as their actual transportation of the energy is highly compromised; thus, there is a higher than acceptable level of energy/national security vulnerability.

Notionally, three-dimensional or "3D" vulnerability analysis seeks to look at the full volume of space, understanding complex simultaneous factors as well as incorporating time and location factors (Flaherty 2007). The 3D vulnerability analysis techniques are intended to sit under the mandate of CNIP and enable security risk scenarios to be developed. The core aim of which is to "produce" the information (identifying the vulnerabilities) necessary to begin the security risk management cycle, and this applies equally to the question of energy security, either at macro- or microlevels (Flaherty 2007).

The application of the "3D analysis box" (Flaherty 2010) has been designed as a practical aid to achieving the monumental task of assessing vast infrastructure systems, particularly the transportation paths taken such as pipelines and tankers as well as developing an "index" of security risk for energy transport which could feed into the "energy policy topic" in terms of resilience and security of energy imports (for consumers) and exports (for exporters). This can be developed as a security risk or threat model based on the Commission of the European Communities identification of "horizontal convergence."

The 3D vulnerability approach is simple; it is a question-based audit seeking to identify individual vulnerabilities or "fail characteristics" (as these can be known). These are identified in a question-based survey—seeking to identify weak systems linkages or weaknesses in the building frames, fabric, or structures. Once identified, these can all be measured in order to illustrate the possible range of consequences, if these vulnerabilities were to be enlivened, either through an act of nature, or deliberately (terrorism, war, etc.), or accidental human intervention. Applied to the problem of energy security, the 3D vulnerability analysis approach looks at the various stages of a path for the transportation of a particular energy staple. This is built into a multistage and multi-segmented 3D vulnerability analysis of the whole system. The purpose is to illustrate multiple clustering of vulnerabilities which indicate key areas, as well as key hubs along transportation paths for energy transport, connecting a country's energy supply system transnationally. This would identify vulnerability, as it arises from:

1. Clustering
2. When (time-wise) these are stable or unstable
3. Likely points of attack or places where accidents could make this happen
4. How at various times vulnerabilities can appear or disappear

One criticism is that the analysis is specifically microlevel in focus. However, some identified vulnerabilities will be significant from a national security view (at a macrolevel) and others not—as some infrastructure vulnerabilities only ever have local effects that cannot impair energy transport nationally, or internationally, and therefore are not national/energy security issues.

In the case of 3D vulnerability analysis, the object is to illustrate the "how" and the "why" when multiple consequences manifest from failings in systems, buildings, or places. This could be a single failing, or it could involve complex multiple failings simultaneously that are below the visible surface, such as embedded within the infrastructure itself—where a clustering of possible fails could compromise each other. This involves a dynamic approach to modelling, involving factors such as time and phase.

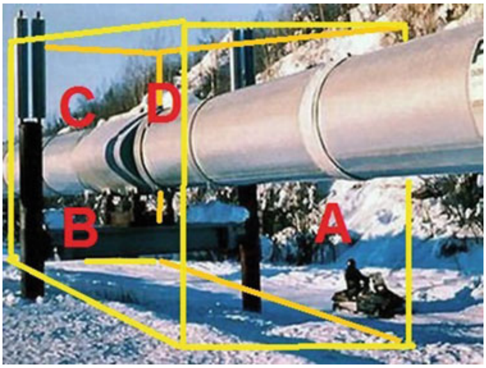

Fig. 1 Illustration of the 3D box technique in regard to a section of the Odessa–Brody oil pipeline

7 Illustrating the 3D Vulnerability Approach: A Simple Model

The “3D analysis box” (Flaherty 2010) is a classical technique illustrated in Fig. 1. This technique also incorporates “cluster modelling” and “linear modelling” (Flaherty 2007). The following is a simplified example of how the 3D vulnerability analysis could be undertaken, in relation to a desktop analysis of a photograph taken of some section of the current Odessa–Brody oil pipeline (using the 3D analysis box).

Illustrated in Fig. 1 is a picture of a segment of Odessa–Brody oil pipeline. This particular example demonstrates some key vulnerabilities and the zone of potential threat, as the greatest concentration or clustering of key assets that can be damaged, during an event (such as an explosion). The 3D analysis box has been overlaid as a technique to assist focusing and identifying key physical vulnerabilities during a simple survey. For instance, the types of vulnerabilities, which could be identified within the oil pipeline’s physical structure (which may be seen in this particular example) are the pipeline itself, as well as individual joinery/banding sections (Fig. 1: A); the aboveground piers and pipe’s supporting connector beam (Fig. 1: B, C); and clamping system (Fig. 1: D). An attack on this cluster renders the greatest damage and cost, as opposed to attacking the pipe on its own.

8 A Horizontal Convergence Approach: GIS Applications

A horizontal convergence approach to the simple model illustrated in Fig. 1 would entail the upscaling into multistage and multi-segmented 3D vulnerability analysis illustrating multiple clustering, as well as key cluster hubs along transcontinental infrastructure. *The main requirement is for an evidence-based approach to* *understanding multiple vulnerabilities that can link consequently to create a hazard impacting on the operation of a site or the safety of people located there. However, attempting to map these consequences, especially those that occur simultaneously across a site, presents a fundamental problem for undertaking vulnerability and counterterrorist assessments.*

The 3D vulnerability analysis approach is a look "ground-level-and-view-up" from a physical vulnerabilities perspective, which helps identify security risks, threats as well as mitigation strategies. In order to have truly national security implications, this process for vulnerability analysis has to be conducted on a sufficient scale to actually have national and international implications. The core aim of vulnerability analysis is to "produce" the information or data necessary to begin the security risk management process, as outlined in various international standards, as this ultimately leads back to the supra-concepts of CNIP, and national security considerations. In addition to which, the following can be added:

- The consequence analysis is merged with an effective tactical analysis, which may include identifying a likely terrorist operational plan (where the analysis is focused on counterterrorist assessments).
- The assessment is intended to be developed as a Geographical Information Systems (GIS) approach, visualizing the vulnerability-risk-threat-security profile, from a CNIP/national security perspective.

The versatility of these types of GIS-based approaches is that these can easily accommodate any volume of data, drawn from a wide variety of sources—such as on-the-ground inspection of actual lengths of infrastructure identifying the vulnerabilities—which then gets swept up into the information, or data matrix, which produces an "index," such as the rating of areas of higher levels of vulnerability. In practice, data about consequences is sourced from a wide examination of the building, system, or space, closely following the question methodology typically derived from the international or US governmental standards such as the FEMA 426 Reference Manual: Chapter 1.6 "Building Vulnerability Assessment Checklist (US FEMA 2002)" or that used by the UK Government National Counter Terrorism Security Office (NaCTSO)'s Vulnerability Self Assessment Tool (VSAT) (NaCTSO 2012).

9 The Concept of Vulnerability: Some Final Comments

Some physical vulnerabilities are not fixed, as these may only occur during particular times and in conjunction with other events (Flaherty 2004). For example, key vulnerabilities may only arise in the segment of Odessa–Brody oil pipeline, illustrated in Fig. 1, in times of peak usage of the pipeline or in circumstances where there is accessibility to the line, as represented by presence of the snow ski driver. Environmental issues may also come into play that coincide with peak usage. For instance, severe cold could weaken the structure, through weathering and fatigue.

The vulnerability information or data collected in a survey can reveal significant clusters of related vulnerabilities (which are the individual “fail characteristics” identified in a question survey). These can be used to illustrate a range of potential security risks or impacting consequences. In the case of 3D vulnerability analysis, the object is to illustrate the “how” and the “why” of multiple consequences and failures occurring simultaneously when many clustered structural and systems vulnerabilities mutually compromise each other, during some even such as an explosion. Essentially, this is a dynamic modelling approach, as factors such as time and phase are important considerations.

10 Conclusion

The aim has been to present a conceptual approach to energy security, linking it to an alternative definition as a subset of national security concepts. The notion of energy security can be defined in one of two ways. It can be viewed as an economic concept or as a subset of national security. Viewed as a subset of national security, it allows for processes such as 3D vulnerability analysis to be used. 3D vulnerability analysis can identify areas of vulnerability in the physical infrastructure carrying energy from place to place, and some of these vulnerabilities can have national and international implications for a country’s energy security.

3D vulnerability analysis itself is derived from supra-concepts such as CNIP. The paper provides a conceptual framework for looking at 3D vulnerability analysis, as a methodology for collecting information or data that allows a security risk analysis to take place at a microlevel, and this information informs the macrolevel relationship between various aspects of critical infrastructure—such as a particular section of transcontinental oil pipeline that if it was to fail would seriously weaken the energy security and ultimately national security of the country (or set of countries) reliant on it. One of the key aims of 3D vulnerability analysis is to provide “a set of definitions and observations” (Flaherty 2010). The approach is intended to build up a picture “from the ground-up” of the vulnerabilities and major clustering of these for built or physical infrastructure or systems. This then enables analysis of multiple consequences and multipolar risks using GIS-based methodologies, such as cluster modelling and linear modelling.

The core aim of vulnerability analysis is to “produce” the information or data necessary to begin the security risk management process, as outlined in various international standards, as this ultimately leads back to the supra-concepts of CNIP and national security considerations. The versatility of these types of GIS-based approaches is that these can easily accommodate any volume of information or data, drawn from a wide variety of sources—such as on-the-ground inspection of actual lengths of infrastructure identifying the vulnerabilities—which then gets swept up into the data matrix, which produces an “index” of the critical areas of vulnerability in the physical infrastructure that carries energy from one place to the next.

Developing a horizontal approach (in line with the EU policy concepts underpinning CNIP) to energy supply paths, given the scale of these, entailing transcontinental and global linkages requires the upscaling of the basic 3D vulnerability analysis, with the use of the "3D analysis box" into multistage and multi-segmented 3D vulnerability analysis. These would illustrate issues: multiple clustering as well as key cluster hubs along transcontinental infrastructure. The aim would be to help identify vulnerability phenomena, as they arise from clusters, when these are stable/unstable, as well identifying the point of an attack designed to make this happen (and various relevant timescales).

The "3D analysis box" provides a reproducible methodology, focused on cutting complex infrastructure paths into components that can be analyzed individually or in groups in order to illicit security risk information or data (within a GIS-based framework). This is actually (or should be) the "breadmeal" of core national CNIP programs in terms of identifying the risks in the system. Namely elements such as (1) autonomous and heterogeneous agents, (2) organizational relationships, (3) nonlinear dynamics, (4) knowledge levels, (5) local interactions, and (6) the explicit space these occupy geographically, along the lengths of transcontinental infrastructure that not only has energy security but the national security needs of a country firmly in sight.

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Chris Flaherty is a PhD graduate from the University of Melbourne in 2002. Based in London since 2008, he is an active contributor on security, terrorism early warning, and related international intelligence issues. He is currently involved in developing a "Scripted Agent Based Microsimulation Project" (University of Wollongong NSW, Australia). He currently specializes in the area of Mass Gathering Vulnerability analysis in the UK and the USA. He advises on risk analysis projects for building facilities. His work covers a broad spectrum of risk-related endeavors including resilience, counterterrorism, critical infrastructure protection, 3D tactics, fragmentation, and vulnerability analysis.

Walter Leal Filho Prof. Dr. (mult.) Dr. h.c. (mult.) is Senior Professor and Head of the Research and Transfer Centre Applications of Life Sciences, Hamburg University of Applied Sciences in Germany.

Challenges to Global Energy Policy and Supply Security

Michael Jefferson

Abstract **Purpose** To review the challenges for energy policy and supply security from the global down to national levels, pointing out failures to meet goals, the internal contradictions of stated policies, the challenges for both fossil fuels and renewable sources of energy to meet future requirements for modern energy services, and the huge scope for raising the efficiency of energy use.
Approach A review of statements, claims, and performance from the global to national levels over the past 20 years and review of realistic prospects.
Findings Although there are numerous constraints confronting fossil fuel extraction and use, there are also severe limitations on the expansion of renewable energy supply in the quantities and of the qualities that modern energy services are expected to provide for consumer societies. The likely consequence is that there will evolve an involuntary move towards more conservation-minded societies as conflicts intensify and earlier goals remain out of reach.
Value A plain statement of facts about what has occurred (or has failed to be achieved) and what is not likely to occur, given the unreality of targets and exaggerated claims of vested interests involved.

Keywords Human population growth • Desire for modern energy services • Efficiency • Fossil fuel dominance • Security and other availability concerns • Suboptimal renewable energy support • Greater focus on energy efficiency required • Lifestyle challenges

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M. Jefferson (✉)
ESCP Europe Business School, 527 Finchley Road, London, NW3 7BG, UK
e-mail: mjefferson@escpeurope.eu; michael.jefferson@buckingham.ac.uk

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1 Introduction

The 1992 Rio Earth Summit placed great emphasis on energy efficiency in its opening session. With world population growth, the huge number of people unable to access modern energy services, the beginning of concerns about climatic change perhaps of anthropogenic causation, and the pressures to provide more "clean" energy for the services sought, this emphasis on raising efficiency was not surprising. Yet that message, and the subject of energy more generally, largely disappeared in Agenda 21's 600 pages. This situation has largely remained in subsequent UN deliberations. Concerns about fossil fuel availability and use have continued. Promotion of, and subsidies to, renewable energy have often been suboptimal. Closer focus on climate change, deforestation, and poverty has failed to produce significant benefits. Differences of view between major states on how to proceed have continued, and divisions between East and West, and North and South, are probably even deeper now than they were 20 years ago.

By 2010 world carbon dioxide emissions from fossil fuel use were 46 % above 1990 levels. In 2012 they were believed to be 50 % up on 1990. Renewable energy projects have been pursued with scant regard for efficiency or costs to users. Still 2.7 billion people—about 40 % of the world's population—rely overwhelmingly on traditional biomass; 1.5 billion others have no electricity supply; a further one billion only have sporadic supply. Fossil fuels continue to provide nearly 85 % of the world's primary energy, while renewable energy sources provide about 13 %—of which traditional biomass accounts for 10.2 %—and all other renewable resources for only 2.8 %. Of this 2.8 %, hydropower accounts for 2.3 %, wind power for 0.2 %, and direct solar energy and geothermal for 0.1 % each.

Recently there have been some signs that the UN system may be reappraising the need to focus more closely on energy efficiency. The UN's General Assembly proclaimed in 2012 the International Year for Sustainable Energy, and the Rio+20 Conference took place—and was widely regarded as a disappointment among those interested in promoting sustainable development. This paper argues that there should be greater, and more effective, focus on raising efficiency in energy provision and use. However, there are those who argue cogently that simply pursuing greater efficiency will not be enough to permit access to the energy services that modern societies increasingly demand or the security of supplies required. Instead, much greater emphasis should be placed on the need to conserve finite resources, extend their lifetimes, and move from the current fixation with consumer societies to simpler lifestyles either voluntarily or—in the last resort, as it will need to be—involuntarily.

2 Background

There are many fields of human endeavor where policies, measures, and actions are marked by internal contradictions. The field of energy as it relates to sustainable development is no exception.

The world's human population passed seven billion in 2011 and, although the rate of expansion is slowing, is expected to pass nine billion by the year 2050. The migration of human populations to areas deemed more economically attractive, where perceived threats from climatic change are considered lower and access to modern energy services greater, is causing rising tensions in many of the recipient countries. Some of these tensions arise from racial, religious, or cultural differences exacerbated by rising population densities in urban areas or whole regions. Others arise from concerns about food and water availability and prices and from concerns about the supply security and prices of modern energy services. This chapter focuses upon concerns about access to modern energy services.

It is often claimed that universal access to energy is a vital step for sustainable development. This should not be accepted at face value. For example, many poor families in India can access volumes of primary energy relatively easily—from fuelwood and animal dung—and the volumes of these in relation to needs at face value might seem greater than their requirements. In sub-Saharan Africa several hours per day can be spent searching for, and collecting, fuelwood—sometimes traveling over 30 km to do so [although the average by the year 2000 was found to be 1.6 km per day per household (Goldemberg et al. 2000, p. 52)]. The problem is, of course, that transforming these forms of primary energy to useful energy involves great losses, possible adverse health effects and both poor and limited final energy services. A major global energy industry report published in 1993 found that the use of fuelwood, together with inefficient cooking facilities, meant that the average family in sub-Saharan Africa used five times as much energy as a European family to cook the evening meal (World Energy Counci1 1993, p. 70). In other words, this is a very inefficient use of energy resources. Also, by using large quantities of fuel wood, it can undermine sustainable use of land and, by using human energy and time in its collection, undermines sustainable human development by diverting time from educational and income-generating activities as the recently published "Global Energy Assessment" has highlighted (Johansson et al. 2012).

Then there is the question of whether a particular form of energy or transforming technology is regarded as socially desirable. For example, in South Africa it was noticed as far back as the 1980s by ESKOM that local people had a strong preference for grid-connected electricity, rather than solar panels for electricity or for water heating, not because the latter failed to provide a superior service compared with what had hitherto been available but because grid connection was regarded as a superior and more socially desirable form of transmission. There was also found to be great concern for many people in Southern Africa at pressure to shift from personally gathered firewood to solar cookers (Darnell and Jefferson 1994, p. 121). This was one of the examples then drawn upon to illustrate the fact that a great deal is required in order to educate people towards understanding energy issues in general and the advantages of solar energy in particular. The problem identified then still continues.

These examples also illustrate the point that people do not want energy as such but the services it offers—lighting and heating, cooking, transportation, and motive power—with as much comfort, affordability, and reliability as feasible. In other words, people expect, and certainly aspire to, the comfort, affordability, and reliability that they associate with modern forms of energy. These features they commonly associate with the efficiency of their provision (Nakićenović et al. 1998; Goldemberg et al. 2000). But the issues which confront those in the economically poorer nations of the world cannot be transcended simply by looking at the more developed countries for readily available answers.

3 Some Fundamental Challenges for Energy Supply

In recent years the search for low carbon technologies and introduction of lower emissions targets among industrialized countries, especially many of those designated as Annex I Countries under the UN Framework Convention on Climate Change, have led to many initiatives which seem counterintuitive. This especially applies in the area of renewable energy, where there has been little emphasis on backing more advanced, theoretically large-scale, and sustainable technologies. Instead more traditional, intermittent sources of energy, or more environmentally sensitive ones, have been given widespread priority. For example, the push for wind energy to the point where ever-larger wind turbines are placed where mean wind speeds are relatively low, capacity factors achieved are well below those widely claimed, and the problems of variability loom large. Supporting solar PV in areas where solar irradiation levels are poor, which unavoidably means that the results will be modest and almost certainly an unwise use of resources. The drive to expand biomass and biofuel availability with scant regard for their wider implications—such as impacts on food availability and prices, water requirements, associated emissions, and loss of biodiversity and species' habitats. Talk of tidal range technologies (estuarine barrages) without adequate recognition of their wider ecological consequences. In these fields severe adverse impacts on sustainable development may be inherent and are insufficiently taken into account (Jefferson 2008a). Some may consider that other renewable energy technologies—for example, large hydropower schemes, wave and tidal stream, and Concentrating Solar Power (CSP)—can also have serious negative consequences. The need to balance the implications for sustainable development of the various renewable energy technologies, having taken into account the likely eventual scale of operations and net benefits on the one hand and the need to consider the constraints on the availability and use of the fossil fuels on the other, should be obvious (Jefferson 2008b). One reason is that these other sources of renewable energy have higher power densities than wind power, biomass, and even solar PV unless situated in a sunny location.

All renewable energy sources have lower power densities than the fossil fuels or nuclear energy. The latter, in turn, are trivial in relation to the power densities of such phenomena as tornadoes, thunderstorms, earthquakes, or even hurricanes and monsoons. Fossil fuels as primary energy have far greater power densities than renewable energy sources, although the latter can range widely (from some 80 W/m^2 for flat plate solar heat collectors to about 1 W/m^2 for biomass).

Power densities (W/m^2)	
Natural gas	1,000–5,000
Coal	100–1,000
Flat plate solar collectors	80
Solar PV panels	10–50
Solar "parks"	4–11
Concentrating solar power	6–10
Wind	0.5–1.5
Biomass	0.5–0.6

(*Source*: Smil 2008)

These figures indicate that although renewable energy sources are sometimes claimed to be "free," which before any investment may be true, their efficiency is generally low and highly variable. Land usage, intermittency, state of technology, and cost of investments and subsidies all come into the equation.

4 Energy Efficiency and the Role of the UN

Maurice Strong, Secretary-General to the UN Conference on Environment and Development held in Rio in 1992, stressed in his opening speech:

> "Nowhere is efficiency more important than in the use of energy. The transition to a more energy-efficient economy that weans us off our overdependence on fossil fuels is imperative to the achievement of sustainable development" (Johnson 1993, p. 53)

Yet the subject of energy efficiency, and of energy more generally with its links to sustainable development, failed to warrant its own chapter in what became known as Agenda 21. Instead, energy issues were confined to Chapter 9: "Protection of the Atmosphere". This eight-page chapter proved to be the most difficult and protracted to negotiate in Rio after the discussions on finance. It has been claimed: "The Arab Group maintained that the chapter was not only duplicative of the work of the Climate Change negotiations, but that it placed an over-emphasis on energy efficiency and conservation" (Johnson 1993, p. 213). While some may cavil at this claim, it would surely have been wiser to have two separate chapters, one covering protection of the atmosphere and the other on the full range of energy issues relating to sustainable development. The result of bringing the two topics together into one chapter was a loss of focus on the many sound statements on energy in the chapter, not least the call under objectives for "more efficient energy production, transmission, distribution and use" (para. 9.11). This is not to claim that, if there had been this tighter focus (looking at the doubtful outcome to date of the two international treaties opened for signature in Rio—on climate change and biodiversity), developments since would have been very different.

Under activities, intergovernmental, governmental, nongovernmental and private sector bodies were urged to cooperate in identifying and developing commercially viable and environmentally sound energy sources to promote sustainable development; to promote integrated energy, environment and economic policy decisions for sustainable development; to promote R&D and the transfer and use of improved energy-efficient technologies; and to support environmentally sound energy from new and renewable energy sources. Cost-effective policies, measures, standards, labeling, education, and awareness raising were all to be encouraged in order to promote energy efficiency. The chapter then paid particular attention to the transport and industrial sectors. All are worthy sentiments, but the effectiveness of the message was lost among all the other messages being conveyed.

5 Input from Energy Specialists

Much of the world's energy sector was well aware of the dangers at the time. The World Energy Council had established a Commission in 1990 to try and get a balanced and proportionate view on the importance of energy supply and use in relation to sustainable development. In a report entitled "Energy for Tomorrow's World" (1993), a balanced overview was given of prospects and needs, including a 24-page chapter on energy efficiency and conservation. All the regional reports submitted to the Commission and the report's author stressed "the need to give very high priority to increasing the overall efficiency of energy use—indeed this was one of the most widely supported of all aims in the energy sector" (World Energy Council 1993, p. 109). The report concluded that "There are many fields where current policies do not promote efficiency in energy provision and use, nor encourage conservation" (World Energy Council 1993, p. 42).

This remains the case. One of the problems was the subsidies going to safeguard fossil fuels and/or to keep energy prices down, which for many countries also remains the position. It was pointed out that there was huge technical potential for meeting the needs and aspirations of society with much less energy use. Moreover, it was also pointed out that the aim should be to seek a theoretical minimum energy use for performing a required or desired task and anything above that should be regarded as wasted energy. This concept of useful energy was, and is, termed "exergy." End-use energy efficiency in the USA was estimated to be only 2.5 %; in other words, in principle the same final services could have been obtained by the expenditure of only 1/40th as much energy as was actually used. Western Europe and Japan were considered to be more efficient, in the 4–5 % range, while Eastern Europe and the CIS were estimated to be in the 1.5–2 % range. Overall, the world's energy efficiency rating was estimated to be then no greater than 3–3.5 %, after Robert Ayres (World Energy Council 1993, pp. 113–114).

Examples of the potential for improving energy efficiency were drawn from the manufacturing, agricultural, residential and commercial, and transport sectors as well as from energy supply and conversion. This report was referred to by a number of energy specialists not linked with the World Energy Council as "The Bible" on energy for several years thereafter. In its assessment of the potential for improving energy efficiency, "Energy for Tomorrow's World" did not overlook the challenge of what is called "the rebound effect"—that in improving energy efficiency resources will be freed up (to an unknown extent) to consume more energy (World Energy Council 1993, p. 110).

Then in 1998 there followed from the World Energy Council and senior staff members of the International Institute for Applied Systems Analysis (IIASA) "Global Energy Perspectives," where the scope for energy intensity improvements and technological change was thoroughly aired. This study also announced a departure from the traditional analytic separation of energy supply and demand, treating the energy system holistically from the primary sources to the services provided. It demonstrated and concluded that in 1990 global energy flows had been 9 Gtoe (gigatonnes oil equivalent), of which 3.3 Gtoe had provided useful services and 5.7 Gtoe (63 %) had been "wasted or rejected" (Nakićenović et al. 1998, Box 5.1, p. 64). This analytical framework has now become standard, although it does not plumb the future possibilities for efficiency improvements suggested by the principle of exergy.

A similar flow chart was produced for energy use in the USA in 2008, by the Lawrence Livermore National Laboratory. Here 57.5 % of primary energy inputs were diagnosed as "rejected" (or wasted). Although there have been many suggestions that a disproportionate amount of energy is wasted in the USA compared to most other countries, the more important point would seem to be that little progress has been achieved in reducing the volumes and proportions of wasted energy in the world over the past 20 years. Indeed, Robert Ayres has suggested that official data often overstate the level of energy efficiency achieved (Ayres 2011). Thus, for the USA, he contrasts US Energy Information Administration claims with his own findings:

Current US energy efficiencies

	USEIA	Ayres' est.
Electric power generation and distribution	33 %	33 %
Industrial sector	80 %	30 %[a]
Transportation services	27 %	<1 %[a]
Residential and commercial buildings	80 %	10 %
Total	42 %	8 %

[a]Regarded by Ayres as consistent with other engineering studies

The overall picture that emerges from such work is that about 60 % of primary energy is wasted or rejected in the USA, 48 % of which is wasted or rejected in the process of electricity generation and 37 % in the transportation sector. These two sectors therefore account for 85 % of wasted or rejected primary energy in the USA, a figure which will vary somewhat between countries. The broad order of magnitude does, however, give an indication of the scope in principle for raising efficiency in provision and use.

6 The Response of UN Agencies

These studies and findings did not go entirely unnoticed among some of those engaged in the UN system. One result was an initiative of a World Energy Assessment conducted by personnel from UNDP (UN Development Programme), UNDESA (UN Department of Economic and Social Affairs), and the World Energy Council. This 500-page study was published in September 2000 and contained a major chapter on energy end-use efficiency (pp. 173–217), other material on supply-side efficiency, and in the chapter "Energy Policies for Sustainable Development," a section on "Raising Energy Efficiency" pointed out the potential and the need to exploit it as a matter of urgency (pp. 427–429) (Goldemberg et al. 2000). Chapter 6, on "Energy end-use efficiency," provided a wide range of energy efficiency potentials from many countries and regions even by 2020.

Regrettably, the process of producing and promoting this major study was undermined somewhat from two quarters. UNDESA's role was not entirely helpful, and divisions and political maneuvring within the World Energy Council even more so. Yet it remains a major contribution, even though in the same month that it was published the eight Millennium Development Goals (MDGs) were issued without a single reference to energy or energy efficiency. This was despite the MDGs intended purpose of promoting environmental sustainability and developing a global partnership for sustainable development. This could not have been for lack of space. The Millennium Declaration itself runs to 32 paragraphs over nine pages.

The UN system is severely challenged by questions on its record in the 20 years since the Rio Declaration, as was seen at Rio+20, and will be again when in 2015 performance towards the MDGs is examined. But there have been some more hopeful responses from within the UN system in recent years—along with many simultaneous signs of unrealistic targets and failure to meet them, and disparate aims and conflicts with reality.

One of the most encouraging signs was the appearance of "Energy Services for the Millennium Development Goals," produced by UNDP, the World Bank, and ESMAP (Energy Sector Management Assistance Programme) in 2005. This report recognized that "much wider and greater access to energy services is critical in achieving all of the MDGs." It pointed out that "without scaling up the availability of affordable and sustainable energy services, not only will the MDGs not be achieved, but by 2030 another 1.4 billion people are at risk of being left without modern energy." It noted that "no MDG refers to energy explicitly," yet improved energy services are necessary for meeting all the goals. The report recommended that the issue of energy services be placed on a par with other MDGs, that measures be taken to ensure reliable electricity supply, and that a sharper focus on the availability of modern energy services was essential for human welfare and increased productivity. In summary, the report concluded:

> "It is clear that energy services have an impact on all of the MDGs and associated targets. Access to energy services facilitates the achievement of these targets. Failure to consider

> the role of energy in supporting efforts to reach MDGs will undermine the success of the development options pursued, the poverty reduction targets, as well as the cost effectiveness of the resources invested." (UNDP/World Bank/ESMAP 2005, p. 32)

Perhaps the main weakness of this report was its avoidance of any specific reference to energy efficiency. However, there were various references to the need for reliable supplies and specifically under "Challenges Facing Energy Institutions and Systems" (ibid, p. 66) to "technical problems such as electric utilities with limited generation capacity and losses in transmission and distribution that nonetheless face high and growing demand." This topic will be returned to below in discussion of the concerns many people have over the reliability of some forms of renewable energy in terms of variability and need for backup of electricity supply from traditional sources and well-founded concerns about the implications of having this "spinning reserve."

Thus it was that in 2009 a UN Advisory Group on Energy and Climate Change was established under the chairmanship of the Director-General of UNIDO (UN Industrial Development Organization), Kandeh Yumkella. This Advisory Group identified two priorities: improving energy access and strengthening energy efficiency. The Chairman pointed out that the "vast potential for energy efficiency improvements across the energy supply and delivery chain remains largely untapped." (UN 2010). In the main body of the report it is stressed:

> "Energy efficiency is one of the few 'no-regret' policies that can offer a solution across challenges as diverse as climate change, energy security, industrial competitiveness, human welfare and economic development." (UN 2010, p. 18)

The report estimated that in capturing all cost-effective energy efficiency measures, the growth of global energy consumption could be reduced from currently forecast levels of 2,700–3,700 Mtoe (million tonnes oil equivalent) in 2030 to 700–1,700 Mtoe. The reduction would be split fairly evenly between high-income countries and the rest of the world, much of the former coming from retro-fitting existing infrastructure in the developed economies. The large potential for improving efficiency in power generation, and reducing transmission and distribution losses, was covered as well as the potential for exploiting opportunities in industry, buildings and transport. By applying the best currently available technologies, it was estimated that potential savings in the building sector are around 1,500–2,000 Mtoe, in power generation around 1,000 Mtoe, in the industrial sector some 600–900 Mtoe, and in the transport sector around 500 Mtoe.

These matters are still, for the most part, aspirational. As was pointed out at the Vienna Energy Forum in June 2011, there are still 2.7 billion people (40 % of the world's population) who rely overwhelmingly on traditional biomass. A further 1.5 billion have no electricity supply. A further one billion have only a sporadic supply of electricity. There are fears that, unless there is careful re-examination of the reliability of large-scale electricity generation from renewable energy sources, not only will the aim of meeting the needs of all those currently without access to modern energy services by 2030 fail by a large margin, there are also concerns that a growing number of people in many industrialized countries will also be reduced to sporadic electricity supplies due to overdependence on wind and solar energy.

An additional cause for concern is the little progress being made towards shifting the world away from reliance on fossil fuels. As the IPCC Special Report on Renewable Energy Resources, published in 2011, pointed out, 85 % of the world's primary energy still comes from fossil fuels, and use of fossil fuels accounts for about 56 % of all anthropogenic greenhouse gas emissions. There are profound concerns about "peak oil" (the constrained volume of estimated ultimately recoverable conventional oil), the security of natural gas supplies, the economics and technical feasibility of carbon capture and storage from coal exploitation, and uncertainties about recoverable shale gas resources (including reductions of ultimately recoverable resource estimates for the USA and Poland in recent months). Renewable energy on the other hand accounts for about 13 % of global primary energy use. Unfortunately, this breaks down into 10.2 % traditional biomass, 2.3 % hydro, and others about 0.5 %. Of this last figure, wind power accounts for about 0.2 %, and solar energy and geothermal for 0.1 % each (Intergovernmental Panel on Climate Change 2011). Nuclear accounts for the remaining 2.1 % and in many countries is again under general threat because of the particular circumstances of the Fukushima incident. As already indicated, there are reasonable fears that in shifting from reliance on fossil fuels (albeit there now being enhanced potential to shift away from coal to gas) and nuclear power too hastily, a loss of reliability will occur for many electricity users.

Not surprisingly, therefore, as pointed out at the prelaunch of the "Global Energy Assessment" in Vienna on June 21, 2011: "Efficiency improvement is the most cost-effective option" (Davis 2011). There are also other encouraging signs. The year 2012 has been designated the "International Year of Sustainable Energy for All," and the International Energy Agency (IEA) issued a report in 2009: "Towards a More Energy Efficient Future" which pointed out yet again the "increasing consensus that improving energy efficiency is often the most economic, proven, and readily accessible means of ensuring a better use of the world's energy resources." The report focussed on rising household energy use due to increasing ownership of small appliances, increased use of electricity in the services sector, passenger and freight transport increases, and electricity generation growth (which increased by 37 % within IEA member countries between 1990 and 2006 alone) (International Energy Agency 2009).

7 Risks for Energy Efficiency and Sustainability

There are a number of other issues which have relevance to the underlying challenges of driving for energy efficiency and sustainable development. One is the question of accounting for greenhouse gas emissions. To date international convention makes no allowance for the large rise in manufactured goods imported into industrialized countries from such countries as China and India, where dependence on coal-fired electricity generation is high. Thus the UK officially claims carbon dioxide emissions fell by some 20 % between 1990 and the end of 2011. In fact, if the emissions exported to such countries as China, India, and others where manufacturing capacity has in effect been transferred, then the UK's emissions of carbon dioxide actually rose some 16 % between 1990 and 2011. This should not cause surprise. Sir Robert Watson, the UK Government's Chief Scientist in its Department of Environment (DEFRA), "called for more openness in admitting Britain's apparent cuts in greenhouse gases are an illusion". He, a former Chairman of the Intergovernmental Panel on Climate Change, said, "if emissions 'embedded' in imported goods are counted, UK emissions are up, not down." He is again quoted as saying: "At face value UK emissions look like they have decreased 15 % or 16 % since 1990. But if you take in carbon embedded in our imports, our emissions have gone up about 12 %. We've got to be more open about this." Not surprisingly perhaps, though disingenuously, the official response of the UK Department of Energy and Climate Change (DECC) was "Our position is that greenhouse gas emissions in the UK have been cut by 22 % since 1990." The Chief Scientist to DECC, Professor David MacKay, has also raised concerns about failure to include "embedded emissions" in national inventories, without success (Watson 2010). These reports led to calls for the UK to start measuring its full carbon footprint, but to no effect as yet. (One intriguing feature of the 2011 Vienna Energy Forum was that there was no mention of Austria's 10 % increase in carbon dioxide emissions from fossil fuel use between 1990 and 2010.)

The UK is not, of course, alone in this situation. Germany, which has decided to abandon nuclear power from 2022, has led the reduction in greenhouse gas emissions in Western Europe since 1990 (assisted by reunification). BP's 2011 Statistical Review gave Germany a 19.6 % reduction in carbon dioxide emissions from fossil fuel use between 1990 and 2010 (and for the UK a 27.1 % reduction). But Germany imports two-thirds of its energy. China accounts for over 8 % of Germany's imports, with a value in excess of 55 € billion per year, well in excess of Germany's exports to China.

The contribution of renewable energy to Germany's primary energy use has been rising in recent years, from 12 % in 2009 to 20 % in 2011. But reliance on oil remains at over 30 %, natural gas and coal at over 20 % (equally split between bituminous coal and lignite), and nuclear at 10 % (but still over 20 % of electricity supply). In 2011 wind energy supplied some 7.5 % of Germany's energy requirements and solar 3.5 %, within the 20 % contribution of renewable energy to electricity generation. Germany announced in September 2010 that renewable energy sources would provide 35 % of its electricity requirements by 2020 and 80 % by 2050. Furthermore, renewable energy sources would provide 30 % of primary energy by 2030 and 60 % by 2050. A reality check is required on the future targets being bandied about. Huge subsidies have gone into wind energy (mean wind speeds in the inner Länder are low and capacity factors achieved often below 12 % in these areas) and into solar PV (Germany, even in the South, is not among the world's leading countries in terms of solar insolation, and subsidies have recently been heavily cut back resulting in the bankruptcy of some solar energy companies—as has occurred in a number of other industrialized countries recently). Although Germany has taken a leading position in support of the Desertec concept (placing large sets of parabolic trough mirrors in the Mediterranean region—notably in North Africa—and transmitting electricity from these Concentrating Solar Power plants by ultra high-voltage direct current transmission to Northern Europe), sociopolitical uncertainties in North Africa have been compounded by the "Arab Spring." Then in March 2012, the closure of 17 nuclear reactors was announced.

The UK has apparently eagerly followed the German example in terms of emissions' reduction and renewable energy targets, though not yet in the abandonment of nuclear power. Thus, the UK has called for the EU to adopt a 30 % reduction in greenhouse gas emissions from 1990 levels by 2020 and an 80 % reduction by 2050. As we have seen, the adoption of rational emissions' accounting standards would quickly expose the irrationality and lack of realism of such targets.

Another area where UK data and targets require close examination is the efficacy of renewable energy. Capacity (or load) factors achieved in electricity generation are provided by the UK's Department of Energy and Climate Change:

UK capacity factors achieved by electricity generating type—2010	
Combined cycle gas turbines	61 %
Nuclear power stations	60 %
Conventional coal-fired stations	41 %
Onshore wind	22 %
Offshore wind	30 %
Hydro	30 %
Biomass (including co-firing)	53 %
Landfill gas	57 %

Source: UK Digest of Energy Statistics, July, 2011, pps. 146 and 214

These figures raise a number of questions. At a relatively trivial level, it may be noted that the UK's nuclear sector once averaged a capacity factor of around 80 %. Given its low power density, the figure for biomass may be considered rather misleading. More intriguing are the claims that UK wind energy developments "typically" achieve a capacity factor of 30 %, and at least one author has claimed 35 % is closer to modern reality. The official UK planning guidance for renewable energy (the Companion Guide to Planning Policy Statement 22 or PPS 22) claims wind turbines "typically" achieve a capacity factor of 30 % within a range of 20–50 % (Planning for Renewable Energy 2004). These claims are fanciful and readily challenged by reference to the data provided by the wind energy operators themselves (Jefferson 2012a, b).

Thus, for onshore developments in England, the annual average capacity factors achieved were 22.7 % in 2007, 26.2 % in 2008, 21.2 % in 2009, and 18.7 % in 2010. The calendar year figure for 2011 was 22.9 %. More disturbingly, a significant proportion (two-thirds in 2010, one-third in 2009) of these onshore developments fell below the 20–50 % range of capacity factor achievement claimed in PPS 22. These figures belie claims that the UK is the windiest, or one of the windiest, countries in Europe. For example, a glance at the European Wind Atlas shows that, although Scotland may be the windiest country in Europe, most of England is not very windy. In Scotland average capacity factors for onshore wind energy developments have generally fallen within the range 23.5–28.5 % in recent years, with many achieving over 30 % (a few over 40 %) and few achieving under 20 %. Thus, in the country where electricity demand is greatest, the onshore mean wind speeds are among the lowest in Europe; and where onshore wind speeds are highest, electricity demand is modest and grid connection to the country on its southern boundary is poor (see Jefferson 2012a, b, for a fuller description). Denmark suffers some of the same problems: an inadequate grid system is among the reasons why only about half the wind-generated electricity it produces can be harnessed to the benefit of the Danish electricity consumer.

Not only are the capacity factors claimed for wind energy in the UK greatly exaggerated, there is little official discussion of the estimated costs of building 17 new gas-fired plants (over £10 billion) to provide a “spinning reserve” in the event that there is insufficient wind. There is a high likelihood that by the early 2020s, there will be days when the UK will be able to supply over 20 % of its electricity requirements from wind energy—only to be confronted a few days later with wind energy scarcely able to provide 2 %. This seems neither efficient nor sustainable. Furthermore, if the industry and government are in denial about the existence of aerodynamic modulation from wind turbines, visual intrusion, and adverse effects on residential property values (England’s population density now exceeds 407 people per square kilometer and in its South East region approaches 1,700), social acceptability will remain a major issue.

But in the context of efficiency, perhaps the most remarkable statement that has emerged is the following from the British Wind Energy Association (now RenewableUK): “the meaning of efficiency is a redundant concept to apply to wind energy, where the fuel is free” (Bruce 2008). This appears to overlook the wider implications of variability in the relevant resource (wind or solar especially) and the importance of selecting optimal sites. It also appears to overlook the industry’s claims that they have spent £ billions in investments and the cost of subsidies. It is estimated that the current UK program will cost domestic and business electricity customers £100 billion by 2030 in subsidies alone. The cost of that subsidy per worker employed in the UK wind energy sector in the year to March 2010 was £57,000 (compared to the median public sector income of £29,000 and median private sector income of £25,000) (Constable 2011). The nearest comparable figures are for Spain’s subsidies to wind power and solar PV, which have now largely collapsed due to the global financial and Eurozone crises, of around 8 € billion between 2000 and 2008, with an average subsidy per renewable energy sector worker of 571,138 € (Constable 2011, pp. 92–93).

The variability of wind also places large question marks around UK energy supply security and the wisdom of erecting at least 10,000 more turbines. (By May 2012, there were 3,730 wind turbines operational in the UK, over 1,300 under construction; and more than a further 2,100 consented. Of those offshore 568 were operational, 665 under construction, and a further 300 approved.) It is highly likely that, with coal-fired power stations being decommissioned under the EU's Large Combustion Directive and withdrawal of existing nuclear power stations (most of them well before new plants come on stream, a subject which in turn has become more challenging as two major companies withdrew from the UK market early in 2012), there will be severe disruptions to electricity supplies in the UK before 2016. Exacerbating this concern is the UK's failure to expand its storage capacity for natural gas, making it far more vulnerable to supply disruption than is the case for Germany and France, despite this weakness being highlighted since the year 2000. There are also grounds for believing that where a country has decided to rely heavily upon intermittent wind energy for electricity generation, then conventional generating plants with relatively low capital costs (though their operating costs may at times be higher) will be favored. The result is likely to be even greater reliance upon open cycle and combined cycle gas turbine plants rather than, say, nuclear. This is again likely to increase supply security risks.

There are question marks over the use of other sources of renewable energy where the impacts may be severely adverse (such as exploitation of biomass/biofuels) or their contribution marginal or inefficient because of the relative lack of resource (e.g., lack of solar irradiation). Among the most disturbing cases are planning decisions which permit the simple burning of palm oil in proposed electricity generating plants in rural England, even when the Planning Inspector involved is informed about associated emissions (on average 33 tonnes of carbon dioxide are estimated to be emitted for every tonne of palm oil produced in Indonesia, before its transportation to the generating plant). In such cases the Planning Inspector has claimed that palm oil is defined as a renewable source of energy under UK Planning Guidance (PPS 22 again), apparently regardless of deforestation and species' habitat loss, and has approved the burning of palm oil.

There is also a growing literature on the impacts of biomass and biofuel production on food availability and prices, on water requirements, and on biodiversity. Many of these highlight diversion of agricultural land from food production, with adverse consequences for food availability and prices, as well as adverse environmental impacts. The technical potential of second- and third-generation biofuel technologies is interesting, but the time horizon and scale of output provide little ground for optimism in the short and medium term (OECD/IEA 2008). There are ecological concerns about estuarine barrages (the La Rance scheme "destroyed the local ecology" according to its developer) (Rodier 1992). Unless and until political stability is assured in North Africa, Concentrating Solar Power is unlikely to take off on the required large scale. In short, the potential for large-scale efficient and sustainable renewable energy schemes on the supply side appears to be far more modest than usually claimed.

The distortions which have arisen in the renewable energy sector are partly the result of excessive or poorly targeted subsidies. (The £100 billion plus subsidy program for the UK wind energy industry, funded by electricity customers, has already been noted. Germany's solar PV subsidies have been widely criticized as excessive.) This is an important issue. Yet the subsidies still going to fossil fuels—globally over US$550 billion per year (IEA estimate for 2008)—and with organizations like the World Bank involved (over US$3 billion in 2008, with lending to the coal sector 256 % up on 2007) and countries such as Germany still involved (Germany's coal sector enjoyed 16 € billion of subsidy in the period 2005–2012, and no cut in subsidies to the coal sector is proposed before 2018) are surely even less acceptable.

8 Planet Under Pressure

Of the nine "Policy Briefs" prepared for the UN Conference on Sustainable Development (Rio+20) by "the scientific community," No. 8 covered "An energy vision for a planet under pressure." (Rio+20 2012). It agreed that the world faces an array of challenges, from access to modern energy services for the poor to the reliability and security of supply. It called for "a transformation" of the global energy system, where "Improving energy efficiency is the single most important option." It recognized that there needs to be greater emphasis on demand-side efficiency in particular. It raised "the question of whether institutional and political impediments to achieving more integrated policy-making can be overcome, given vested interests."

This chapter has expressed severe doubts whether the hoped-for transformation is feasible, whether voluntarily or involuntarily, as a realistic "vision towards 2050." Whether we look at the plight of the 40 % of the world's population that does not yet have access to modern energy services; or the global concerns about the continuing availability of "conventional oil," the scale of recoverable shale gas resources, the acceptability of continued coal combustion, the security of natural gas supplies, and the failure to focus on thorium as a non-fissile alternative to uranium in the regeneration of nuclear energy's prospects; or the realism of claims about the supply of modern energy services from future renewable energy supplies, there are solid grounds for deep pessimism.

Our global and, where they exist, regional negotiating systems have been found not fit for purpose over the past twenty years—whether in relation to energy policy issues or environmental ones. National policies have similarly been characterized by internal contradictions and failure to meet stated (frequently unrealistic) targets.

Some 40 years ago there began a period during which there was espousal of the hope that social values and individual lifestyles would transform towards "voluntary simplicity" (Mitchell 1973). This appeared unrealistic though arguably attractive then, as it does now. But, as we observe the energy return on (energy) invested flagging (the concept of EROI), the traditional modes of thinking and action—in economics, politics, and energy—appear seriously inadequate to meeting the challenges of global energy policy and security (Hall and Klitgaard 2012, etc.). Closer attention now seems needed to the ideas and works of those, such as Ted Trainer, who believe that the various forms of renewable energy cannot sustain current forms of "consumer society" and that unless we shift as a world towards a "simpler way" of a "conserver society" voluntarily, then it will be forced upon us involuntarily. But in the process there will be massive conflict and dislocation (Trainer 1996, 2007, 2010, etc.).

9 Conclusions

The past 20 years have seen an unfortunate path of evolution in the energy sector. Largely ignored, or mixed up with other aims and targets, energy as a general topic and energy efficiency as a particular one have failed to get sufficient recognition or rational support in policies, measures, and investments. Part of the problem has been the uncertain path trodden by UN agencies and the UN system more generally. Part has arisen at regional or national levels. Partly this has been due to lobbying by vested interests.

These years, like the 20 years before them, have generally been marked by suboptimal investments on a grand scale which have done little to relieve poverty in general or energy poverty more particularly. They have failed to meet or address effectively the need to ensure that development meets the needs of the present without compromising the ability of future generations to meet their own needs as set out in the 1987 (Brundtland) Report of the World Commission on Environment and Development. They have frequently undermined conservation and efficiency goals and other measures. They have done little or nothing to curb carbon emissions or their atmospheric concentration, supposing anthropogenic causation is a real threat, on sound emissions' inventory criteria. There remain disconcerting levels of subsidies to fossil fuels and perverse incentives for renewable sources. Although there are signs of greater recognition of energy efficiency as being the most cost-effective route to tackling a range of pressing sustainability issues, whether these signs will be translated into effective action and desired results remains an open question. One ongoing challenge will be the "rebound" effects of resources freed up by such energy efficiency improvements as occur being plowed back into higher energy use (the Jevons paradox pointed out as long ago as 1865). Yet a more fundamental question remains: will our world find itself required to abandon traditional economic growth and consumption criteria and obliged to embrace simpler, more conservation minded, lifestyles at the individual and societal level?

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Michael Jefferson is Editor of the journal 'Energy Policy'; Affiliate Professor at ESCP Europe Business School (London campus); and an Advisory Board Member of ESCP Europe's Research Centre for Energy Management. He is also Visiting Professor in the Department of Economics and International Studies at the University of Buckingham, UK. He has been the Chief Economist of The Royal Dutch/ Shell Group, Head of Planning and of Supply Strategy for Shell International's European Organisation, and a Director of Oil Supply and Trading in Shell. He was Deputy Secretary-General of the World Energy Council 1990–1999. From 1988 to 2013 he was Professor of International Business and Sustainability at London Metropolitan Business School. He has contributed as Lead Author, Contributing Author, Editorial Reviewer, Expert Reviewer, and Synthesis Report drafting team member in various IPCC Assessments and was awarded the IPCC's Certificate for his contributions to the IPCC's award of the Nobel Peace Prize in December 2007. He was the Convening Lead Author of the energy policies chapter in the UN's 'World Energy Assessment' (2000) and for many years chaired the Policies Committee of the World Renewable Energy Network/Congresses. He has worked with 17 UN Agencies over the years.

Change in Energy Structure and Energy Security under Climate Mitigation Scenarios

Ken'ichi Matsumoto

Abstract Purpose The purpose of this study is to investigate how energy structure and energy security of the world and countries will change in the future under various climate change policies, and to better understand the relationship between climate and energy issues that could be used in the related policy discussions.
Design/Methodology/Approach The study is conducted by a simulation model. A reference scenario and three policy scenarios, based on the Representative Concentration Pathways, are analyzed until the end of this century using the AIM/CGE [Global] model. The scenarios are compared from primary and final energy structure and trade of fossil fuels.
Findings Fossil-fuel-centered energy structure shifts to rely more on renewables by introducing climate change policies. Furthermore, the percentage of the trade amount of fossil fuels is smaller in the policy scenarios than in the reference scenario. The findings reveal that energy security also improves by taking climate change measures.
Originality/Value The paper studies an energy security issue in a global framework. In addition, the analysis is based on a long-term perspective. The results of this research could be used for exploring the solutions for both energy and climate change issues simultaneously in a global basis.

Keywords CGE model • Climate mitigation • Energy structure • Energy security • RCPs

K. Matsumoto (✉)
School of Environmental Science, The University of Shiga Prefecture, Shiga, Japan
e-mail: matsumoto.k@ses.usp.ac.jp

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1 Introduction

Climate change is one of the most significant global environmental issues for the present society, and policy discussions from mid- to long-term perspectives are continuing all over the world and the international arena such as in the United Nations Framework Convention on Climate Change (UNFCCC). The Copenhagen Accord was made at the fifteenth session of the Conference of the Parties (COP) to UNFCCC in December 2009, and the Annex I parties and some major non-Annex I parties submitted their pledge on greenhouse gas (GHG) emission reduction by the end of January 2010. Although the second commitment period of the Kyoto Protocol and a mandate to get all countries in 2015 to sign a deal that would force them to cut GHG emissions no later than 2020 are agreed at COP17, some important developed countries such as Canada, Japan, and Russia will not have their emission reduction targets in the second commitment period.

On the other hand, energy has been a significant global issue such as rise in the price and depression of the resources. In recent years, energy demand is dramatically increasing in large emerging countries such as China and India accompanying the economic and population growth, and the demand is expected to increase further (BP 2011; IEA 2010). As a result, there are growing concerns about tight energy supply and demand in the future. In addition, since production and reserves of fossil fuels such as crude oil and natural gas are predominately located (BP 2011), countries poor in energy resources such as Japan will face substantial price fluctuation and geopolitical risks.

Climate change measures[1] are to reduce GHG emissions, especially reducing CO_2 emissions is most effective. In order to reduce CO_2 emissions, promotion of energy savings and shifts to low-carbon energy, namely, shifts from coal to natural gas and from fossil fuels to renewables, are necessary. It is required to further promote energy savings and renewables use to realize tougher emission reduction.

If energy savings and renewables use, which is basically domestic energy, are enhanced as climate change measures in this way, the volume and dependence of import of energy will decrease. It is also effective for an energy security issue. The relationship between climate change and energy security issues is indicated in Stanislaw (2007). In addition, the role of energy in climate change policies is discussed such as in IEA (2008).

Comprehensive research on energy security has been done targeting Asian countries as a part of the Asian Energy Security Project (Falk and Settle 2011; Huang et al. 2011; Kalashnikov et al. 2011; Katsuta and Suzuki 2011; Kim et al. 2011; Takase and Suzuki 2011; Toan et al. 2011; Valentine 2011; Von Hippel and Hayes 2011; Von Hippel et al. 2011a, b, c, d, e; Wang et al. 2011). They analyze the issue for some Asian countries such as Japan, Korea (North and South), and China and the region as a whole from either the narrowly

[1] In this study, only mitigation measures are considered as climate change measures (policies), and adaptation measures are not considered.

defined energy security (i.e., considering energy security from energy supply) or broadly defined energy security (i.e., considering energy security not only from energy supply but also from economy, technology, environment, society and culture, and military) using the LEAP (Long-range Energy Alternatives Planning) software system developed by the Stockholm Environment Institute (Von Hippel et al. 2011d, e). LEAP is a scenario/energy path-based energy-environment modeling tool to create models of different energy systems, supporting a wide range of different modeling methodologies from bottom-up to top-down. Energy paths/scenarios are self-consistent storylines of how an energy system might evolve over time (often around 20–50 years) in a particular socioeconomic setting and under a particular set of policy conditions (Heaps 2008; Von Hippel et al. 2011d). The results from multiple energy paths within a country or region are compared to indicate which path is preferable with regard to different measures of energy security, such as cost, physical energy output, fuels imports and exports, technological development, or environmental emissions. In addition, other external methods such as diversification indices, multiple-attribute analysis and matrices, and qualitative analysis can be applied using the results from LEAP for further analysis on energy security (Von Hippel et al. 2011d). Since their interest is Asia, they do not mention about other countries and regions and the world. However, it is indispensable to see in a global basis when considering the energy security issue, since energy resources are actively traded and used in a global system, and a lot of important suppliers are in non-Asian regions such as Middle East, Russia, and the USA.

In this study, we analyze the global and national energy structure and energy security when introducing climate change policies using a computable general equilibrium (CGE) model. We focus on the narrowly defined energy security.

2 Methodology

In this study, we use the AIM/CGE [Global] model (Masui et al. 2011; Matsumoto and Masui 2010) for the analysis. The AIM/CGE [Global] model is a multi-sector and multiregional recursive dynamic CGE model. The model is disaggregated into 24 geographical regions each producing 21 goods and services (Tables 1 and 2). Basically, each goods is produced by a single sector, but multiple power sources are considered for power generation. In this study, electric power can be generated using thermal, hydro, and nuclear, as well as renewables including solar, wind, and biomass. Future thermal power plants, including integrated gasification combined cycle (IGCC), are assumed to be available both with and without carbon capture and storage (CCS) technology. Biomass energy is also used for producing bioethanol and biogas, which are alternatives for direct use of fossil fuels. Each sector in the economy is estimated by a nested constant elasticity of substitution (CES) production function. As an example of a CES production function, assuming a goods/service in sector s is

Table 1 Structure of regions

Code	Region
JPN	Japan
CHN	China
KOR	Korea
IDN	Indonesia
THA	Thailand
XSE	Other Southeast Asia
IND	India
XSA	Other South Asia
AUS	Australia
NZL	New Zealand
XRA	Other Asia Pacific
CAN	Canada
USA	United States
MEX	Mexico
BRA	Brazil
ARG	Argentine
XLM	Other Latin America
XE15	EU15 (Western Europe)
XE10	EU10 (Eastern Europe)
RUS	Russia
XRE	Other Europe
XME	Middle East
ZAF	South Africa
XAF	Other Africa

produced using labor (L), capital (K), and intermediate inputs (M) as the inputs, the function is expressed by Eq. (1):

$$Q_s = A_s(sl_sL_s^{\rho_s} + sk_sK_s^{\rho_s} + sm_sM_s^{\rho_s})^{\frac{1}{\rho_s}} \quad (1)$$

where Q is the quantity of production, A is a scale parameter, sl, sk, and sm are shares of each input ($sl + sk + sm = 1$), ρ is a substitution parameter ($= (\sigma-1)/\sigma$), and σ is elasticity of substitutions.

Resources, including COA, OIL, GAS, and OMN, are produced subject to finite and depletable resource limits. Specifically, the relationship between the magnitude and associated extraction costs of COA, OIL, and GAS is taken from Rogner (1997) (Fig. 1). In the model, it is assumed that the more resources are extracted, the higher the extraction costs and the more costly the resource use (and substitution to other inputs can occur as a result). Likewise, AGR, LVK, FRS, and biomass energy production require land, also a finite resource, in addition to other economic resources.

Each produced goods are delivered to final consumption, investment, intermediate inputs, and/or exports. The time period of the model is from 2001, the base year, to 2100. Aggregate investment demand in each period is set exogenously to meet prescribed GDP growth rates. Future GDP values are taken from the Sustainability

Table 2 Structure of commodities

Code	Goods and service
AGR	Agriculture
LVK	Livestock
FRS	Forestry
FSH	Fishing
OMN	Mining (except fossil fuels)
EIS	Energy intensive products
M_M	Metal and machinery
FOD	Foods
OMF	Other manufacturing goods
WTR	Water
CNS	Construction
TRT	Transportation
CMN	Communication
OSG	Public services
SER	Other services
COA	Coal
OIL	Crude oil
GAS	Natural gas
P_C	Petroleum products
GDT	Gas distribution
ELY[a]	Electricity

[a]In ELY, following subsectors (power sources) have been considered: coal fired, petroleum products fired, gas fired, nuclear, hydro, biomass, waste, geothermal, solar, wind, and other renewables. As for the advanced technology, IGCC and thermal power plant with CCS are available

First scenario in the Global Environment Outlook (GEO) 3 (UNEP 2002) and GEO4 (UNEP 2007) of the United Nations Environment Programme (UNEP). The rates of energy efficiency improvement are also set exogenously using those derived from the Special Report on Emission Scenarios (SRES) B2 scenario (Nakicenovic and Swart 2000). The model applies a putty-clay approach for capital. Capital is divided into an old capital stock and new capital. Old capital cannot move between sectors, while new capital can be installed in any one sector. However, once new capital is assigned to a sector, it becomes old capital in all subsequent periods. The energy efficiency improvements and other technology changes are applied to new capital only. Productivity of aggregate capital is the weighted sum of technology levels in old and new capital. The increase rates of labor are also set exogenously based on the population growth rates of the UN medium variant until 2050 (UN 2007) and UN long-term estimation beyond 2050 (UN 2004).

The AIM/CGE [Global] model is constrained to follow the global GHG emission pathways[2] obtained from the AIM/Impact [Policy] model (Hijioka et al. 2008)

[2] In this study, not only six Kyoto GHGs (i.e., CO_2, CH_4, N_2O, HFCs, PFCs, and SF_6) but also CO, NO_X. NH_3, SO_2, non-methane volatile organic compounds, black carbon, and organic carbon are considered.

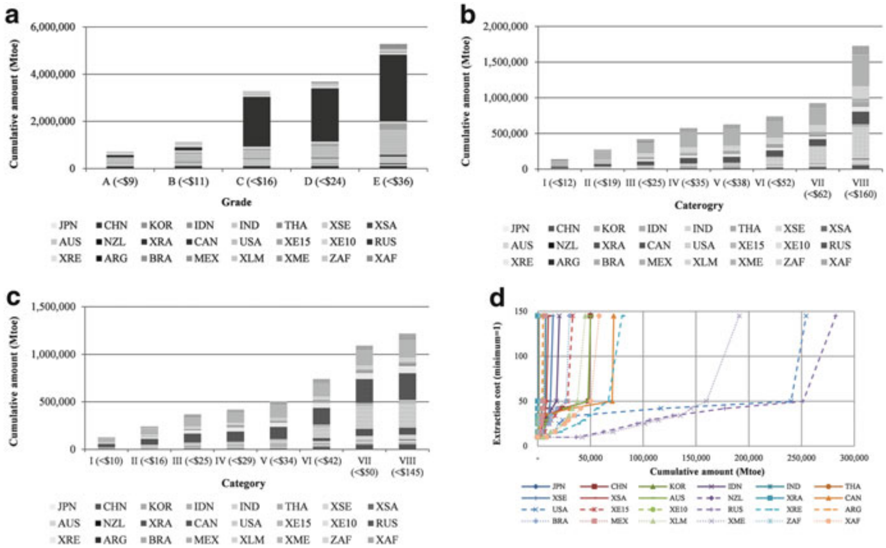

Fig. 1 Cumulative extractable amount of resources in each grade/category [(**a**) *upper left*, COA; (**b**) *upper right*, OIL; and (**c**) *bottom left*, GAS] and relationship between cumulative extractable amount of resources and extraction costs for GAS by region [(**d**) *bottom right*]. The grade/category and the corresponding costs are based on Rogner (1997), and the amount of resources in each region is based on Rogner (1997) and our own calculation

for the policy scenarios (see Sect. 3.2 for each scenario). The global GHG emissions are assigned to the regions in proportion to their population in 2050 and beyond. Between 2001 and 2050 regional GHG emission limits are set by linear interpolation of the emissions in 2001 and the assigned limits in 2050. In the model, GHG emission rights are freely traded between regions globally for all gases.

The household sector is assumed to own all production factors (i.e., capital, labor, land, and resources) in each region and to supply them to the production factor markets. The income is derived from sale of these factors. The household sector distributes its income between final consumption goods and services and savings. Savings rates are set equal to investment, which is set exogenously to meet prescribed GDP growth rates as described above. The demand for final goods and services is derived as the result of utility maximization subject to an unsaved income constraint in each period.

The model is calibrated to reproduce economic and energy activity levels in 2001 using the GTAP6 database (Dimaranan 2006) for economic activity levels and the energy balance of the International Energy Agency (IEA 2007a, b) for energy and benchmark GHG emission rates.

3 Scenarios

3.1 Reference Scenario

As a first step in the process of developing policy scenarios, we develop a "no-climate-policy" reference scenario. This scenario assumes that policies and measures undertaken to control other environmental problems are adopted but is constructed so that no policies motivated purely to control GHG emissions, except for those already in place, are undertaken and that existing policies are not renewed when they expire.

The reference scenario in this study is an updated version of the SRES B2 [AIM] scenario (Nakicenovic and Swart 2000). Updates include demographic and economic assumptions as described in the previous section. That is to say, the former is based on UN (2004, 2007) and the latter is based on UNEP (2002, 2007) instead of the original B2 scenario.

In the reference scenario, the global population grows from 6.1 billion to 9.8 billion between 2001 and 2100, with a peak between 2080 and 2090. Global GDP grows from $30 trillion to $225 trillion between the same periods. Primary energy supply in the world in 2100 reaches 1189EJ/year, and China becomes the largest economy in terms of both GDP and energy demand. Renewable potential and other new technology capacities follow the World Energy Outlook (IEA 2008) and Masui et al. (2010). Annual CO_2 emissions become 27.7 GtC in 2100. As a result, total radiative forcing reaches 7.3 W/m^2 in 2100.

3.2 Policy Scenario

In this study, the Representative Concentration Pathways (RCPs) are used for the climate change policy scenarios.[3] RCPs are the first step toward the next IPCC Assessment Report (fifth version) and one of the latest scenario families in climate change research. RCPs are defined by radiative forcing levels in 2100 and consist of four scenarios, namely, the lowest 2.6 W/m^2, the highest 8.5 W/m^2, and the two middle scenarios of 4.5 W/m^2 and 6 W/m^2 [Fig. 2. For the original RCPs, see 2.6 W/m^2: Van Vuuren et al. (2011b); 4.5 W/m^2: Thomson et al. (2011); 6 W/m^2: Masui et al. (2011); and 8.5 W/m^2: Riahi et al. (2011)]. CO_2 emissions in 2100 are 29.6 GtC (8.5 W/m^2), 13.0 GtC (6 W/m^2), 5.0 GtC (4.5 W/m^2), and 0.47 GtC (2.6 W/m^2), respectively (Fig. 3).

In this study, these policy scenarios are analyzed using the AIM/CGE [Global] model and compared with the reference scenario.[4]

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[3] See Moss et al. (2008, 2010) and Van Vuuren et al. (2011a) for the details of RCPs.

[4] Since the model used in this study is different from those used in the original RCP analyses, the features are different from them except for the 6 W/m^2 scenario. Radiative forcing of the 8.5 W/m^2

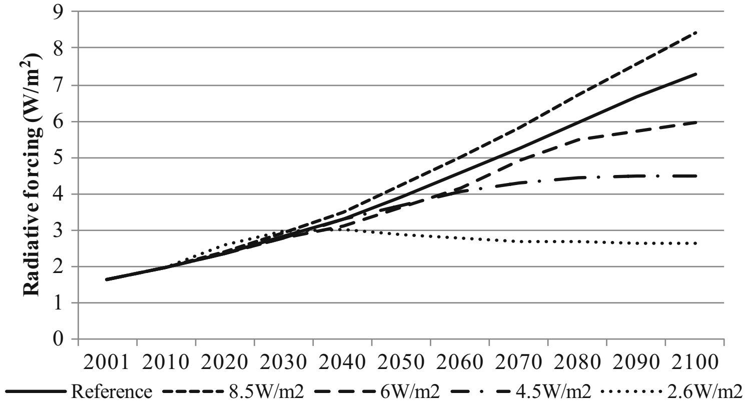

Fig. 2 Radiative forcing levels (Since these radiative forcing pathways are our calculation, they are different from original RCPs)

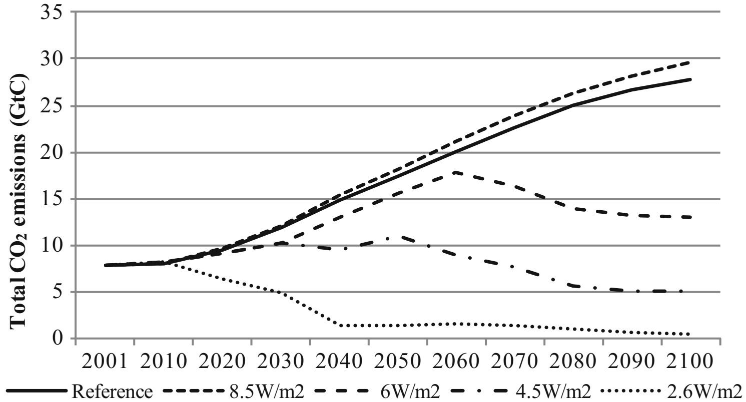

Fig. 3 Total CO_2 emissions (Since these emission pathways are our calculation, they are different from original RCPs)

4 Results and Discussions

Concerning primary energy in the world, although the demand increases in all the scenarios until 2100, it lowers in the stricter scenarios (the demand is 429EJ in 2001, and 1189EJ in the reference scenario and 651EJ in the 2.6 W/m^2 scenario in 2100). In addition, energy structure changes drastically (Fig. 4). In the reference scenario, fossil fuels occupy 90 % of the global primary energy demand in 2100.

scenario is higher than that of the reference scenario of this study, meaning that it is required to increase GHG emissions from it. Since such operation has little meaning, we do not show the result of the 8.5 W/m^2 scenario below.

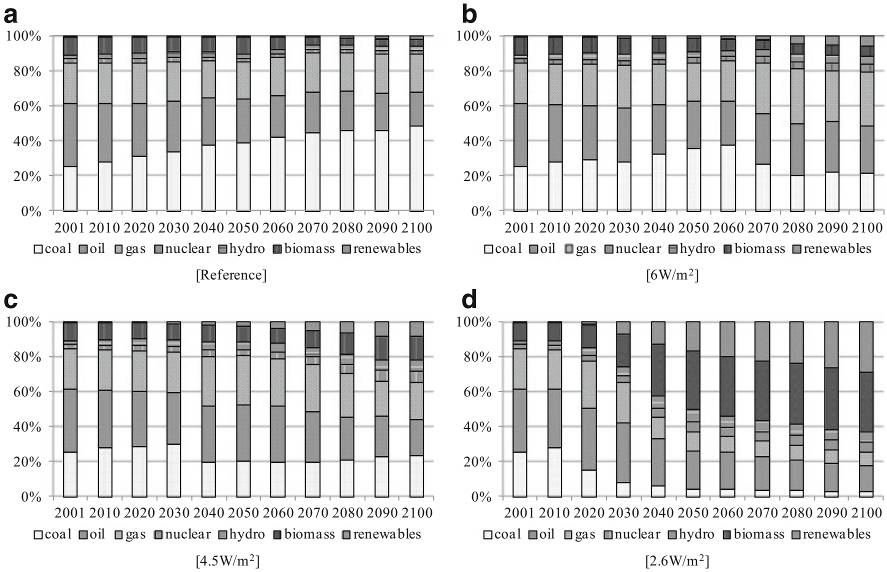

Fig. 4 Structure of primary energy in the world (“renewables” in the graphs include renewables except hydropower and biomass)

It is due to dependence on coal, the price of which is relatively low in its no-GHG-constraint situation. In the policy scenarios, on the other hand, the percentage of fossil fuels, especially that of coal, becomes lower and that of renewables becomes higher instead. The percentage of renewables is remarkably high in the 2.6 W/m^2 scenario, higher than 60 %. In the renewables, except for hydropower and biomass, the percentage of wind power is the highest, about 75 % in the reference scenario. The larger the amount of emission reduction, the higher the percentage of solar power (the percentage of wind power is 58 % and that of solar power is 40 % in the 2.6 W/m^2 scenario).

As a metric for energy security implications of different patterns of energy supply, the Herfindahl index [Eq. (2)], which is based on diversity indices in the economic and financial analysis, is available (Neff 1997; Von Hippel et al. 2011d). The index has a maximum value of one when there is only one energy type and goes down with increasing diversity of energy types, so that a lower value of the index indicates more diverse supply conditions:

$$H = \sum_i x_i^2 \tag{2}$$

where H is the Herfindahl index and x_i is the fraction of primary energy demand by energy type i.

Applying the index to the scenarios, the value in 2001 is 0.26; those in 2050 are 0.27 (reference), 0.26 (6 W/m^2), 0.24 (4.5 W/m^2), and 0.21 (2.6 W/m^2); and those in

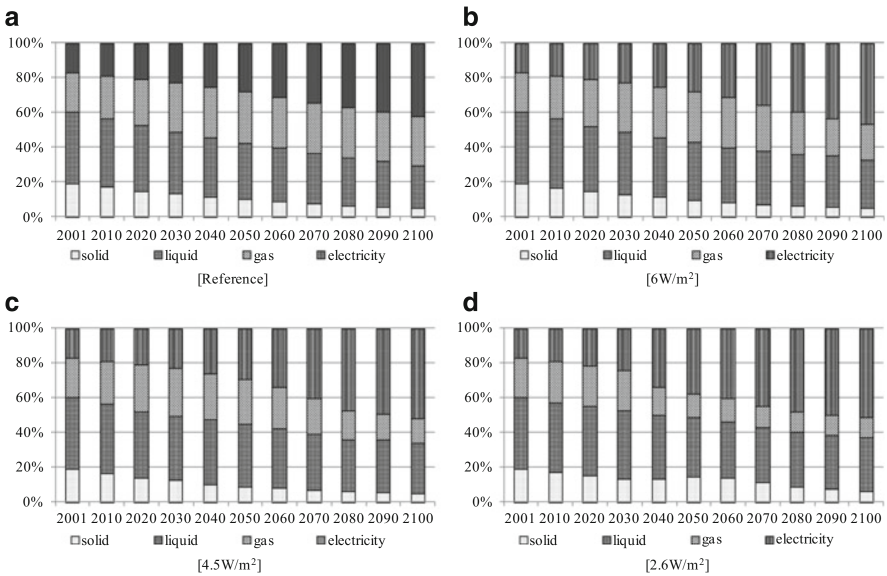

Fig. 5 Structure of final energy in the world

2100 are 0.33 (reference), 0.23 (6 W/m^2), 0.18 (4.5 W/m^2), and 0.24 (2.6 W/m^2). The diversity worsens with time in the reference scenario because of its dependence on coal, while it improves in the three policy scenarios. Although the value in the 2.6 W/m^2 scenario is lowest in 2050, it worsens and becomes higher than the others in 2100. However, since it is due to increase in the percentage of renewables, it does not necessarily mean worsening of the energy security.

Since most of renewables are used for power generation, the percentage of electricity in final energy demand also increases in the stricter scenarios (Fig. 5). Although it increases from 17 % in 2001 to 42 % in 2100 even in the reference scenario, it exceeds 50 % in 2100 in the 2.6 W/m^2 scenario.

Observing the trade amount of fossil fuels in the world, it doubles in 2100 compared to the 2001 level in the reference scenario. On the other hand, although the trade amount also increases compared to the 2001 level, about 154 %, in the 6 W/m^2 scenario, it is 25 % smaller than the reference scenario. In the 4.5 W/m^2 and 2.6 W/m^2 scenarios, the trade amount in 2100 is 92 % and 52 % in 2100, which is lower than the 2001 level. Observing it by fossil fuel, although the trade amount of natural gas and crude oil relatively increases accompanying decrease in coal demand in the policy scenarios, the trade amount of both becomes smaller in absolute terms compared to that of the reference scenario and even smaller than the 2001 level in the strict scenarios.

These results are also true in a regional basis. For example, in China and the USA, which are the two most energy-consuming countries, the percentage of renewables tends to increase in the stricter scenarios (Fig. 6). The Herfindahl

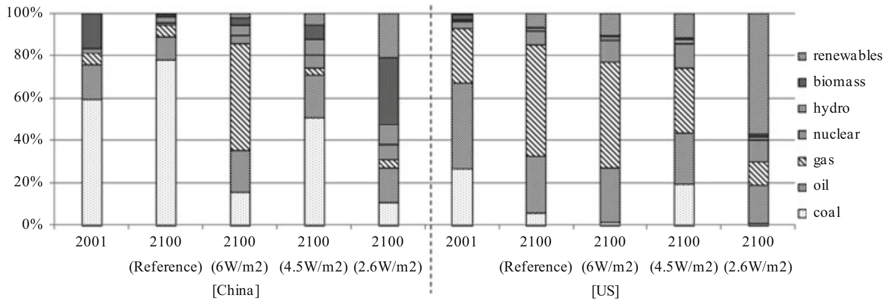

Fig. 6 Structure of primary energy in China and the USA

index values in China are 0.41 in 2001 and 0.62 (reference), 0.32 (6 W/m^2), 0.31 (4.5 W/m^2), and 0.20 (2.6 W/m^2) in 2100 and those in the USA are 0.30 in 2001 and 0.36 (reference), 0.33 (6 W/m^2), 0.21 (4.5 W/m^2), and 0.27 (2.6 W/m^2) in 2100. As a result, the percentage of electricity in final energy in 2100 increases from 44 % in the reference scenario to 64 % in the 2.6 W/m^2 scenario in China and from 38 % to 48 % in the USA. In addition, the import amount of fossil fuels becomes 141 % of the 2001 level in 2100 in the 2.6 W/m^2 scenario, which is lower than the reference scenario (530 %), in China. Likewise, the amount is 31 % of the 2001 level in 2100 in the 2.6 W/m^2 scenario, which is lower than the reference scenario (65 %), in the USA.

From the above analysis, it is necessary to decrease the dependence on fossil fuels and to increase the amount of renewables compared to the reference scenario in order to reduce GHG emissions. It also links to reducing the trade amount of fossil fuels. That is to say, the self-sufficiency of energy supply will increase by promoting climate change measures; especially energy-importing countries can also improve their energy security. Conversely, such situations can negatively affect the economy of energy-exporting countries.

5 Concluding Remarks

In this study, we analyzed the change in energy structure and impacts on energy security when introducing climate change policies by using the AIM/CGE [Global] model. In the analysis, we used RCPs for the policy scenarios and compared them with the reference scenario.

As a result, in order to reduce GHG emissions, we need to shift energy structure from the fossil fuel centered to the more renewables used. The stricter the emission reduction, the larger shifts will be required. It is also indicated that such shifts also improve the self-sufficiency of energy supply and are consequently effective from the viewpoint of energy security.

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Ken'ichi Matsumoto is an Assistant Professor at School of Environmental Science, the University of Shiga Prefecture. He is also a Visiting Research Associate at London Metropolitan Business School, London Metropolitan University. He received his Ph.D. in Policy Studies from Kwansei Gakuin University.

Insights on Cooperative Electricity Consumption in Human Aggregates from a Thermodynamic Analysis: Implications for Energy Policies

Klaus Jaffe

Abstract Purpose Successful energy policy and energy security are dependent on political decision making based on a deep comprehension of the relationship between human behavior and energy use. Political and economic phenomena of society are the emergent product of the interactions of individuals with different characteristics. Understanding the complexities of such systems will eventually improve the rate of success of political and economic actions, minimizing the environmental impact and maximizing human satisfaction.

Design/Methodology/Approach Thermodynamics is the science best designed for the study of the emergence of novel properties from the interaction of particles. It has successfully described closed systems near equilibrium and is expanding its scope of applications to evolving open systems. Here, irreversible thermodynamics and computer simulations are used to understand the dynamics of the emergence of prosocial behavior that allows sustained large-scale cooperation and its possible application to manage future energy policies.

Findings Computer simulations identified the relevant aspects that allow for the sustained administration of public goods. They also tested for social arrangements that favor cooperation. Empirical studies based on these findings revealed the existence of synergies that arise from aggregate energy use in humans and animal societies.

Practical Implications Humanity will keep growing in the total number of individuals and in the intensity of per capita consumption, increasing global energy needs. This provides an incentive to improve the efficiency in energy production and use, which can be achieved with improved national and international cooperation. Policies addressing cooperation are essential for a better management of the side effects of energy consumption that are not amenable to control by market forces alone, allowing to achieve successful energy policies that provide for better energy security.

K. Jaffe (✉)
Universidad Simón Bolívar, Apartado 89000, Caracas 1080, Venezuela
e-mail: kjaffe@usb.ve

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Originality/Value The interdisciplinary approach to complex global dynamics of energy consumption allows identifying some basic issues on which sustained international cooperation can be built.

Keywords Energy • Electricity • Biology • Thermodynamics • Global • Consumption • Synergy • Complexity • Evolution • Entropy • Negentropy • Cooperation • Altruism • Society

1 Introduction

Complex systems are constituted by many different component parts. The interactions of these component parts produce outcomes that result in emergent properties at higher aggregate levels of the system. The most developed science studying this kind of phenomena is certainly thermodynamics. Application of thermodynamics to social dynamics is not new. I will cite just a few examples.

Erich Muller (1998) and Libb Thims (2007) describe loose analogies between intermolecular forces that govern the observable behavior of fluid systems and the social forces that drive human behavior. They (and many others) claim, based on this premise, that at least in principle, thermodynamics can be used to describe social systems (see also Encyclopedia of Human Thermodynamics). A different approach, acknowledging the peculiarities of open systems, was undertaken by Ilya Prigogine and colleagues (1972) which developed some starting points for applying irreversible thermodynamics to biological and social processes. Practical applications of thermodynamics to understand human history have recently been undertaken by Thomas Wallace (2009) and Ian Morris (2010). Morris, for example, uses a quantitative "Social Development Index" to analyze human history during the last 100,000 years with consistent and robust reference points. This index, despite its apparent complexity, is basically an estimate of per capita energy consumption of a society.

The most influential approach in applying thermodynamics to understanding life, however, has been that of Erwin Schrödinger's "What is Life?" (1944); Schrödinger used the paradoxical idea that the negative value of entropy is a measure of order of the body in question, and that life is something that feeds on energy and order or negative entropy. My aim here is—more than a generation later—to address these issues using modern tools of irreversible thermodynamics and complex system sciences.

Thermodynamic concepts have important uses in modern energy policy and energy security (see, for example, Dincer 2000; Li 2005) and seem to form a sound basis upon which to increase the understanding of the complex phenomena involved. These phenomena include aspects of ecology, biology, economics, sociology, and others and are very difficult to grasp comprehensively without a common conceptual framework that allows relating relevant features among them. The present work aims to contribute in building this common conceptual base that should help in designing successful energy policies allowing for increased energy security.

1.1 Background: Evolutionary Dynamics (Cultural, Biological, or Otherwise)

Using thermodynamics and evolutionary theory might allow identifying states in complex living systems that are more or less likely to exist. One such tool is stability analysis. Before engaging in such an exercise, however, a good understanding of the dynamics of evolution is required.

Regarding the dynamics of evolution, it is often argued that biological evolution based on information stored in genes, random mutations and reproduction, differs from that of cultural evolution which is grounded on learning from peers and parents, storage of information in individual memory or in many other devices, and reproduction of information through spoken or written information or through imitation. Yet from the standpoint of the dynamics of the memes or genes of information, both systems behave in very similar form. Computer simulations by Jaffe and Cipriani (2007) showed that both cultural and biological evolutionary dynamics are similar. They showed that the evolutionary dynamics in both cases diverges only quantitatively but not qualitatively. Results are summarized in Fig. 1 which represents a phase diagram of the stability of cooperative behavior in evolution assuming pure vertical transmission of information through genes of biological evolution modeled as G, pure horizontal transmission of information as is the case with gossip, modeled as H, and cultural transmission of information with both vertical and horizontal information transmission C. As revealed by this figure, all these evolutionary systems are able to evolve cooperative societies although with culture (G + H) this can be achieved at higher cost of cooperation.

This and other study then suggest that in open systems in far from thermodynamic equilibrium, certain “stable states” exist that might be reached through very different routes. If such stable states can be identified in the evolution of prosocial behavior, many interesting social phenomenon in societies might be explain and predicted.

2 The Model

2.1 Sociodynamica: An Overview of the Simulation Model

Each agent has to eat food in order to survive. They can get food either by collecting it from the food patches if they happen to wander over them or by getting it from other agents through commercial (barter or purchase) or altruistic interactions. Possession of minerals by agents, which could be also acquired by direct collection from the landscape or through interagent exchange, reduces the odds of being affected by catastrophes that occur randomly in time and affected agents randomly.

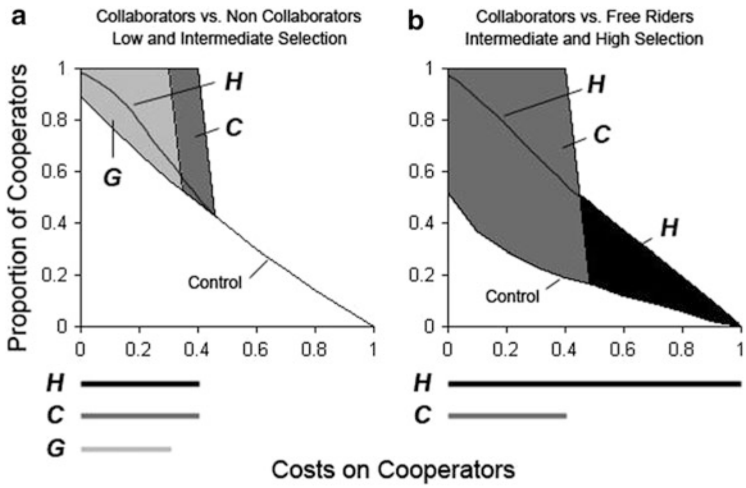

Fig. 1 Schematic representation of scenarios linked to cultural evolution, C and H, allowing collaborators (co) to dominate populations at cooperation costs higher than those allowed by the scenario representing biological evolution, G. *Darkened areas* represent the cost differential attributed to cultural evolution that benefits the dominance of co. The lower limits of *darkened areas* are the co values resulting from control runs. *Bars at the bottom* of each plot show the extent of costs along which different scenarios allow co to become the dominant strategy. G, vertical transmission of information using genes, *gray*; C, horizontal and vertical transmission of nongenetic information, *dark gray*; H, horizontal transmission of nongenetic information, *black*. (**a**) Co competing against non-collaborators (nco) without random shuffling of agent's locations, under an intermediate fitness advantage for grouping or intermediate selection (e.g., p0n = pnco = 0.5) on agents that do not form groups; (**b**) co competing against free riders (fr) without random shuffling, under a strong selection (e.g., p0n = pnco = 0.9) on agents that do not form groups. Costs on cooperators: mco = 0, 0.1, 0.2, ..., 0.9, 1 and mnco = mfr = 0

Agents have a simple memory of the last commercial transaction. The simulations tests for the survival abilities of agents and their capacity to accumulate wealth under variable circumstances. The virtual society can be programmed to have different levels of interaction. A first level simulates interactions with the environment, where agents collected food and/or minerals. A second level simulates the interchange of goods between agents in different economic scenarios.

Exchange of excess food for minerals, or vice versa, can be made by barter, using money but with fixed prices for each commodity or using money with prices fixed by the microlevel perception of supply or demand. Agents were specialized in one of three tasks, collecting food, collecting minerals, and exchanging goods.

Agents moved in random directions each time step. Each time an agent met another at a distance smaller than 20 pixels, an exchange could occurred. There were different scenarios where interactions could happen which included:

(a) *Barter Economy*: *Trading goods through barter and fixed prices*. Food was exchanged for minerals according to the following relation: 2 food units/1 mineral unit. Agents were given an amount of money (3 units) that was not used, serving as a control reference for the money amount for further comparisons.

(b) *Monetary Economy 1*: *Trading goods using money and fixed prices*. Agents were given three units of money. The exchange of goods occurred using money, so that agents could accumulate goods or money when selling their excess of goods. All transactions occurred at a set price for each good.

(c) *Monetary Economy 2*: *Trading goods using money and free prices*. Agents were given three units of money. The exchange of goods occurred using money, so that agents could accumulate goods or money when selling their excess of goods. An initial price for each good (food = 1, mineral = 2) is assigned initially to each agent. When an agent wanted to sell a good, without finding a buyer in a given time step, he/she decreased the price of that good for the next time step in one unit of price. A buyer not finding a seller of a given good in a given time step increased the price of that good for the next time step in one unit of price. The previous dynamic pretends to resemble the impact of scarcity on price setting in a perfect competition market.

2.2 Working with Simulations

The simulation model helped to explore the cost-benefit relationship of a given behavior and so asses the likelihood of it being evolved. Prosocial behavior has a cost to the actor at the start, but then eventually, the behavior will trigger circumstances that might produce positive returns to the group, including to the actor. Such a situation was studied in Jaffe (2002). This paper explored if society is better off, in aggregate economic terms, if altruism was more widely practiced among its members, by using an agent-based computer simulation model of a simple agricultural society. A Monte Carlo exploration of the parameter landscapes allowed the exploration of the range of possible situations of conflict between the individual and the group. The possible benefit of altruism on the aggregate wealth of society was assessed by comparing the overall efficiency of the system in accumulating aggregate utility in simulations with altruistic agents and with equivalent systems where no altruistic acts were allowed. The results showed that no simple situation could be found where altruistic behavior was beneficial to the group. Dissipative and equitative altruistic behavior was detrimental to the aggregate wealth of the group or was neutral. However, the inclusion of a synergic effect in the mutualistic interactions did increase the aggregated utility achieved by the virtual society.

The sum of the cost of all interactions (c) in a society has to be lower than the sum of the benefits of all these interactions (b), if behaviors favoring these interactions are to be maintained in evolution, be they cultural or biological. That is:

$$b/c > 1$$

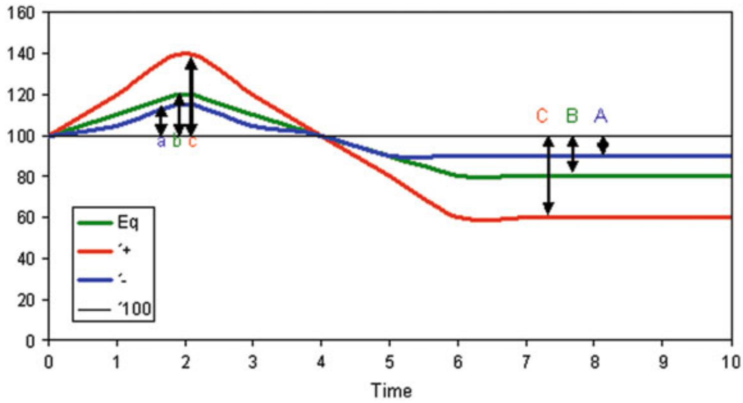

Fig. 2 Free energy diagram of prosocial behavior in time

I propose to call $b/c = s$, where s in the synergy the interactions elicit.

This simulation and many other published later in diverse journals confirm that prosocial behavior will be evolutionary stable only if the aggregate benefits to society compensate the aggregate costs involved. This fact allows us, in analogy of the properties of the free energy of Gibbs in thermodynamics, to draw the following model diagram:

Figure 2 presents three different situations for the evolution or establishment of prosocial behavior with different cost-benefit balances. In the three cases, the costs in the long term (activation energy) are lower than the benefits (drop in free energy). Thus, in all three cases, evolution should favor the establishment of prosocial behavior. Yet, a situation where the costs of prosocial behavior are small (like "a" in Fig. 2) and the benefits are large (like "C" in Fig. 2) should be more likely to evolve and should be more robust to disturbances than a system where the costs are high (like "c") and the benefits low (like in "A").

A way to decrease the costs and increase the benefits of prosocial behavior is punishment. A group of researchers postulated that selectively punishing free riders favored the establishment of prosocial behavior. Certainly, punishment affects the cost-benefit balance. Other simulations showed that in a quantitative formulation based on the cost-benefit analysis of the altruist and of society at large, "altruistic punishment" by itself cannot maintain altruistic behaviors (Jaffe 2004). "Altruistic behavior" is sustainable in the long term only if these behaviors trigger synergetic forces in the society that eventually make them produce benefits to most individuals. The simulations suggest however that "altruistic punishment" may work as a "social investment" and is thus better called "decentralized social punishment." This behavior is very efficient in enforcing social norms. "Altruistic punishment" emerges as here as a type of social investment that can evolve either through individual and/or group selection, as a successful devise for changing or enforcing norms in a society.

Specifically, cooperative punishment applied by institutional enforcement of social norms is especially cost-efficient. Most current attempts to explain the evolution—through individual selection—of prosocial behavior that allows for cohesive societies among non-related individuals focus on altruistic punishment as its evolutionary driving force. The main theoretical problem facing this line of research is that in the exercise of altruistic punishment, the benefits of punishment are enjoyed collectively, while its costs are borne individually. The simulations showed that social cohesion might be achieved by a form of punishment, widely practiced among humans and animals forming bands and engaging in mob beatings, which are referred here as cooperative punishment (Jaffe and Zaballa 2010). This kind of punishment is contingent upon—not independent from—the concurrent participation of other actors. Its costs can be divided among group members in the same way as its benefits are, and it will be favored by evolution as long as the benefits exceed the costs. The computer simulations showed that cooperative punishment is an evolutionary stable strategy that performs better in evolutionary terms than noncooperative punishment, and demonstrate the evolvability and sustainability of prosocial behavior in an environment where not necessarily all individuals participate in cooperative punishment. Cooperative punishment together with prosocial behavior produces a self-reinforcing system that allows the emergence of a "Darwinian Leviathan" that strengthens social institutions. These results are summarized in Fig. 3.

3 Social Synergy

A summary conclusion of all the controversial evidence available is that prosocial behavior can exist only if it favors the emergence of social synergies. But what is social synergy? A way to visualize synergy is through geometry as exemplified in Fig. 4.

The presentation shows two examples in which different geometric forms, when pooled, produce different outcomes regarding the efficiency in filling space. If efficiency in filling space is assessed as the amount of blue area left, it is only the combination of Form 1 + 3 fills the whole space, whereas the combination of Form 1 + 2 reduces the amount of blue space but does not fill it completely. That is, different forms interact with different efficiencies in this example regarding the filling of the blue space. Yet filling completely the blue space eliminates the blue and changes the complexity of the system, producing a new system that is qualitatively different from the first. Here, additive properties produce emergent phenomena that change the system qualitatively so that 1 + 3 is not 4. In this nonlinear context, interaction of forces might produce synergy. In the example, synergy seems to be negative as it reduces the complexity of the system. If the blue space however represents the openings in a filter separating the outlet of a water source from the exterior, eliminating the openings converts the filter in a stopper, changing the dynamics of the flux of water and converting the wet land in dry space,

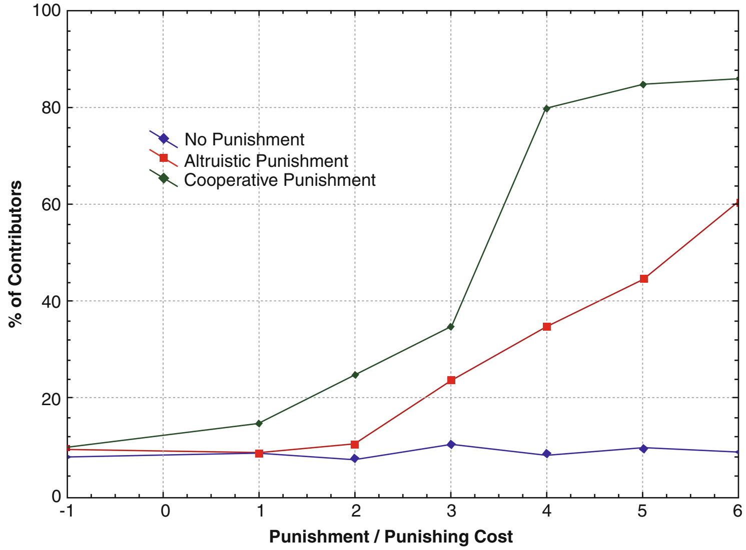

Fig. 3 Summary of simulation results showing the average of the percentage of contributors in the population when simulating three different societies with No Punishment, societies were Altruistic Punishment was possible, and societies were Cooperative Punishment was enforced. The x-axis shows the different ratios between the costs of the punishment (or cost to the punished: K) and the cost to the punishers (Y) used in the simulations. The efficiency of reaching free riders for punishment is $E = 60\ \%$

allowing, for example, a swamp to be converted into agricultural land or a lake in a plain. Here the synergistic effect that might be considered to be negative in relation to the flux of water has positive effects in relation to the use of land by terrestrial organisms such as humans.

This example shows that synergy has a relative aspect to it, which is important in understanding complex open systems following nonequilibrium thermodynamics, where a system can decrease its entropy by increasing the entropy of its surroundings. Here again, decease in entropy or increase in order depends on the definition of the open system and where the borders are drawn.

This relativity of synergy might render it apt for charlatanry as practically always a credible narrative can be found that articulates the facts. Yet, open systems are real entities and are easily defined intuitively. All living organisms are open systems and so are planets, stars, and galaxies. Lakes and forests are open systems and despite their diffuse borders can be recognized as such. Thus, a less narrative and more empirical way (see Jaffe 2010) to describe synergy must be found.

Another way to illustrate synergy is the increased cognitive horizon a group of individual entities, each with limited horizon, can achieve when sharing information or other resources that increase their exploratory potential. This is illustrated in Fig. 5.

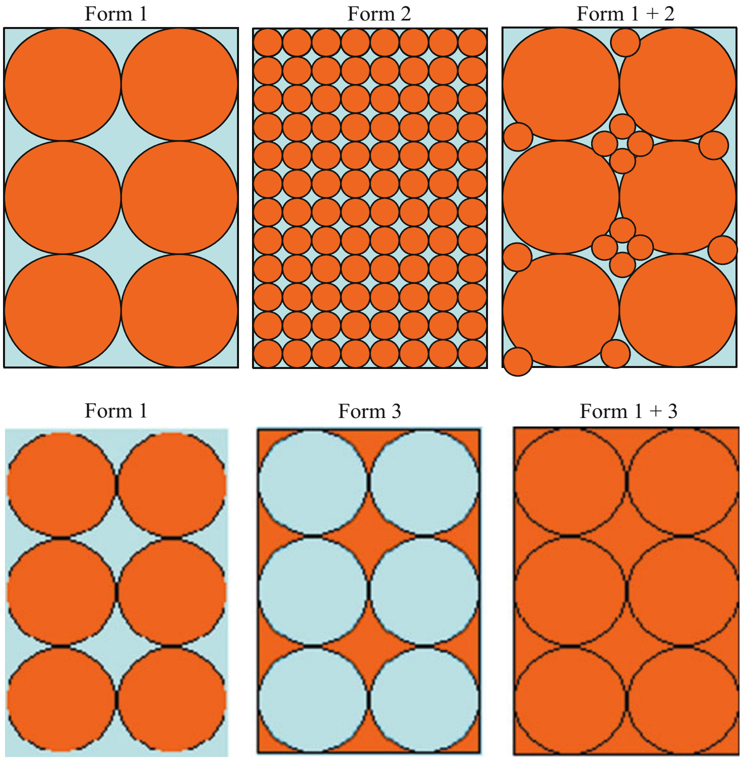

Fig. 4 Graphical presentation of geometrical synergy

The figure tries to compare two situations in which individuals with a limited conceptual vision either cooperate or not. Individuals are represented as spheres with a horizon or border of cognition equivalent to de circumference of the spheres. Dark-blue spheres represent individuals with no communication among them. Light-blue spheres represent individuals among which information about the surrounding environment flows. Each group has individuals located in three distance perspectives of van Goog's drawing. But only in the case of the light-blue individuals can there be a recognition that three levels of perspective exist. Although a single dark-blue individual in this example covers all three levels of perspective, it is less likely to grasp the significance of these three levels as it lacks the more comprehensive view of the light-blue individuals profiting from the view of the whole light-blue group.

A relevant real-life example of this enhanced vision horizon by synergistic cooperation between intelligent agents is that a chain of conceptual visions from physics through chemistry, biology, physiology, behavior, and sociobiology will give us a much deeper vision and a much harder grip on nature than conceptual constructs based on the immediate affective and perceptual inputs of any individual trying to explain fundamental structures of nature by researching a single area of

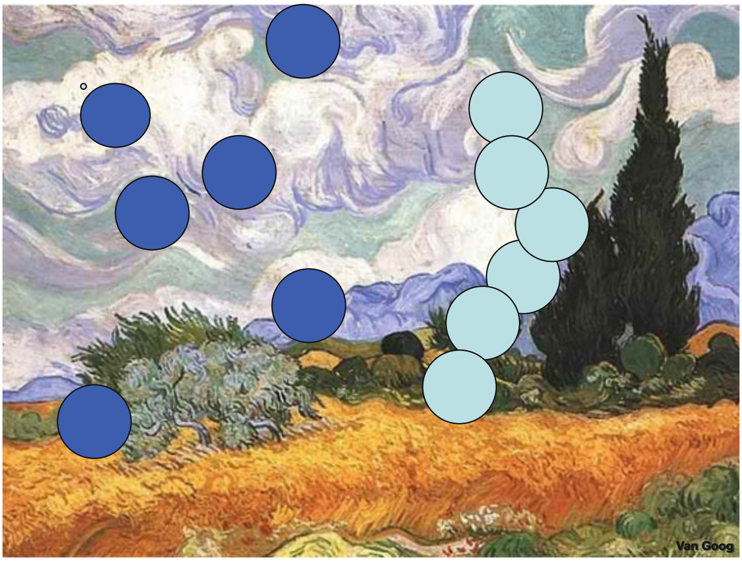

Fig. 5 Artistic representation of environmental synergy

knowledge. That is, a consilient interdisciplinary approach to science creates synergies that enhance human cognitive capacities much above those of isolated self-satisfying world views.

4 Empirical Evidences

Punishment, and more so the cooperative kind, reduces the threshold for engaging in prosocial behavior making it more likely to be established in a given society but does not improve on the benefits that prosocial behavior provides to society members. This benefit, or multiplier effect of prosocial behavior, or synergy effect, is still poorly understood. Empirical evidence however tells us that it does exist.

A review (Jaffe 2010) analyzes several examples of quantitatively assed social synergy which are summarized in Fig. 6.

The empirical data shows that different societies achieve different levels of social synergy. It would be very interesting to be able to relate these different synergies to different combinations or types of prosocial behaviors. A start could be to initiate a comparative study of the behavior of Danish and Brazilian city dwellers as related to improvements in the efficiency of electricity consumption in larger town compared to smaller ones.

Termites, for example, achieve a reduction in energy consumption due to social synergy of nearly four orders of magnitude, and cephalotine ants of two orders of

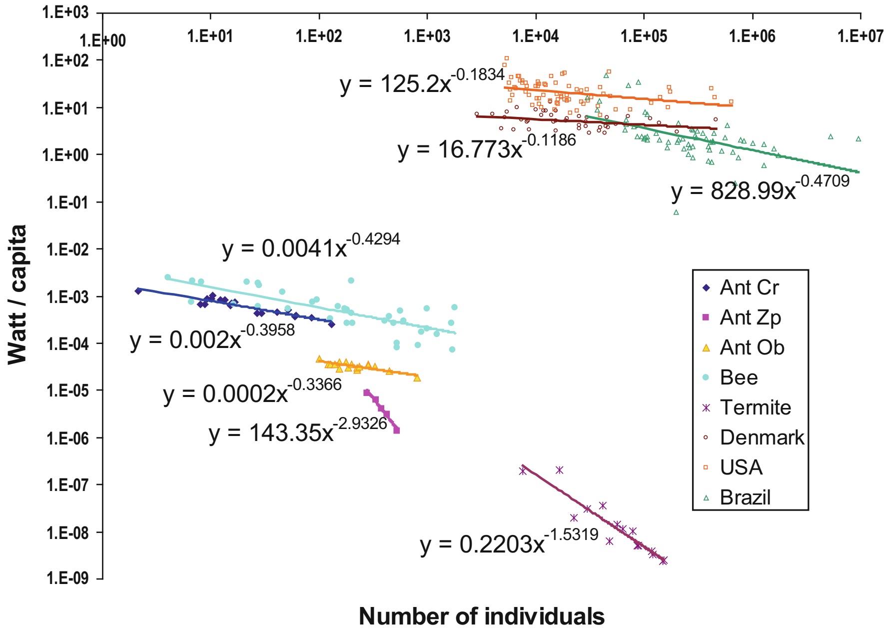

Fig. 6 Comparing energy consumption, in watt per capita, with the number of individuals in the society. Energy data for cities are calculated from electricity consumption, whereas that for insect colonies is calculated from oxygen consumption. Data for ant colonies (Fonk and Jaffe 1996) are from *C. rufipes* (Cr), *Z. pusillus* (Zp), and *O. bauri* (Ob); the termite colonies from *Nasutitermes corniger* (Muradian et al. 1999); and honeybees from *Apis mellifera* (Heinrich 1981). Electricity consumption is from cities in Denmark, Georgia and Tennessee in the USA, and Brazil (Cabrera and Jaffe 1998)

magnitude. Humans in contrast have societies that achieve reductions in per capita energy consumption of less than one order of magnitude in logarithmic terms.

5 Energy Flows

Energy rate density is a measure of how much energy flows through each gram of a system per second (Chaisson 2011). This measure, for example, shows that a star has a much lower energy rate density (2 ergs/gr/s) than a houseplant (3,000–6,000 ergs/gr/s) or the basic rate density of humans (20,000 ergs/gr/s). Estimates for societies are lower for hunter-gatherer societies (40,000 ergs/gr/s) than for technological societies (two million ergs/gr/s).

This high flux of energy can only be sustained in pockets of complexity, even in systems that as a whole decay into disorder. This exploitation of energy disequilibrium has been exploited by living organisms many times in a phenomenon

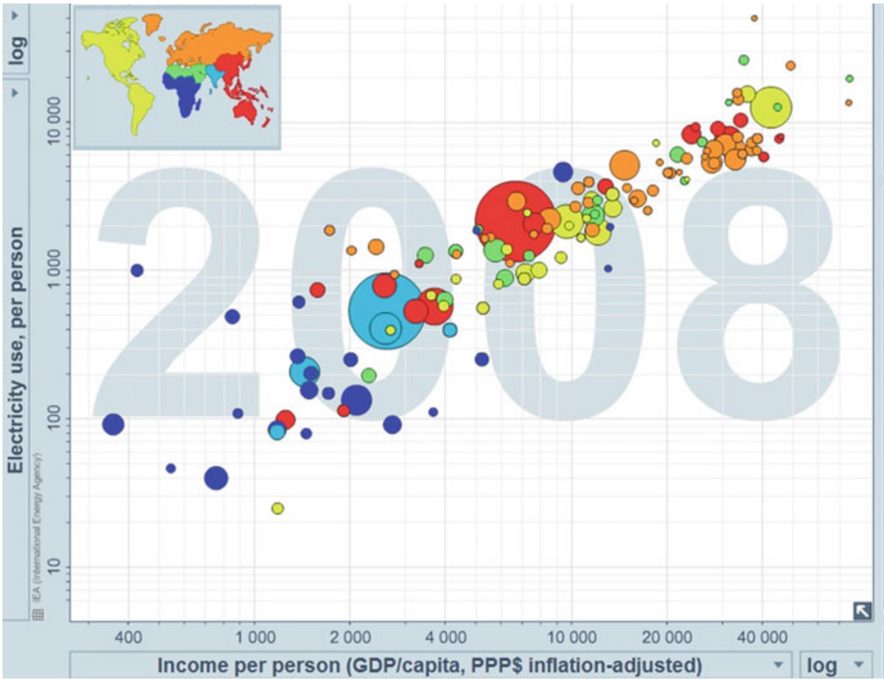

Fig. 7 Electricity consumption per capita, as reliable proxy for total energy consumption for the different nations in 2008, compared to their wealth (GDP per capita), as presented by Gapminder (2012)

described as convergent evolution. That is, different species living in similar environments have independently evolved features harnessing energy gradients using social means or otherwise.

Evolution will favor ever-increasing levels of energy density, as this confers unchallengeable advantages to the bearer of higher energy use rates. Higher energy concentration allows for more power and thus more force a key element in the struggle for survival.

6 Present Trends

Human societies seem to be immersed in a long-term trend of increasing energy density. No end to this trend is in sight at the moment. Figure 7 shows an impressive trend. In this figure, electric energy consumption is used as a proxy for total energy consumption as it is the most reliable data on energy consumption in many countries (Cabrera and Jaffe 1998).

Energy consumption increases as wealth increases, and all nations strive to be better off in material terms. This presages a continuous growth in world energy consumption in the median term, the more so as the most populous nations have a

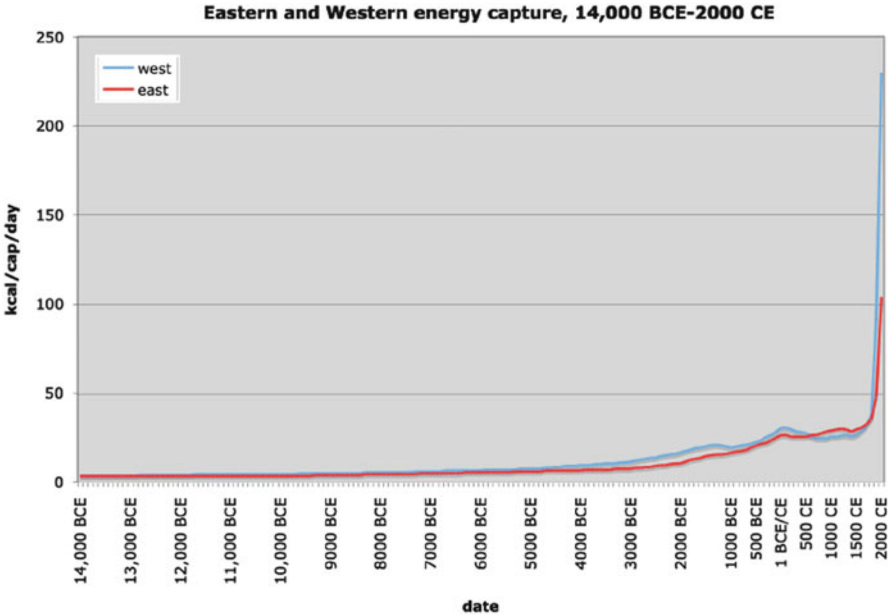

Fig. 8 Estimates of energy consumption per capita per day for average humans for 15 millennia, from Morris (2010)

long way to go in economic development, and thus in increasing their energy consumption.

A long-term perspective is even more dramatic (Fig. 8). Under this perspective, humanity is now in the midst of an exponential expansion of energy consumption. Even if the exponential expansion somehow stops (no evidence for this is known), the dynamics of growth in energy consumption suggests that energy density will keep growing for a long time.

Societies tend to independently evolved many similar kinds of cognition. Yet in a globalized world, the similarities of the cognitive tools used by human societies will be even more remarkable. Science is often called to stop or regulate the use of energy. Yet science is more likely to open new sources of energy allowing for unstoppable increase of energy density. Scientific progress has been impressive all over the world, but especially rich countries are the engines of scientific discovery nowadays. Scientific expansion in rich countries, however, seems to reach limits (Jaffe et al 2013 and Fig. 9).

Thus, an important discontinuity is envisaged in the future: the tendency of increasing energy density will require novel technologies to harness energy from nature, but collective intelligence is reaching limits in its expansion. The increase in scientific productivity needed to cope with the future challenges might be achieved by counties that have lower economic development at the moment. These contrarian trends presage interesting times in the future.

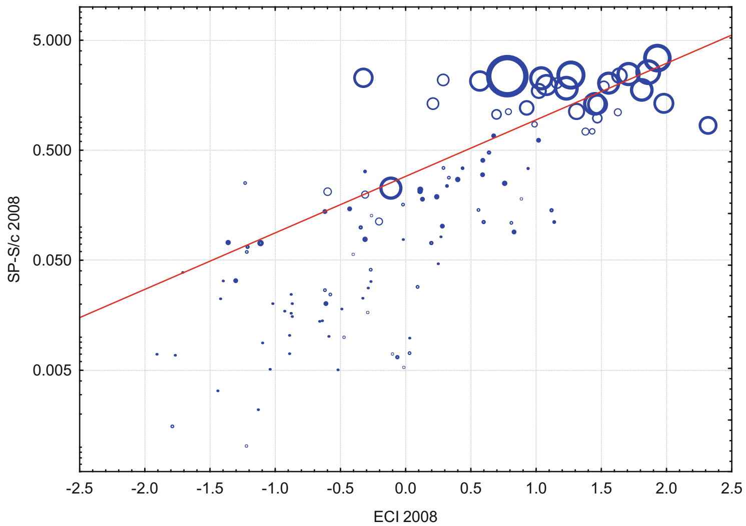

Fig. 9 Level of economic complexity or ECI in 2008 (Hausmann et al. 2011) and scientific productivity per capita in 2008, as measured by Scopus (Scimago 2011) or SP-S/c 2008. The size of the bubbles is proportional to national wealth, measured as GNI per capita in 2009 from World Bank Data

7 Conclusion

The aim here is to understand the dynamics of energy use and the social interactions involved, so as to be able to design policies that minimize environmental impact and maximize human satisfaction. The world will continue to see an important growth in energy consumption in the future, as humanity will keep growing in a number of individuals and in the intensity of per capita consumption. The technological advances needed to guarantee the satisfaction of future energy needs, however, are not guaranteed. Science might allow the development of better and cleaner sources of energy, but it is unlikely that technology alone will resolve all outstanding issues regarding energy security.

Energy resource economics involves the management of public goods and economic externalities, and thus, market forces alone are not enough to organize their rational use. For example, control of excessive carbon dioxide production and the long-term disposal of radioactive wastes are problems that will not be resolved by markets alone but require internationally agreed policies. International cooperation is thus essential for energy policies that increase energy security. Behavioral sciences are advancing the understanding of the relevant properties of individuals and their social arrangements that favor cooperation. Involvement of insights from behavioral economics in energy policy not only will cover technical aspect related to reaching sustainable and equitable growth but will also focus on improving synergies in cooperation and in guaranteeing that all stakeholders are being involved by assuring their benefit from long-term environmental health.

Energy policy has to be founded on cooperation for the exploitation of energy sources, as these do not respect national frontiers. Cooperation is also needed to promote scientific research allowing technological breakthrough to develop efficient and cleaner energy harvesting. In addition, the externalities of energy utilizations affect humanity beyond national borders. Thus, energy policies that do not understand human cooperation are doomed to fail. At the same time, humanity's need for energy provide an incentive to improve the efficiency in energy production and use, which can only be achieved with national and international cooperation, allowing at the same time for better management of its externalities. Stable cooperation, however, is only possible when synergies are created.

The present analysis showed empirically that social synergy exists, that it is omnipresent in different kinds of society, and simulations showed that cooperation can be fomented by managing benefits and costs to the agents involved. These costs and benefits have to be included in energy policies drawing up rules and institutions. Specific policy recommendations include:

1. Cost and benefits for all and each stakeholder in energy security should be made explicit in any energy policy that aims at increasing global energy security.
2. Energy policy should focus on future scientific and technological challenges, with increasing participation of counties that have lower economic development at the moment. These challenges will require novel ways to create synergies in implementing policies with worldwide effects.
3. Simulations of world energy scenarios with different cost-benefit ratios for the different stakeholders, sources, and uses of energy will improve the likelihood of success of future energy policies. Indeed, we have interesting times ahead.

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Klaus Jaffe is a Professor at Universidad Simón Bolívar in Caracas where he founded and coordinates a Doctoral Program in Interdisciplinary Science. His research includes evolution of complex systems, social systems, sex, insect societies, economies, and the thermodynamics of synergies.

The UK Electricity System and Its Resilience

Sara L. Walker

Abstract Purpose Security of supply is a relatively outdated concept for the twenty-first-century electricity systems in a low-carbon future. Resilience is proposed as an alternative, and application of the term to the UK electricity system is discussed.

Approach Security of supply within the context of the UK electricity system is described. Key pressures on the UK electricity system to develop towards a low-carbon future are explained, and a justification is made that security of supply should be replaced with the concept of resilience. Resilience is described, along with technology transitions.

Findings It is proposed that resilience as a concept offers greater flexibility to represent a changing concept of acceptable performance for an electricity system. Additionally, resilience as a concept incorporates all scales, from macro-level socioeconomic landscape to micro-level local issues.

Practical Implications Further research is needed to provide a practical framework within which resilience of an electricity system can be described. This framework does not lend itself to a single indicator of resilience and the framework is likely to comprise qualitative as well as quantitative aspects.

Keywords Electricity system • Security of supply • Resilience

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This study investigates the policy approaches to electricity sector security in the UK and proposes electricity sector resilience as a more appropriate policy focus. Historical approaches to electricity sector security are described, approaches to resilience in other disciplines are considered, and a framework for the use of electricity sector resilience is proposed, all within the context of the UK as it makes the transition to a lower carbon energy future.

S.L. Walker (✉)
School of the Built and Natural Environment, Northumbria University, Newcastle, UK
e-mail: sara.walker@northumbria.ac.uk

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Lecture Notes in Energy 16, DOI 10.1007/978-1-4471-5286-6_6,

1 Introduction

The electricity sector worldwide is facing considerable pressure arising out of rising global demand for energy services, geopolitical issues around the location of remaining fossil fuel reserves, in addition to climate change issues.

1.1 Rising Demand and Geopolitical Issues for the Energy Sector

Rising energy demand, particularly in the growing Asian economies and BRIC countries (Brazil, Russia, India, China), can be seen in statistics from the International Energy Agency (IEA) (see Tables 1 and 2). The IEA predicts a doubling in world energy demand from 2009 to 2035. The most significant percentage growth in demand for energy occurs in the Middle East (growth of 1,100 %), China (growth of 432 %), Asia (growth of 327 %), and Africa (growth of 223 %). In 2035,the IEA predicts that fossil fuel still dominates the energy supply mix, with coal and peat (29.3 %), oil (27.8 %), and natural gas (22.4 %) together comprising 14,248 Mtoe or 79.5 % of world energy supply (Table 2). Growth in demand is also predicted by energy models, which are often applied to specific countries (e.g., Karlsson et al. 2010; Wolfram et al. 2012) or specific sectors (e.g., Issac and van Vuuren 2009; Chingcuanco and Miller 2012).

Where is this growing energy demand being supplied from? Table 3 shows the top five oil-exporting countries were responsible for 47 % of global oil exports, four of which are members of OPEC (Organization of the Petroleum Exporting Countries 2011). The top five gas-exporting countries were responsible for 61 % of global gas exports. The top five coal-exporting countries were responsible for 80 % of global coal exports. Middle East and North Africa (MENA) countries are home to 60 % of world oil reserves and 49 % of world gas reserves. Widespread political and social instability in this region, particularly the 2010 and 2011 “Arab Spring”, led to oil price increases during that period (MENA-OECD Investment Programme 2011).

1.2 Rising Demand and Geopolitical Issues for the Electricity Sector

In 2009 electricity consumption accounted for around 17 % of world energy consumption, up from 9 % in 1973 (Table 4). The generation of electricity has more than doubled between 1973 and 2009, from 6,115 TWh to 20,055 TWh, respectively. Fossil fuels dominate the electricity generation fuel mix, and a drop in use of oil has been compensated for with growth in use of natural gas and nuclear

Table 1 Total world primary energy supply by region, 1973 and 2009 (International Energy Agency 2011)

	Primary energy supply (Mtoe[a])	
Region	1973	2009
OECD[b]	3,746	5,238
Middle East	49	588
Non-OECD Europe and Eurasia	941	1,050
China	427	2,272
Asia (excluding China)	342	1,459
Latin America	214	540
Africa	208	673
Bunkers	183	330
Total	6,111	12,150

[a]Million tonnes of oil equivalent
[b]Organization for economic co-operation and development

Table 2 Total primary energy supply by fuel type, 1973, 2009, and 2035, based on existing energy policies (International Energy Agency 2011)

	Primary energy supply (Mtoe)		
Fuel type	1973	2009	2035
Coal and peat	1,501	3,300	5,288
Oil	2,815	3,987	5,017
Natural gas	979	2,540	4,043
Nuclear	53	703	1,083
Hydro	110	280	433
Other[a]	653	1,340	2,184
Total	6,111	12,150	18,048

[a]Other includes biofuels and waste, geothermal, solar, wind, and heat

fuel (Table 5). Significant growth in electricity consumption is occurring in China, Asia, and Latin America (Table 6). The patterns seen in the energy sector are, therefore, repeated in the electricity subsector.

So with a doubling expected in energy demand, continued dominance of fossil fuels, and concentration of supply of coal, oil, and gas amongst a small number of nations (particularly Middle East and North Africa), pressure around rising global demand and geopolitical issues remain a concern for the short to medium term.

1.3 *Climate Change*

With respect to climate change as a key pressure on energy policy, the only legally binding international agreement to tackle greenhouse gas emissions is the Kyoto Protocol. This was agreed at a Conference of the Parties (COP) meeting under the

Table 3 Major world energy exporters, gas, coal, oil, and electricity (International Energy Agency 2011)

Oil net exporters	Amount exported (million tonnes)	Gas net exporters	Amount exported (billion m^3)	Coal net exporters	Amount exported (million tonnes)	Electricity net exporters	Amount exported (TWh)
Saudi Arabia	313	Russian Federation	169	Australia	298	Paraguay	45
Russian Federation	247	Norway	101	Indonesia	162	Canada	34
Islamic Republic of Iran	124	Qatar	97	Russian Federation	89	France	26
Nigeria	114	Canada	72	Colombia	68	Russian Federation	15
United Arab Emirates	100	Algeria	55	South Africa	68	Czech Republic	14
Iraq	94	Indonesia	42	United States	57	Germany	12
Angola	89	Netherlands	34	Kazakhstan	33	China	11
Norway	87	Malaysia	25	Canada	24	Norway	9
Venezuela	85	Turkmenistan	24	Vietnam	21	Spain	8
Kuwait	68	Nigeria	24	Mongolia	17	Ukraine	6
Others	574	Others	165	Others	19	Other	50
Total	1,895	Total	808	Total	856	Total	230

Table 4 Total world final energy consumption, 1973 and 2009 (International Energy Agency 2011)

Fuel source	Final energy consumption (Mtoe) 1973	2009
Coal/peat	640	835
Oil	2,248	3,450
Natural gas	654	1,270
Biofuels and waste	617	1,078
Electricity	439	1,445
Other	78	276
Total	4,674	8,353

Table 5 World electricity generation fuel mix, 1973 and 2009 (International Energy Agency 2011)

Fuel source	Percentage contribution to electricity generation fuel mix 1973	2009
Coal/peat	38.3	40.6
Oil	24.7	5.1
Natural gas	12.1	21.4
Nuclear	3.3	13.4
Hydro	21.0	16.2
Other	0.6	3.3
Total electricity generation	6,115 TWh	20,055 TWh

Table 6 Regional share of electricity generation, 1973 and 2009 (International Energy Agency 2011)

Region	Regional share of electricity generation (percentage) 1973	2009
OECD	73.1	52.0
Middle East	0.5	3.7
Non-OECD Europe and Eurasia	16.7	8.0
China	2.8	18.6
Asia (excluding China)	2.6	9.6
Latin America	2.5	5.0
Africa	1.8	3.1
Total	6,115 TWh	20,055 TWh

United Nations Framework Convention on Climate Change (UNFCCC) in 1997 and ratified in 2005. Despite high hopes for COP15 in Copenhagen and subsequent meetings, COP17 in Durban, South Africa (28/11/2011–9/12/2011), concluded without any future targets. There was, however, an agreement of the Parties to adopt further legally binding targets by no later than 2015.

Whilst international agreements on carbon emissions reductions have faltered at recent COP meetings, the European Commission passed six acts in 2009 to create legally binding targets for 20 % reduction in greenhouse gas emissions and 20 % contribution of renewable energy sources to overall energy consumption by 2020, known as the "20-20-20" targets (for more information on the six acts, see European Commission 2010a). These targets are legally binding. The Lisbon Treaty, which came into force in 2009, gave the European Union the legal framework to tackle energy as a shared responsibility and enabled a common energy policy across Europe (De Graco Carvalho 2012). There has also been coordination at the European level with respect to trans-European energy networks (Trans-E) (European Parliament and the Council of the European Union 2006), security of supply (European Commission 2011), protection of critical infrastructure (Council of the European Union 2008), and a proposal for strategic networks and storage (European Commission 2010b).

1.4 Security of Supply

The energy sector is seen as a critical infrastructure, interwoven with many other critical infrastructures (e.g., transport, water, waste) and pervasive within the economy and society (Yergin 2006). These linkages are most frequently exposed under stress, for example, damage to the nearby Verizon building during the US World Trade Center terrorist attacks led to the closure of a telecoms office, affecting the New York stock exchange, 14,000 business and 20,000 residential customers (O'Rourke 2007). Immediately following Hurricane Katrina in the USA, a loss of electricity supply caused disruption to communications, which contributed to difficulties getting aid to the worst hit areas, as well as disrupting ATM services and electricity supply to crude oil pumping stations, affecting supply (Egan 2007; O'Rourke 2007). In the summer of 2007 in the UK, flooding and heavy rainfall caused delays on the rail network due to bank slippage, which caused consequential disruption to bulk supply of fuel to terminals and storage facilities for the energy sector (Parliamentary Office of Science and Technology 2010; Cabinet Office 2008). In 2005 the Buncefield oil-storage depot explosion affected a nearby data management center, which hosted NHS patient records for the area as well as a North London payroll scheme worth £1.4 billion (Bloomfield et al. 2009a).

Whilst the media focus on problems during emergency situations (Jansen and Seebregts 2010), longer term issues such as electricity network security margin erosion by private company owners (Kirschen and Strbac 2004) and the potential for demand side energy consumption reduction to contribute to security of supply (Jansen and Seebregts 2010) are seen as political policy decisions. Historically, the security of supply discussion has been around supply side (Barrett et al. 2010; Cohen et al. 2011; Grubb et al. 2005; Jamasb and Pollitt 2008) and technology performance (Amin 2008; Chiaradonna et al. 2011; Grave et al. 2012; Moreno et al. 2010a). However, several research groups are investigating a wider concept of security (see e.g., Stirling 1994, 2009; Nuttal and Manz 2008; Jansen and Seebregts 2010; O'Brien and Hope 2010; Goldthau and Sovacool 2012; Barrett et al. 2010). Included in these wider concepts is consideration of terms such as robustness, diversity, stability, durability, adaptability, sustainability, vulnerability, redundancy, and resilience.

Much of the action being taken globally with respect to climate change and energy policy, in the face of pressure on the electricity sector, is happening at the national level. For this reason, this study will focus on the UK. What follows is a short introduction to the UK context.

1.5 The UK Energy and Climate Change Policy

The UK Government has a legally binding target to reduce greenhouse gas (GHG) emissions by 80 % by 2050, compared to 1990 levels (Climate Change Act 2008). Associated with this target is a plethora of government reports and legislation which consider how this challenging target can be achieved (e.g., Department of Energy and Climate Change 2009a, b; Energy Act 2010, 2011). The 2050 pathways report (Department of Energy and Climate Change 2010) demonstrated that scenarios achieving the 80 % target involved significant electrification of the heat, transport, and industry sectors in parallel with considerable decarbonization of the electricity sector. Therefore, regardless of relatively slow growth predicted in the UK population, the growth in demand for electricity is predicted to be significant over the next 40 years. For example, all the 2050 pathways analysis scenarios show a doubling in electricity demand from 2007 to 2050 (Department of Energy and Climate Change 2010), although the UK Renewable Energy Strategy assumes no electricity demand growth to 2020 (Department of Energy and Climate Change 2009b). Only six 2050 pathways are shown in the report, but other pathways are possible without such significant growth in demand.

Alongside targets for overall GHG reduction, the UK Renewable Energy Strategy (Department of Energy and Climate Change 2009b) proposes a target of 15 % of UK energy demand from renewable energy sources by 2020 (which is legally binding and derived from the EU target of 20 % by 2020). Given the low starting point for renewable energy contribution in the heat and transport sectors, targets for those sectors are low and the required contribution from renewable energy to electricity generation is 30 % by 2020. The renewable energy target is part of a wider objective to decarbonize the electricity sector, along with proposed new nuclear, carbon capture and storage, and energy efficiency.

This focus on policy for the electricity sector is complicated by the fact that energy is integral to our social and economic structures. This is recognized in the National Infrastructure Plan 2010 (HM Treasury 2010), where energy, transport, digital communications, flood management, water, and waste are seen as critical to the support of economic growth. Energy as a sector is also intermeshed with the other critical infrastructures (Royal Academy of Engineering 2011). For example, in the summer of 2007 in the UK, flooding and heavy rainfall caused delays on the rail network due to bank slippage, which caused consequential disruption to bulk supply of fuel to terminals and storage facilities (Parliamentary Office of Science and Technology 2010; Cabinet Office 2008).

Key pressures to the UK electricity system in developing towards a low-carbon future are therefore recognized within government policy as climate change targets, growth in demand, and stability of supply routes.

Section 2 contains a discussion of key issues around the traditional approach to security of supply, including the fuel mix, infrastructure investment, capacity margins, network performance, equity, homeland security, interconnections between infrastructures, and development of "smart" network technology. In Sect. 3 the concept of resilience is described and its potential application to the UK electricity sector is analyzed. Within the discussion is a consideration of socio-technical transitions theory. The concept of resilience is then considered, along with socio-technical transitions, in light of the UK 2050 scenarios recently published by the Department of Energy and Climate Change (2010).

2 Security Concerns

Whilst the UK Government has prioritized climate change, energy security (with respect to origin of imports), and growth in demand as key policy issues, the industry itself has some slightly different security concerns. In investigating the security and risks to the UK electricity sector, Hammond and Waldron (2008) questioned 35 "experts" on their perception of risk with respect to the severity and likelihood of 15 risks. Equally weighting severity and likelihood, the top five risks were found to be (in rank order):

- Energy security or reliance on primary fuels for electricity generation
- Lack of investment in new infrastructure
- The decommissioning of nuclear plants
- Severe weather conditions
- Inadequate spare capacity margins generally

2.1 Reliance on Primary Fuels for Electricity Generation

Diversification in sources of fuel for energy supply, or the degree of market concentration, has been measured using the Herfindahl–Hirschman index (HHI), as shown in (1) (Grubb et al. 2006):

$$\mathrm{HHI} = \sum_{i=1}^{I} {p_i}^2, \tag{1}$$

where p_i is the percentage of the total energy supply which is derived from the ith type of source (or from the ith company). Values of 1,800 or less are considered to represent a concentrated market with few actors/sources. Grubb et al. (2006) use the Shannon–Wiener index (SW) to describe degree of diversity of fuel sources, which is also used by Stirling (1994), as shown in (2). The SW has a minimum value of zero, which represents just one fuel source:

$$\mathrm{SW} = \sum_{i=1}^{I} -p_i \,\mathrm{Ln}(p_i), \tag{2}$$

where p_i represents the proportion of generation which is from the ith type. In considering fuel mix under a carbon-constrained scenario, Grubb et al. (2006) found a higher SW and HHI when compared to a scenario with no carbon emissions reduction due to the decline in dominance of natural gas under a carbon-constrained scenario. Shannon–Wiener is now used by the UK Government in reporting on the diversity of primary fuels and for electricity generated from different fuels (Department of Energy and Climate Change 2011a).

A country's reliance on imports can be expressed as a country-specific diversification index (CDI) as shown in (3) and is a version of the HHI (Cohen et al. 2011). A lower value indicates more diversity in the sources of energy being imported to a country:

$$\mathrm{CDI} = \sum_{i} \left(\frac{\mathrm{NPI}_i}{C}\right)^2 \times 100, \tag{3}$$

where C is country j's total fuel consumption and NPI_i is the net positive import from country i to country j. Cohen et al. (2011) propose adjustments to the CDI to account for political risk, country size, and the distance between country i and j (as a proxy for the risk associated with transportation). Results for oil and gas indicate the UK has a low vulnerability in terms of the adjusted CDI values.

Very little research has been done to investigate the potential of electricity demand to improve or reduce the security of the overall electricity sector. However, it is conceivable that demand response could be incorporated into the Shannon–Wiener index or the Herfindahl–Hirschman index.

2.2 Infrastructure Investment

The scale of investment needed in the electricity sector (generation and transmission) is estimated at more than double the current investment rate, at up to £110 billion (Department of Energy and Climate Change 2011b) by 2020. Private sector investment in infrastructure is to be stimulated by government through policies

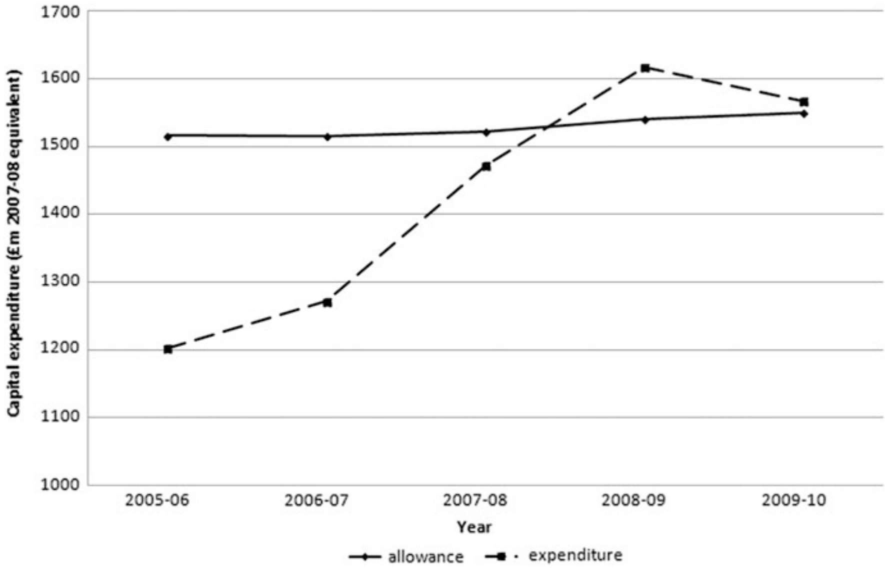

Fig. 1 Capital expenditure (actual and allowance) for all GB distribution network operators [distribution network operators (DNOs) own and operate the distribution network in the UK and currently (2012) comprise seven companies responsible for networks at voltages of 132 kV and below, except for Scotland where the 132 kV network is the responsibility of the transmission system owner (TSO)]

such as the Overarching National Policy Statement for Energy (Department of Energy and Climate Change 2011c), National Policy Statement for Electricity Networks Infrastructure (Department of Energy and Climate Change 2011d), National Policy Statement for Renewable Energy Infrastructure (Department of Energy and Climate Change 2011e), and Smarter Grids: The Opportunity (Department of Energy and Climate Change 2009c). The focus of UK Government analysis has been primarily on the transmission infrastructure at voltages of 132 kV, 275 kV, and 400 kV. The scale of infrastructure investment to date is shown in Fig. 1 (distribution network) and Fig. 2 (transmission network) (OFGEM 2008a, 2009, 2010a, 2011a). Future transmission infrastructure investment, in order to enable connection of renewable energy generation predicted as a result of the government's target for 30 % of electricity from renewable sources by 2020, is shown in Table 7 (Electricity Networks Strategy Group 2012).

2.3 *Capacity Margins and Retirement of Generation Plant*

Neoclassical economic theory implies that the market delivers the goods and services demanded at the price which the market will pay. Less than optimal resource allocation is deemed a market failure, to be corrected through regulation

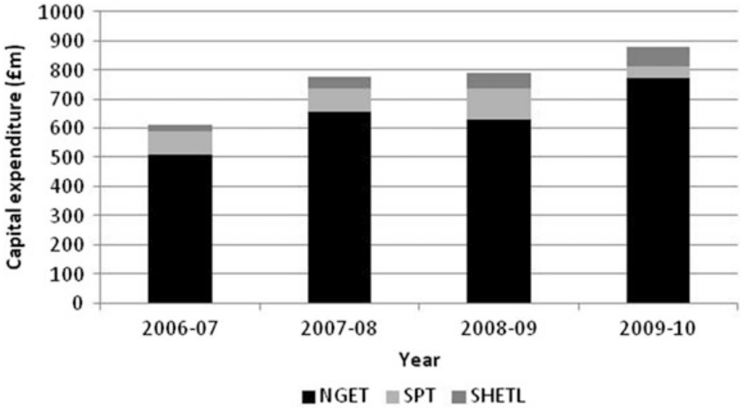

Fig. 2 Capital expenditure (actual) for all GB transmission system owners [National Grid Electricity Transmission (NGET) plc; ScottishPower Transmission (SPT) Ltd.; Scottish Hydro Electricity Transmission Ltd (SHETL)]

Table 7 Predicted transmission infrastructure investment required across GB for connection of renewable energy generation to meet the government's 30 % target

Region	Generation accommodated	Estimated capital cost
Scotland	10.2 GW	£2.5 billion
Scotland-England	1.1 GW	£3.6 billion
North Midlands and South Midlands	3.7 GW	–
North and Central Wales	3.8 GW	£1.1 billion
Mid Wales	0.4 GW	£200 million
South West	6.0 GW	£450 million
English East Coast and East Anglia	10.8 GW	£790 million
London	3.3 GW	£200 million
Total	39.3 GW	£8.8 billion

and market incentives. The UK electricity sector was privatized in 1998 and has since been regulated by the Office of Gas and Electricity Markets (OFGEM). For the "wires" section of the business, electricity transmission and distribution, there remains a natural monopoly which has had levels of revenue and investment heavily regulated under periodic price control reviews.

One electricity sector service currently at risk of under-delivery in the privatized UK electricity system, and hence considered a market failure requiring intervention, is the issue of generation capacity margin. Capacity margins in the winter of 03/04 fell to 16.5 % (Hammond and Waldron 2008). The regulator OFGEM has recognized that increased use of intermittent generation means that capacity margin becomes a less reliable measure of the ability of the electricity system generation to meet demand. Derated capacity is to be used for reporting capacity margin under new requirements in the Energy Bill 2010 (OFGEM 2011a). Derated capacity margin is the excess of *available* generating capacity when compared to demand.

With 12 GW of coal and oil to close by 2015 and 7.1 GW of nuclear to close by 2020 (Department of Energy and Climate Change 2011f), modeling of the UK electricity system indicates that the derated capacity margin could fall to as low as 5 % by 2020 without new generation capacity (Department of Energy and Climate Change 2011b), down from 16 % in 2009 (OFGEM 2011b).

The retirement of nuclear power plant and fossil fuel power plant would be of less concern if the sector was able to deliver reductions in electricity demand or accept operation of the system at much lower derated capacity margin.

2.4 Network Performance

Regulation for security is through the GB Security and Quality of Supply Standards (SQSS). The SQSS states that the GB electricity transmission system must cope with simultaneous outages of "*k*" elements from a total "*N*" elements of generation, network elements, or the demand side, without unsupplied demand and without violating operating limits. The emphasis in the document (National Grid 2011) is on the reinstatement of the system to its pre-event operation levels, should an outage occur:

> "Following the occurrence of a secured event on the onshore transmission system, measures shall be taken to re-secure the system to the above operational criteria as soon as reasonably practicable." (National Grid 2011)

Moreno et al. (2010a) recommend updating the regulations given the barriers inherent for non-network solutions to security concerns. In a separate publication, Moreno et al. (2010b) argue that "*N–k*" cannot easily incorporate the multiple factors for efficient and secure operation. It has also been suggested that an "*N–1*" approach does not prevent network failure, with protection malfunction contributing to the risk of failure (Kirschen and Strbac 2004).

Measures of network failure are reported through OFGEM by distribution network operators (DNOs). Definitions of customer interruptions (CI) and customer minutes lost (CML) are shown in (4) and (5) (OFGEM 2011c):

$$\mathrm{CI} = \frac{\text{Number of customers interrupted, all incidents}}{\text{Total number of customers}} \times 100 \tag{4}$$

$$\mathrm{CML} = \frac{\text{Sum of customer minutes lost, all incidents}}{\text{Total number of customers}}, \tag{5}$$

where an incident is any occurrence which results in an interruption of supply to the customer for 3 min or more, prevents a circuit or item from carrying normal load current or being able to withstand through fault current for 3 min or more.

As regards the location of the network fault, Fig. 3 shows that between 75 % and 91 % of CI on the DNO network originate on the high voltage (HV, greater than

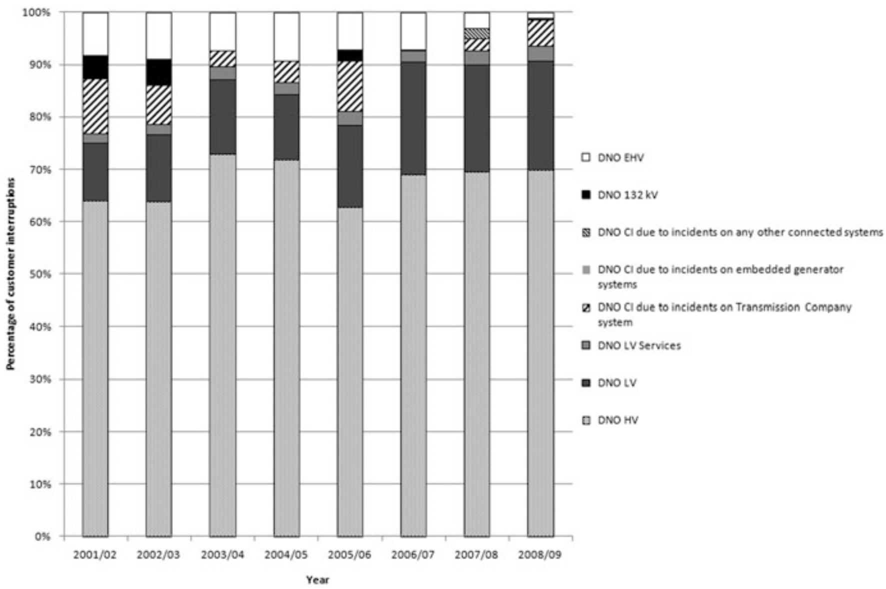

Fig. 3 Percentage of CI at a given network voltage level, one DNO

1 kV but less than or equal to 20 kV) or low voltage (LV, less than or equal to 1 kV) network (OFGEM 2005a, b, c, d, 2007a, b, 2008b, 2010b). The associated CML on the DNO HV and LV network account for between 91 % and 97 % of all CML for the period 2001/2002 to 2008/2009 (see Fig. 4). Over the same period, failure on the transmission network accounted for between 0 and 10 % of all CI and between 0 and 4 % of all CML. A similar pattern is evident if reviewing the GB data for the same period. Note that EHV, extra high voltage, refers to voltage levels greater than 20 kV but less than 132 kV.

Network performance with respect to CI and CML is, therefore, an issue occurring on the distribution network at voltages of 20 kV or lower.

2.5 Concerns Around Equity

In the UK, all household, commercial, and industrial electricity users are connected to the electricity system, and all new customers have the right to request, and to be provided with, a connection. Equity is not an issue of access in the UK. Equity is an issue of affordability.

It is a stated government priority within the DECC Business Plan 2011–2015 to "deliver secure energy on the way to a low carbon future" and specifically to "reform the energy market to ensure that the UK has a diverse, safe, secure and affordable energy system and incentivise low carbon investment and deployment"

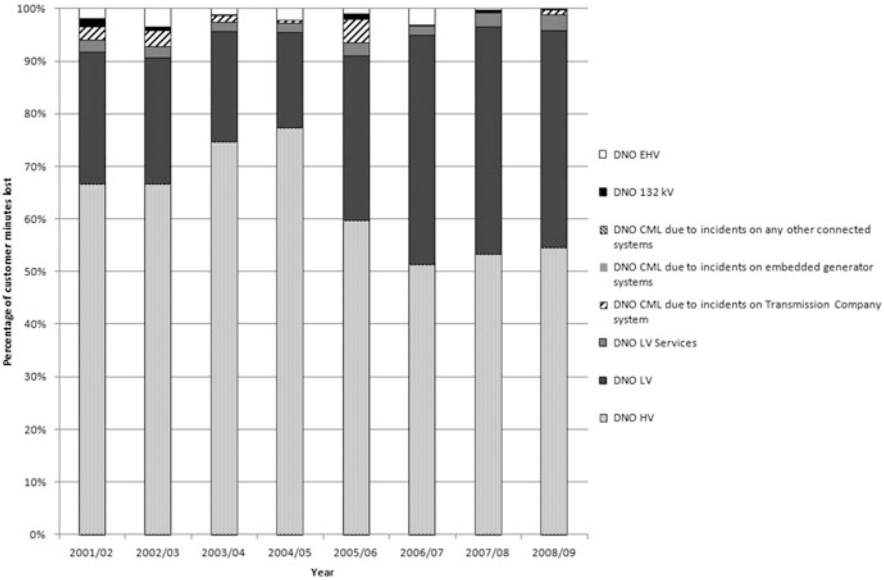

Fig. 4 Percentage of CML at a given network voltage level, one DNO

(Department of Energy and Climate Change 2011g, p. 3). Affordability has been a key phrase used in relation to energy policy [see e.g., the 2003 White Paper which stated one of four key priorities is to "ensure that every home is adequately and affordably heated" (Department of Trade and Industry 2003)].

Whilst the UK Government does not define affordability, it does report on progress towards reducing the number of households in fuel poverty. In 2009, 5.5 million UK households were estimated to be in fuel poverty [defined as households spending more than 10 % of their gross income on fuel to maintain an adequate level of warmth, 21 °C in the main living area, and 18 °C in other occupied rooms (Department of Energy and Climate Change 2011h)]. This was an increase of around one million households from 2008 and equates to just over 20 % of all UK households in 2009.

There are several variables which play a role in determining fuel poverty. Fuel poverty is affected by income: UK median household income was £407 per week for 2008/2009. Poverty is defined by the UK Government as an income of 60 % of median, £244 per week, with 18 % of the UK population on incomes which are below the poverty threshold for 2008/2009 (Office for National Statistics 2011). Fuel poverty is affected by fuel price: a weighted average dual fuel energy bill was £1,170 for 2011–2012, and for separate gas and electricity, the weighted average total energy bill was £1,200 for the same period (OFGEM 2012). Fuel poverty and fuel bills are affected by fuel usage, which is a combination of lifestyle and building performance. Statistics from National Energy Action indicate that a far greater proportion of fuel poor households are in poor-quality housing, compared with the average [data for England, 39.8 % of fuel poor households in housing of SAP rating below 30, compared to 9.2 % of all households, in 2001 (National Energy Action 2008)].

2.6 Homeland Security

Following the terrorist attacks on the US World Trade Center on 9/11, the USA expanded its list of critical infrastructure to 17 (O'Rourke 2007). Homeland security became a key priority for the White House and security was ramped up at airports around the world following the incident. The threat of terrorist activity is seen by some as a fundamentally different type of disruption to critical infrastructure, with characteristics such as large-scale disruption over large areas, mass media coverage of events, and a lack of historical precedent (for some nations) on which to base solutions (La Porte 2006). Al-Qaeda's most deadly European attack was the Madrid train bombing in 2004 which killed 190 (known in Spain as 11-M). London's own experience of an Al-Qaeda-claimed attack on 7/7/2005, involving the bombing of the London underground and a London bus and resulting in 37 deaths, is not the UK's only experience of terrorist attack. In the 1980s and 1990s, a number of terrorist attacks by the IRA took place in the UK, predominantly in Northern Ireland but also in London, Brighton, Bristol, and Manchester. The terrorist attack resulting in the highest number of British deaths was 9/11 (67 British lives lost), whilst the greatest number of lives lost on UK soil due to a terrorist attack was the Lockerbie bombing in 1998 (270 lives lost).

Whilst there is increased concern regarding the threat of terrorism, and the potential for critical infrastructure such as electricity systems to be the target for such attacks, analysis of global data on terrorist activity indicates just 1.5 % of world terrorist incidents from 1998 to 2007 had targeted energy infrastructure, with attacks concentrated in Columbia, Iraq, Pakistan, and India (around 70 % of all energy-related terrorist activity in these four countries) (Toft et al. 2010). The concern for the UK, therefore, is more likely to be based around disruption to supply as a result of terrorist activity overseas than terrorist activity on home soil leading to supply disruption.

Whilst reliance on fossil fuels from unstable parts of the world is highlighted in the government's National Security Strategy (HM Government 2010), terrorism and cyber terrorism are also considered key threats. Priorities with the National Security Strategy are defined through a National Security Risk Assessment methodology, which evaluates each threat on the basis of likelihood and impact. Using this methodology, the UK Government has identified international terrorism, cyber attack, major accident or natural hazard, and an international military crisis priority risks. Risks are also highlighted in the National Infrastructure Plan 2010 (HM Treasury 2010) as climate change and natural hazards, cyber attack, and more complex interdependencies.

2.7 Infrastructures and Their Connections

Research into electricity infrastructure has recognized the complexity of the system and convergence of the energy sector with telecommunication, transportation, Internet, and electronic commerce (Amin 2002). Interaction between infrastructures is recognized as an important issue by the Royal Academy of Engineering report (2011), which considered energy, water, telecommunications and transport sectors. Eleven interdependent infrastructures have been identified by Reed et al. (2009) when considering critical infrastructure. This critical infrastructure approach is adopted more widely outside of the UK. For example, the US Government considers critical infrastructure to include "*food, water, public health, emergency services, defence industrial base, telecommunications, energy, transportation, banking and finance, chemicals and hazardous materials, and ports and shipping*" (Egan 2007).

De Bruijne and Van Eeten (2007) identified energy, water, communication and transportation as key critical infrastructures. Their work investigated the operation of critical infrastructure by private owners and found the ability to reliably manage critical infrastructures was pushed to the last minute based on information, resources and authority in real time. The authors proposed that resilience in such circumstances is less about anticipating risks and mitigating for them and more about using a general pool of resources (capacity, wealth, knowledge) to respond flexibly to problems.

Bloomfield et al. (2009b) describe the modeling of infrastructure interdependency using Leontif-based models, generic cascading models and common-mode failure models. Leontif-based models are suitable for smaller systems, generic cascading models for larger networks. The authors found that static models can underestimate network vulnerability and that dynamic models better reproduce transient effects. In considering some UK examples of infrastructure failure, Bloomfield et al. (2009a) identified key themes affecting interdependency: geographical dependency, competition for resources, long-term effects (such as on tourism), cascading effects, and recovery.

2.8 Distribution and Smart Grids

The concept of a smart grid is one which, with respect to electricity, enables two-way flow of power managed intelligently through the use of embedded control and communication. With trends in greater complexity expected as the UK electricity sector moves towards decarbonization and greater geographical distribution of electricity generation, smart grids are perceived as offering the opportunity of a more reliable and efficient system (Department of Energy and Climate Change 2009c) at a cost saving when compared to conventional approaches (SmartGrid GB 2012). In the UK, the industry and regulator have been in dialogue regarding future smart grid networks, technology and trading arrangements for some time (e.g., OFGEM 2008c).

With respect to smart grids and security, the smart grid concept is seen as extending the role of balancing to the distribution voltage level and the individual home (Electricity Networks Strategy Group 2009). Trials of approaches to, and technology for, smart grids is under way with finance from the Low Carbon Networks Fund (Electricity Networks Strategy Group 2010). Demand and supply matching is the key security concern within government policy documents, although increased use of information and communication technologies (ICT) in smart grid infrastructure links to concerns regarding cyber security (see Sect. 2.6). As smart electricity grids embed more communication hardware and software into them, it is expected that ICT and electricity infrastructure shall become inherently more interconnected (Frantzeskaki and Loorbach 2010) and that IT capabilities shall be key to successful implementation of the smart grid (Ipakchi and Albuyeh 2009).

3 Electricity System Resilience

Historically, security with respect to energy has been a supply issue. The UK Government has focussed on security of supply with respect to reduced reliance on imports and robust supply chains and partnerships. For electricity in particular, the engineering focus has been on a robust system able to operate under loss of components, the "*N*–*k*" approach.

With changes to the electricity infrastructure and reduced national self-sufficiency in oil and gas, it is an appropriate point to reconsider security as more than simply an "*N*–*k*" capability. It is no longer technical risk of outage, but geopolitical uncertainties, price shocks, and homeland security that have recently entered the vocabulary when discussing the UK electricity sector (Coaffee 2008; Chaudry et al. 2009). It is also timely to consider indicators which go beyond the financial, such as value of lost load (Chaudry et al. 2009; Moreno et al. 2010b). Given the historical focus on security as an issue of supply of primary fuel, alongside more recent developments in the way we view issues of terrorism, interconnected infrastructure, and smart grids, "security" as a term no longer seems appropriate.

> "...many regard security as a notion overly tainted by these 'establishment'...agendas" (Philo 2012 p. 2.)

Resilience has been used in ecology to define the magnitude of disturbance which an ecological system can absorb before the system structure changes, described in work by Holling in 1973 (Davoudi 2012). Holling (an ecologist) described engineering resilience as the ability of a system to return to equilibrium after a disturbance and described ecological resilience as the magnitude of the disturbance which can be absorbed before the system structure changes and a new

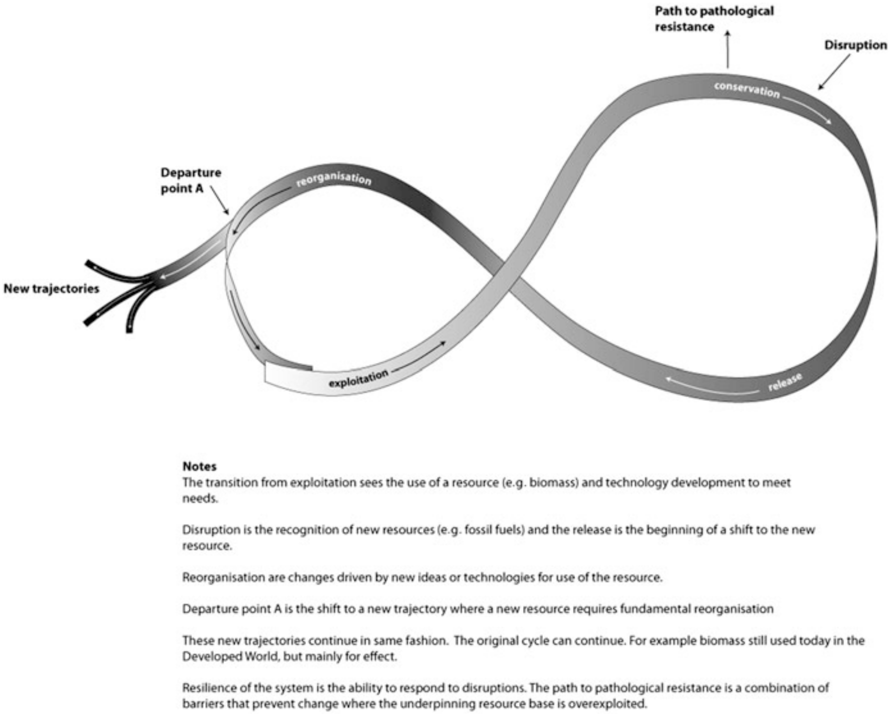

Fig. 5 Holling's adaptive cycle [Reproduced with permission (O'Brien and Hope 2010)]

equilibrium is reached. So the concept is not a return to the status quo but the ability to adapt, change, and transform. Holling's work has been expanded upon, for example, Walker et al. (2004) define resilience as the ability to reorganize during change, to enable continued functionality. Resilience has also been used in socioecological systems work (e.g., Cote and Nightingale 2012; Newell et al. 2011; Fiskel 2003).

Within resilience thinking, the concept of change and evolution of systems is represented by the "adaptive cycle" (Gunderson and Holling 2002). The cycle comprises four stages. There is a period of growth, with an abundance of resources, and an accumulation of structure. There is a period of conservation, with a slowing of net growth, greater system interconnection, and less flexibility. There is a stage of release of bound-up resources where disturbance leads to accumulated structure collapse. Finally, there is a reorganization stage where novel practice or technology can take hold (Walker et al. 2006). The concept is one of panarchy, whereby stages of the cycle are not necessarily sequential and one system may have elements with nested adaptive cycles operating at different scales and time frames (Fig. 5).

Resilience as a term therefore enables a discussion of the electricity system's ability to adapt, change, and transform rather than its ability to return to "normal" within some prescribed range of operating conditions. Resilience as a concept can be applied to much more than the supply side and hardware. Instead, it enables a holistic approach to the system which is the electricity sector and about the components which make up that sector. It brings in to the discussion a richness which addresses the social and the technical. Resilience provides a new definition of a healthy system. This is a departure from the UK electricity industry approach, typified in operational documents:

> *"Following the occurrence of a secured event on the onshore transmission system, measures shall be taken to re-secure the system to the above operational criteria as soon as reasonably practical"* (National Grid 2011).

The existing perception is the need to maintain the status quo, where measures of system performance become the goal. Resilience as a concept allows that the system may, following short-term shock or long-term stress, move to a new equilibrium. This ecological view of resilience can be defined as

> *"Resilience is the capacity of a system to absorb disturbances and reorganize while undergoing change so as to still retain essentially the same structure, function, identity, and feedbacks"* (Walker et al. 2004). This is an update to the original 1973 definition by Holling of "*a measure of the persistence of systems and of their ability to absorb change and disturbance and still maintain the same relationships between populations or state variables*" (Brand and Jax 2007).

Figure 6 shows a hypothetical system response to a disturbance. At time *A*, the system experiences a shock, and as a result, the system capacity drops. After a short period of time, a response is formulated and implemented (length of time to response depends upon the nature of the shock and lost capacity). Over time, system capacity is restored until the response intervention is complete and the system returns to a new equilibrium state.

Brand and Jax (2007) discuss many definitions of resilience, appropriate to the context within which the concept is applied. They consider the concept to be useful in enabling cross-discipline discussion, although they propose application of the concept across disciplines is not without difficulty. Cote and Nightingale (2012) evaluate the usefulness of the concept for socioecological systems and consider the dynamics of adaptation to change as useful, rather than consideration of control of, or avoidance of, change. Their work emphasizes the contextual aspects of social systems and the influence which culture, world view, gender, class, and race may have on decision-making. Davoudi (2012) highlights issues of justice and fairness in application of resilience to social systems.

Within the adaptive cycle concept, where do the disturbances originate which lead to change? Multilevel perspectives in transitions theory are complementary to resilience theory in this regard, since a multilevel perspective considers niche technologies at the microscale putting pressure on the incumbent system (described in the theory as a "regime") at the meso-level and macro-level pressures from the overall socio-technical landscape (Geels 2002). This concept of a multilevel perspective enables an electricity sector resilience dialogue to incorporate global and

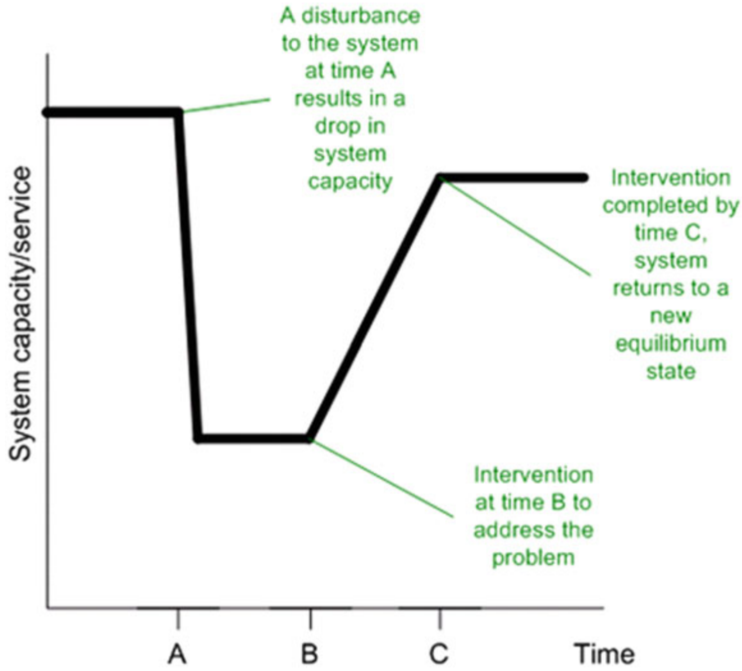

Fig. 6 Hypothetical system capacity over time, before and after a system shock

local issues. Global issues within the socio-technical landscape can include international trade and associated security concerns, issues of climate change, and greenhouse gas emissions. Local issues can, for example, reflect concerns regarding a lack of modern energy carriers in some areas of the world, which is a health issue due to the indoor air pollution, and the use of traditional biomass, which causes a disproportionate impact on women and children. This is no minor issue; by 2035 it is estimated that 1.5 million premature deaths per year will arise due to air pollution from indoor biomass use (Goldthau and Sovacool 2012).

Specifically within the UK, the landscape can incorporate policy drivers or political processes which impact on energy-consuming practices, such as building regulations and appliance labeling. Landscape is identified as a key issue by Cote and Nightingale (2012), who argue that social response to change is embedded in historic, place, cultural, and political values. Frantzeskaki and Loorbach (2010) argue further that the regime and the landscape coevolve and that regimes such as electricity systems are large scale, are capital intensive, have a long life cycle, and have a large number of actors. Application of transitions theory to the electricity system (e.g., Verbong and Geels 2010) is worthy of further exploration given the weaknesses within transitions theory identified by Genus and Coles (2008).

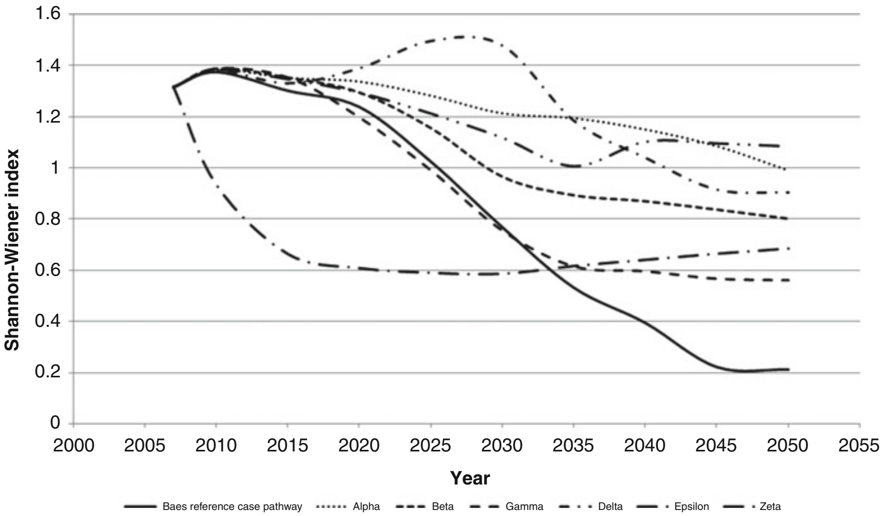

Fig. 7 Shannon–Wiener index, 2007–2050, based on 2050 pathways analysis of installed generation capacity

How can transitions theory and resilience be combined and operationalized? Applying the two in combination to a complex system requires a move away from the purely quantitative approaches of the Shannon–Wiener index (calculated for the UK 2050 pathways, see Fig. 7) or engineering measures of system performance such as *N*–*k* and the definition of system resilience from Reed et al. (2009) shown in (6):

$$R = \frac{\int_{t_1}^{t_2} Q(t)\mathrm{d}t}{(t_2 - t_1)}. \tag{6}$$

I propose a nested resilience model comprising environment, society, political processes and electricity infrastructure, incorporating global, national and local issues. This is shown in Fig. 8. Qualitative and quantitative measures within each element of the resilience model can then be chosen, appropriate to the context under consideration. For example, in considering indicators of resilience for the UK electricity system, an appropriate national-scale societal indicator may be the number of households in fuel poverty. For the Sudan, it may be the number of households without a supply of electricity. A global indicator may be electricity consumption per capita (shown in Fig. 9). The collection of qualitative and quantitative indicators can then be presented as a score card. Amalgamation of indicators to provide one measure of resilience relies heavily on quantitative measures and subjective weighting of components and so is not recommended.

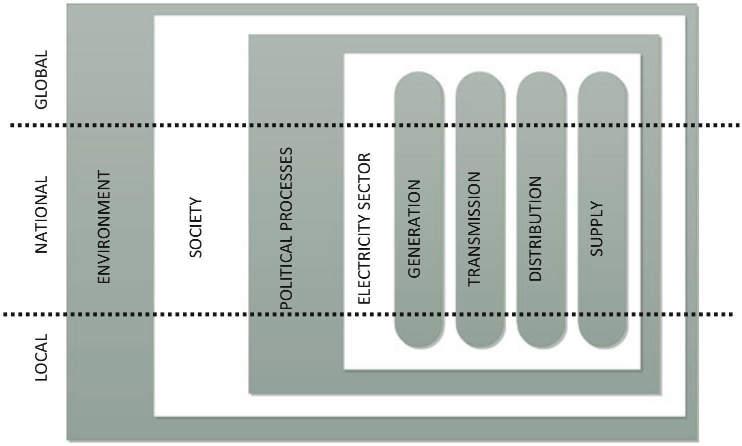

Fig. 8 Representation of three scales, applied to a nested system to represent the electricity sector and its relationship to politics, society, and the environment

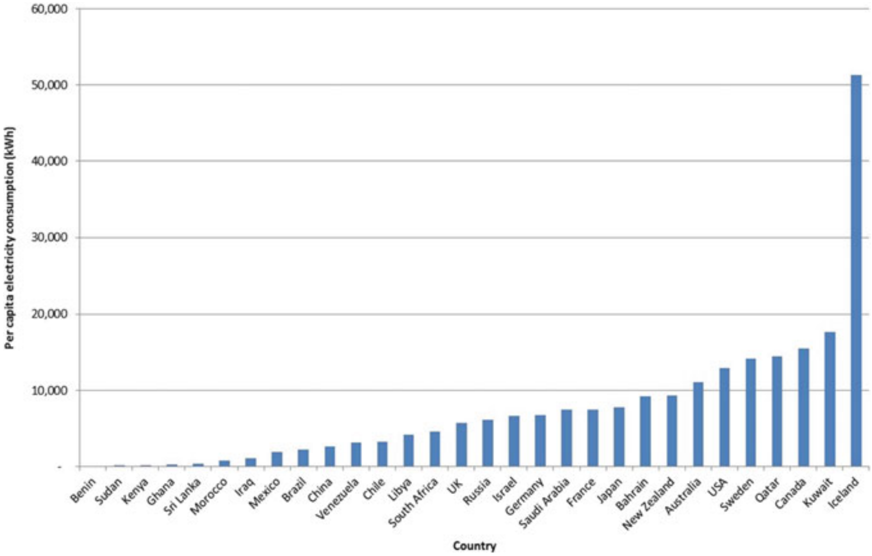

Fig. 9 Electricity consumption per capita, for a number of countries, 2009 (World Bank 2012)

4 Conclusions

With climate change policy at the global level progressing extremely slowly and no replacement for binding Kyoto targets yet agreed, EU policy and UK policy have developed such that the UK has a binding target to reduce GHG emissions by 80 %. To achieve this, there are associated policy targets for decarbonization of the electricity sector and a target to increase electricity generation from renewable energy sources to 30 % by 2020. The importance of national infrastructure in delivering these targets has been recognized in the UK, contributing to the drive to create the National Infrastructure Plan 2010 and the creation of a unit within HM Treasury, Infrastructure UK.

Historical energy security concerns have grown around security of supply of primary fuels. The diversity of fuel mix for energy and for electricity has been expressed using the Shannon–Wiener index. For transmission and distribution systems, security standards require continued operation under $N - 1$ conditions, this requirement having been in place for some time now in the UK.

There are growing concerns that a lack of investment in transmission and distribution infrastructure, and generation capacity, will result in low-capacity margins and reduced performance of the network. Analysis of customer interruptions and customer minutes lost demonstrates performance issues for the distribution network at voltages of 20 kV or lower. UK energy policy also prioritizes delivery of energy services at a fair price, with 20 % of UK households estimated as being in fuel poverty in 2009. The electricity system is becoming more complex as research indicates interconnectedness (with the energy sector, transport, communications, water, and waste) and as the electricity system trials smart grid technologies. Combined with concerns of terrorist threat, the landscape of the UK electricity sector is such that security has become a more complex issue than that of supply of fossil fuels.

Resilience as a term enables a discussion of the electricity system's ability to adapt, change, and transform rather than its ability to return to "normal" within some prescribed range of operating conditions. Combined with multilevel perspectives used in transitions theory, resilience as a concept offers qualitative and quantitative discussion of the socio-technical landscape, the incumbent "regime" and its actors, and niche practices. Whether we are attempting to describe the ability of the electricity system to cope with transient shocks or longer term stress, and whether action is directed at control of or response to shocks and stresses (Stirling 2009), is the finer detail beneath the wider umbrella of resilience. The key overarching theme of resilience applied to the electricity sector is of a system able to undergo change following pressure at the global, national, and local level whilst enabling the continuation of a level of service (power, light, heat, mobility) over time and geography.

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Sara Walker graduated from Leicester University with a bachelor's degree in Physics and went on to teach Physics at GCSE and A-level standard. A short while later, Sara undertook a master's degree in Environmental Science at Nottingham University and moved into her first academic role with De Montfort University. For 7 years at De Montfort University, Sara undertook many research projects in the general areas of renewable energy and energy efficiency. She advised Nottinghamshire Derbyshire Energy Partnership on their energy strategy, she developed a strategy for renewable energy with Newark and Sherwood Energy Agency, and she worked closely with Leicester City Council to evaluate work engaging with the fuel rich to encourage energy efficiency. She also worked on European projects with Vergnet wind turbines, to look at contracts and how they could be simplified for UK applications of small-scale wind. As part of the team at De Montfort University, she contributed to the development of a distance learning master's degree in Energy and Sustainable Development. For the following 5 years, Sara worked in the commercial sector for energy consultancies. She had the opportunity to develop policy advice for governments on renewable energy certificate schemes and worked on grid connection of renewable energy projects. At Econnect, she was the project manager responsible for the influential report "Potential for micro-generation: study and analysis" which was produced in partnership with Element Energy for Energy Saving Trust. In 2007 Sara returned to academia, as Subject Director for the Sustainable Buildings and Energy Systems group in the School of the Built and Natural Environment, Northumbria University. Sara teaches heat transfer, renewable energy technologies, sustainability, and management. Her research interests include performance of renewable energy technologies, energy efficiency retrofit of housing, human behavior in respect to interaction with energy technologies, and energy policy.

The Macroeconomic Effects of Energy Purchases

Carlo Di Maio

Abstract **Purpose** To assess whether the switch in energy source and/or the associated change in trade partners affect the Euro–Dollar exchange rate and how the countries react strategically, adjusting their energy policy.
Approach Dynamic partial equilibrium model.
Findings First, the effect of the energy purchases on the exchange rate dynamics ultimately depends on the preferences over assets and goods of the supplier countries. Second, the import preferences of the energy exporters are what determine the long-run impact of the oil and gas purchases. Therefore, when energy producers have different preferences, switching the supplier or the source can clearly alter the impact on the exchange rate.
Value An analysis of the strategic interaction on the energy markets under the assumption that all assets are not perfect substitutes.

Keywords Euro–Dollar exchange rate • Strategic interaction • Preferences • Trade partners • Energy sources substitutability

Essentially, all models are wrong, but some are useful.
George E. P. Box

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C. Di Maio (✉)
Deutsche Bank S.p.A., P.za Del Calendario 5, Milan 20126, Italy
e-mail: dimaiocarlo@gmail.com

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1 Introduction

Historical trends of energy consumption in the European Union clearly show the process of fuel, from crude oil and coal to natural gas, and supplier, from OPEC to Russia, switching (CSI 029/ENER 026). The first objective of this chapter is to provide an answer to the following question: "How does a switch in energy source and/or the associated change in trade partners affect the Euro–Dollar exchange rate?"

The crucial hypothesis is that this shift has an (major) effect on exchange rates, which is arising from the different preferences of the trade partners in term both of savings and consumption, both assets and goods. If asset preferences and spending patterns were identical in the two countries, an increase in disposable income for Russia and a symmetric decrease in Saudi Arabia would exert no pressure on the exchange rate. When preferences are not identical, wealth transfers are equivalent to a shift in the world demand for assets and goods. This shift gives rise to the exchange rate movements.

The role of preferences has been widely investigated in the literature. However, when it comes to asset preferences, authors have mostly preferred to work under the assumption of perfect substitutability. The most notable example of imperfect substitution is Kouri (1983), where he stated:

> In many of the recent models, including Dornbusch (1976), it is assumed that all other assets but monies are perfect substitutes. In such models balance of payments pressures have no effect on the exchange rate, which can deviate from its purchasing power parity, or long run equilibrium, value only to the extent that monetary conditions permit differences in interest rates, as is shown in Kouri and de Macedo (1978). These models cannot, however, explain observed movements in exchange rates in recent years because these movements have been far in excess of differences in inflation rates even if allowance is made for anticipated differences in future inflation rates as reflected in interest rate differentials. The models of perfect substitutability simply assume away market pressures that could account for the observed behaviour.

To cope with this issue, I present a simple dynamic partial equilibrium model to study the theoretical effect on the Euro–Dollar exchange rate of a change in the energy supplier. There is no immediate implication of the shift. Exchange rates could move any way, with the movement eventually being determined by the comparison between the assets and goods preferences of the countries involved.

1.1 Stylized Facts

In the two decades following the 1979 energy crises, oil prices dropped by almost 60 %. There were many reasons for the fall. We essentially observed a decrease in the demand for oil, due to the combination of the following forces: the recession that hit the USA in the early 1980s, the beginning of oil production from the Prudhoe Bay (Alaska) field and from the North Sea, and the greater availability of alternative fuels, such as the nuclear. To sustain the prices, Saudi Arabia cut its own production, but prices kept falling. In a desperate attempt to push out of the market the more expensive production from the USA and UK, Saudi Arabia engaged in a price war, setting the price at the "netback value." The effect was an instantaneous drop of the prices under $8 a barrel, as the strategy failed and the production from the non-OPEC fields continued at the same rate. Saudi Arabia had not considered the effect of the previous increase in oil prices, which allowed the USA and UK to make marketable their own oil. By 1986, the nominal dollar price of oil was back to the precrises level. The never-ending spiral of price drops entailed the infringement of quotas by OPEC members, especially the small ones, more interested in the revenues maximization.

This story is of extremely important for the analysis. Western countries started worrying about the security of energy supply only in the late 1990s because cheap oil was uninterruptedly available for almost 20 years. The strategic selection of energy partners is a recent story, at least for European Union. The USA considered the problem decades before, trying to both ensure the constant flow of desired fuels and to tether moderate oil nations to the US economy. Kissinger wrote in his memories:

> Our primary goal was to create incentives for the producing nations to become responsible participants in the international economy, [. . .] to encourage the use of surplus dollars for development projects, to reduce producers' free funds for waging economic warfare or blackmail against the industrialized democracies, and to return some of the extorted funds to our economy.

American diplomacy was very successful: by 1979, the Saudis were the largest holders of dollars and US Government securities. Moreover, their military purchases from the USA jumped from $305 million in 1972 to $5 billion in 1975.

The turning point is March 1999. After the decision to increase production to sustain the Asian economies in 1997, prices fell to $10/barrel. In the attempt to save the Russian economy from the default, the USA pressured the Saudis and OPEC to cut oil production to drive up the prices. An agreement between OPEC, Norway, Mexico, Oman and Russia was reached shortly after. Prices recovered immediately, but the threat of a new wave of cheating was substantial. OPEC realized that the greatest incentive to cheat was the availability of spare capacity. Therefore, the new production strategy included the control of the production capacity of the members. Since then, prices begun a shocking rise up to the level reached on July 3, 2008: $145.29.

European Union started immediately worrying about the effect of high oil prices on its economy. A defensive strategy needed to be settled. The reality was rather bleak: EU natural resources were almost exhausted and no other source of energy could sustain the whole economic activity. Eventually the European Commission managed to adopt a Green Paper on the security of energy supply by November 2000 (COM 2000, 769). The message was clear:

> The European Union lacks the necessary powers to act on supply conditions to ensure the best possible management of security of supply. Although room for maneuver is limited,

> two avenues can be explored. First of all, if only because it is an attractive market, the European Union can negotiate a strategic partnership with its supplier countries in order to improve security of supply. It has begun to do this with the Russian Federation by offering it aid to improve its transport networks and develop new technologies within a political framework that could stabilize supply and guarantee investment. Secondly, the European Union must focus particular attention on generating financial aid for renewable sources of energy which, in the very long term, are the most promising in terms of diversification of supplies.

In other words, the development of a long-term energy partnership with Russia was considered essential. Talks started between EU and Russia, the latter expressing openness towards the EU problem of security of the supply as long as she was ensured the desired level of revenues.[1] Especially after the EU enlargement, the economic links between Russia and the EU have extremely reinforced. Even if the euro has also gained importance within the Central Bank of Russia, the dollar remains the preferred international currency in Russia, in particular for its strong role in the global oil markets.

We have now on the table all the elements to understand the model, which is presented in the next section.

2 The Model

The major inspiration to this chapter is Krugman (1980), who developed a simple theoretical model of the effect of an oil price increase on the Dollar–Mark exchange rate. His model shows that the direction of the initial effect is opposite to the one in the long run. Krugman argues that the interaction between oil prices and exchange rates is a problem of multilateral economic relations. Therefore, even a minimal model must include at least three countries. Indeed, the common simplification brought by the "small country" assumption is misleading and never justified.

The model is based on three main ideas. First, preferences play an important role in understanding the effect of oil imports. It is not the total oil expenditure that affects the exchange rate; rather, it is the relation between OPEC preferences and the import bill. Second, the fact that OPEC adjusts its expenditure on goods with a lag implies that the dynamics of the exchange rate will be affected by the preferences of OPEC on assets relative to the preferences on goods. Third, the wealth transfer effect is crucial for explaining the exchange rate behavior. As the exchange market clears, the short-run equilibrium is determined as to equilibrate flow demands for and supply of foreign exchange derived from capital flow on one side and the current account on the other for each country. The burden of balance of payments adjustment falls on the exchange rate alone. When the extra demand by the three countries for domestic and foreign assets in excess of the

[1] EU–Russia summit, Paris, October 30, 2000.

existing holdings is balanced, the long-run equilibrium of the exchange rate is determined by the condition that the current accounts are at normal level.

We notice that the effect of the price of oil depends on whether the burden of the balance of payments of one country resulting from higher oil imports is greater or lower than the benefits from the increase in OPEC investments and purchase of goods. In particular, OPEC preferences over the latter are what define the long-run behavior of exchange rates.

2.1 The Features of the Baseline Model

The model of Krugman is extended to include a fourth country, Russia, and a second commodity, Gas. The World is composed by four countries: the USA, EU, Russia, and OPEC. In the following, it is described how this simplified World works:

- Each country produces. OPEC and Russia produce both Oil and Gas, the USA produces Cars, and EU produces Pasta. Each country buys all the other goods, except for OPEC and Russia which do not exchange their respective commodities.
- Only two assets, Dollar and Euro, are available on the market. The four countries allocate their wealth between the two.
- The wealth of both Russia and OPEC is denominated in Dollar.
- Real income and prices are given for the USA and EU, while they are endogenous for Russia and OPEC. Oil and Gas prices are fixed in the baseline model.
- EU trade balance with respect to the USA depends on the exchange rate. The USA and EU import fixed quantities of Oil and Gas. The imports of OPEC and Russia depend on their income. However, their spending does not adjust immediately as their income changes. It is rather a lagged process.
- The USA and EU hold a fixed amount of each other's currency in their portfolio and their wealth is exogenous. Russia and OPEC hold a fixed fraction of their wealth, endogenous, in Euro and the remaining in Dollar.

2.2 The Goods Market

US and EU intertrade is fixed. As prices and incomes are given, the trade balance (from now on, T_t) only depends on the exchange rate, e_t, that is, the dollar ($) price of euro (€). The EU trade balance with respect to the USA, expressed in Dollar,[2] is:

[2] I will express all the values in dollar unless otherwise stated.

$$T_t = T_t(e_t)$$

$$\frac{\partial T_t}{\partial e_t} < 0.$$

The sign of the derivative of the trade balance with respect to the exchange rate implies that the appropriate Marshall–Lerner condition holds. Note that $e_t = \frac{€}{\$}$, so when e_t increases, the Euro appreciates and the trade balance worsens. I am assuming no *J*-curve effect.

The current accounts of EU and the USA include the energy imports too. Total energy production is assumed to be fixed. The structure of the oil and gas markets is similar, as EU and the USA split the imports of the total world energy production. The prices of all the commodities, P_t^i—where *i* is either o for oil or g for gas and *t* is the time index—are expressed in Dollars. Therefore, energy prices for EU at time *t*, $\frac{P_t^{i,\mathrm{E}}}{e_t}$, depend on the exchange rate in the same period. The markets for oil from OPEC and Russia at time *t*, $O_t^{j,h}$, *j* being the exporter, R for Russia or O for OPEC, and *h* being the importer, E for EU or A for the USA, are specified as follows:

$$\frac{P_t^{\mathrm{o,E}}}{e_t} O_t^{\mathrm{O,E}} = \eta P_t^{\mathrm{o}} O_t^{\mathrm{O}}$$

$$P_t^{\mathrm{o}} O_t^{\mathrm{O,A}} = (1-\eta) P_t^{\mathrm{o}} O_t^{\mathrm{O}}$$

$$P_t^{\mathrm{o}} O_t^{\mathrm{O,A}} + \frac{P_t^{\mathrm{o,E}}}{e_t} O_t^{\mathrm{O,E}} = P_t^{\mathrm{o}} O_t^{\mathrm{O}}$$

$$\frac{P_t^{\mathrm{o,E}}}{e_t} O_t^{\mathrm{R,E}} = \phi P_t^{\mathrm{o}} O_t^{\mathrm{R}}$$

$$P_t^{\mathrm{o}} O_t^{\mathrm{R,A}} = (1-\phi) O_t^{\mathrm{R}}$$

$$P_t^{\mathrm{o}} O_t^{\mathrm{R,A}} + \frac{P_t^{\mathrm{o,E}}}{e_t} O_t^{\mathrm{R,E}} = P_t^{\mathrm{o}} O_t^{\mathrm{R}}.$$

The share of EU imports of oil from OPEC is η while the share of EU imports from Russia is ϕ. It follows that the total US import of oil from OPEC at time, $O_t^{\mathrm{O,A}}$, may be higher or lower than those of EU, $O_t^{\mathrm{O,E}}$. The same is true for the imports of Russian oil.

The Gas market works similarly. The total gas exported from each country, G_t^j, is allocated to the consumer countries according to the following rules:

$$\frac{P_t^{g,E}}{e_t} G_t^{O,E} = \psi P_t^g G_t^O$$

$$P_t^g G_t^{O,A} = (1 - \psi) P_t^g G_t^O$$

$$P_t^g G_t^{O,A} + \frac{P_t^{g,E}}{e_t} G_t^{O,E} = P_t^g G_t^O$$

$$\frac{P_t^{g,E}}{e_t} G_t^{R,E} = \omega P_t^g G_t^R$$

$$P_t^g G_t^{R,A} = (1 - \omega) P_t^g G_t^R$$

$$P_t^g G_t^{R,A} + \frac{P_t^{g,E}}{e_t} G_t^{R,E} = P_t^g G_t^R.$$

In the gas market, ψ is the share of gas exported from OPEC to EU and ω is the share of gas that EU imports from Russia. Their value is of fundamental importance for understanding of the exchange rate dynamics.

The imports of OPEC and Russia depend on their incomes: while Oil and Gas constitute almost the entire income of OPEC and Russia, they account only for a minor percentage of US and EU spending. In addition, I also consider the lag in the expenditure and the marginal propensity to consume in goods an extra unit of income.

OPEC has fixed preferences: it spends a portion $\gamma(e_t)$ of its total expenditures at time t, X_t^O, in Pasta from EU and a share $1 - \gamma(e_t)$ in Cars from the USA. I assume that OPEC wealth is held in dollars, so the imports are paid in the same currency. For this reason, the spending in imports from EU, $X_t^{O,E}$ depends on the exchange rate e_t through the parameter γ.

$$X_t^{E,O} = \gamma(e_t) X_t^O$$

$$X_t^{A,O} = [1 - \gamma(e_t)] X_t^O$$

$$X_t^O = X_{t-1}^O + \lambda (P_t^O O_t^O + P_t^g G_t^O - X_{t-1}^O).$$

The parameter λ is the share of the surplus (deficit) of the current account used to finance the consumption of goods (financed via a reduction of the consumption).

Imports from Russia are determined in the same way. Clearly, the Russian propensity to import from EU, $\delta(e_t)$, is different from the one of OPEC. Russian imports from EU need to be paid in Euro. Therefore, $X_t^{R,E}$ equals the share of total Russian imports from EU, $\delta(e_t)\ X_t^R$, converted in Euro.

$$X_t^{\mathrm{E,R}} = \delta(e_t)X_t^{\mathrm{R}}$$

$$X_t^{\mathrm{A,R}} = [1 - \delta(e_t)]X_t^{\mathrm{R}}$$

$$X_t^{\mathrm{R}} = X_{t-1}^{\mathrm{R}} + \rho(P_t^{\mathrm{O}}O_t^{\mathrm{R}} + P_t^{\mathrm{g}}G_t^{\mathrm{R}} - X_{t-1}^{\mathrm{R}}).$$

In this case, the marginal propensity of Russians to consume an extra unite of income is ρ.

2.3 The Capital Market

I assume that the marginal propensity of the USA and EU to hold an extra unit of wealth in the foreign currency is zero. As none of the market considered has an extreme wealth effect on both the USA and EU, the assumption is reasonable. Conversely, the change in wealth is significant for both Russia and OPEC. At each point in time, the holdings of foreign assets by the USA and EU, A_t^j, where j is either A or E, are functions of the exchange rate and of the fixed amount expressed in the home currency allocated to the foreign currency.

$$A_t^{\mathrm{A}} = \frac{€_t^{\mathrm{A}}}{e_t}$$

$$A_t^{\mathrm{E}} = \$_t^{\mathrm{E}} e_t.$$

The asset holding of OPEC and Russia is linked to their wealth. In particular, as I assume away the effect on preferences of the expected rate of returns, the oil and gas producers allocate fixed fractions of their wealth between the two assets.

As both OPEC and Russia are assumed to hold their wealth, Z_t^j, in dollars, their holdings of Euro assets at time t, $A_t^{j,€}$, has to be converted in euro.

$$A_t^{\mathrm{O},€} = \frac{€_t^{\mathrm{O}}}{e_t} = \alpha Z_t^{\mathrm{O}}$$

$$A_t^{\mathrm{O},\$} = \$_t^{\mathrm{O}} = (1 - \alpha)Z_t^{\mathrm{O}}$$

$$A_t^{\mathrm{R},€} = \frac{€_t^{\mathrm{R}}}{e_t} = \beta Z_t^{\mathrm{R}}$$

$$A_t^{\mathrm{R},\$} = \$_t^{\mathrm{R}} = (1 - \beta)Z_t^{\mathrm{R}}.$$

α and β are, respectively, the fractions of the wealth of OPEC and Russia allocated to Euro assets. An appreciation of the Euro will negatively impact on the wealth of OPEC and Russia, which will experience a loss in the share of their Euro holdings, α and β.

The change in wealth is affected by the marginal propensity to save. I previously defined the marginal propensity to consume as ρ for Russia and λ for OPEC. The remaining surplus—or deficit—of the current account is thus transferred to the capital markets for investment purpose.

The change in wealth is thus function of the share of current account surplus invested (deficit financed by liquidating assets) minus the capital loss on Euro holdings (plus capital gains on Euro holdings).

$$\dot{Z}_t^{\mathrm{O}} = (1-\lambda)B_t^{\mathrm{O}} - \alpha Z_t^{\mathrm{O}}\left(\frac{\dot{e}_t}{e_t}\right)$$

$$\dot{Z}_t^{\mathrm{R}} = (1-\rho)B_t^{\mathrm{R}} - \beta Z_t^{\mathrm{R}}\left(\frac{\dot{e}_t}{e_t}\right).$$

The complete model is now specified.

2.4 The Dynamics

Commodity exporters adjust their spending with a lag while no temporal limitation is imposed on the investment decision. The time difference between the allocation on the world markets of financial resources and the spending on goods of extra revenues is what determines the dynamic movements of exchange rates. In the short run, we require the current and the capital account to balance. The exchange rate must move to offset the capital flow generated from OPEC and Russia. In the long run, when the imports of oil and gas producers reach their new level, the new equilibrium of the exchange rate is determined so that the current accounts are at their normal level.

2.4.1 The Short Run

In the short run, the balance of payments must be in equilibrium. In a two-currency world, the equilibrium condition imposed on the EU balance of payments is equivalent to the one imposed on the US balance of payments.

The EU current account, B_t^{E}, equals the sum of the EU net exports to the USA plus exports to OPEC and Russia minus the energy imports.

$$B_t^{\mathrm{E}} = T_t(e_t) + \gamma(e_t)X_t^{\mathrm{O}} + \delta(e_t)X_t^{\mathrm{R}} - \eta P_t^{\mathrm{o}}O_t^{\mathrm{O}} - \phi P_t^{\mathrm{o}}O_t^{\mathrm{R}} - \psi P_t^{\mathrm{g}}G_t^{\mathrm{O}} - \omega P_t^{\mathrm{g}}G_t^{\mathrm{R}}.$$

The EU capital account is given by the net flow of capital into the European Union, which is given by the difference between purchases of Euro assets by the USA, OPEC, and Russia minus purchases of the US assets by EU.

$$K_t^{\mathrm{E}} = \frac{€_t^{\mathrm{A}}}{e_t}\left(\frac{\dot{e}_t}{e_t}\right) + \frac{€_t^{\mathrm{O}}}{e_t}\left(\frac{\dot{e}_t}{e_t}\right) + \frac{€_t^{\mathrm{R}}}{e_t}\left(\frac{\dot{e}_t}{e_t}\right) - \$_t^{\mathrm{E}}\left(\frac{\dot{e}_t}{e_t}\right).$$

When defining the capital markets, I assumed that the flow of capital was function of the change in wealth. Substituting for the wealth of OPEC and Russia in the capital account yields the following equation[3]:

$$\begin{aligned} K_t^{\mathrm{E}} = {} & \frac{€_t^{\mathrm{A}}}{e_t}\left(\frac{\dot{e}_t}{e_t}\right) - \$_t^{\mathrm{E}}\left(\frac{\dot{e}_t}{e_t}\right) + \alpha\left[(1-\lambda)B_t^{\mathrm{O}} - \alpha Z_t^{\mathrm{O}}\left(\frac{\dot{e}_t}{e_t}\right)\right] \\ & + \beta\left[(1-\rho)B_t^{\mathrm{R}} - \beta Z_t^{\mathrm{R}}\left(\frac{\dot{e}_t}{e_t}\right)\right] + \alpha Z_t^{\mathrm{O}}\left(\frac{\dot{e}_t}{e_t}\right) + \beta Z_t^{\mathrm{R}}\left(\frac{\dot{e}_t}{e_t}\right). \end{aligned}$$

The previous condition shows that the capital account is function of net flow of capital from the USA and the change in the wealth of OPEC and Russia.

The balance of payments is then derived setting $K_t^{\mathrm{E}} + B_t^{\mathrm{E}} = 0$. That is,

$$\begin{aligned} & \frac{€_t^{\mathrm{A}}}{e_t}\left(\frac{\dot{e}_t}{e_t}\right) - \$_t^{\mathrm{E}}\left(\frac{\dot{e}_t}{e_t}\right) + \alpha\left[(1-\lambda)B_t^{\mathrm{O}} - \alpha Z_t^{\mathrm{O}}\left(\frac{\dot{e}_t}{e_t}\right)\right] + \beta\left[(1-\rho)B_t^{\mathrm{R}} - \beta Z_t^{\mathrm{R}}\left(\frac{\dot{e}_t}{e_t}\right)\right] \\ & \quad + \alpha Z_t^{\mathrm{O}}\left(\frac{\dot{e}_t}{e_t}\right) + \beta Z_t^{\mathrm{R}}\left(\frac{\dot{e}_t}{e_t}\right) \\ & \quad = -B_t^{\mathrm{E}}. \end{aligned}$$

Solving for the exchange rate, I get the rate of change of the exchange rate:

$$\frac{\dot{e}_t}{e_t} = \frac{B_t^{\mathrm{E}} + \alpha(1-\lambda)B_t^{\mathrm{O}} + \beta(1-\rho)B_t^{\mathrm{R}}}{\frac{€_t^{\mathrm{A}}}{e_t} - \$_t^{\mathrm{E}} + \alpha(1-\alpha)Z_t^{\mathrm{O}} + \beta(1-\beta)Z_t^{\mathrm{R}}}.$$

In the short run, the exchange rate moves according to the ratio of EU combined current account—that is, the EU current account plus the part of the energy exporters' current account recycled into Euro assets—on the size of the international investment pool. Euro will depreciate (appreciate) if the recycling of OPEC and Russia is not enough (enough) to offset the deficit induced by energy purchases and net flow of capital in EU is negative (positive). If α and β are low, this is likely to be the case. The magnitude of the effect is very difficult to detect and depends on a number of factors, including the marginal propensity to save by Russia and OPEC,

[3] The proof of each step from now on is in Appendix.

their total wealth and the share of wealth that they hold in euro. The EU current account deficit or surplus alone does not give any information on the fluctuation of the exchange rate. For the Euro to appreciate, the sum of the planned spending on Pasta from EU—remember that the import decisions are lagged—and of the capital inflow into EU must be such to offset the outflow of money from EU to pay for its energy bill.

2.4.2 The Long Run

From the dynamics outlined in the previous section, after the initial shock to the international payments, the spending of the USA and EU in energy remains constant. The exchange rate is affected by two factors:

- The dynamics of the wealth of OPEC and Russia
- The dynamics of the expenditures of OPEC and Russia

Eventually, when the current accounts of OPEC and Russia are in equilibrium, there will be no other source of fluctuation and the world will reach the new exchange rate. Equally, in the long run all of the equations in the dynamic system are constrained to be zero. The total effect on the exchange rate will then be given by the following:

$$\mathrm{de} = \frac{(\alpha(1-\lambda)-\gamma)dX^{\mathrm{O}} + (\beta(1-\rho)-\delta)dX^{\mathrm{R}}}{(\partial T/\partial e) + (\partial\gamma/\partial e)X^{\mathrm{O}} + (\partial\delta/\partial e)X^{\mathrm{R}}}.$$

The denominator is negative by the Marshall–Lerner condition. This is obvious for the EU–US trade balance, but it is true also for OPEC and Russia spending. The numerator can be either positive or negative, depending on whether the investment propensity of OPEC and Russia is greater or lower than their spending propensity in EU. Under the assumption that both OPEC and Russia spend more on EU products of what they invest in EU, the long-run effect of an increase in energy purchases is an appreciation of the euro. However, a very important role is played by the marginal propensity to save in the two countries. As they do not invest all of their earnings on the capital markets, but just a fraction $(1-\lambda)$ for OPEC and $(1-\rho)$ for Russia, the lower is the propensity to save, the higher is the long-run effect of the import of goods on the exchange rate.

Table 1 summarizes the range of all possible effects and the impact of switch in energy source or partner.

The other four cases follow by induction.

Table 1 The range of all possible effects and the impact of switch in energy source or partner

Preferences	Long-run exchange rate dynamics	Switch	Effect of the switch
1. $\alpha(1-\lambda) > \gamma$ 2. $\beta(1-\rho) > \delta$	The euro depreciates	From OPEC to Russia or vice versa	No effect
1. $\alpha(1-\lambda) < \gamma$ 2. $\beta(1-\rho) < \delta$	The euro appreciates	From OPEC to Russia or vice versa	No effect
1. $\alpha(1-\lambda) > \gamma$ 2. $\beta(1-\rho) < \delta$ $1 > 2$	The euro should depreciate, unless dX^{R} is high enough	From OPEC to Russia	dX^{R} increases, the depreciation of the euro is less strong or it is reversed
1. $\alpha(1-\lambda) > \gamma$ 2. $\beta(1-\rho) < \delta$ $1 > 2$	The euro should depreciate, unless dX^{R} is high enough	From Russia to OPEC	dX^{R} decreases, the euro depreciates more or appreciates less
1. $\alpha(1-\lambda) > \gamma$ 2. $\beta(1-\rho) < \delta$ $1 < 2$	The euro should appreciate, unless dX^{O} is high enough	d{{X}^ {R}} ~ beta OPEC to Russia	dX^{R} increases, the euro appreciates more or depreciates less
1. $\alpha(1-\lambda) > \gamma$ 2. $\beta(1-\rho) < \delta$ $1 < 2$	The euro should appreciate, unless dX^{O} is high enough	From Russia to OPEC	dX^{R} decreases, the euro appreciates less or depreciates more

3 Introducing the Strategy

The world is not made of price takers—at least in the long run. Consumers do play a great role in shaping the market. Their strategy is composed of three related goals: diversify the energy suppliers, reduce the imports of energy, and reduce the energy consumption overall. The EU policies contemplate both an increase in the energy efficiency to reduce the energy intensity of the GDP and a series of major investments in the development of renewable backstops. This two combined may be effective in tackling the second and the third issue presented above.

As long as the price of oil and gas were linked, there was not much the consumer countries could do to avoid the burden of the increased energy bill. In the years before the global recession, several actions were taken to mitigate the effect of energy prices, including the creation of new infrastructures—LNG terminals, pipelines, and power plants. Importing countries have now increased flexibility in switching source. While the effect in the switch of the supplier may be determined in the baseline model framework, some extra restrictions will have to be imposed to find the effect on energy purchases of the increase in prices by the energy producers. I will also assume that there is no constraint—both technological and legal—to the amount of energy demand that can be switched.

I partially relax the assumption that oil and gas imports are fixed, and I match this with the hypothesis that total energy imports must be constant. Focusing on EU only, the total energy purchases are given by:

$$\eta \frac{P_t^{o,E}}{e_t} O_t^O - \phi \frac{P_t^{o,E}}{e_t} O_t^R - \psi \frac{P_t^{g,E}}{e_t} G_t^O - \omega \frac{P_t^{g,E}}{e_t} G_t^R = \bar{E}.$$

$\bar{E}$ is the total of oil and gas imported by EU, which is constant over time.

$$d\bar{E} = 0.$$

As a consequence, any change in the structure of energy imports must be such that total energy imports are held constant.

$$d\left(\eta \frac{P_t^{o,E}}{e_t} O_t^O - \phi \frac{P_t^{o,E}}{e_t} O_t^R\right) + d\left(\psi \frac{P_t^{g,E}}{e_t} G_t^O - \omega \frac{P_t^{g,E}}{e_t} G_t^R\right) = 0.$$

With G_t^E total gas imports and O_t^E total oil imports of EU, I derive how oil imports change from time to time:

$$d(O_t^E) = \frac{O_t^E\left(\frac{P_t^{o,E}}{e_t} de_t - d(P_t^{o,E})\right) - d(G_t^E)}{P_t^{o,E}}.$$

What do we learn about the EU strategy? When the price of oil increase, EU is interested in buying more gas, if cheaper. However, the appreciation of euro has a positive impact on the purchases of oil. Total changes in oil imports are given by the difference between the effect on the oil and gas markets of the exchange rate and the prices.

What is the effect of this switch on the exchange rate? It depends. The switch affects EU preferences in terms of energy—η, ϕ, ψ, and ω. Should such a change happen, this is going to impact on the exchange rate dynamics. Recalling the long-run effect in the baseline model:

$$\text{de} = \frac{(\alpha(1-\lambda) - \gamma)dX^O + (\beta(1-\rho) - \delta)dX^R}{(\partial T/\partial e) + (\partial\gamma/\partial e)X^O + (\partial\delta/\partial e)X^R}.$$

When the change in the energy source is realized by changing the supplier, the switch is going to affect the exchange rate dynamics if the new supplier has different preferences from the previous. For instance, considering the EU import structure after the recession, the major tool available is the LNG, which is mainly imported from OPEC. As long as new pipelines are not completed, a substitution of oil with gas from OPEC may induce a long-run depreciation of the dollar, given that OPEC buys more EU goods of what it invests in EU assets. Since the shape of energy markets is changing fast, new technologies, the availability of new infrastructures, or simply the discovery of new fields in other regions of the world—like the Marcellus Shale Natural Gas Field in Pennsylvania—might change the picture. This is likely to impact on the exchange rate movements.

4 Conclusions

In this chapter a simple model was presented to study the interactions between energy markets and the Euro–Dollar exchange rate. The hypothesis is that the behavior of energy producers and suppliers is highly strategic and one has to account for it when modelling the energy markets. In particular, I proposed a simple partial equilibrium model where a simple world of four countries, two currencies, two energy sources, and two goods was represented. Although the model is extremely simple and relies heavily on very strong assumptions, it proves to be a useful tool to consider the channels through which a change in the energy source or in the energy supplier can impact on the exchange rate dynamics.

Several considerations arise from the analysis of the model. In particular, two are key to answer to the research question of this chapter. First, the effect of the energy purchases on the exchange rate dynamics ultimately depends on the preferences over assets and goods of the supplier countries. Second, the import preferences of the energy exporters are what determine the long-run impact of the oil and gas purchases. Therefore, when energy producers have different preferences, switching the supplier or the source can clearly alter the impact on exchange rate. In the second part of my analysis, I focused my attention on the strategic actions of the energy market players and their long-term energy policies. Specifically, I assumed that the USA and EU aim at reducing their energy bills—switching source of energy. I found that, *ceteris paribus*, the effect of the switch in energy source might be significant when it is combined with a substitution of the supplier, especially since the link between oil and gas prices is starting to vanish. The impact on the exchange rate dynamics is higher when the new trade partner has different preferences with respect to assets and goods compared to the previous supplier. This is a very powerful strategic tool for importing countries, especially when the infrastructure constrain in the energy markets is reduced.

While my results might be affected by a number of factors, including the effect of speculation and the level of the economic activity, they still deserve attention as a good example of the study of a very strategic, fast-changing market. Future efforts should be devoted to understanding how the interaction between energy players will change when new infrastructure—pipelines, IV generation nuclear plants, and renewable power plants—go into operation. According to my framework, this is likely to have a strong impact on the structure of the market, where there will be room for a flexible energy policy.

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Carlo Di Maio is credit risk analyst at Deutsche Bank. He is a contributor of the ACEGES tool. In his previous roles, he has worked as an equity research analyst, Deutsche Bank, and as a research assistant, Centre for International Business and Sustainability at London Metropolitan Business School and IGIER at Università Luigi Bocconi.

EU's Dynamic Evaluation of Energy Efficiency: Combining Data Envelopment Analysis and Multicriteria Decision Making

Georgia Makridou, Kostas Andriosopoulos, Michael Doumpos, and Constantin Zopounidis

Abstract Purpose This chapter applies an integrated methodology for energy efficiency evaluation and benchmarking, based on nonparametric techniques. The analysis is well suited to the multidimensional nature of energy efficiency. An up-to-date panel data set is used, consisting of countries from the European Union over the period 2000–2010.

Approach The analysis is based on a methodology combining data envelopment analysis for energy efficiency evaluation with a multicriteria classification technique for building an operational benchmarking evaluation model. Indicators on energy efficiency, environmental indicators, as well as economic and growth variables are aggregated to obtain a global evaluation of the countries.

Findings The energy efficiency of countries in the European Union has been affected by the recent economic crisis. This is verified through the developed models that consider a refined breakdown of input and output variables related to economic activity and the consumption of different energy sources. Except for

G. Makridou (✉)
Research Centre for Energy Management, ESCP Europe Business School, London, UK

Technical University of Crete, Chania, Greece
e-mail: gmakridou@rcem.eu

K. Andriosopoulos
Research Centre for Energy Management, ESCP Europe Business School, London, UK
e-mail: kandriosopoulos@escpeurope.eu

M. Doumpos
Department of Production Engineering and Management, Financial Engineering Laboratory, Technical University of Crete, University Campus, Chania 73100, Greece
e-mail: mdoumpos@dpem.tuc.gr

C. Zopounidis
Department of Production Engineering and Management, Financial Engineering Laboratory, Technical University of Crete, University Campus, Chania 73100, Greece

Audencia Group, School of Management, Nantes, France
e-mail: kostas@dpem.tuc.gr

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energy intensity, the efficiency of the countries is also determined by factors related to their level of economic activity, competitiveness, and growth.
Value The proposed multidimensional framework for analyzing energy efficiency would be useful for policy makers and stakeholders in identifying trends over time as well as to perform benchmark comparisons across countries.

Keywords Energy efficiency • Data envelopment analysis • Multiple-criteria decision aiding

1 Introduction

In the 1970s and early 1980s, energy efficiency emerged as a major issue for sustainable economic growth. Even after the counter-oil shock of 1986 and the decline of oil prices, environmental concerns continued to rise, especially in the context of the growing debates on global warming and climate change, which gave energy efficiency improvement a new perspective. The latter, in combination with the sharp increase in oil prices during the 2000s, has brought energy efficiency into the policy agenda of many countries as a top priority issue.

Energy efficiency is now recognized as an essential component of sustainable development policies, which seek to achieve a well-balanced trade-off between economic growth and competitiveness, energy security, and environmental sustainability. However, as McKibbin et al. (2011) point out, adoption rates for energy efficient technologies fall short of the levels that many believe are justified by the potential returns on such investments. Therefore, the reevaluation of the connections between energy efficiency, growth, and economic performance is of major importance and has direct implications for the policies implemented at the country level. Researchers have developed appropriate indicators for monitoring economy-wide energy efficiency trends over time or comparing energy efficiency performances across countries/regions.

In this chapter, energy efficiency is considered in a multidimensional context, evaluated using indicators related to environmental pollution, country characteristics, the use of renewable sources, as well as energy consumption. This framework enables the isolation of the "underlying energy efficiency" for each country after controlling for economic output, environmental issues, as well as effects due to differences in the structure of the economy. Consequently, once the latter effects are adequately controlled for, the estimation of the underlying energy efficiency for each country is performed which shows (1) the change of efficiency over the estimation period and (2) the differences in efficiency across the panel of countries aligned with Filippini and Hunt (2011). The analysis is based on data collected for European Union countries over the period 2000–2010.

On the methodological side, at the first stage, we use data envelopment analysis (DEA) to measure the relative efficiency of the countries. DEA is a popular nonparametric efficiency analysis technique with many applications in energy management and environmental planning (see among others, Hu and Kao 2007; Ramanathan 2005; Zhou et al. 2007). At the second stage, the DEA efficiency classifications are used as inputs to a multicriteria decision-making approach, which is employed to build an operational model that combines energy efficiency, economic, and environmental indicators. The resulting multicriteria model evaluates all countries in a common setting, and it can be easily used for benchmarking purposes.

The remainder of this chapter has the following structure: Sect. 2 presents a literature review, followed in Sect. 3 by the presentation of the main methodological tools employed in the analysis. Section 4 describes the data and variables used in the analysis, whereas Sect. 5 presents and discusses the obtained results. Finally, Sect. 6 concludes the chapter and outlines some future research directions.

2 Literature Review

The directive on energy end-use efficiency and energy services of the European Council and the Parliament defines energy efficiency as "a ratio between an output of performance, service, goods or energy, and an input of energy" (EU 2006). In order to measure energy efficiency changes over time at the economy-wide level and to be able to make cross-country comparisons, a rich body of research has emerged.

A significant part of the literature considers energy efficiency within a framework where energy is one of the many inputs of production, with the most widely used technique being data envelopment analysis (DEA). A recent literature survey by Zhou et al. (2008) lists a total of 100 studies published from 1983 to 2006 using DEA in the area of energy and environmental analysis, with 72 studies published between 1999 and 2006. Zhou and Ang (2008) presented several DEA-type linear programming methods for measuring economy-wide energy efficiency performance using labor, capital stock and energy consumption as inputs, and GDP as output.

Bampatsou and Hadjiconstantinou (2004) used DEA to develop an efficiency index which combines economic activity, CO_2 emissions, and energy consumption of the production process in 31 European countries for the year 2004. In a similar context, Ramanathan (2005) used DEA to analyze the performance of 17 countries from the Middle East and North Africa in terms of four indicators of energy consumption and CO_2 emissions for the period 1992–1996. Lozano and Gutiérrez (2008) applied a number of nonparametric, linear programming (LP) models for measuring energy efficiency in 21 OECD countries during 1990–2004, using the environmental DEA technology concept. Lanfang and Jingwan (2009) proposed a nonparametric method based on DEA to measure energy efficiency, taking into account undesirable factors such as water, gas, and solid wastes. Zhou and Ang (2008) presented several DEA formulations for measuring economy-wide energy efficiency.

DEA has also gained popularity in environmental performance measurement. Färe et al. (2004) provided a formal index of environmental performance using DEA techniques, taking into account three pollutants (CO_2, SO_X, and NO_X) as undesirable outputs. The proposed index suggests that there may be no clear-cut relationship between pollutants and per capita income. Zhou and Ang (2008) applied environmental performance measures to study the carbon emission performance of eight world regions in 2002 under different reference technologies. The results show that the environmental performance index of a certain country may change under different environmental DEA technologies because different models are adopted under different situations. Furthermore, the study shows that the undesirable outputs' orientation DEA model is particularly attractive because it provides a pure environmental performance measure. Finally, DEA has also been applied to study the productive efficiency of some specific energy sectors such as district heating plants (Lygnerud and Peltola-Ojala 2010), as well in the oil, gas, and coal industries (Hawdon 2003; Azadeh et al. 2007; Fang et al. 2009).

Except for DEA models, multicriteria decision making (MCDM) have also been extensively used for energy management and efficiency evaluation. MCDM is involved with decision problems under the presence of multiple (conflicting) decision criteria, which require the selection of the best alternatives, the ranking of the alternatives according to their overall performance, or their classification into predefined performance groups.

Diakoulaki et al. (1999) used a multicriteria methodology for the determination of the relative contribution of different factors in reaching a desired level of energy efficiency. Their analysis focused on 13 EU countries and the USA in three points in time (1983, 1988, 1993), using data on economic growth and energy consumption. The results showed that richer countries achieve better energy intensity than less developed ones. Appropriate pricing policies (mainly on electricity) and long-term structural changes of the energy system were the main means for achieving efficient energy use in the late 1980s and early 1990s.

Neves et al. (2009) used the Soft Systems Methodology (SSM) and value-focused thinking to elicit and structure objectives for the evaluation of energy efficiency initiatives. The study proved that SSM was useful, helping to define clearly the decision problem context and support the main players involved, as well as to unveil the relevant objectives for each stakeholder.

Mavrotas and Trifillis (2006) used some basic principles from DEA to facilitate the evaluation of the environmental performance of 14 EU countries through a MCDM approach. Their analysis was based on indicators related to energy and emission intensity, the countries' energy mix, the use of land, and recycling. The results show that countries which exhibit a wide range of performances across the criteria result are more sensitive to modifications in the relative importance of the evaluation criteria.

In addition to the aforementioned studies related to energy efficiency and environmental performance at the country level, the review of Wang et al. (2009) verifies the increasing interest in using MCDM approaches in other related areas such as energy resource allocation, energy exploitation, energy policy setting, building energy management, and transportation energy systems. Pohekar and Ramachandran (2004) also reviewed the literature from a sustainable energy planning perspective and identified an increasing popularity and applicability of

MCDM methods beyond 1990, which is indicative of a paradigm shift in energy planning approaches. MCDM methods were found to be more popular in renewable energy planning followed by energy resource allocation. Zhou et al. (2006) attributed the increased popularity of MCDM especially in decision making for sustainable energy to the multidimensional nature of the sustainability goal and the complexity of the socioeconomic and biophysical systems.

The above overview indicates that despite the rich literature on the use of DEA and MCDM for energy efficiency analysis and planning, there has been almost no attempt to combine the information that the two approaches provide in a unified context. Thus, this study contributes to the literature by adopting an integrated DEA/MCDM approach. Furthermore, we use the most up-to-date data available for EU countries (from 2000 to 2010), which enables the identification of the impacts that the economic crisis has on the energy efficiency performance of the countries in the EU.

3 Methodology

3.1 Data Envelopment Analysis

DEA, originally proposed by Charnes et al. (1978), is a nonparametric frontier technique where efficiency of a particular entity is measured by its distance from the best-practice frontier constructed by the best entities within a sample. It is a well-established methodology for the evaluation of the *relative* efficiencies of a set of comparable entities (decision-making units, DMUs) which transform multiple inputs (energy and nonenergy inputs) into multiple outputs (desirable and undesirable). Relying on LP techniques and without having to introduce any subjective or economic prices (weights, costs, etc.), DEA provides a nonparametric estimate of the efficiency of each DMU in comparison to the best-practice frontier constructed by the best-performing DMUs (Zhou and Ang 2008).

In particular, assume that there are data on K inputs and M outputs for N DMUs. For the ith DMU, these are represented by the vectors $\mathbf{x}_i$ and $\mathbf{y}_i$, respectively. The $K \times N$ input matrix $\mathbf{X}$ and the $M \times N$ output matrix $\mathbf{Y}$ represent the data for all DMUs. Then, the efficiency of the ith DMU is measured by the ratio

$$\theta_i = \frac{\mathbf{u}_i \mathbf{y}_i}{\mathbf{v}_i \mathbf{x}_i} \in [0, 1],$$

where $\mathbf{u}_i, \mathbf{v}_i \geq \mathbf{0}$ are weight vectors corresponding to the outputs and inputs for the ith DMU. DEA provides an assessment of the relative efficiency of a DMU compared to a set of other DMUs. Under constant returns to scale (CRS) and assuming an input orientation, the maximum efficiency for the ith DMU can be estimated through the LP formulation introduced by Charnes et al. (1978), which is expressed in dual form as follows (CCR model):

$$\begin{array}{ll} \min & \theta_i^{\mathrm{C}} \\ \text{Subject to}: & \theta_i^{\mathrm{C}}\mathbf{x}_i - \mathbf{X}\lambda \geq \mathbf{0} \\ & \mathbf{Y}\lambda \geq \mathbf{y}_i \\ & \lambda \geq \mathbf{0},\ \theta_i^{\mathrm{C}} \in \mathbb{R} \end{array}.$$

With the solution of this LP problem, a country i is classified as efficient if $\theta_i^{\mathrm{C}} = 1$ or inefficient if $\theta_i^{\mathrm{C}} < 1$. Variable returns to scale (VRS) can be introduced by simply adding the convexity constraint $\lambda_1 + \cdots + \lambda_N = 1$ to the above model. This constraint ensures that a DMU is benchmarked only against other units of similar size. The resulting model is known as the BCC model (Banker et al. 1984).

The characteristics of DEA and in particular (a) the lack of restrictive assumptions on the form of the production function that relates input(s) to output (s) and (b) the possibility of using simultaneously multiple inputs and outputs, which can be specified by different units of measurement, provide the possibility of considering alternative approaches, based on different input and output combinations, thus enabling the in-depth examination of complicated issues (Bampatsou and Hadjiconstantinou 2004). In addition to efficiency estimates, DEA also supports the identification of the sources of inefficiency, as well as the specification of performance targets.

3.2 Building an Operational Efficiency Evaluation Model Through a Multicriteria Approach

The efficiency analysis results obtained with DEA provide useful indications on the relative performance of the countries. However, in the context of DEA, each country is evaluated with different weightings of the input and output variables, thus making it difficult to interpret the results in a common setting that would be applicable to all countries as the results are sample dependent. Furthermore, DEA does not discriminate among efficient cases, as they all receive the same efficiency score. Alternative techniques, such as stochastic frontier analysis (Coelli et al. 2005), quantile regression (Kokic et al. 1997), and expectile smoothing (Voudouris et al. in press), address some of the shortcomings of DEA, but they assume specific input–output functional forms, and their implementation with multiple outputs is often troublesome (Whiteman 1999).

To overcome these issues, we perform a second-stage analysis aiming towards the development of a global evaluation model common for all countries. Such a model is particularly useful to decision and policy makers, and it can be easily used for benchmarking purposes without requiring performing the DEA analysis every time when one needs to evaluate the efficiency of a single country. Thus, using the results from DEA on a selected panel data sample of country-year observations, the model developed at this second stage enables the evaluation of energy efficiency for any other country at different time periods, using the selected sample as a reference benchmark.

This second stage of the analysis is implemented using a multicriteria classification technique, which enables the consideration of multiple performance criteria that take into account in a comprehensive way the multiple aspects (inputs and outputs) of energy efficiency and its relationship to economic and environment performance. The multicriteria evaluation model is built on the basis of the DEA results. In particular, the countries are classified as efficient or inefficient according to their DEA efficiency scores, and a multicriteria model is constructed, which combines n criteria so that the model's classifications are as close as possible to DEA's efficiency classification. The UTADIS multicriteria method is used for this purpose (Doumpos and Zopounidis 2002). The UTADIS method leads to the development of an additive value function of the following form:

$$V(\mathbf{x}_i) = \sum_{j=1}^{n} w_j v_j(x_{ij}) \in [0, 1],$$

where w_j is a nonnegative trade-off constant for evaluation criterion j and $v_j(x_j)$ is the corresponding marginal value function normalized between 0 and 1. The marginal value functions have a functional-free piecewise linear monotone form and provide a decomposition of the aggregate result (global value) in terms of individual assessments at the criteria level.

According to its global value, a country i is classified as efficient if $V(\mathbf{x}_i) > t$, where t is a cut-off point that distinguishes efficient countries ($\theta_i^{\mathrm{C}} = 1$) from inefficient ones ($\theta_i^{\mathrm{C}} < 1$). Denoting by E the set of efficient countries, the estimation of the additive value function and the optimal cut-off point is performed through the solution of the following optimization problem ($\delta > 0$ is a small user-defined constant):

$$\begin{array}{lll} \min & \sum_i \sigma_i & \\ \text{s.t.} & V(\mathbf{x}_i) - t + \sigma_i \geq \delta & \forall i \in E \\ & V(\mathbf{x}_i) - t - \sigma_i \leq -\delta & \forall i \notin E \\ & 0 \leq V(\mathbf{x}_i) \leq 1 & \forall i \\ & t,\ \sigma_i \geq 0 & \end{array} \cdot$$

This formulation seeks to find an optimal additive value model that minimizes the overall classification error, as defined by the nonnegative error variables $\sigma_1, \sigma_2, \ldots$. The above optimization problem can be reformulated in a linear programming form [for details, see Zopounidis and Doumpos (1999) and Doumpos and Zopounidis (2002)].

Table 1 Input and output variables

Type	Variable	Unit	M1	M2	M3	M4
Outputs	Greenhouse gas emissions	Thousands of tons (CO_2 equivalent)	✓	✓	✓	✓
	Gross domestic product	Millions of Euros	✓	✓		
	Industry, value added	Millions of Euros			✓	✓
	Services, value added	Millions of Euros			✓	✓
Inputs	Total energy consumption	Thousand tons of oil equivalent	✓		✓	
	Fossil fuels energy consumption	Thousand tons of oil equivalent		✓		✓
	Other fuels energy consumption	Thousand tons of oil equivalent		✓		✓
	Labor force	Economically active population	✓	✓	✓	✓
	Domestic material consumption	Thousands of tons	✓	✓	✓	✓

The resulting additive evaluation model provides a global energy efficiency score for each country, estimated under a setting which is common for all countries, and over different time periods. This facilitates cross-country comparisons as well as the analysis of time trends, as the results of the model are not sample dependent.

4 Data and Variables

For the empirical analysis, we use a panel data set for 26 EU countries[1] over the period 2000–2010. All data have been obtained from Eurostat (except for labor force data which were collected from the World Bank). The choice of a proper set of indicators and evaluation criteria is clearly an important issue. The multidimensional character of energy efficient and its multiple aspects (e.g., environmental, socioeconomic, and technical) make it very difficult to specify a comprehensive set of relevant measurement indicators universally applicable under all contexts. In this study, on the basis of data availability and the existing literature, the input and output variables presented in Table 1 were selected. In the analysis we consider two different settings for the input variables and two different settings for the output variables, thus leading to four DEA models (henceforth denoted as M1, M2, M3, M4).

The first setting for the output variables considers greenhouse gas emissions (GHG) and gross domestic product (GDP), whereas in the second setting GDP is replaced by the value added for the industry and the services sectors, thus providing a more detailed insight in the economic output of each country. Several indicators, such as the gross domestic product (GDP) and greenhouse gas emissions are widely

[1] Malta is excluded due to unavailability of some data.

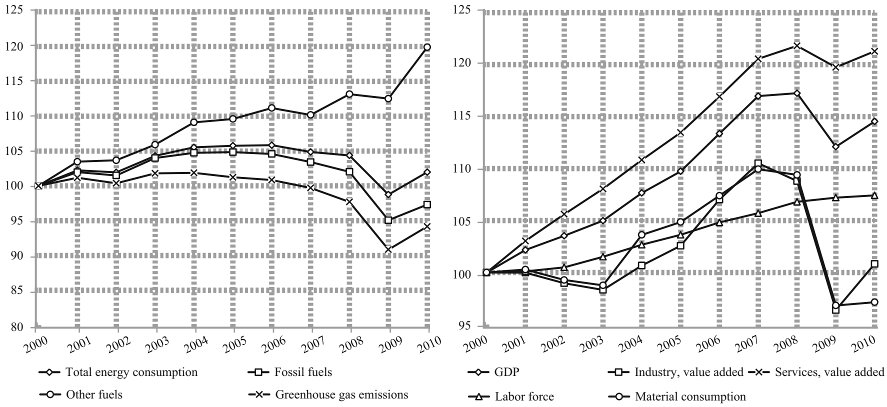

Fig. 1 Evolution of the selected variables over the period 2000–2010

used to monitor or track a country/region's performance in energy efficiency (Zhou and Ang 2008; Zhou et al. 2012). On the other hand, the relationship between the contribution of industry and services in a country's economy and its energy efficiency is also important. As the industry sector is more energy intensive than the services, a shift from an industry-focused economy to a services-based economy may lead to an improvement in the overall energy efficiency, solely due to structural changes in the economic activity of a country.

Similarly to the outputs, two settings are also used for modeling the inputs. In particular, the first setting has three inputs involving total energy consumption, labor force (treated as a nondiscretionary input), and materials consumption. In the second setting, total energy consumption is replaced by fossil fuels consumption and the consumption of other energy sources (renewables and nuclear), thus providing a more refined view of the energy mix that each country employs. The majority of studies that measure energy efficiency using the DEA framework choose inputs such as energy consumption, capital, and labor. Ramanathan (2005) also used the fossil fuels energy consumption as a minimization indicator, in the sense that countries with lower values in this indicator are more preferred, whereas Mandal (2010) considered the use of raw materials as an additional input. Finally, Hu and Kao (2007) found that energy efficiency could be overestimated or underestimated if energy consumption is taken as a single input and a certain portion of GDP output is produced, not only by energy input but also by labor and capital. Hence, employing a multiple-input framework is important in order to correctly evaluate energy efficiency.

Figure 1 presents the evolution of the selected variables over the period of the analysis. As can be seen, all the variables present an upward trend until 2006–2007 and then a downward trend. Only the consumption of other fuels has an upward trend even after 2007 due to the increased use of renewable sources.

While the selected input and output variables are meaningful in the context of DEA, they are not useful in a multicriteria setting, as they do not allow for direct

Table 2 Evaluation criteria for building the second-stage multicriteria model

Energy intensity	Current account balance/GDP
Gross fixed capital formation/GDP	Unemployment rate
Environmental taxes/GDP	Greenhouse gas emissions/GDP
Resource productivity (GDP/domestic material consumption)	Primary energy source indicator
GDP growth	Economy focus indicator

comparisons among the countries. Thus, in the second stage of the analysis, a set of ten evaluation criteria are employed in order to build the final multicriteria evaluation model. Similarly to the modeling approach employed in DEA, the selected criteria (Table 2) combine energy efficiency indicators, economic growth and competitiveness indicators, environmental indicators, as well as two original indicators related to the primary energy source and the focus of the economy in each country. The primary energy source indicator is used to take into consideration the energy focus of a country in a particular year, indicating whether renewables, nuclear, natural gas, solid fuels, or petroleum consumption was the main energy source for the country. Economy focus is modeled as a binary indicator, designating whether the value added by the industrial sector of a country at a given year (as a percentage of GDP) was above or below the overall average of all countries. The introduction of this indicator in the analysis enables the consideration of the differences between the various countries in terms of their level of industrial development (as industry is generally more energy intensive than services).

5 Results

5.1 DEA Results

Figure 2 illustrates the average constant returns-to-scale (CCR) and variable returns-to-scale (BCC) efficiency scores of the four models, over the whole period of the analysis. The ratios between the CCR and BCC efficiency scores are in all cases above 0.9, thus indicating that the scale effect is only marginal, which implies that the inefficiencies are mostly due to the policies implemented at the country level. Generally, there are high correlations between the results of the four models, with the correlation coefficient ranging between 0.94 (between models M2 and M3) and 0.97 (between models M1 and M3). Of course, the models with more inputs and outputs lead to higher efficiency estimates, but this is fairly common in DEA (i.e., the efficiency scores in DEA generally increase with the number of inputs and outputs).

When examining the efficiency trends over time, one can observe some minor, yet noticeable, differences between the four models. In particular, under both constant (CCR efficiency) and variable (BCC efficiency) returns to scale, the period

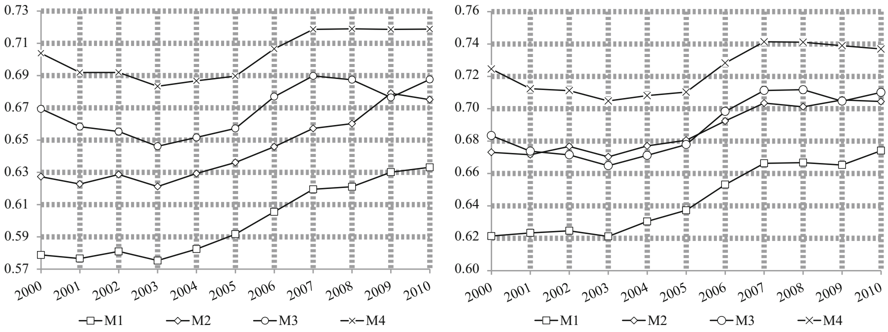

Fig. 2 Average efficiency scores for the four models (CCR *left*, BCC *right*)

2000–2003 is characterized by stable efficiency scores according to models M1 and M2, whereas models M3 and M4 indicate a slightly decreasing trend. In the subsequent period up to 2007, steady improvement is observed under all models, with the improvement being larger in the case of models M1 and M2. Finally, during 2008–2010, models M1 and M2 indicate further (minor) improvement, whereas under models M3 and M4 the efficiency scores are almost stable.

These differences among the pairs of models {M1, M2} and {M3, M4}, as far as the observed efficiency trends are concerned, indicate that the decomposition of the GDP output in models M3 and M4 does affect the results. Indeed, if GDP is taken as a single output of economic activity (models M1, M2), the efficiency trend is clearly positive (at least after 2003). But if the structure of the economies is explicitly taken into consideration (i.e., separation of GDP into the value added by industry and services in models M3 and M4), then the efficiency improvements decrease. In that regard, models M1 and M2 act more like multidimensional proxies of energy intensity, whereas models M3 and M4 provide a better representation of the dynamics and trends in the actual energy efficiency of the countries. On the basis of these findings, the subsequent analysis focuses on model M4, which provides the most comprehensive consideration of the economic outputs of the countries and their energy mix.

Table 3 presents the countries' global CCR efficiency scores averaged over all years of the analysis, as well as the percentage changes over the whole period of the analysis and during the period of the recent economic crisis (2008–2010). Luxembourg, Ireland, Netherlands, the United Kingdom, and Cyprus achieved the highest efficiency scores (overall), whereas Hungary, the Czech Republic, Poland, Bulgaria, and Romania have the lowest scores. Nevertheless, most of the low-performing countries (except for Romania) achieved considerable improvements over the period of the analysis, including the period 2008–2010.

Table 4 summarizes the estimated input and output improvements (averaged by year) that inefficient countries should seek to achieve in order to improve their efficiency status (under the BCC model). The results are reported for all outputs and inputs, except for labor force, which is treated as nondiscretionary (uncontrolled)

Table 3 Overall CCR efficiency scores (averaged over 2000–2010) and percentage changes (model M4)

	Average	2000–2010	2008–2010		Average	2000–2010	2008–2010
LU	1.000	0.0	0.0	SI	0.759	−1.3	−4.2
IE	0.993	−4.2	−4.2	BE	0.759	−9.6	−6.9
NL	0.988	0.0	1.2	ES	0.658	7.1	6.1
UK	0.980	0.6	0.0	GR	0.595	25.2	2.0
CY	0.968	−3.0	2.5	LT	0.576	−3.9	10.9
DK	0.960	2.7	2.2	PT	0.549	5.6	10.6
SE	0.960	9.2	0.0	EE	0.537	−23.7	0.1
DE	0.928	5.2	−5.0	SK	0.349	24.1	−5.8
AT	0.908	1.0	−0.4	HU	0.341	18.6	4.9
LV	0.900	−12.6	1.9	CZ	0.332	32.5	3.5
IT	0.894	−2.6	−8.3	PL	0.312	21.0	5.2
FR	0.846	20.9	7.7	BG	0.203	28.6	16.2
FI	0.781	−2.1	−11.1	RO	0.195	−0.5	−2.6

Table 4 Suggested average improvements in input and outputs (% changes)

	Greenhouse gas emis.	Industry, value added	Services, value added	Fossil fuels	Other fuels	Domestic mat. cons.
2000	6.2	4.1	37.2	2.3	9.6	3.1
2001	6.5	3.8	32.4	2.5	10.1	2.4
2002	6.2	2.7	28.0	2.5	9.6	2.9
2003	7.0	2.1	23.6	3.1	8.9	3.2
2004	7.0	2.1	21.4	3.4	8.3	3.7
2005	6.4	1.3	18.6	2.8	8.4	4.1
2006	5.5	0.8	18.8	2.4	7.3	4.9
2007	4.6	1.1	18.3	1.9	5.8	5.3
2008	4.5	1.6	17.4	1.7	6.6	6.4
2009	5.8	1.6	16.7	1.6	8.9	7.1
2010	5.0	0.8	18.1	1.9	7.9	7.6
Average	5.9	2.0	22.8	2.4	8.3	4.6

input. Given the rapid growth of the services sector (see Fig. 1), it is of no surprise that the corresponding variable is the one where most of the improvement efforts should focus. The consumption of renewables and nuclear energy (other fuels) is also an area where improvement should be sought after, followed by greenhouse gas emissions and the consumption of materials.

5.2 Second-Stage Results

For the reasons explained in the previous subsection, the development of the multicriteria evaluation model in the second stage of the analysis is based on model M4. Given their CCR efficiencies under model M4, all countries are

Table 5 The mean of the selected indicators for efficient and inefficient countries

	Efficient	Inefficient
Energy intensity	152.64	354.08
Gross fixed capital formation/GDP	3.39	3.12
Environmental taxes/GDP	2.98	2.67
Resource productivity	1.82	1.13
GDP growth	3.03	2.64
Current account balance/GDP	3.49	−3.25
Unemployment rate	4.93	8.71
Greenhouse gas emissions/GDP	0.42	0.91
Primary energy source indicator	2.05	1.70
Economy focus indicator	0.70	0.44

Notes: Primary energy source is modeled through a three-point scale (1 = solid fuels, 2 = gas, petroleum, nuclear, 3 = renewables), and economy focus is a binary indicator (0 = industry focused, 1 = services focused)

classified as efficient (efficiency score equal to 1) or inefficient (efficiency score lower than 1).

The objective of the second-stage analysis is to construct an operational multicriteria evaluation model for evaluating the energy efficiency of all countries in a multidimensional context. For this purpose, the UTADIS multicriteria method is employed to fit a model that combines the selected set of criteria presented in Sect. 4 (Table 2) in order to replicate the DEA-based efficiency classification of the countries as accurately as possible. Overall, the sample includes 37 efficient country-year observations and 249 inefficient cases. Table 5 presents the means of the selected indicators for each group. All differences are statistically significant at the 5 % level according to the nonparametric Mann–Whitney test (except for gross fixed capital formation/GDP and GDP growth).

Figure 3 presents the criteria trade-offs in the multicriteria additive model fitted on the above data. These trade-offs can be regarded as proxies of the relative importance of the criteria, whereas Fig. 4 illustrates the marginal value functions for the four most important criteria, which indicate the decomposition of the global performance into partial scores at the criteria level. The indicators' trade-offs indicate that the energy intensity of the economy is the most important factor with a weight of 25.77 %, followed by current account balance/GDP, resource productivity, and unemployment. Thus, the model puts emphasis on a mixture of factors combining energy intensity, the competitiveness of the countries (as measured by the current account balance/GDP ratio), as well as structural indicators related to the economic activity in a country, such as unemployment, and resource productivity. The remaining five factors contribute a total of 37.47 % in the model.

Figure 5 presents a comparison of the multicriteria evaluation results to the efficiency scores obtained under the DEA model M4 (CCR model). To facilitate the comparison, the annual averages are indexed using 2000 as the base year. Overall, the multicriteria results are more volatile compared to the CCR efficiency estimates

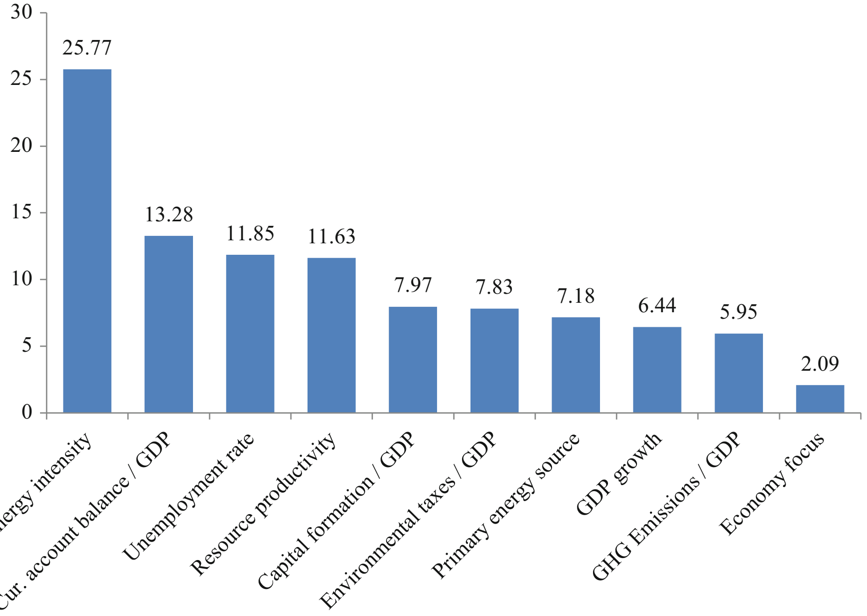

Fig. 3 Criteria's trade-offs (weights in %)

obtained with DEA. This is of no surprise given that the multicriteria model takes into consideration a wider set of evaluation criteria of diverse nature. Nevertheless, there is a very strong overall correlation between the multicriteria results and the DEA efficiency scores, as the Pearson correlation[2] equals 0.821 and Kendall's tau[3] rank correlation coefficient equals 0.682.

Furthermore, the discrepancies between the classification of the countries according to their CCR efficiencies and the classification induced by the multicriteria results are limited, as the accuracy rate is 86.5 % for the DEA efficient countries and 93.4 % for the DEA inefficient ones, with the overall accuracy rate equaling 93 %. Table 6 summarizes the differences in the DEA and the multicriteria classification results.

[2] Pearson's correlation coefficient between two variables is defined as the covariance of the two variables divided by the product of their standard deviations. It is a measure of the strength of linear dependence between two variables, ranging between [−1, 1].

[3] The Kendall's tau coefficient is a statistic used to measure the rank correlation between two measured quantities. Similarly to other correlation measures, Kendall's tau ranges in [−1, 1], with larger positive/negative values indicating a stronger (positive or negative) rank association of the two variables.

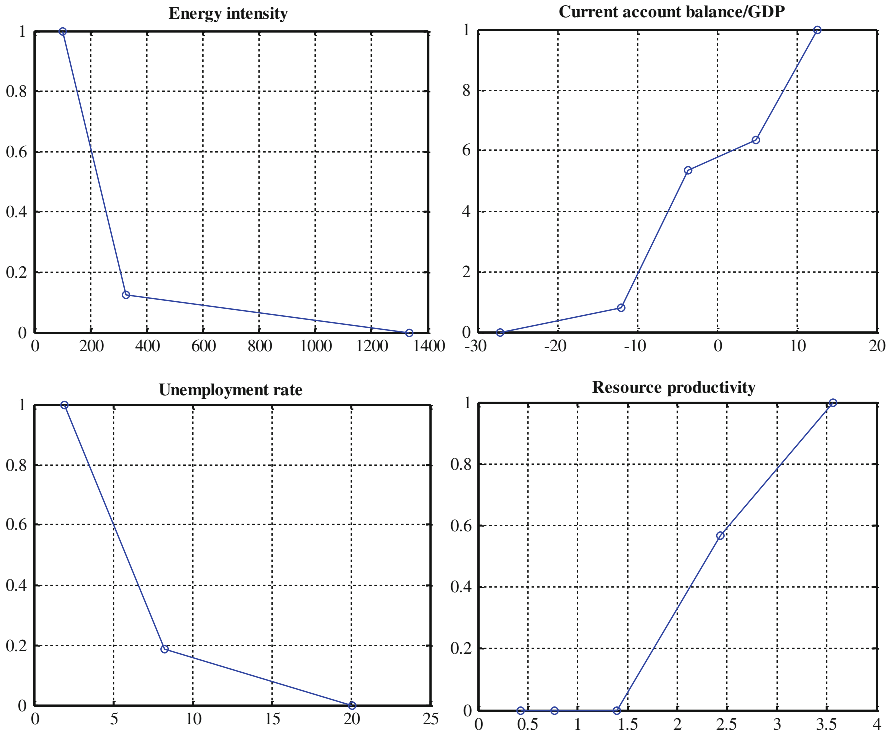

Fig. 4 Marginal value functions for the criteria for the largest trade-off constants

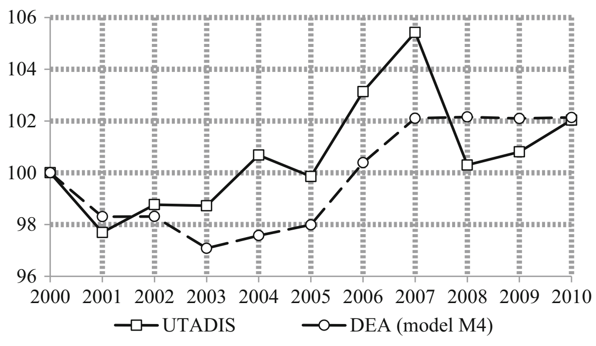

Fig. 5 Comparison of the average multicriteria scores in each year to the DEA efficiency scores

6 Conclusions

In this study, an integrated approach to energy efficiency evaluation is developed and implemented in the context of EU countries. The proposed approach considers energy efficiency in a multidimensional context, combining multiple energy

Table 6 Discrepancies between the DEA efficiency classification and the multicriteria classification results

DEA inefficient countries classified as efficient	DEA efficient countries classified as inefficient
Denmark (2000, 2006, 2007)	Cyprus (2000, 2001, 2004)
Luxembourg (2005)	Denmark (2010)
Netherlands (2001–2005, 2007, 2009)	Germany (2007)
Sweden (2008)	
United Kingdom (2003–2006)	

consumption data, economic outputs, structural indicators, and environmental factors. DEA is employed under different modeling settings to perform a relative evaluation of the efficiency of the EU countries over the period 2000–2010. The results obtained with a more comprehensive consideration of economic outputs and energy consumption provide a better indication of the true energy efficiency, compared to simpler models that consider only aggregate energy and GDP data.

Combining the results of DEA with a multicriteria classification technique enabled the construction of an operational model that provides analysts and policy makers with evaluations of the countries' energy efficiency in absolute terms, based on a common setting for all countries, without the need to perform DEA analysis again.

Overall, the results indicate that despite the considerable improvements achieved in terms of energy intensity, a more refined view of energy consumption and economic activity data indicates that there is still much to be done towards the improvement of the actual energy efficiency of EU countries. The economic crisis over the past few years had negative effects (on average).

Future research could consider a wide range of issues. Among others, these may involve the consideration of more detailed data on structural factors, the analysis of specific energy-intensive business sectors, the enrichment of the data set with countries outside the EU and a more extensive time period, as well as the evaluation of the actions and policies implemented to improve energy efficiency at the country level.

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Georgia Makridou holds a diploma in Electronic and Computer Engineering (2009) from the Department of Electronic and Computer Engineering and an M.Sc. in Business Administration (2011) from the Department of Production Engineering and Management of the Technical University of Crete. She is now a Ph.D. candidate at the Financial Engineering Laboratory at the Technical University of Crete and a Research Assistant at the Research Centre for Energy Management (RCEM) at ESCP Europe Business School. Her research interests include the evaluation of the EU energy markets on the country and firm levels using sophisticated econometric and multicriteria methodologies.

Dr. Kostas Andriosopoulos is an Assistant Professor in Finance & Energy Economics and Executive Director of the Research Centre for Energy Management at ESCP Europe Business School. He holds a PhD in Finance (2011) from Cass Business School, City University London. In support of his PhD studies he has been the recipient of the prestigious Alexander S. Onassis Public Benefit Foundation's scholarship. He also holds an MBA and MSc in Finance (2006), both with distinction, from Northeastern University, Boston, USA, and a bachelor's degree in Production Engineering & Management (2004) from Technical University of Crete, Greece. He is also a member of the Beta Gamma Sigma honour society. His current research interests include price modelling, financial engineering and the application of risk management techniques and innovative investment strategies in energy, shipping and agricultural commodities' markets, and international trade. He has edited special issues, organised international conferences, and his research papers have been published in international finance and commodities related Journals, and have been presented in established and recognized conferences world-wide.

Dr. Michael Doumpos holds a Ph.D. in operations research (2000) and an M.Sc. in Production Engineering and Management (1997) from the Technical University of Crete, where he currently holds an Assistant Professor position. His research interests include multicriteria decision making, decision support systems, computational pattern recognition, and financial risk management. He has published over 70 research articles in premier international journals. He has also coauthored several books, edited volumes, book chapters, conference papers, and edited special issues.

Constantin Zopounidis Professor Constantin Zopounidis is the Director of the Financial Engineering Laboratory. He has received his Doctorat D'Etat (1986) in Management Science, a D.E.A. (1982) in Financial Management from the University of Paris IX Dauphine, and a B.A. in Business Administration from the University of Macedonia. His research interests include financial engineering, financial risk management, and multicriteria decision making. He has published over 300 papers in premier international journals, edited volumes, and conference proceedings. He has also published several books and edited volumes on financial engineering and operations research. Prof. Zopounidis is Editor in Chief and member of the editorial board of several international journals. For his research work, Prof. Zopounidis has received awards and honorary distinctions from international research organizations, including among others ESCP Europe Business School, the MOISIL International Foundation, the Decision Sciences Institute, the European Association of Management and Business Economics, the Royal Academy of Doctors of Spain, the Hellenic Operational Research Society, the International Association for Fuzzy Set Management and Economy, and the International MCDM Society.

The Availability of European Oil and Gas Resources

Roberto F. Aguilera and Ronald D. Ripple

Abstract Purpose This study constructs supply cost curves for conventional and unconventional oil and gas to assess the availability of indigenous resources in the region.

Design/Methodology/Approach Estimated volumes are distributed across resource quality categories that are based on production costs. The resulting supply figures are intended to be long-term representations of how quantities vary with production costs. Both economic and physical measures are used since each provides practical information with respect to the concerns some energy commentators have expressed about oil and gas scarcity in the near future. Supply cost curves incorporating the effect of annual technological advancement on production costs to the year 2030 are also estimated. On the quantity side, the curves include volumes from geological provinces not previously assessed.

Findings Results indicate that conventional and unconventional oil and gas resources in Europe are abundant and can be produced at costs below current and projected market prices.

Practical Implications In spite of the findings, future development may continue to face regulatory, investment, and market challenges.

Originality/Value With oil and gas providing approximately two-thirds of primary energy consumption in Europe, energy security remains a concern due to high import dependency. This study could be used to examine the possibility of developing indigenous oil and gas in order to alleviate the problem.

Keywords Availability • Conventional and unconventional oil and gas • Europe • Technological progress

R.F. Aguilera (✉) • R.D. Ripple
Centre for Research in Energy and Minerals Economics (CREME), Curtin Business School, Curtin University, GPO Box 1987, Perth 6845, Australia
e-mail: r.aguilera@curtin.edu.au; r.ripple@curtin.edu.au

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1 Introduction

Oil and gas resources have provided much of the world's energy in the twentieth century and are expected to be an important part of the energy mix well into the twenty-first century (International Energy Agency, IEA 2011). Currently, oil and gas provides approximately 63 % of primary energy consumption in Europe (British Petroleum 2011). However, energy security in the region remains a concern. The concern is reinforced due to Europe's dependence on oil and gas from other regions. In addition, many commentators fear domestic oil and gas resource depletion will produce significant supply scarcities in the short term, i.e., well before 2020. Thus, the purpose of this analysis is to address the subject by estimating conventional and unconventional oil and gas supply cost curves for the region.

Continued demand for oil- and gas-based energy services throughout the twenty-first century is expected to induce technological change that could lower future production cost levels. On the other hand, environmental considerations could adversely affect oil and gas production costs, especially when unconventional resources are considered. Production of these resources typically has larger environmental impacts, including increased greenhouse gases emitted during the extraction and upgrading processes. Emissions penalties could change the shapes of the supply curves, as unconventional oil and gas would become relatively more expensive. The implementation of carbon capture and storage (CCS) at extraction sites could also increase cost, though presumably the cost would be lower than that resulting from the imposition of emissions penalties. Meanwhile, enhanced oil and gas recovery based on CO_2 injection would be potentially less expensive due to emissions offsets based on sequestered CO_2.

From an economic point of view, relative prices will determine the dominance of oil and natural gas versus other fuels (Wonglimpiyarat 2010). To give an example, a significant tax on carbon would increase the relative price of coal versus gas. This would lead to investment and technological advancement across the gas industry and thus induce substitution from coal to gas by decreasing the relative price of gas.

The approach for developing the supply cost curves in this study is based on Rogner (1998) and begins by using European conventional oil and gas volumes estimated by the Variable Shape Distribution (VSD) model (Aguilera 2010). The volumes are distributed into several classes based on resource quality. Every class is then assigned lower and upper bounds of production costs (based on Aguilera et al. 2009), resulting in supply cost curves. The unconventional oil and gas quantities are taken from the Global Energy Assessment (GEA 2012), while the associated production costs are based on IEA (2008, 2009, 2012). For both oil and gas, two curves are developed—one assumes current technology and the other technology performance for 2030.

2 Paradigm Choice

There are two common paradigms for assessing nonrenewable resources: the fixed-stock versus opportunity cost paradigms. The former observes that the earth is finite; therefore, the supply of any commodity, such as oil or gas, must also be finite. Demand, on the other hand, is variable. Consequently, it is only a matter of time before demand consumes all of the fixed stock. Although the fixed-stock paradigm seems logical, economists often argue that the methodology is less useful than the opportunity cost paradigm (Tilton 2002). The latter uses measures—such as prices, production costs, and the value of reserves in the ground—of what society has to give up to produce another unit in order to assess the effects of depletion and long-run trends in availability. If the real price of oil rises over the long run, for instance, this would imply the oil is becoming more scarce.

In spite of the appropriateness of the opportunity cost paradigm, the fixed-stock paradigm may be useful when assessing oil and gas resources in particular. The reason is that these may be the only major commodities where commentators are predicting shortages in the near term. Therefore, if reasonable estimates of oil and gas volumes available at some specified price level appear sufficient to cover reasonable estimates of future demand, this provides practical information with respect to the concerns some have expressed.

In this chapter, we use both economic and physical measures to assess the availability of oil and gas resources in Europe. First, we distribute estimates of the stock of available supply across various production cost categories. We also introduce a time dimension into the supply curve estimation by assessing the role of technological change to the year 2030. In particular, by incorporating the effects of productivity gains on production costs over time, we are also utilizing the opportunity cost paradigm.

The resulting supply cost curves can be considered long-term availability curves, or approximate cumulative supply curves. There are some important differences between that traditional supply curve and the cumulative supply curve. The latter, which was first proposed by Tilton and Skinner (1987), shows how the total or cumulative supply of oil and gas varies over all time with price (see Fig. 1). It differs from the traditional supply curve, which shows the quantity of a resource offered to the market at various prices during a specific time period, such as a month or year (see Fig. 2). In addition, the supply figures provided by the cumulative supply curve are stock variables, unlike the traditional supply curve where they are flow variables that can continue from one period to the next.

3 VSD Model

Conventional oil and gas endowment volumes, which are inputs into the supply cost curves, are estimated with a previously defined Variable Shape Distribution (VSD) model (Aguilera 2006). According to the United States Geological Survey (USGS)

Fig. 1 Cumulative supply curve representing stocks for all time

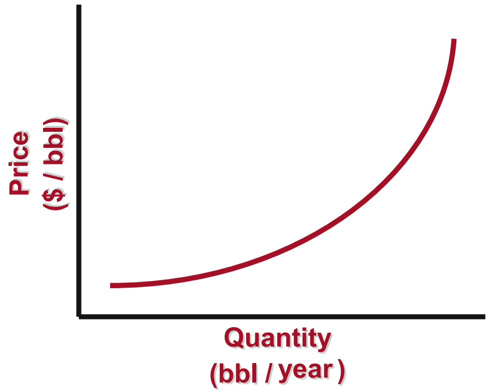

Fig. 2 Traditional supply curve representing a specified time period, such as a month or year

World Petroleum Assessment (2000), endowment refers to the sum of known volumes (cumulative production plus remaining reserves) and undiscovered volumes. The VSD, a statistical method known as size distribution analysis, calculates the endowment volumes in European provinces that have not previously been assessed.[1] This type of analysis has historically been successful in complementing geological techniques used to estimate resources in previously unassessed areas (Barton 1995). In this study, the VSD model is only briefly

[1] As defined by USGS (2000, p. GL-4), a petroleum province is an “area having characteristic dimensions of perhaps hundreds to thousands of squared kilometers encompassing a natural geologic entity (e.g., sedimentary basin, thrust belt, delta) or some combination of contiguous geologic entities.”

described as the focus is on supply cost curve estimation. For a detailed mathematical description of the VSD, refer to Aguilera (2006) and Aguilera and Ripple (2011).

Traditionally, all the methods used to forecast oil and gas volumes have been "based on an assumed form of the size-frequency distribution of the natural population of oil and gas accumulations" (Barton 1995). The lognormal and Pareto (fractal) distributions are common size distribution models used to estimate volumes of unassessed areas. These types of statistical distributions are believed to be representative of many natural and social occurrences (e.g., resource distribution in nature, income distribution across population). Some researchers believe that the distribution of nature's resources follow lognormal distributions (Kaufman 2005), while others claim the lognormal distribution provides overly pessimistic results (Drew 1997). More recently, it has generally been acknowledged that the Pareto distribution tends to overestimate oil and gas resources, while the lognormal distribution tends to underestimate them.

The VSD is unique in that we first observe the curvature (on a log–log plot) given by the size and number of assessed provinces by USGS (2000). We then develop the VSD model which allows the data to determine the specified relationship between the size and number of provinces. In Aguilera (2006), the model has been used successfully, typically with coefficients of determination (R^2) equal to or greater than 0.98, to match available global data for conventional oil, gas, and natural gas liquids (NGL). The close matches allow us to extend the model out of sample to include previously unassessed provinces in the analysis. As is common in size distribution models, the original sample contains the largest provinces, meaning that most of those previously unassessed will be smaller in terms of volumes (Tangen and Molnvik 2009). This allows us to estimate key parameters including the slope and intercepts of the theoretical Pareto (fractal) straight line given by the largest provinces.

The selection by the USGS of provinces for assessment represents a data generation process and affects the ultimate estimate of the endowment volumes in the unassessed provinces. As stated by USGS (2000), "the assessed areas were those judged to be significant on a world scale in terms of known petroleum volumes, geologic potential for new petroleum discoveries, and political or societal importance." Given that the subdivision of Europe by the USGS is based on natural geological features, theory would indicate that methods like the VSD model are dependent on this type of natural disaggregation.

Equation (1) presents the VSD as a nonlinear least squares model. In particular, the problem is:

$$\min_{\{V_x, a_p, V_s, \psi, S\}} \sum_{i=1}^{n} \left(V_i - \hat{V}_i\right)^2. \tag{1}$$

Subject to:

$$\hat{V}_i = \frac{\left\{\left[\left(\frac{1}{N_t} - \left(\frac{V_m}{V_x}\right)^{\left(\frac{\log N_x - \log N_m}{\log V_x - \log V_m}\right)}\right)^{\frac{1}{a_p}} + \frac{V_m}{V_x}\right] \cdot V_x\right\} \times (\psi)}{(\psi) + [1-(\psi)] \cdot \left[1 - \exp\left(-\left\{\left[\left(\frac{1}{N_t} - \left(\frac{V_m}{V_x}\right)^{\left(\frac{\log N_x - \log N_m}{\log V_x - \log V_m}\right)}\right)^{\frac{1}{a_p}} + \frac{V_m}{V_x}\right] \cdot V_x\right\} \div V_s\right)\right]^S}, \tag{2}$$

where a_p—slope of straight line approximated from USGS sample points (same as slope of Pareto distribution); N_m—minimum number of USGS provinces (= 1); N_t—cumulative number of provinces; N_x—maximum number of provinces; S—severity exponent that controls the steepness of the slope of the estimated VSD curve where it separates from the Pareto straight line (on the right tail of the distribution, typically near the largest volumes); V_m—minimum USGS province volume; V_s—approximate volume at which the USGS data begins to deviate from the Pareto straight line (on the right tail of the distribution, near the largest volumes); $\hat{V}_i$ —estimated volume of a province; V_x—maximum volume (boe) given by the Pareto straight line (at $N_m = 1$). The actual maximum volume could be larger, equal to, or smaller than V_x; ψ—separation ratio that controls the amount of separation between the Pareto straight line and the estimated VSD curve (on the right tail of the distribution, near the largest volumes).

Equation 1 shows five parameters of the VSD model that are estimated with nonlinear regression: V_x, a_p, V_s, ψ, and S. They are used to obtain the best possible fit of the sample of provinces for which petroleum endowment data from USGS (2000) exists. The parameters are estimated by examining the coefficients of determination (R^2), comparing the USGS- and VSD-calculated endowments, and visually inspecting the curves. The exact same parameter values used to obtain a good fit of the provinces evaluated by USGS (2000) are used to forecast the petroleum endowments of unassessed provinces in the region.

Recently, the VSD model was validated in Aguilera (2010) by comparing VSD-calculated and actual European endowment volumes published by USGS (2000). Examples of the results, for conventional oil (including NGL) and gas, are presented in Fig. 3. The plots show the number (rank) versus size of oil and gas endowment provinces estimated by the two studies.

For the case of oil, the actual endowment represented by the lower curve in Fig. 3 corresponds to 12 geological provinces assessed by USGS (2000). This endowment, estimated at approximately 102 billion barrel of oil equivalent (BBOE), compares well with the 101 BBOE calculated by the VSD model. The coefficient of determination (R^2) is equal to 0.99. Note that these volumes do not include heavy oil, oil sands, oil shale, and offshore provinces with water depths greater than

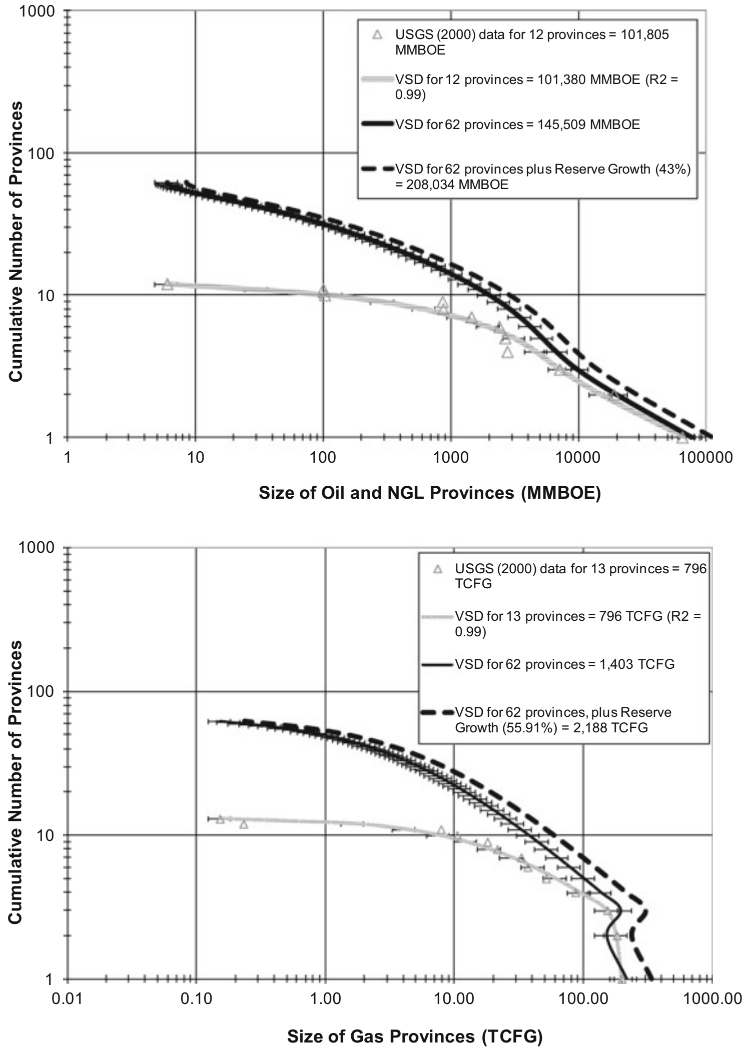

Fig. 3 European conventional oil and gas endowments as estimated by Aguilera (2010) and USGS (2000)

2,000 m in some cases and 4,000 m in others.[2] Using the same parameter values, the VSD model was then used to estimate the conventional oil volumes of the 62 provinces recognized by the USGS to exist in Europe, out of which 50 had not been evaluated previously. The black solid curve, generated by the VSD model,

[2] Originally, USGS (2000) delineated offshore province areas to water depths of 2,000 m but then extended the analysis to several 4,000 m areas due to rapidly developing drilling and production technology.

corresponds to 62 provinces and gives an oil endowment of 146 BBOE. Finally, we estimate reserve growth of oil by assuming that the reserve growth percentage estimated by USGS (2000) for the world (43 %) will be applicable to both the assessed and unassessed provinces of Europe. When this factor is taken into account, the volume increases to 208 BBOE and is represented by the dashed curve. It shows that at each province, each corresponding volume is now 43 % greater than the original estimate. Thus, the ranking of endowment volumes plus reserve growth, by size, will be the same as the ranking of the endowment volumes without reserve growth. For more on reserve growth and its application, refer to Aguilera (2010) and Verma (2000). The lower graph in Fig. 3 shows results for conventional gas in Europe. The total gas endowment in all 62 provinces, including reserve growth, is approximately 2,188 trillion cubic feet (TCF).

Probability distributions are used in USGS (2000) to account for the uncertainty in estimating oil and gas volumes. Fractiles (F95, F50, F5, and the mean) are shown graphically in the study for undiscovered oil and gas. For instance, the value of F50 would imply there is a 50 % chance of the existence of at least the volume estimated. Inevitably, the uncertainties present in USGS (2000) extend to the VSD model.

The predictive power of the VSD model has been partly validated by a good fit of the size distribution of previously assessed European provinces. The fit is supported by high coefficients of determination and estimated VSD volumes that are close to those published by the USGS. Nevertheless, a comparison of the VSD curves with the USGS data points shows there are some differences at certain levels. The differences are accounted for in Fig. 3 by plotting 20 % horizontal error bars. As can be seen, the 20 % error bars exceed the difference between the USGS- and VSD-calculated points in almost all cases.

4 Unconventional Oil and Gas

Given the potentially significant contribution that unconventional oil and gas may have in Europe, it is important to include these sources in the supply cost curves. Unconventional oil quantities—composed of heavy oil, oil sands, and shale oil—are taken from the GEA (2012). Although unconventional oil is more abundant than the conventional on a global scale, it is relatively scarce in Europe—where heavy oil is the largest (3.2 BBOE), followed closely by shale oil (2.3 BBOE) and oil sands (1.0 BBOE). The total is approximately 6.5 BBOE, which pales in comparison to the conventional oil endowment estimated in the previous section at about 208 BBOE. By contrast, the unconventional gas endowment—composed of coalbed methane (CBM), tight gas, and shale gas—is vast and has the potential to contribute to European demand if regulatory and environmental hurdles can be overcome. Shale gas is the most abundant (1,251 TCF), followed by CBM (833 TCF) and tight gas (416 TCF). The total, approximately 2,500 TCF (GEA 2012), is somewhat larger than the conventional gas endowment estimated in the previous section at about 2,188 TCF.

5 Oil and Gas Production Costs

Detailed oil and gas production costs are difficult to find. Data collected from conventional oil and gas fields in Europe show a wide spread of operating and capital costs (Aguilera et al. 2009). In 2009, production costs for conventional oil ranged from 3.00 to 35.00 USD per barrel of oil equivalent (BOE), with the majority being around 15 USD/BOE. The conventional gas production costs ranged from 0.50 to 3.75 USD per thousand cubic feet (MCF), with the majority costing around 0.90 USD/MCF. The cost figures include capital and operating costs, including a rate of return on invested capital, but do not include taxes and royalties.

Some of the cost estimates refer to relatively shallow and favorable production conditions, while deep offshore production, for instance, can be significantly higher. Cost of oil and gas production is influenced by factors such as geological conditions, depth of accumulations, regulatory environments, and project lengths (Adelman 1993). Offshore capital cost increases at greater depths are mainly due to the higher cost of platform drilling, the cost of new technology to cope with depressurization of reservoirs, and the cost of pipeline transportation. Nevertheless, considerable cost savings have been achieved over the past decades on account of improved operating methods.

Longer term projections of oil and gas production costs should account for the cost-reducing effects of improved technology versus the cost-increasing effects of depletion. As oil and gas fields at shallow depths will likely be exploited first (assuming suitable market and regulatory conditions), there will be a gradual shift towards deeper drilling, including offshore, as well as a shift towards unconventional sources of oil and gas. This will require increased investment costs for new wells and higher operating expenditures due to additional costs for enhanced recovery. In the absence of advanced innovation, these factors are likely to drive up long-run production costs. However, though the past is not always an indication of the future, history would suggest that producers may develop the technologies needed to offset the cost-increasing effects of deeper, more remote, and increasingly unconventional resources. For example, the costs of producing unconventional oil and gas have been lowered to the point of being comparable in some cases to the development of the conventional. In this study, a uniform production cost is applied to each of the unconventional sources. The estimates, based on IEA (2008, 2009, 2012), are not significantly higher than those of the conventional resources (see Tables 1 and 2).

6 Supply Cost Curves

Although various organizations publish estimates of reserves and resources, it is challenging to categorize these definitions under a consistent classification system. The respective organizations tend to report their quantities using different terms,

Table 1 Conventional and unconventional oil production costs for 2009 and 2030 in USD/BOE

Cost category	Production costs (2009)[a] Lower bound (USD/BOE)	Production costs (2009)[a] Upper bound (USD/BOE)	Technology change in %/year[b]	Production costs (2030)[c] Lower bound (USD/BOE)	Production costs (2030)[c] Upper bound (USD/BOE)
Oil and NGL					
CI	3.00	7.00	1.50	2.20	5.10
CII	7.00	13.00	1.50	5.10	9.45
CIII	13.00	20.00	1.00	10.55	16.20
CIV	20.00	29.00	0.50	18.00	26.10
CV	29.00	35.00	0.50	26.10	31.50
Heavy oil[d]		35.00	0.50		31.50
Oil sands		50.00	0.50		45.00
Shale oil		60.00	0.50		55.00

[a]2009 production costs for conventional oil based on Aguilera et al. (2009)
[b]Technology change rates assumed in this study, based on Rogner (1998)
[c]2030 production costs for conventional oil estimated in this study
[d]Cost estimates for heavy oil, oil sands, and shale oil based on IEA (2008)

Table 2 Conventional and unconventional gas production costs for 2009 and 2030 in USD/MCF

Cost category	Production costs (2009)[a] Lower bound (USD/MCF)	Production costs (2009)[a] Upper bound (USD/MCF)	Technology change in %/year[b]	Production costs (2030)[c] Lower bound (USD/MCF)	Production costs (2030)[c] Upper bound (USD/MCF)
Natural gas					
CI	0.50	0.90	1.50	0.35	0.65
CII	0.90	1.40	1.50	0.65	1.00
CIII	1.40	2.30	1.50	1.00	1.65
CIV	2.30	3.10	1.00	1.85	2.50
CV	3.10	3.75	1.00	2.50	3.00
CBM[d]		3.75	1.00		3.00
Tight gas		4.00	1.00		3.25
Shale gas		5.00	1.00		4.00

[a]2009 production costs for conventional gas based on Aguilera et al. (2009)
[b]Technology change rates assumed in this study, based on Rogner (1998)
[c]2030 production costs for conventional gas estimated in this study
[d]Cost estimates for CBM, tight gas, and shale gas based on IEA (2009, 2012)

concepts, and boundaries. Attempts to create universal resource classification systems have been undertaken by SPE/WPC/AAPG/SPEE (2007) and UNFC (2009). In the present study, conventional oil and gas volumes are distinguished on the basis of five production cost categories.

The first category (CI) represents favorable production conditions such as shallow reservoirs with high-quality oil. The standard definition of proved reserves (P90; 1P), for instance, falls under CI. This category often serves as a public policy tool for many economic, political, technical, and environmental considerations.

Countries often utilize proved reserves to gain leverage in foreign policy, to design economic plans, and to form regulatory, market, and climate policies. The reason is that the proved reserve definition represents quantities that are recoverable under existing prices and technologies. Its use for long-term investment decisions or policy analyses is thus restricted.

The second category (CII) represents quantities that may be currently undiscovered but have a reasonable probability of being found. Probable reserves (P50; 2P) belong to CII. In time, these volumes will presumably come online as exploration and production efforts expand. As CI oil and gas is exhausted, CII will replace them and move into the CI category themselves.

Quantities that fall under the third category (CIII) are of a more speculative nature in terms of geological information and economic feasibility. Possible reserves (P10; 3P) fall under CIII. Over the medium to long term, as the CI and CII categories begin to dwindle, market and technological conditions should shift the CIII volumes into the CII and CI categories.

Categories CI to CIII represent conventional oil and gas volumes that can be delineated with current geological techniques. The main characteristic of these categories is the uncertainty associated with their eventual discovery. The fourth and fifth categories encompass increasing uncertainty with respect to economic, geological, technical, and environmental factors.

The possibilities of enhanced oil and gas recovery through tertiary production methods are classified as CIV and, however, may also apply to CI–CIII. Additions to reserves due to increased recovery factors from advanced technologies (e.g., steam injection, the use of solvents, chemical methods, CCS) are included in the CIV category.

Oil and gas located in deep offshore reservoirs falls under the fifth category (CV). These quantities cannot usually be produced with traditional methods because of technical and economic limitations. Some assessments may even consider CV quantities as "unconventional" due to the novelty of deep sea drilling, even though the hydrocarbon itself is "conventional" by geological definitions.

Supply cost curves are a function of remaining oil and gas volumes, production costs, and technological change. Table 1 shows the current oil production costs per BOE in 2009 USD (Aguilera et al. 2009), the assumed annual rates of technological improvement per production cost category (based on Rogner 1998), and the projected production costs for 2030. There are five assumed conventional oil cost categories with a lower and upper bound for each category. The assumed rates of technological improvement, ranging from 0.50 % to 1.50 % per year, reflect the observed fact that advancement is greater under favorable production conditions.[3] Applying an assumed rate is based on recent approaches to modeling technological

[3] Studies show that low initial learning rates in the early phases of commercial deployment (e.g., deep offshore production) result in increased costs (Yeh and Rubin 2012). On the other hand, greater experience—such as that occurring in categories CI and CII—leads to lower costs and faster improvements in technology. For the latter, Rubin et al. (2007) uses the example of power plants with CO_2 capture.

change that capture the effect of progress occurring exogenously over time (Yeh and Rubin 2012). For example, Nordhaus (2009) argues that there is a constant rate of exogenous technological change associated with time. In highest cost category (CV), for instance, compounded technological advancement of 0.50 % per year until 2030 reduces the upper bound from 35.00 to 31.50 USD/BOE. Annual productivity gains in the upstream oil and gas sectors have historically been observed at an average of about 1 % (Rogner 1998). However, periods of two-digit growth (usually in the short run) have often been followed by zero or negative increases, making productivity estimates highly uncertain (Adelman 1995). Thus, our projected rates may prove to be pessimistic or optimistic. As stated in Adelman (1993, p. 81), "the most important variable in the long run is the least predictable: technical progress both in supply and in utilization."

Table 2 presents 2009 and 2030 gas production costs in USD per MCF, as well as technological improvement rates. In this case, technological advancement is assumed to range from 1.00 % to 1.50 % per year. The upper bound of the fifth cost category, CV, has decreased from 3.75 USD/MCF in 2009 to 3.00 USD/MCF in 2030, assuming compounded technological change of 1.00 % per year. It is important to note that the assumed rates of technological progress will not occur automatically over time. Rather, significant investments will be necessary to allow for productivity gains. Reduced interest rates should lead to increased investment in oil and gas projects, particularly those with a high proportion of capital costs. Considering our time horizon (to 2030), the eventual result would be increased production and cost reductions due to technological learning. Conversely, an increase in interest rates will discourage investment, leading to reduced future supply and augmented prices and costs. For a detailed analysis on the relationship between interest rates and supply curves, refer to Bauer et al. (2008).

Applying the cost ranges of the five categories to the earlier-reported conventional oil and gas volumes in a fixed proportion leads to estimated oil and gas supply cost curves for Europe. Based on Aguilera et al. (2009), the proportion of conventional oil volumes across categories is assumed to be 5 % (CI), 15 % (CII), 60 % (CIII), 17.5 % (CIV), and 2.5 % (CV); for conventional gas, it is 30 % (CI), 47.5 % (CII), 15 % (CIII), 5 % (CIV), and 2.5 % (CV). In order to provide a greater level of detail, each cost category has been broken up into additional categories. These subcategories are created by evenly dividing the costs into five classes. For example, the subcategories for CI (oil) in USD/BOE are as follows: 3.00–3.80, 3.80–4.60, 4.60–5.40, 5.40–6.20, and 6.20–7.00.

The lower portions of Tables 1 and 2 show single production cost estimates for each of the unconventional sources. The 2009 estimates are simplistically based on the ranges presented in the oil and gas supply curves of IEA (2008, 2009, 2012). Shale oil and shale gas are the most expensive, though still less than market oil and gas prices. Each of the reported costs is attached to the corresponding unconventional quantity presented in Sect. 4. Technological progress is also assumed to benefit the costs of unconventional production in 2030 at the same rates as category CV.

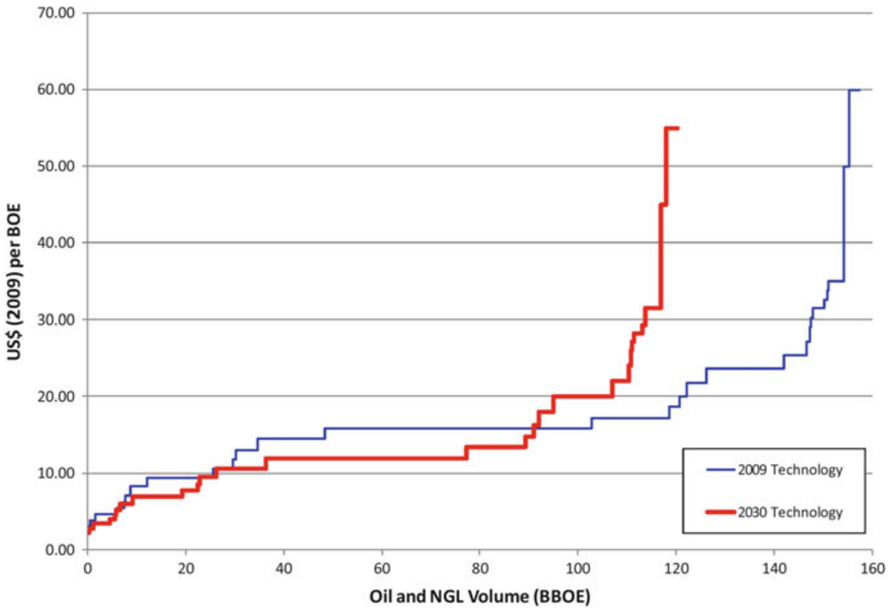

Fig. 4 2009 and 2030 supply cost curves for conventional and unconventional oil and NGL in Europe

Figure 4 shows two oil supply curves—one for the volumes based on performance, productivity, and costs associated with 2009 technology and one for the volumes, performance, and production technology expected by 2030. The 2030 curves reflect production cost reductions due to technological advances over the period. However, the volumes in 2030 exclude any potential enhancement to the accessible oil resource base made possible by technological change and different market conditions but reflect the oil produced between 2009 and 2030 (assuming constant 2009 production levels). In any case, the estimated volume for 2009 already includes the oil from previously unassessed provinces as well as reserve growth. Figure 5 follows the same procedure but presents supply curves for conventional gas.

The potential conventional and unconventional oil volume assessed for 2009 amounts to some 158 BBOE. This is calculated by subtracting European cumulative oil production until 2009, 57 BBOE (British Petroleum 2010), from the VSD-calculated conventional endowment plus the GEA-estimated unconventional endowment (215 BBOE). As defined above, endowment includes cumulative production, so cumulative oil production must be subtracted from the endowment in order to give the remaining volume. Assuming a constant oil production rate of 1.7 BBOE per year from 2009 to 2030 (British Petroleum 2010), the remaining total decreases to 120 BBOE in 2030.

For the case of conventional and unconventional gas, the total remaining volume in 2009 amounts to 4,378 TCF. This is equal to the VSD-calculated conventional total plus the GEA-estimated unconventional total (4,688 TCF) minus cumulative

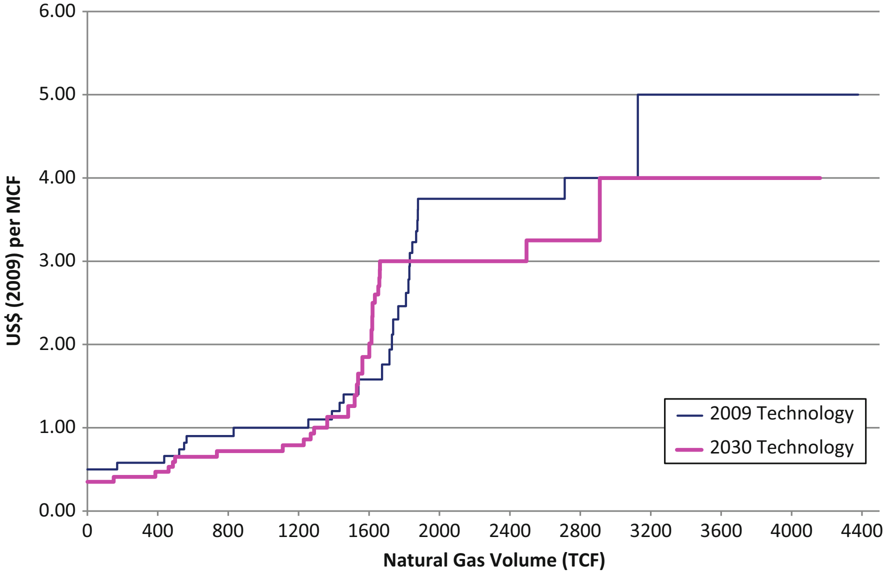

Fig. 5 2009 and 2030 supply cost curves for conventional and unconventional gas in Europe

gas production until 2009 (310 TCF). A constant production rate of 9.8 TCF per year (British Petroleum 2010) is used to derive the volume in the 2030 supply curve, 4,162 TCF.

7 Conclusions

This study assesses the availability of conventional and unconventional oil and gas in Europe by estimating supply cost curves. The curves are intended to show how the long-term supply of oil or gas to the year 2030 varies with costs of production.

To begin with, we find that oil and gas resources may be more abundant than many commentators assume. This is due to the significant yet-to-be-found volumes estimated to exist in previously unassessed provinces, the additions that could occur as a result of reserve growth, and the vast unconventional quantities (especially gas). The USGS (2000) conventional oil and gas study itself recognizes that their "assessment is not exhaustive, because it does not cover all sedimentary basins . . .The estimates are therefore conservative" (Ahlbrandt and McCabe 2002). Our VSD-calculated conventional oil endowment volume, plus reserve growth, for all 62 provinces in Europe amounts to 208 BBOE, while the conventional gas endowment including reserve growth is estimated at 2,188 TCF. For the unconventional quantities, GEA (2012) gives an estimate of 6.5 BBOE for oil (heavy oil, oil sands, and shale oil) and 2,500 TCF for gas (CBM, tight gas, and shale gas).

Another finding is that the oil and gas volumes are likely to be economic. This is deduced from the supply cost curves estimated in the previous section. The curves are constructed by attaching the production costs presented in Sect. 5 to the conventional and unconventional quantities presented in Sects. 3 and 4. With technological advancement over time, the production costs may decrease further. The projected productivity gains in upstream oil operations are assumed to vary between 0.5 % and 1.5 % per year. For natural gas, the productivity gains vary between 1.0 % and 1.5 % per year. Although the rates are speculative, they approximate the average long-term historically observed rates in the hydrocarbon upstream sectors. In 2009, estimated production costs of oil ranged from 3.00 to 35.00 USD/BOE for conventional and 35.00 to 60.00 USD/BOE for unconventional, while gas costs ranged from 0.50 to 3.75 USD/MCF for conventional and 3.75 to 5.00 USD/MCF for unconventional. By 2030, the projected oil production costs range from 2.20 to 31.50 USD/BOE for conventional and 31.50 to 55.00 USD/BOE for unconventional, while those for gas range from 0.35 to 3.00 USD/MCF for conventional and 3.00 to 4.00 USD/MCF for unconventional.

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Roberto F. Aguilera is a Curtin Research Fellow with the Centre for Research in Energy and Minerals Economics (CREME) at Curtin University, Australia.

Ronald D. Ripple is Professor of Energy Economics and Director of CREME.

Energy Security: Stochastic Analysis of Oil Prices

Konstantinos Skindilias and Chia Chun Lo

Abstract **Purpose** In this chapter we perform a comprehensive analysis of energy price dynamics. A variety of diffusion processes widely used in finance area calibrated from historical prices over periods of high uncertainty.
Design/Methodology/Approach We compute the maximum-likelihood estimates based on the density expansion technique when the density function of underlying process is unknown. We aim to identify the most appropriate functional specification for energy price modeling in terms of different model selection criteria.
Findings We found that the standard geometric Brownian motion and AR(1) type mean-reverting process perform poorly in our prediction exercise. The nonlinear drift diffusion model and variance-gamma process, on the other hand, generate satisfactory outcomes in this competition. Furthermore, the nonlinear drift model indeed produces the narrowest prediction interval and the highest fifth percentile of oil price among all models.
Practical Implications Our finding may suggest that the variation of the oil price dynamics at least can be partially explained by the nonlinear drift specification (or nonlinear mean reverting). A model without the nonlinear drift specification may simply overestimate the volatility and value at risk.
Originality/Value Of the leading threats to energy security is a significant increase in energy prices. Having a better understanding about uncertainty in the energy price can add stability in decision and policy making. As a result, this area has attracted attention from policy makers to speculators, to assess energy security and diversification. In this chapter we perform a comprehensive analysis of energy price dynamics.

K. Skindilias (✉)
ABM Analytics, 145-157 St John Street, EC1V 4PW, London, UK
e-mail: K.Skindilias@londonmet.ac.uk

C.C. Lo
University of Macau, Avenida Padre Tomas Pereira, Taipa, Macau, China
e-mail: chiachunlo@umac.mo

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1 Energy Security, Oil, and Prices

Energy security that fuelled the creation of the international energy agency (IEA) in 1974 relates the concepts of national security and the availability of natural resources for energy consumption (between its member states).

Historically, the concept of energy security was primarily linked to securing oil supply. The availability or uninterrupted physical delivery at a price which is affordable, in the light of the 1973 oil crisis, was a key concern for modern and developing economies whose functioning was heavily dependent on. In the subsequent years, the rate of industrial and population growth of developing countries, as much as the excessive reliance of developed countries to energy supply, has given rise to the uneven distribution of energy supplied among countries. In response to the finite availability of energy sources, rising costs of extraction, and other energy security threats, recent literature of energy security aims to delineate its dimensions. van Vuuren et al. (2009) and a recent study of the US Chamber of Commerce (2010) represent (in an equivalent manner) energy security, at least in the longer term, as availability (geological), accessibility (geopolitical), affordability (economic), and acceptability (environmental and social). Further studies by Gupta (2008) emphasize the definition of energy security, at least in the short term, as the economic cost and physical availability. This definition comes in the sound of the IEA's definition, which in a recent study Jewell (2011) defines the factors of energy security at an international level to risk exposure and resilience, associated with potential disruptions of energy imports and the ability of energy systems to adapt to or withstand disruptions, respectively. Policy makers often equate the attainment of energy security with energy independence, which looks at reducing country imports of foreign sources of energy. Each term length in energy security has the relevant implications. Longer term is mainly linked to timely investments to supply energy in line with economic developments and environmental needs. It also implies the requirement to address sustainable developments as alternatives to conventional technologies. On the other hand, short-term energy security is the ability of the energy system to react promptly to sudden changes in supply and demand that directly affect the price of the energy product. In addition in Jaromir et al. (2012), it is argued that equating security with independence also leads policy makers to focus on expanding domestic supplies,[1] rather than on efficient methods to manage risk by diversifying suppliers or diversifying fuel types.

Though alternative technologies may have a promising and prominent effect in the view towards a sustainable economic growth, world fossil fuel demand is likely

[1] Through subsidies or quotas, see, for example, Jaromir et al. (2012).

to grow at least over the next decade and remain a significant part of the energy mix (Wicks 2009). Remaining reserves of the fundamental factors of energy production, gas and oil, are increasingly concentrated in a limited number of countries increasing the relationship of price and demand.

The United States official international oil policy during the 1980s and early 1990s was to ensure a smooth transfer of Middle East oil to support world market demand. The energy security at that stage aimed to ensure stability in oil prices. It is argued that the economic growth during the mid-1990s, especially in Asia, in relation to the increased demand for oil during that period, had similarities with the period of the early 1970s as noted in El-Gamal and Jaffe (2010). The large increase in oil prices over the 2007–2008 period did raise again the profile of energy security with relation to demand/supply imbalances. While energy security focus has many aspects, it is argued that the notional driving force to energy security, apart the finite resources that produce the worlds energy, is the price of oil. In the early 2011, even with domestic tax components being reduced, the prices of fuel in many countries reached top levels at the height of the Lybia crisis. The primary driving force of oil prices now, compared to 2011, is the emerging market demand through the means of commodity intense nations. According to a statement at J.P. Morgan Asset Management, the risk is not how high prices are elevated, but the length of the period that prices will remain high. The effect of current oil price changes to equity markets is well documented in current literature. Arouri et al. (2012) examine the impact of oil price changes to the equity sector and, in particular, examine the necessity of making oil assets part of a well-diversified portfolio of sector stocks to effectively hedge the oil price risk. This comes into agreement with the established argument of a well-diversified portfolio of many different assets. Banks as a whole are typically very well diversified and aware of the benefits of diversification in their daily balances. The essence of energy security is again at focus of oil prices either through the means of diversifying the energy sources (in the longer term horizon) or by creating a hedge portfolio to minimize the impact of price spikes (in the shorter-term horizon). Practically, short-lived price spikes are not the driving force that leads an economy into recession nor the cause of investors changing significantly their asset allocations. Looking at the oil price changes from mid-2011 to early 2012, we note that it took approximately 6 months for oil prices to return to their pre-distressed level.

Kilian (2009) distinguishes between three major drivers of oil price changes. He notes that aggregate demand for goods and precautionary demand for oil are the main drivers for oil price spikes and that disruptions in oil supply in the form of political instability or similar reasons are negligible in price changes. Contradictory, Hamilton (2009) finds that temporarily physical oil supply disruptions had a major role in explaining historical dynamics of oil movements and argues that stagnating world oil production may also be accounted for the 2007–2008 oil price trending. The author argues that it is the short-run elasticities of substitutions between oil and other factors of production and notes that these elasticities get larger over longer horizons, as agents seek to diversify to oil substitutes. Further, it is essentially the argument that oil reserves are ultimately finite, and the fact that oil which is extracted easy and at lower cost is produced (and refined first), and cumulated amount of oil already produced, makes the process more expensive.

The future price of oil is notoriously difficult to predict. The studies of Alquist et al. (2011) find that oil price forecasts based on the monthly spreads of oil futures markets and with oil spot markets provide no better forecasts than random walk models. The conflicting results in the academic and practitioner literature are heavily biased by the definition of oil price forecasts. Alquist et al. (2011) further note that when it comes to describing oil price forecasts, there is not precise reference to whether the corresponding study emphasizes in prices of oil in real or nominal terms. Further, the estimation and evaluation period needs to clarified. The most common question in estimating parameters of the underlying model/ process has to do with the sample period used. While including longer periods one manages to capture the business cycle, estimation in shorter periods tend to reflect more accurately short-term price dynamics.

In the light of the above discussion, as many authors have realistically shown that even a multifactor model cannot predict oil price changes, we provide a comprehensive empirical analysis of oil price dynamics using documented and well-known (in the field of finance) continuous-time processes, rather than providing a framework that aims to forecast the future price of oil. Our focus lies on the management of risk perspective. As oil spikes can last from days to week, we note that it is not possible to determine the exact period that prices will change or stay elevated. In contrast, we provide the tools for modeling perspectives with respect to managing as accurately as possible oil price risk by looking at the underlying process distribution. Policy makers who seek to get an empirical view of price evolution in the short run or portfolio managers to aim to diversify their portfolios as best as possible may employ the process that suitably fits the current market dynamics. We partially examine whether the dynamics of the market are more suitably represented by a continuous-time process with complicated drift and volatility dynamics. We also investigate, in the light of the paper of Geman (2005), whether processes with mean-reverting drift to a long-run equilibrium can still provide a better fit.

For the estimation of the parameters of the underlying process, we make use of the maximum-likelihood estimation. Given that our continuous-time process estimation is relied on discretely sampled data and the fact that for some processes we use the density function is not known, we employ the likelihood expansion method of Ait-Sahalia (2002), who treats effectively the above problems. Alternative methods to the maximum-likelihood estimation for approximating parameters are solving numerically either the corresponding Fokker–Planck–Kolmogorov partial differential equation [e.g., see Lo (1988)] or simulation methods for large sample paths as in Pedeersen (1995). The method of Ait-Sahalia not only provides a closed-form solution (so everything is computed analytically) but it has also been shown in Jensen and Poulsen (2002) to outperform such methods.

The rest of the chapter continues as follows: in Sect. 2, we discuss the selected models chosen for this empirical study and look at the implications of the different functional forms for the drift and variance components of the underlying process.

The following section deals with the empirical analysis. Within, we discuss the characteristics for the data series and the implications of parameter estimation associated with discretely monitored data. In particular we outline the selected method for estimating the parameters of the underlying process, the likelihood expansion methods of Ait-Sahalia (2010). In Sect. 4, we provide the calibration results and discuss the implications of the results. The following section concludes.

2 Stochastic Analysis of Oil Prices

The continuous-time processes discussed in this section are mainly characterized by two components, the drift and stochastic component:

$$dX = \text{deterministic term} + \text{stochastic term},$$

where the term dX represents the change in the market underlying variable X, over the instantaneous time period dt. The deterministic term is the drift term which represents the expected value of the underlying dX. The stochastic term represents the portion of the market variable that is random and cannot be predicted. Putting together, a stochastic process is a family or random variables $\{X(t)|t \in T\}$ defined on a given probability space, indexed by the time variable t. In continuous time, $t \in \mathbb{R}$ varies continuously in a time interval, typically $\{0 \le t \le T\}$. Formally, a stochastic process is $(X_t)_{0 \le t \le T}$. A special property of stochastic processes is its Markovianity where only the present value of X_t is relevant for its future motion.

The diffusion process dX is a differential equation whose components are the drift term (mean) and the diffusion term (volatility). Given its properties, a stochastic differential equation (SDE) is fully characterized by its first and second instantaneous moments. Knowledge of the first two moments, namely, the mean and standard deviation, allows full implementation of the process. Figure 1 plots the deterministic term (mean) + the combined deterministic and stochastic terms for two different volatility regimes. When modeling, the annualized mean function will indicate us the annual expected return on the underlying (also the trend). Volatility is a key factor when modeling price changes, especially for oil importing countries. Different functional forms for either the drift or the variance of the process allow one to capture more complicated dynamics which we are going to discuss. We show several cases in the sections below.

2.1 Underlying Models

Model 1. The Brownian motion is of the most important continuous-time models historically for modeling stock prices. Owing its name to Robert Brown, and its

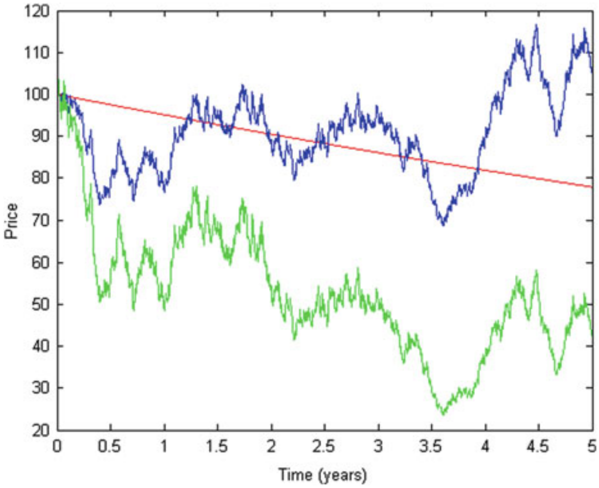

Fig. 1 The deterministic part (*line* plot) and combined deterministic and diffusion part for daily simulations over a period of 5 years. We present two volatility regimes: high (*bottom*) and low (*top*)

seminal application to finance by Bachelier in the 1900s for stochastic analysis of the stock and option markets, has become due to its properties a foundation for mathematical finance.[2] The geometric Brownian motion (GBM)[3] that ensures positivity of the underlying process models the relative price change (return) dS/S of a security's value S in the interval dt

$$dS = \mu S dt + \sigma S dW_t. \tag{1}$$

The term W_t is the so-called Brownian motion (or Wiener process), essential to the SDE, has increments that are independently and identically distributed $\mathcal{N}(0, dt)$.[4] The SDE is linear in S_t, where μS_t is the drift component with expected rate of return μ, and σ is the volatility of the return.

The predicability of returns is an important issue. As the normal distribution is the first choice, if we let the return dS/S to be normally distributed, we are facing the following two problems. First, limited liability is violated since $Pr[dS/S < -1] > 0$, and second, multi-period returns are not normal as they are the product of normals. As a result, effectively treating both problems, we tend to work with log-returns. The theoretical solution to Eq. (1), after applying the change of variable $x = \ln(S_t)$ using Itós lemma [see Hull (2000) for a detailed treatment], is given by

[2] For more details on the history of Brownian motion in finance, the reader will find extensive literature. The book of Mandelbrot (2004) provides an elegant discussion.

[3] For the unfamiliar reader, the GBM is the reference model to the Black and Scholes (1973) option price formula.

[4] We refer the reader to Karlin and Taylor (1975) and Hull (2000).

$$dx = \left(\mu - \frac{1}{2}\sigma^2\right)dt + \sigma dW_t. \quad (2)$$

The discrete representation is given as

$$\Delta x = \left(\mu - \frac{1}{2}\sigma^2\right)\Delta t + \sigma\sqrt{\Delta t}Z,$$

where $Z : \mathcal{N}(0, 1)$. As the SDE is fully characterized by its first two instantaneous moments, the relevant probability density function is given by

$$f(\Delta x; \mu, \sigma) = f_{\mathcal{N}}\left(\left(\mu - \frac{\sigma^2}{2}\right)\Delta t, \sigma^2\Delta t\right). \quad (3)$$

Unfortunately, historical asset log-returns do not appear to be normally distributed, as they exhibit excess skewness and kurtosis. Further, we have repeatedly observed that the underlying price exhibits jumps which come in contradiction with the path continuity of the GBM.

Model 2. With a simple extension to the geometric Brownian motion, one can include a jump part to allow for positive or negative jumps of a given jump amplitude. In this case we shall work with the well-known Merton (1976) jump-diffusion process, which adds a normally distributed jump to the process with arrival rate given by a Poisson process. The model SDE can we written as

$$dS(t) = \mu S(t)dt + \sigma S(t)dW_t + (J - 1)S(t)dN_t. \quad (4)$$

With everything remaining equal as in Eq. (1), J represents the jump size that under Merton (1976) is $J : \mathcal{N}(\mu_J, \sigma_J)$.[5] $(N_T)_{T\geq 0}$ follows a homogenous Poisson process with jump intensity λ and is thus distributed as a Poisson distribution with parameter λT. The probability of the number of jumps within one instance is given by

$$Pr(Jump = 1) = \lambda\Delta t$$

$$Pr(Jump = 0) = 1 - \lambda\Delta t.$$

Performing the change of variable as before for $x = \log S$, the transformed process takes the form

[5] We treat J as the absolute price jump. The relative price change is then treated as $dS_t/S_t = (JS_t - S_t)/S_t = J_t - 1$.

$$dx = \left(\mu - \frac{1}{2}\sigma^2\right)dt + \sigma dW_t + \log\left(J_{N(t)}\right)dN_t \text{ or, equivalently}$$

$$dx = \left(\mu - \frac{1}{2}\sigma^2 + \lambda\mu_J\right)dt + \sigma dW_t + \left[\log\left(J_{N(t)}\right)dN_t - \mu_J\lambda dt\right]. \tag{5}$$

The discretized version of the above SDE for simulation purposes is

$$\Delta x = \mu^*\Delta t + \sigma\sqrt{\Delta t}Z_t + \Delta J_t^*,$$

with $\mu^* = (\mu + \lambda\mu_J - (1/2)\sigma^2)$ and $\Delta J_t^* = \sum_{j=1}^{n_t}\log(J_j) - \lambda\Delta_t\mu_J$.

We have followed the notation as in Brigo et al. (2009) and the standard manipulation to remove the mean from both the jump and diffusion shocks. Due to the separability of the jump diffusion to a continuous and a jump part, we are allowed to write

$$\mathbb{E}(\Delta x) = \mu^*\Delta t + (n_t - \lambda\Delta t)\mu_J$$

$$\text{Var}(\Delta\log\ x) = \sigma^2\Delta + n_t\sigma_J^2.$$

The density function for this process is then given by

$$f(\Delta x;\mu,\sigma,\mu_J,\sigma_J) = (1-\lambda\Delta t)f_{\mathcal{N}}\left(dx_i;\left(\mu - \frac{\sigma^2}{2}\right)\Delta t, \sigma^2\Delta t\right)$$
$$+ \lambda\Delta t f_{\mathcal{N}}\left(x_i;\left(\mu - \frac{\sigma^2}{2}\right)\Delta t + \mu_J, \sigma^2\Delta t + \sigma_J^2\right).$$

Figure 2 plots a 5-year simulated path for a geometric Brownian motion (GBM) and one that exhibits jumps. The bottom part of the figure plots the differences in returns when a jump occurs. The rational in introducing a jump process lies in the fact that prices do exhibit abnormal changes more often that the classic normal distribution would allow and further there is no continuous trading implying that each price change can be characterized even by a very small jump.

Model 3. We further look into a process that exhibit mean reversion. Following the work of Pindyck (2001) who notes that after 1999 to early 2001 there are no significant evidence of mean reversion, also supported by Geman (2005), we instead couple the mean-reversion feature together with that of fat tails by including jumps. Mean-reverting processes are borrowed from interest rate modeling where we observe a long-run mean level at which the underlying is reverting back. We will show that as time increases, the mean tends to the long-term value and the variance remains bounded, implying mean reversion.

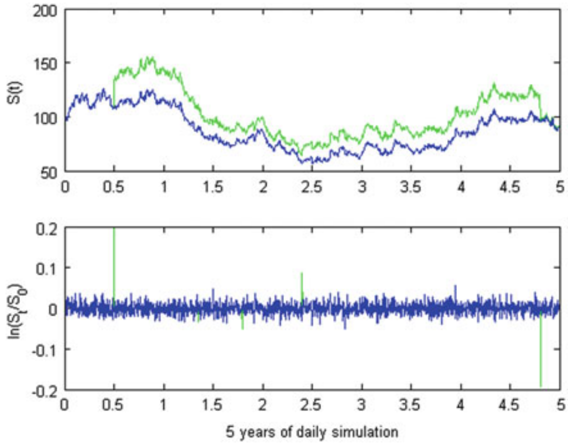

Fig. 2 Simulated daily asset prices (*top*) and returns (*bottom*) for pure-diffusion and jump-diffusion process

Adding jumps to a mean-reverting model such as the Vasicek (1977) model reveals the form (for $x = \log\ S$)

$$dx(t) = \alpha(\theta - x(t))dt + \sigma dW(t) + J_{N(t)}dN(t), \tag{6}$$

where as before $N(t)$ is a Poisson process with intensity λ and J are the iid random variables. We follow again Brigo et al. (2009) to have zero-mean shocks, and we rewrite the SDE as

$$dx(t) = \alpha(\theta_J - x(t))dt + \sigma dW + \left[J_{N(t)}dN(t) - \lambda\mathbb{E}(J)dt\right],$$

with the long-term mean modification as $\theta_y = \theta + \lambda\mathbb{E}(J)/\alpha$. The transition density is straightforwardly given by

$$\begin{aligned} f(x(t)|x(t-\Delta t)) = \lambda\Delta t f_{\mathcal{N}}(x; m_x(\Delta t, x(t-\Delta t)) + \mu_J, u_x(\Delta t) + \sigma_J^2) \\ + (1 - \lambda\Delta t)f_{\mathcal{N}}(x; m_x(\Delta t, x(t-\Delta t)), u_x(\Delta t)), \end{aligned} \tag{7}$$

where [see Brigo et al. (2009) for a detailed treatment and extension]

$$m_x(x_s, t-s) = \theta\left(1 - e^{-\alpha(t-s)}\right) + x_s e^{-\alpha(t-s)}$$

$$u_x(t-s) = \frac{\sigma^2}{2\alpha}\left(1 - e^{2\alpha(t-s)}\right).$$

Model 4. We further work with a process that allows wider modeling of skewness and kurtosis than the Brownian motion does. It further has naturally built in the frequency of occurrence of large numerical changes than that of a normal distribution. Having an infinite amount of jumps cannot be easily simulated though a jump-diffusion process. For that purpose Lévy processes are used which are constructed via the Wiener process but are subjected to random times. Such processes have a time subordinator (i.e., business time) which runs faster than calendar time, i.e., when trading volume is high. The $\tau(t)$ subordinator replaces the ordinary deterministic time t. As example of such processes are the variance-gamma (VG) process that we choose to use for modeling price changes. The VG process has exponential tails and tail decay rate smaller than of the normal distribution and thereby allows flexibility in capturing the stylized facts of financial returns. Introduced by Madan and Seneta (1990) for modeling financial returns, the VG holds the following structure for the log price $x = \log\ S$

$$dx(t) = \bar{\mu}dt + \bar{\theta}dg(t) + \bar{\sigma}dW(g(t)), \tag{8}$$

where $\bar{\mu}, \bar{\theta}$, and $\bar{\sigma}$ are constants and $\bar{\sigma} \geq 0$. The term $g(t)$ with stationary increments that makes the process different from the GBM characterizes the market activity time and is gamma distributed. The stationary independent increments imply that $\{g(u) - g(t)\} : \Gamma((u - t/v), v)$ with parameter v.

The probability density function for the VG process is given by

$$f_{\Delta x_{\Delta t}}(dx) = \frac{2\mathrm{e}^{\frac{\bar{\theta}(dx-\bar{\mu})}{\bar{\sigma}^2}}}{\bar{\sigma}\sqrt{2\pi}v^{\Delta t/v}\Gamma(1/v)} \left(\frac{|dx-\bar{\mu}|}{\sqrt{\frac{2\bar{\sigma}^2}{v}+\bar{\theta}^2}}\right)^{\Delta t/v-1/2} K_{\Delta t/v-1/2}\left(\frac{|s-\bar{\mu}|\sqrt{\frac{2\bar{\sigma}^2}{v}+\bar{\theta}^2}}{\bar{\sigma}^2}\right), \tag{9}$$

with $K_\eta(\cdot)$ a modified Bessel function of the third kind with index η, given for $\omega > 0$ by

$$K_\eta(dx) = \frac{1}{2}\int_0^\infty y^{\eta-1}\exp\left\{-\frac{dx}{2}(y^{-1}+y)\right\}dy.$$

Model 5. Our last model refers to a model with complicated functional form for the drift and diffusion process. Given the following general form of a SDE

$$dX(t) = a(X(t);\vartheta)dt + b(X(t);\vartheta)dW(t), \tag{10}$$

where

$$a(X(t)) = \frac{a_{-1}}{X} + a_0 + a_1 X + a_2 X^2$$

$$b(X(t)) = (b_0 + b_1 X^{b_3})^{1/2}$$

ϑ represents the set of unknown parameters, namely, $\{a_{-1}, a_0, a_1, a_2, b_0, b_1, b_2, b_3\}$ for this model.

This class of process belongs to nonparametric models for estimating the drift and diffusion term in a general dynamic market (Ait-Sahalia 1996). This general model can capture the short rate features of being a random walk at the middle level (central region) of the interest rate but fast mean reverting at the extreme low and high level of interest rate environments. Using such a model, we attempt to capture any nonlinear mean reversion that may be present.

The density function of above model is unknown. Therefore, we make use of likelihood expansion method taken from Ait-Sahalia (2008) to find the approximated density function. The likelihood expansion approach transforms the original diffusion into the one that is closer to normal and build on it in order to obtain an approximation for the transition density. Given Eq. (10), one can transform X into a unit diffusion process $y = g(X)$. Suppose $g(X) = \int x(dy/\sigma(y(t);\theta))$ is well defined. After using Ito's lemma, we obtain $y_t = y_0 + W(t) + \int_0^t ds((\mu(g^{-1}(y)))/(\sigma(g^{-1}(y))) - (1/2)\sigma'(g^{-1}(y);\theta))$. In the case when y_t is not close to normal density, one can standardize the process as $z_t = (y_t - y_0)/\sqrt{\Delta_t}$. An explicit transition density function for z_t can be obtained using, for example, Hermite expansions. Finally, one can use the Jacobian formula for the inverted change of variables to approximate the transition density of x_t from the transition density of y_t and z_t. For a detailed discussion on this subject, please see Ait-Sahalia (2008), Yu (2007), and reference therein.

3 Empirical Analysis

In financial time series, data are not only sampled at discrete points in time but they are also sampled at random time intervals. Given that one trusts the model specification, maximum-likelihood estimation (MLE) is the reference choice; it holds the lowest asymptotic variance amongst other estimators. Given the diffusion process X is a Markov process, the likelihood function conditioned on X_0 is given by

$$L_n(\vartheta) = \prod_{i=1}^{n} p(t_i - t_{i-1}, X_{t_{i-1}}, X_{t_i}; \vartheta),$$

where $p(s, x, y; \vartheta)$ is the transition density. Since the transition density is not always known (an explicit solution of the density does not exist), depending on the specification, there are numerous methods that seek to approximate the maximum-likelihood function numerically (see Sect. 1). Further, as most of the models used so far assume that the underlying modeling process is in continuous time, the data at which we monitor are always sampled in discrete time.

With regard to the above observations, we have chosen to work with the likelihood expansion method. Ait-Sahalia constructs an explicit sequence of closed-form functions (based on the Hermite expansion discussed for model 5 of the previous section) that converges to the true (and unknown) likelihood function. This method makes maximum likelihood a practical choice to use the maximum likelihood to estimate parameters with discretely sampled diffusions. For a detailed description of the method, we refer the reader to Ait-Sahalia (2010) and Ait-Sahalia (2002) and for extensions to multidimensional diffusions to Ait-Sahalia (2008). Ait-Sahalia and Mykland (2003) study the impact of including or disregarding observations with discrete sampling interval in parameter estimation.

3.1 Parameter Estimation

The maximum-likelihood estimate for i.i.d variables of the parameter set ϑ for a corresponding density $p(s,x,y;\vartheta)$ is in general

$$L_n(\vartheta) = f_\vartheta(x_1, x_2, \ldots, x_n) = \prod_{i=1}^{n} f_\vartheta(x_i).$$

The maximum-likelihood estimate is the one that maximizes the sample likelihood. Since the product of density values can be very small and that this maximum will be the same under an increasing transformation, we usually work with the log-likelihood of the sample

$$LL_n(\vartheta;x) = \sum_{i=1}^{n} \log f(x_{i+1}|\vartheta, x_1, x_2, \ldots, x_n). \tag{11}$$

Given the probability density functions for each model (in Sect. 2.1), the maximization of the log-likelihood can be carried analytically using Eq. (11).

It is a challenging task to calibrate a high dimensional log-likelihood function. The maximum-likelihood estimates are very sensitive to the initial values of unknown parameters used in the optimizer. In most applications, testing over a range of different starting values or introducing a penalty function may act as a remedy to calibrating a unique set of parameters. An alternative is that we can discretize the model and run a two-stage nonlinear generalized least squares (GLS) regression to obtain our initial values of unknown parameters in the drift and diffusion function. We may then use GLS estimates as priors for the maximum-likelihood estimates. We take model 5 as an example for illustration. In the first stage we discretize the model 5 and ignore the diffusion term. The OLS estimates $\{\hat{a}_{-1}, \hat{a}_0, \hat{a}_1, \hat{a}_2\}$ in the drift function are then obtained by running the following regression:

$$\frac{X(t)-X(t-\Delta t)}{\Delta t} = \frac{a_{-1}}{X(t-\Delta t)} + a_0 + a_1 X(t-\Delta t) + a_2 X^2(t-\Delta t) + e_t, \quad (12)$$

where $e_t : \mathcal{N}(0, \sigma_e^2)$.

In the second stage we calibrate the diffusion function based on that fact that

$$Var(X(t)-X(t-\Delta t)) = \left(b_0 + b_1 X^{b_3}(t-\Delta t)\right)^2 \Delta t$$

or equivalently

$$Var\left(\frac{X(t)-X(t-\Delta t)}{\Delta t}\right) = \frac{\left(b_0 + b_1 X^{b_3}(t-\Delta t)\right)^2}{\Delta t}.$$

We make the use of the residual variance estimate $\widehat{V}ar\left(\frac{X(t)-X(t-\Delta t)}{\Delta t}\right) = \hat{e}_t^2$ from the first OLS equation and find the estimates $\left\{\widehat{b_0}, \widehat{b_1}, \widehat{b_3}\right\}$ in the diffusion function using the following nonlinear regression model:

$$\exp\left\{\frac{\ln(\hat{e}_t^2 \Delta t)}{2}\right\} = b_0 + b_1 X^{b_3}(t-\Delta t) + \eta_t, \quad (13)$$

where $\eta_t : \mathcal{N}(0, \sigma_\eta^2)$. Finally, based on the estimates of $\left\{\widehat{a}, \widehat{b}\right\}$ from above two regressions, the standard weight-adjusting procedure is applied to compute the GLS estimate $\left\{\widehat{a}, \widehat{b}\right\}^{\mathrm{GLS}}$. We use the GLS estimates as priors in the optimizer for running the maximum-likelihood algorithm.

3.2 Methodology and Empirical Results

For the data series we use daily closing prices of the light crude oil West Texas Intermediate (WTI). The WTI grade crude oil is usually employed as a benchmark in oil pricing. We rely mostly on the period over the last decade approximately, namely, 3 January 2000 to 20 May 2012. It is important to note the historical trading anomalies with regard to its counterpart benchmark Brent crude. Typically, WTI crude trades higher than Brent crude.[6] On 24 May 2007, while WTI was trading at \$63.58 per barrel, trading on Brent was at the range of \$71.39 per barrel. Further, in February 2011, WTI was trading at \$85 per barrel against the higher Brent price of

[6] The difference is in the quality: the less sulfur, the easier it is to refine the crude into gasoline.

$103 per barrel.[7] This was a result of the large stockpile at the Cushing reaching capacity.[8]

Working with the time series over the whole time interval (Fig. 3a), our starting point is to examine whether the series departs from normality. Figure 3b plots the quantile–quantile (QQ) plot of the return series against that of the normal distribution. It is clear that the return series is nonnormal, a result that will allow us to assume that the GBM model should can only provide a rough approximation of the return series. Further, as independence of returns is an important assumption for Markovian processes, we first examine our series for independence. The equivalence of independence from a statistical point of view is the presence of autocorrelation in past returns. A series free of autocorrelation allows us to accept the independence assumption. We may also check the partial autocorrelation function which examines the extent of the lag presence. Figure 4 plots the autocorrelation and partial autocorrelation function. No significance lags are determined for the WTI return series, which allows us to accept the independence assumption for our modeling processes.

Earlier work on crude oil prices, Geman (2005) shows that a mean-reversion pattern prevails over 1994–2000, whereas the pattern changes after that period. Since one of our processes is of the linear mean-reverting form (model 3), we need to examine if the series exhibits mean reversion. Testing for mean reversion is equivalent to testing for $AR(1)$ effects. In the presence of a unit root, the process is a random walk. Rejecting the hypothesis of a unit root enables us to use a mean-reverting process to model our series. The most well-known tests for unit roots are:

- The augmented Dickey and Fuller (ADF) test (Said and Dickey 1984)
- The Phillips and Perron (1988) (PP) test

Since both tests are sensitive to outliers in the dataset, it is suggested to remove them before examining for mean reversion. Looking at the complete period,[9] the ADF and PP tests both reject any evidence of mean reversion for the complete series of our dataset. The test statistic for the ADF test of 0.0185 accepts the null hypothesis of a unit root at the 5 % ($c.v. = -1.9416$) and 1 % ($c.v. = -2.5686$).

We further test each model over a moving window, for which we use historical prices over the past 12 months to calibrate the model parameters from. The window is not constant; in certain cases, we change every 6 months and in others every 12 months with no particular preferences. Nevertheless, we aim to account for the main price spikes and drops. Figure 6 plots these windows.[10] To assess the

[7] Source: Bloomberg Energy.

[8] Practically, the first instance was due to the closure of the refinery, while the second owes to the unrest in Lybia.

[9] Since we are using a mean-reverting jump-diffusion model in our analysis, we also perform the tests over the periods we use to calibrate model parameters for every of our runs. We discuss this further in the text.

[10] To save space, we have not included our first estimation windows that start on 3 January 2001 and use the previous 12 months to estimate model parameters.

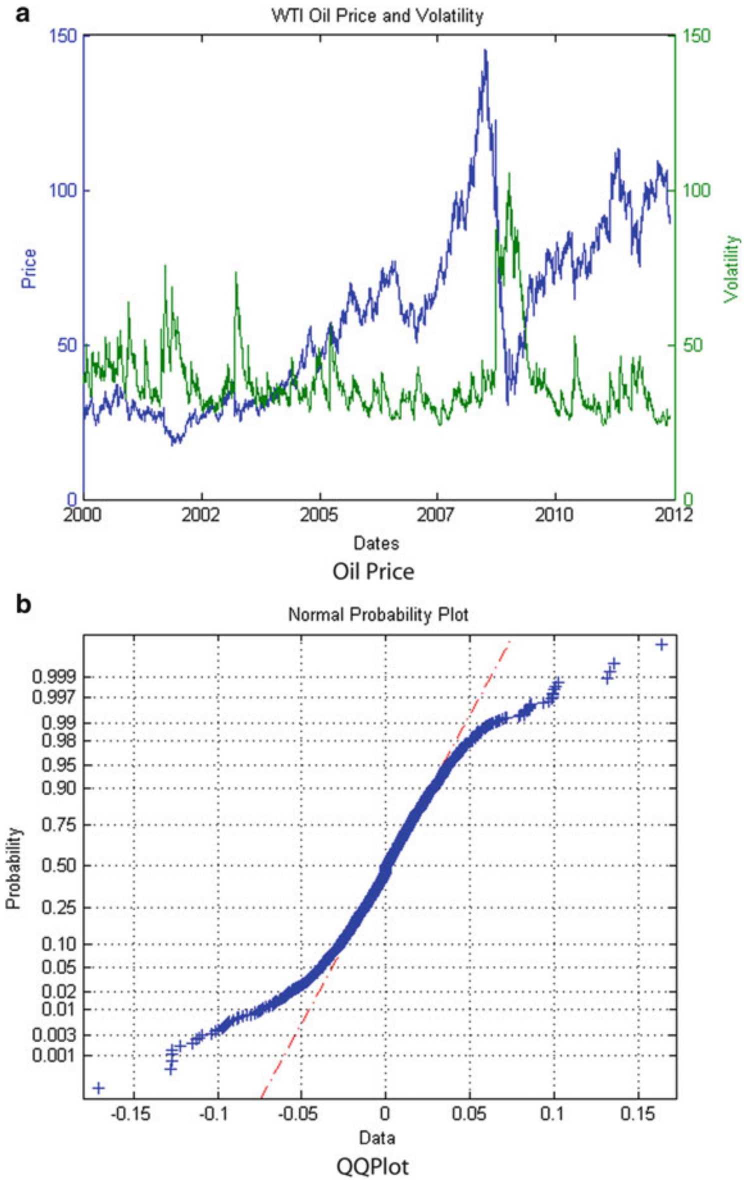

Fig. 3 (**a**) WTI light sweet crude oil prices and historical volatility (Garch (1,1)) for the period 3 January 2000 to 15 May 2012; (**b**) QQ plot of oil return series (against normal)

performance for each of the five models, based on the calibrated parameters, we run Monte Carlo simulations for selected out-of-sample periods of 1 week and 1, 2, and 6 months. In this respect select the model with the lowest mean square error (MSE) and mean percentage error (MPE). Table 1 shows the “winners” for each of our

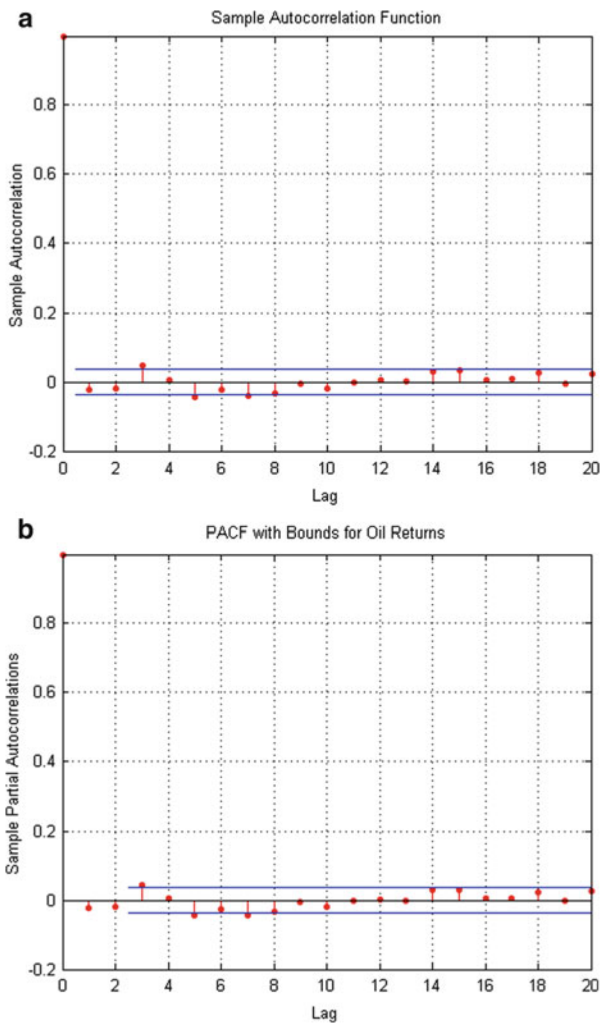

Fig. 4 Autocorrelation and partial autocorrelation function for WTI returns. (**a**) ACF and (**b**) PACF

calibration periods. It is clear that there is no best performing model, but what we can conclude is that we may prefer some models from others given the period of interest. From a quick look the best performing models are the process with complicated (nonlinear) drift and diffusion functional forms, model 5 above (*NDD* hereafter) and model 4, the variance-gamma (VG) process. Then the jump-diffusion process (model 2—JGBM) follows relatively close. The models with the lowest "scores" are the geometric Brownian motion (model 1—GBM) and the mean-reverting jump-diffusion model which in most cases fails to accurately estimate the jump intensity λ (model 3—MRJD).

As there is no apparent winner over the complete estimation interval, we wish to identify if any of the models have outperformed others in specific periods. Before we proceed we explain the implications of the nonlinear drift functional for *NDD*.

In Fig. 5a we plot the drift functional for a particular period. What we observed comes in very close agreement with Geman (2005) who notes that mean reversion is dead. We only observe a negative drift when WTI prices reach very high levels that accounts for prices to revert back to a lower level. For all other price levels the drift is nearly constant. A result of the above observation is that the models with linear mean-reversion features will tend be outperformed by models with nonlinear drift. In Fig. 5b, we plot the volatility structure imposed by model *NDD*, which suggests that the volatility increases as price increases/decreases. This is quite contradictory with the leverage effect observed in the past in crude oil, where invertors who have more long interest in crude oil than hedgers do.[11] In Fig. 3a the leverage effect argument is supported, which states that high prices have low volatility, but we also see in early 2007 that the upward trending oil price is not followed by a rapid decrease in volatility. Observing the option market implied volatility surface may shed more light to this. Previous research supports the leverage effect throughout.

Taking a closer look at each estimation window and forecast horizon, we first note that when considering longer term forecasts (6 months), the VG is preferable.[12] Looking at the particulars of the VG process, we further note. In the period that VG has outperformed the other candidates consistently, namely, July 2008, the price of oil has gained in the period preceding April 2008 more than 70 % of its value. The market dynamics that characterize the periods that *NDD* outperforms all other models are the periods that the price of oil within the 12-month period either started from high, reached even higher and ended up at lower (see Fig. 6 middle rows). As we proceed to periods closer to 2012, resolving to a model that captures best the market dynamics becomes an even harder task. The selection is between our three best competitors, namely, NDD, VG, and JGBM, with JGBM being the favorite (at least for this type of analysis) for early 2012 and up to a 6-month horizon.

Since it is practically impossible to select a single model, we propose switching between models.[13] In the following analysis we focus on candidates NDD, the VG, and the JGBM. We further plot a selection of the density function fits to the historical data for each model and also present the percentiles (5 % and 95 %) for each model to the forecast horizons. We let then the reader to draw conclusion that suits his/her economic perceptions and horizon. In Fig. 7 we plot the MLE fit to the complete calibration period, using all historical prices to fit the return distribution. Figure 8 (left column) plots for selected periods the return density function against the histogram of the returns used for the MLE estimation. In the right column we plot the percentiles of the simulated series for the three selected processes, together with the realized prices. Specifically for the nonlinear drift and diffusion process (*NDD*), we note that it produces a narrow "prediction band" (at the 5 % and 95 %

[11] The inverse leverage effect is usually observed in agricultural commodities.

[12] We note to the reader that the errors for so long-term forecasts the errors are substantially high.

[13] It is out of the scope of this chapter to propose the methodology for switching between models.

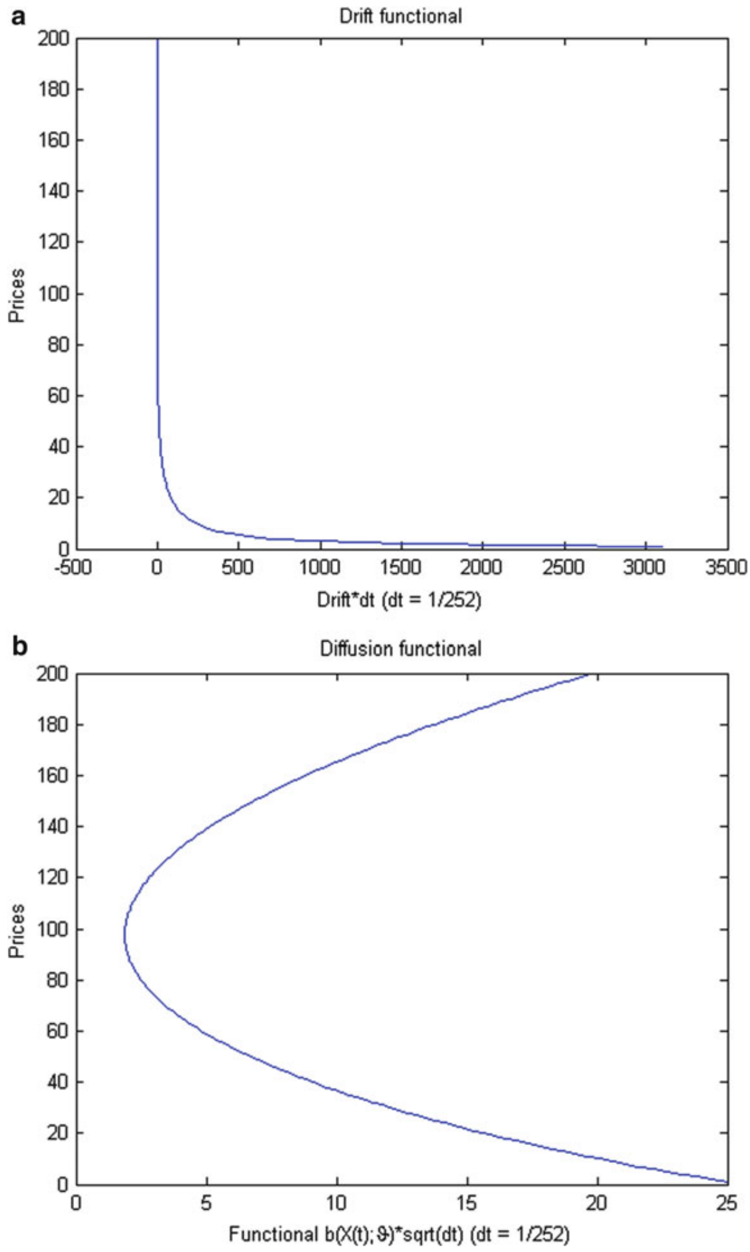

Fig. 5 The drift and diffusion functionals for model 5, as of 8 March 2011. (**a**) Drift function and (**b**) Diffusion

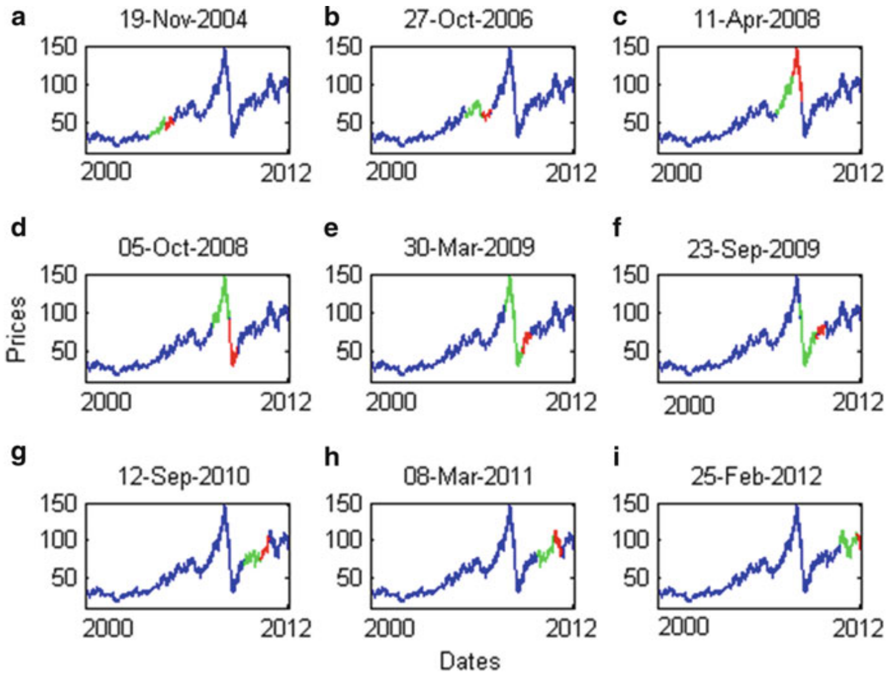

Fig. 6 Calibration periods. The MLE (12-month) estimation window and the maximum out-of-sample window

Table 1 The "winners" for the out-of-sample periods in MSE sense

MSE	1 week	1 month	2 months	6 months
3 January 2001	NDD	NDD	NDD	VG
2 January 2005	JGBM	JGBM	JGBM	JGBM
1 January 2007	VG	GBM	GBM	NDD
2 July 2008	VG	VG	VG	VG
1 January 2009	VG	NDD	NDD	VG
1 July 2009	NDD	NDD	VG	VG
31 December 2009	JGBM	NDD	NDD	VG
31 December 2010	MRJD	NDD	NDD	JGBM
1 July 2011	NDD	NDD	VG	VG
31 December 2011	JGBM	JGBM	JGBM	GBM

The corresponding date indicates the date at which the out-of-sample period starts. ML estimation takes place 12 months prior to that date

percentile). Given that one trusts the model specification, the higher 5 % percentile implies that the Value-at-Risk amount. Therefore, the capital required as a "cushion" against downside risk is less.

Each of the selected model offers the flexibility for the researcher/practitioner to adjust for any preferences. In the jump-diffusion case, one is able to assign to the jump size an arbitrary distribution. A notable example is the Kou (2002)

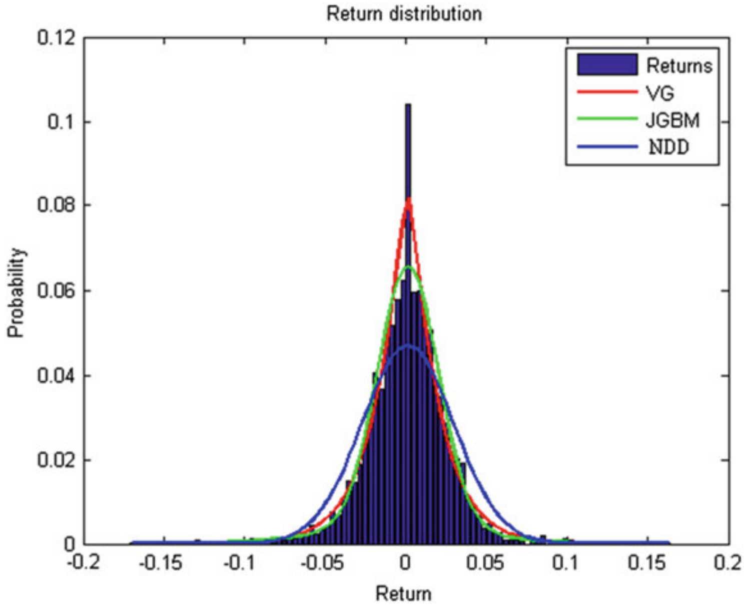

Fig. 7 Return density fit to the historical time series returns of WTI for the three candidates, the variance-gamma (VG), the jump diffusion (JGBM), and the process with nonlinear functional drift and diffusion (NDD)

jump-diffusion process. Setting the jump intensity or jump amplitudes time or state dependent may help address the frequency and level of the jump. Such treatment though becomes complicated, and a numerical method to compute the MLE is usually required. Even with the constant coefficient jump diffusion, calibration is not trivial. Jump-parameter estimation is usually ill-posed (Cont and Tankov 2002). The VG model is a very flexible model with only a few parameters to calibrate. Its flexibility in capturing fat tail features and high kurtosis of some historical financial distributions makes it a good choice. Application to pricing derivative contracts is found in Madan and Seneta (1990). For capturing market-complicated dynamics, the nonlinear drift and diffusion process (NDD) has proved to be a useful tool. The application to the oil market needs to be investigated further. With this process we managed to capture the dynamics for the drift of the underlying oil price argued in Geman (2005). Under this setting we are left with a large number of parameters to calibrate and a volatility function that does not agrees with the leverage effect. The out-of-sample simulation results allows us to consider similar processes with different diffusion dynamics to work with.

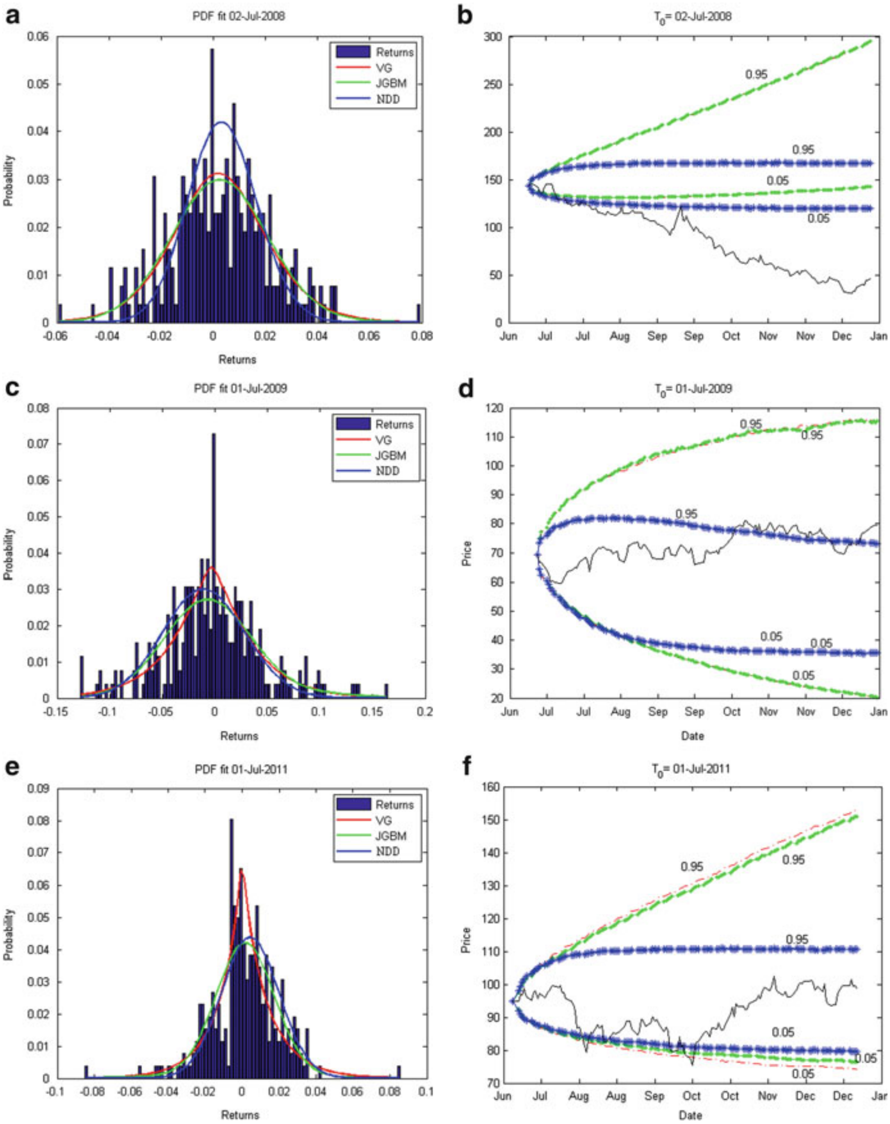

Fig. 8 (continued)

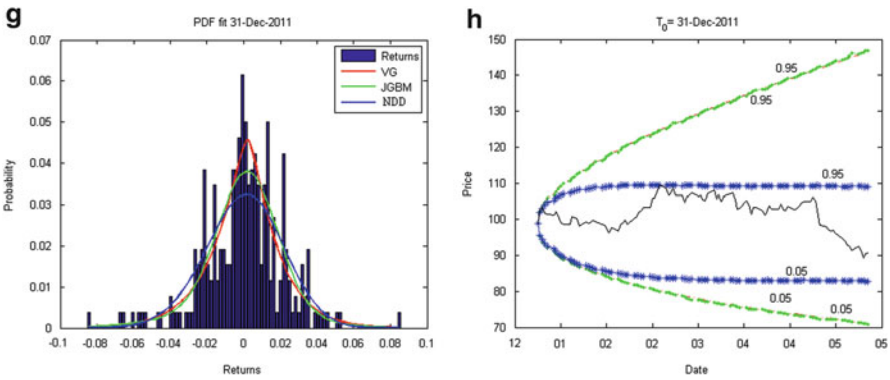

Fig. 8 MLE estimation period fit (*left*) and simulated percentiles (*right*) for four different windows. JGBM (*thick dashed*), VG (*dashed*), NDD (*), and actual (*solid*)

4 Conclusion

Historically, every US recession is tied up to high oil price changes. The first two lasted 16 months. The first followed the 1973 Embargo started in November 1973 and the second in July 1981. The latest began in December 2007 and lasted 18 months. Being more precise last year, it was 6 months before oil prices returned to their pre-turmoil levels.[14] Therefore, understanding the risk behind oil price dynamics is very important to not only the industry practitioners but also the fiscal and monetary policy makers.

In this chapter we have run an empirical study of the most common settings of continuous-time processes that have been frequently used in finance. Our conclusions suggest neither the standard geometric Brownian motion nor AR (1) type mean-reverting process is supported by the historical daily price data of oil. However, the nonlinear drift model shows that the oil price presents a constant growth rate at most of time while mean reversion is only appear at very high or low level of oil price. Furthermore, we consider the variance-gamma process and jump-diffusion processes. The forecasting experiments illustrate the fact that there is very hard to select the best one amongst the models that are considered in this chapter. This may indicate that the structural breaks in the oil price time series data are present. The study of structural breaks is accounted in our current research. It is worth mentioning that both the standard geometric Brownian motion and AR (1) type mean-reverting process perform poorly in our prediction exercise. The nonlinear model and variance-gamma process, on the other hand, generate satisfactory outcomes in this competition. We further investigate the prediction performance by examining the (5 %, 95 %) interval of the simulated oil price generated by each model, over selected periods that incorporate the turbulent periods of oil

[14] Dan Morris, Global Strategist at J.P. Morgan Asset Management (in March 2012).

prices. The interesting finding is that the nonlinear drift model indeed produces the narrowest prediction interval and the highest fifth percentile of oil price among all models. This may suggest that the variation of the oil price dynamics at least can be partially explained by the nonlinear drift specification (or nonlinear mean reverting). A model without the nonlinear drift specification may simply overestimate the volatility and Value at Risk.

There are appropriate models that suit specific economic conditions and users objectives for instance trading or risk management. Using such a model strictly relies on the understanding in the economic conditions and the market dynamics which the selected model addresses. We argue that the best alternative is to build a framework which, based upon scenario analysis and decision support systems, allows for appropriate model selection and time interval to be used. Our current research tries to address such issues.

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Konstantinos Skindilias is a research associate at ABM Analytics and a senior lecturer at the Centre of International Business and Sustainability (CIBS) at the London Metropolitan Business School, UK. He holds a Ph.D. in Computational Finance from the Centre of Computational Finance and Economic Agents (CCFEA), University of Essex, UK.

Chia Chun Lo is an assistant professor in finance at University of Macau, Macau. He holds a Ph.D. in Computational Finance from the CCFEA, Essex. He is a financial risk manager certified by the Global Association of Risk Professionals.

Green Energy Development in China: The Case of Clean Coal Technologies

Jude Clemente

Abstract Purpose This study examines the three main reasons why China is primed to vigorously pursue clean coal technologies in the years ahead: (1) coal stimulates economic development, (2) improving coal efficiency can immediately reduce demand and emissions, and (3) the Large Substituting for Small program has been a success.
Design/Methodology/Approach The study uses a wide range of data, including both primary and secondary sources, to demonstrate why China will use more coal to feed its rapidly expanding appetite for energy. Projections of future energy demand and economic data are derived from the International Energy Agency's World Energy Model and the US Energy Information Administration's National Energy Modeling System.
Findings China has no scalable alternative to coal. In fact, large emerging nations, such as India and Indonesia, view China's coal utilization strategy as an example to follow in meeting their own expanding needs. Simply put, coal's unique (1) availability, (2) reliability, (3) versatility, and (4) affordability make it the fuel of choice in the developing world.
Practical Implications Looking forward, coal-based electricity can be increasingly clean through the deployment of advanced generation technologies. Energy policies to achieve sustainability must recognize that technological advancement constantly gives us the ability to utilize fossil fuels differently tomorrow than we do today.
Originality/Value This study demonstrates that developing countries see the virtue of decreasing emissions without a legally binding quantitative commitment.

Keywords Clean coal technologies • Large substituting for small program • Supercritical • Coal plant efficiency • Carbon capture and storage

J. Clemente (✉)
Department of Homeland Security, JTC Energy Research Associates, LLC, San Diego State University, 322 Arbor Way, State College, PA 16803, USA
e-mail: judeclemente21@msn.com

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1 Background

Energy is a key factor in economic development, transforming agrarian cultures into modern industrialized nations. This societal evolution, driven by the accumulation of income and wealth, eliminates many contagious diseases, reduces child mortality, and lengthens adult life expectancy. This cycle has been demonstrated over the past 150 years in dozens of countries around the world. The emergence from poverty begins as countries develop transportation networks using petroleum and electricity networks, often based upon coal. These systems are capable of achieving massive economies of scale that provide large amounts of energy at low cost. Abundant and reliable supplies of energy spur technological change, productivity growth, and higher standards of living.

The utilization of large fossil fuel reserves and the development of technology to deliver energy from these resources provide the fuel for a growth engine in which declining costs for energy contribute to lower prices for goods and services. Increasing demand for these lower priced outputs then drives costs down even further due to economies of scale and learning effects. Classic studies in energy economics support the strong positive correlation between energy use and economic output. For example, Schurr (1984) demonstrated that the increased use of more flexible energy forms, especially electricity, significantly enhances "the discovery, development, and use of new processes, new equipment, new systems of production and new industrial locations." The effect is powerful enough in terms of raising labor and capital productivity that the energy intensity of output falls. In other words, changes in the *quality* of energy services drive broader economic productivity, apart from the physical availability of energy. The USA during the late-nineteenth and early-twentieth centuries presents a classic example of this process.

Currently, China is providing a template of how coal can be the lever to pull citizens out of poverty and lift an entire society to higher living standards. India, Indonesia, South Africa, and other developing countries are learning from China and following suit. The present analysis is founded on the premise that increased coal-based generation efficiencies, coupled with carbon capture and storage (CCS), can help the world meet the goals of a vast reduction in carbon dioxide (CO_2) emissions, sustained economic growth, and the eradication of energy deprivation—1.32 billion people still lack access to electricity. Under the direction of the United Nations Framework Convention on Climate Change, one of the objectives of the Cancun Agreements of 2010 is to "mobilize the development and transfer of clean technology to boost efforts to address climate change, getting it to the right place at the right time and for the best effect" (United Nations 2011). As demonstrated here, China is quickly moving down that path.

The International Energy Agency (IEA 2011) projects that coal will still meet over 60 % of China's total energy demand and generate 70 % of the country's electricity in 2035.[1] At 4,800 terawatt hours (TWh), China will account for 60 % of incremental coal-based power generation around the world from 2009 to 2035, or more electricity than the USA now generates in an entire year—from all sources. If coal is to remain a cornerstone of socioeconomic progress in China, however, it is a matter of concern over the potential impact on climate change through the emission of greenhouse gases (GHGs), most notably CO_2. A debate in the literature over possible CO_2 leakage is noteworthy (see Shaffer 2010; Dooley 2010), but the Massachusetts Institute of Technology (2007) hails CCS as "the critical enabling technology" for the significant reduction of emissions from coal-based power generation.[2] These systems, however, are not expected to be commercially available until the early-2020s. Today, a cost-effective and readily available option to slash emissions per unit of electricity generated is to increase a power plant's efficiency, so that less coal is consumed.

Implemented in 2007, China's Large Substituting for Small (LSS) program is helping to meet immediate needs with reduced emissions per kilowatt hour (kWh) by deploying larger and more efficient supercritical (SC) and ultra-supercritical (USC) coal plants more apt to CCS retrofit. As affirmed by the IEA (2007): "Electrification in China is a remarkable success story [. . .] the most important lesson for developing countries [is] that electrified countries reap great benefits, both in terms of economic growth and human welfare [. . .] China stands as an example."

Now, by highlighting advanced coal plants, China is setting another example because SC plants are some one of the most affordable sources of electricity: costing $33 (all $ in USD) per megawatt hour, compared to $39 for natural gas, $50 for large hydropower, $53 for nuclear, $71 for onshore wind, and $185 for solar photovoltaic (IEA 2010a). High electricity prices wreak even more havoc in the developing world than in the West because these populations have almost no economic capacity to absorb them. Indeed, analysis of the dangers posed by society's use of lower-cost coal and the emission of CO_2 generally focuses on the potential for climate change impacts (see Stern 2006; Hansen et al. 2008). It is important, however, in the context of assessing the societal risk of CO_2 emissions, to also examine the reasons why CO_2 is emitted in the first place. CO_2 is not released in a socioeconomic vacuum; it is emitted as the inevitable by-product of combusting coal, long the world's main source of electricity.

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[1] Alternatively, under the IEA's (2011) 450 Policies Scenario (where the use of fossil fuels unrealistically peaks before 2020), China uses coal for only 34 % of its energy demand and 26 % of its electricity in 2035.

[2] The safety of CCS is generally accepted (see IPCC 2005). Shaffer (2010), however, reports on the long-term impact of less than perfect retention of anthropogenic CO_2 stored in deep geologic reservoirs and in the ocean. Dooley (2010) challenges by stating that the central thesis of Shaffer's article is predicated on two "deeply flawed assumptions": (1) the implicit assumption that CCS is the only means to reduce CO_2 emissions and (2) "there is absolutely no geophysical nor geomechanical basis for assuming an exponential decay of CO_2 stored in deep geologic formations as done by Shaffer."

This chapter seeks to contribute by suggesting a balance in the equation—both an assessment of the dangers posed to the atmosphere by CO_2 emissions and the powerful benefits created by the energy usage that results in these emissions. Electricity produced from coal has been, is, and will remain the cornerstone of modern life. Thus, policymakers should appreciate the constant of technological advancement: renewable energy systems will not be competing against fossil fuels as they are now but as they will become. Coal can be increasingly clean.

2 Coal Stimulates Economic Development

Through a series of Five-Year Plans, China has utilized coal-based power generation to catapult itself to the center of the world's economic stage. Since 1990, China has provided electricity access to over 450 million people or almost 1.5 times the population of the USA. No nation has made more progress on the United Nations Millennium Development goals than China. Data gathered from the World Bank (2011) indicate that ~85 % of the global population that has ascended from poverty since 1990 is Chinese. This rapid advance can largely be attributed to improved electricity access.[3] Over the past two decades, China's per capita electricity consumption has surged from 480 to 2,800 kWh (IEA 2011). This is the direct result of more coal-based power, which extended its share of China's power supply from 70 to 80 %. In 2010, China passed the USA as the largest energy consumer in the world, and China could have the largest economy in as little as 15 years.

From 2010 to 2030, the US Department of Agriculture (Shane 2012a) projects that China's total gross domestic product (GDP), in real 2005 US$, will quadruple to $16.4 trillion. Indeed, on a per capita basis, staggering demand growth potential awaits, especially for coal-based electricity. There has been a remarkably stable linear relationship between power consumption and GDP over the decades. In fact, Lacko (1999) observed a near one-to-one ratio in a number of different countries. With Americans (5×) and Europeans (2.5×) using far more electricity, it is no wonder that China cites hypocrisy when resisting the West's calls for reduced energy consumption. China's GDP per capita is only around $3,400, compared to $43,000 for the USA and $29,000 for the European Union (Shane 2012b).

China has been, is, and will continue to be a coal-powered economy. By 2035, the IEA (2011) projects that coal will provide 7,750 TWh of electricity in China, or more power than the USA and European Union together now derive from all fuels combined. To generate this immense amount of electricity, China will construct some 880 GW of new coal-based generation capacity or the equivalent of more than eight times the US world-leading nuclear fleet of 104 units (IEA 2011). Not only will coal-based power increase by 140 % in the next 25 years, but the use of coal in

[3] The link between more electricity usage and human development has been well documented (see Pasternak 2000; Yeager 2007; Clemente 2010).

industry will expand significantly as well. More steel, concrete, and liquid fuels are needed to advance a population of 1.34 billion people into the modern age. Platts (2010) reports that China's coal use could more than double to seven billion tonnes by 2030. This is about as much coal as the entire world consumed in 2011.

The rise of information and communication technology (ICT) and consumer electronics (CE) will continue to have major implications for electricity consumption not only in China but throughout the world. In the 2009 study, *Gadgets and Gigawatts*, the IEA (2009a) noted that by 2030 global electricity used by household ICT and CE equipment could rise to 1,700 TWh, requiring the addition of about 280 GW of generating capacity. Coal will be the primary source of the electricity that powers China's digital transformation, and coal is the foundation of the Internet-based information and technological revolutions occurring in both urban and rural areas. McKinsey & Company (2010) indicate that China is adding six million people to the Internet each month—about the population of Jinan city. By 2015, China will have 770 million users or more people than there are in the whole European Union plus two Japans. In 2005, China had just 100 million Internet users.

Other key building blocks of China's urban future will depend upon coal, like steel and cement. Roughly half of the $586 billion stimulus package installed in 2008 was allocated to railways, highways, airports, and power grids. China is in the midst of the largest and fastest infrastructure build out in world history—and it will necessarily continue for decades (Table 1). China's massive urbanization will require much more coal to produce steel for skyscrapers and other urban accoutrements. By 2025, McKinsey & Company (2009) report that China will have 221 cities with a population in excess of one million people (Europe today has just 35). China will build up to 50,000 skyscrapers before 2030, the equivalent of 10 Manhattans.

Dargay et al. (2007) project that China will have the world's largest vehicle fleet by 2030: 390 million vehicles and an astounding 12-fold jump in a generation. Considering that even small vehicles can contain over 1,200 lb of steel, domestic steel production is set to soar (Automotive News 2007). In turn, this equals more coal since 80 % of China's steel output depends upon coal (Steel Guru 2010). China's steel production even grew by 13 % during the recession year of 2008, and the country now accounts for nearly half of the world's total (EIA 2010). Coal is widely utilized as an energy source in cement manufacturing. PricewaterhouseCoopers (2009) indicates that kilns usually burn coal in the form of powder and consume around 450 g of coal for about 900 g of cement produced.

Coal's unique versatility can yield a wide range of products including coal-to-liquids (CTL), substitute natural gas (SNG), and chemicals. For liquid fuels, both the IEA (2011) and the US Energy Information Administration (EIA 2011a) project that China will be consuming roughly 17 million barrels per day (b/d) in 2030, compared to 9 million b/d in 2010. This incremental increase in demand will need to be met by imports, mostly from the destabilizing Middle East, because maturing basins (e.g., Daqing oilfield) will keep domestic crude oil production flat at around four million b/d. Unconventional liquids like CTL are the only chance that China has to feed its surging oil appetite from the domestic stockpile. China has an overall commitment to coal conversion:

Table 1 The backdrop of China's energy and economic evolution

Indicator	2000	2010	2020	2030
GDP in billions (Real 2005 US$)	$1,417	$3,835	$8,322	$16,371
GDP per capita as a % of world average	17 %	39 %	64 %	98 %
Urban population (millions)	350	600	750	1,000
Vehicle fleet (millions)	20	65	220	390
Coal's share of primary energy supply	64 %	68 %	62 %	60 %

Note: China has 14 % of the world's proven coal reserves, 1 % of the oil, 1.5 % of the gas, and 3 % of the uranium

Sources: Shane (2012a, b), McKinsey & Company (2009), Dargay et al. (2007), International Energy Agency (2011), BP (2011)

- In 2002, Shenhua Group initiated the world's first commercial direct CTL plant in Inner Mongolia. Eventually, the plant will produce about 0.9 million tonnes of oil products and chemicals per year based on the consumption of 3.11 million tonnes of coal (Hydrocarbons-Technology 2011).
- Datang Group has two coal SNG projects in northeastern China. One of the projects is designed to produce four billion Nm3 of SNG each year, which will mainly be transmitted through a pipeline (Asia Chem 2010).
- In 2010, Shenhua Group completed the construction of the world's largest coal-to-olefins plant in Inner Mongolia. The plant is designed to produce nearly 1.6 million tonnes of methanol for ~540,000 tonnes of polyethylene and polypropylene per year (Manufacturing.Net 2010).

3 Improving Coal Efficiency Can Immediately Reduce Demand and Emissions

The development of SC and USC coal-based power plants is an evolutionary advancement towards greater power output per unit generated and higher energy efficiency. Coal-based power plants using SC boilers produce hotter steam to run the turbines, 580 °C compared to around 440 °C in an older (subcritical) plant. This higher temperature makes more efficient use of the energy created by coal's combustion, so there is less consumption and fewer emissions. Energy conversion efficiency of a steam turbine cycle can be improved by increasing the main steam pressure and temperature. As a readily available technology, the efficiency benefits of SC units are particularly relevant. The United Nations (2008) finds that "the capital cost of an SC plant is more or less the same as that of a subcritical plant," and SC plants have lower operating costs due to their higher efficiency. Highly efficient modern coal plants have almost 40 % fewer emissions than the average coal plant currently installed, and if biomass is mixed in with the coal, emissions can be cut even further (IEA 2009b). Overall, a 1 % increase in efficiency reduces by 2 % specific emissions such as CO_2, nitrogen oxides (NO_x), sulfur oxides (SO_x), and particulate matter. The IEA (2010b) reports:

> The overall thermal efficiency of some older, smaller units burning, possibly, poor quality coals can be as low as 30 % [. . .]. New plants, however, with supercritical steam can now achieve overall thermal efficiencies in the 43–45 % range" and "net efficiencies of 45–47 % are achievable with supercritical steam using bituminous coals and currently developed materials.

SC power plants have been in service since the 1950s, but the technology struggled to take off due to problems of reliability, especially from the metallurgical perspective. Today, the single most important factor that determines the use of higher pressure and temperatures is the availability of materials to withstand these conditions. SC units use special materials for the boiler tubes, such as superior-grade steel, and the turbine blades are also of improved design and materials. As more of these materials are being used around the world, the more expensive advanced coal projects could become. Thus, the EIA (2011b) now concludes that, for plants entering service in 2016, SC plants could have 15 % higher capital costs and total system levelized costs per megawatt hour generated than subcritical units. In any event, the principal advantages of SC steam cycles would help compensate:

- Reduced fuel costs and use due to higher plant efficiency
- Significant reduction in CO_2, NO_x, SO_x, and particulate emissions
- Established technology with an availability similar to that of existing subcritical plants
- Plant costs comparable with subcritical technology and less than other clean coal technologies
- Compatible with biomass co-firing and can be more fully integrated with appropriate CO_2 capture technology
- High part-load efficiencies, typically half the drop in efficiency experienced by a subcritical plant

As described by Powell and Morreale (2008), by raising the temperature from 580 °C to 760 °C, USC thermal generation is a clean coal technology that can improve SC efficiency by about 4–46 % and higher. There are several years of experience with these highly efficient plants in service with excellent availability. Advanced 700 °C USC coal plants are now being planned which could constitute a benchmark for at least 46 % efficiency. Beer (2009) reports that if the 45 GW of new coal-based capacity expected to come online in the USA before 2020 are USC units instead of subcritical steam plants, "CO_2 emissions would be about 700 million metric tons (tonnes) less during the lifetime of those plants, even without installing a CO_2 capture system." For China, this equates to ~10 % of total CO_2 emissions (EIA 2011a).

Higher efficiency for coal-based power generation plants is crucial to the long-term solution for curbing CO_2 emissions with CCS because it mitigates the higher cost of CCS application. In fact, more efficient coal plants are a prerequisite for retrofitting with CCS because the capturing, transporting, and storing of a plant's emitted CO_2 lowers its efficiency by absorbing quantities of energy. Because they have the shortest lead times, increased plant efficiencies are particularly essential for large developing countries like China and India. These nations have traditionally used energy less efficiently, and their growing need for coal-based power is a steady drumbeat. Accordingly, a massive build out of SC generating units is taking shape. From 2007 to 2015 alone, China will be quadrupling its supercritical generating capacity to 240 GW (IEA 2009b).

China's 11th Five-Year Plan (2006–2010) was aimed at reducing energy intensity, measured as units of total energy consumed per unit of GDP produced, by 20 %. Now, with the need to import a rising 180 million tonnes of coal per year at high international prices, the National Development and Reform Commission (NDRC) seeks bigger changes within China's power generation sector. China's 12th Five-Year Plan (2011–2015) sets reduction targets for energy intensity (16 %) and carbon intensity (17 %). The use of high cycle efficiency boilers is China's key strategy to lower GHG emissions, while meeting expanding electricity demand with coal—the fuel that has lifted hundreds of millions of Chinese out of poverty (see Clemente and Considine 2009). Since the mid-1990s, each of China's big three manufacturers of steam turbine and boilers—Shanghai, Dongfang, and Harbin—have organized joint venture companies with foreign technology suppliers to develop SC technologies. China's first domestically manufactured SC unit was operationalized in 2004, releasing 15 % less CO_2 than a normal subcritical plant (Sun 2010).

The lower cost of coal compared to natural gas and nuclear energy, not to mention the energy security advantages (China has 14 % of the world's coal but only 1.5 % of the gas and 3 % of the uranium), makes coal the preferred choice for new baseload power generation. There has been an overriding transformation with China introducing some of the largest and most advanced coal-fired units in the world using SC and USC steam conditions and modern SO_x/NO_x and dust control systems. China is also proceeding quickly with GreenGen, a $1 billion centerpiece initiative to accelerate near-zero emissions coal-based electricity with hydrogen production and CCS. More specifically, GreenGen aims to research, develop, and demonstrate a coal-based power generation system with hydrogen production through coal gasification, power generation from a combined cycle gas turbine and fuel cells, and efficient treatment of CO_2. The first phase of the project in Tianjin came online at the end of 2011, and operations are set to begin in 2016.

4 The Large Substituting for Small Program Has Been a Success

China's electricity consumption increased by nearly 6 % in 2009 and 15 % in 2010, to about 4,200 TWh (Cronshaw 2011), and the IEA (2011) expects that demand will double to 8,800 TWh by 2025. Looking forward, China's electricity will be increasingly clean. The LSS program signifies that over 114,000 MW of small and inefficient coal units will be decommissioned and replaced with SC and USC generating capacity (IEA 2009b). Combined with the Energy Conservation Power

Generation (ECPG) scheduling program, LSS is part of China's twin-track approach to ensuring that only modern units get access to the power grid. China's future growth in generation capacity centers on evolving from 300 to 600 MW subcritical boilers to larger and more advanced boilers ranging from 600 to 1,000 MW. Over the next 10 years, new power plants with unit capacity of 600 MW and above will all be required to be supercritical, roughly half of which will be USC.

The key to installing more SC and USC units in China is to develop boiler materials with good high-temperature resistance characteristics based on domestic coal. More specifically, over the short- to midterm, the State Power Corporation of China sees SC pulverized coal (PC) as the best way to adjust the current composition of installed thermal capacity in China. These units have good operation flexibility, normally employing compound sliding pressure operation mode, and can maintain relatively high efficiency at lower load. The 2007 LSS program was expected to decommission about 50 % of China's existing inefficient small units by end 2011, with the ECPG scheduling program forcing the closure of the remainder (IEA 2009b). The NDRC uses policy instruments to prioritize the scheduling of cleaner and larger coal power plants. In order to build a new 600 MW station, 420 MW of old capacity must be closed, and for a 1,000 MW new unit, the amount is 600 MW (IEA 2009b).

The rise in power plant efficiency in China has meant more power, reduced fuel consumption, and a corresponding reduction in emissions per kWh generated. Over 500 small, inefficient thermal generating units, with the combined generating capacity of 14,400 MW were decommissioned in the first year of LSS alone (IEA 2009b). All the capacity of removed small units has been substituted by more efficient and larger units. Large 600 MW SC/USC plants are now coming to dominate. Over 80 % of the new orders are for the 600/1,000 MW SC/USC units (Mao 2009). From 2006 to 2008, the nationwide average coal consumption for power generation dropped from 366 g of coal equivalent (gce)/kWh to 349 gce/kWh and now stands at roughly 330 gce/kWh, suggesting that the national goal of 320 gce/kWh by 2020 will easily be achieved (Mao 2009; IEA 2011). The LSS program saved 39 million tonnes of coal and 54 million tonnes of CO_2 in its first 2 years alone (Mao 2009).

China has represented some 90 % of the global market for advanced coal power generation systems and associated environmental control systems (IEA 2009b). The average efficiency of China's coal-fired power plant fleet should improve from around 30 % in 2005 to above 40 % in 2030. By 2030, subcritical units are expected to account for only 30 % of China's total thermal generation capacity, against over 85 % in 2006 (IEA 2009b). Importantly, China has a rare advantage when it comes to implanting new power generation systems: the State is either the major or sole shareholder of the industrial companies. Reiner and Liang (2009) find evidence of an "endorsement effect" in China's electricity sector, where stakeholders are more likely to believe that a project is a good investment if it is proposed by government authorities, not another entity. This confidence will continue to make China the major world market for advanced coal-fired power plants with high specification emission control systems.

PC combustion is the most mature of the clean coal options. This has led Chinese policymakers to favor the most advanced PC technology: USC plants. USC plants were backed at the outset of the LSS program because their availability made them 20 % cheaper per unit of power produced than integrated gasification combined cycle plants (see Karplus 2007). All four of the 1,000 MW coal-fired USC pressure boilers at Yuhuan had come online by November 2007. New units incorporate high-efficiency dust removal and desulphurization, and Yuhuan Units 1 and 2 are touted as the "world's cleanest, most efficient and most advanced" PC units, with an efficiency rating of 46 % (Chameides 2010). The five largest power generation companies in China now have their own USC PC units.

As a pioneer in efficient boiler technology, Babcock & Wilcox (B&W) announced in September 2010 that B&W Beijing Company will build two 1,000 MW USC coal-fired boilers for a large power plant project in Zhejiang province. The two Spiral Wound Universal Pressure boilers will use one of B&W's most advanced and efficient coal-fired boiler designs. Contract activities for the Zhejiang project are underway, and delivery is scheduled for mid-2012.[4] Emerson Process Management will install its Ovation expert control system at two new 1,000 MW USC coal-fired generating units under construction in China's Anhui province. The Ovation is now being used to automate and control processes and equipment at more than half the 1,000 MW units in China, including a number of USC plants (Emerson Process Management 2010).

5 General Policy Recommendations for China

Under any foreseeable scenario, coal will at least maintain and possibly even expand its role as the cornerstone of China's energy portfolio. The consumption of coal, however, is bringing about a number of environmental challenges. China now emits more CO_2 than any other country in the world. Despite efficiency upgrades and a strategic shift to more low-carbon energy systems, China's total CO_2 emissions could increase by 60 % over the next 25 years (EIA 2011a). In contrast, those of the USA and European countries will remain basically flat. As such, two sets of general policy recommendations are provided:

1. Cleaner coal technologies

   - Recommendation #1: Promote cleaner coal technologies
     For coal to remain an acceptable component in China's energy mix, progress is required in both technical and nontechnical areas. China has been a global

[4] For a more technical analysis on B&W's coal-based power success in China, see Bennett et al. (2010).

leader in the adaptive process of technology transfer but should examine ways to relax barriers to foreign participation in key energy industries. Joint ventures and foreign investment help new technologies diffuse faster on commercial terms. Effective technology transfer comes from the movement of people, not simply the transfer of information.

- Recommendation #2: Develop cleaner coal technologies
  China is a pioneer in the development of clean coal technologies and should work within the international community to increase funding for research and development. More partnerships with the USA and India in particular would help advance only those technologies that are commercially viable. The IEA (2010c) reports that Chinese equipment manufacturers already have the upper hand in supplying advanced boilers, turbines, and generators, delivering their products in less time and 30 % cheaper.
- Recommendation #3: Advance CCS
  CCS is China's primary opportunity to sustainably meet its rising coal needs and gain a larger share in the emerging global low-carbon technology market. Thus, China should (1) build mechanisms to connect public sector financing with private sector interest, (2) clarify CCS safety regulations, (3) define a coherent CCS development strategy, (4) advance national industrial partnerships, and (5) promote more international collaboration (see Friedmann 2008). China has already built two small pilot CCS plants in Beijing and Shanghai.

2. More sustainable coal use

- Recommendation #1: Consider the "Polluter pays principle"
  Permitting should set standards for land restoration and treatment of subsidence damage. A bond system, for instance, common in other coal industries, would help ensure that such remediation is sufficient. Environmental charges on coal mining have been introduced in China, but they need to be more linked to the related levels of pollution—the "polluter pays principle." The Chinese Government needs to guarantee funding and not rely upon the revenues from penalties.
- Recommendation #2: Better safety and more productivity
  Beyond the human loss, coal mining accidents in China hinder productivity and cause economic waste. The resources and capabilities of China's inspectorate should be expanded. Nondiscriminatory mine permitting would promote greater competition by encouraging the participation of the more efficient international coal companies. This would help establish more reliable, safe, and economical mining practices and technologies.
- Recommendation #3: More competitive markets
  In recent years, China's coal industry has struggled with volatile prices, transport bottlenecks, and coal shortages. Market-based energy and resource pricing should be used to balance supply and demand. Fewer subsidies would allow the industry to grow on a more solid commercial footing. The electricity sector especially requires a timetable to incorporate the full costs of power generation into wholesale and retail rates.

6 Concluding Remarks

The success of China's LSS program demonstrates that the development, production, and deployment of advancing mainstream generation technologies is a cost-effective path to meeting rising energy demand while significantly reducing emissions. China's commitment to cleaner coal demonstrates that developing countries are prepared to decrease GHG emissions, without a legally binding quantitative commitment.[5] Going forward, the global scientific and engineering community has now turned its creative gaze to the safe management of CO_2. Dramatically reducing CO_2 emissions is a major challenge but is tractable through continuously evolving technologies like CCS and advanced coal plants. The parallel question is whether the world will deliver on the second promise out of the Copenhagen Accord 2009: eradication of poverty and energy deprivation. The IEA (2010d) projects a "shameful and unacceptable" 14 % progress from 2010 to 2030. In 2010, the IEA projected that 1.2 billion people will still be "living" without electricity in 2030, compared to 1.4 billion in 2010.

To that end, coal predominates in the world's electricity sector for measurable reasons. The widespread physical distribution of coal readily enhances energy security across broad political arenas, capable of buffering supply disruptions. For example, the three largest nations, China, India, and the USA, have 40 % of the population and 50 % of the coal but only 4 % of the oil and 5 % of the gas (BP 2011). By comparison, the Middle East (including Egypt) and Russia have just 6 % of the population but control 62 % of the oil and 65 % of the gas (BP 2011). And not just cheaper, coal's reliability is unmatched: coal constitutes 32 % of the world's generating capacity but actually produces 41 % of power (IEA 2011).

Now, with the Fukushima accident perhaps dealing a death blow to the "nuclear renaissance," and since technical limitations (e.g., intermittency and no large-scale storage option) and high costs will continue to block widespread deployment of wind and solar power, hugely populated developing countries like India and Indonesia will increasingly turn to their substantial coal resources to elevate dangerously low electricity use rates. Advanced coal plants will allow them to use the very same fuel that China has leveraged to lift the living standards of its people closer to those in the West in a more sustainable and affordable manner.

[5] The 1997 Kyoto Protocol sets legally binding limits on GHG emissions for 39 countries, the Annex B countries. The non-Annex I countries—notably China and India—have no specific commitments.

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Jude Clemente is an energy analyst at San Diego State University and Principal at JTC Energy Research Associates, LLC. He holds a BA in Political Science from Penn State University, an MS in Homeland Security from SDSU, and an MBA in Finance from Saint Francis University. He also holds certificates in infrastructure protection and emergency preparedness from the Federal Emergency Management Agency, American Red Cross, and US Department of Homeland Security. Clemente's research specialization is energy security at the national and international levels, and his most recent work has appeared in *Carbon Capture Journal*, *Managing Power*, *Coal Power*, *American Coal*, *Public Utilities Fortnightly*, *Journal of Energy and Development*, and *Electric Light & Power*.

China's New Energy Security: A Swing of the Pendulum

Guy C.K. Leung, Raymond Li, and Maximilian Kuhn

Abstract Purpose The aim of this paper is to understand and investigate the context of energy security in China.
Design/Methodology/Approach The study was conducted by analyzing and synthesizing the domestic and international literature on China's energy security, including government documents.
Findings The findings reveal that Chinese national leaders have overestimated the external threats of energy security challenges and the actual effectiveness of certain external energy security measures, such as acquisition of foreign equity energy assets and establishment of international pipelines. On the other hand, the internal energy security challenges appear to be more visible and evident but have received disproportionally little attention from Chinese energy leaders.
Practical Implications The conclusions call for a swing of the analytical pendulum—a shift from the narrow understanding that paint "energy security" and "security of oil imports" with the same brush to the broader understanding that "energy security" that takes into account both internal and external challenges.
Originality/Value The paper provides a more reasonable theorization of China's energy security.

Keywords China • Energy security • Oil • Coal • Gas • Environment • Pollution • Climate change • Power shortage

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G.C.K. Leung (✉)
School of Environment and Development, University of Manchester, Manchester, UK
e-mail: guyleung@gmail.com

R. Li
School of Accounting and Finance, The Hong Kong Polytechnic University, Hung Hom, Hong Kong

M. Kuhn
Department of War Studies, European Centre for Energy and Resource Security, King's College London, London, UK

W. Leal Filho and V. Voudouris (eds.), *Global Energy Policy and Security*, Lecture Notes in Energy 16, DOI 10.1007/978-1-4471-5286-6_12,

1 Introduction

Asked by George W. Bush what would keep him up at night, President Hu Jintao said that his biggest concern was "creating 25 million new jobs a year" (Yergin 2011). China overtook Japan and became the world's second largest economy in 2010. However, the Beijing regime realizes that it is a sine qua non for China to sustain rapid economic growth and create enough jobs for the graduates and labor coming from their rural homes and villages every year. Failure to achieve so unsettles the already fragile social stability. China is still essentially a developing country: In 2011, it ranked the 101st in terms of the Human Development Index (HDI), falling behind numerous developing countries, such as Azerbaijan (91st), Dominica (81st), Lebanon (71st), Malaysia (61st) and Cuba (51st) (UNDP 2012). Rapid economic development requires uninterrupted supplies of energy.

The urbanization process per se demands a great deal of energy to materialize. China is experiencing rapid urbanization at a scale unseen in world history. Daniel Yergin (2011) describes this phenomenon as "the great build-out of China," which requires gargantuan energy inputs embedded in the processes of mining, making construction material, and powering construction machines. The increased level of urbanization will in turn create higher demand for energy as urban lifestyle is more energy intensive and urban dwellers have higher disposable income for a wider range of energy services. Since its entry to World Trade Organization (WTO), China has become the "workshop of the world" and attracted a deluge of foreign firms to relocate their energy-intensive and highly polluting processes to the country. As a result, China has engaged in a new round of heavy industrialization since 2002, accelerating its energy demand further (Rosen and Houser 2007; Andrews-Speed and Dannreuther 2011). From 2005 to 2010, China's demand for energy grew staggeringly by 72.6 % in only 5 years, and the country has become the world's largest energy consumer—much sooner than the expected year of 2030 by EIA in 2006 (Kong 2011). The international significance of China's energy needs is evident: the country accounted for 61.7 % of the world's energy consumption growth during 2005–2010, 64.9 % of the world's oil consumption growth, and 91.1 % of the world's coal consumption growth (BP 2011). The fact that China's energy demand is large and quickly growing makes the maintenance of energy security a sheer challenging mission. In this book chapter, we will review the context of China's energy security that has shaped the understanding of energy security of the Chinese leaders and explain why they are traditionally obsessed over the external dependence of oil. We will then debunk some myths and misconceptions associated with this traditional perspective and explain why we should advocate a broader energy security strategy that pays proportional attention to the probably more pressing internal issues of energy security, namely, internal interruptions of energy supplies, environmental degradation, and inconsistent energy governance.

2 Theorization of China's Energy Security

The energy economy of China is predominately driven by coal (see Li and Leung 2012), which has constantly accounted for ~70 % of China's primary energy demand during 1996–2010 (Table 1). In 2010, the primary energy consumption of China amounted to 3,249.4 million tons of coal equivalent (Mtce) and coal accounted for 68.0 % while oil accounted for 19.0 %, primary electricity (nuclear and renewable energies) 8.6 %, and natural gas 4.4 %. Since China is relatively abundant with coal resources, it has maintained an unusually high degree of self-sufficiency of energy—at 92 % in 2009 (IEA 2011, p. II.415). Although oil has never been the dominant fuel in consumption, it has largely dominated the Chinese understanding of, and the policies involved in, energy security. There are different ways to formulate the concept of "energy security" in generic terms. Some disaggregate this concept into two dimensions (physical and economic) (Kendell 1998; Gupta 2008), three dimensions (sovereignty, robustness, and resilience) (Cherp and Jewell 2011), or four dimensions (availability, accessibility, affordability, and acceptability) (Kruyt et al. 2009). Some authors try pushing the concept even further. For example, Alhajji (2007) suggests that the concept needs to consider "economic, environmental, social, foreign policy, technical, and security"; von Hippel et al. (2009) posit a decomposition of the concept as "energy supply, economic, technological, environmental, social-cultural, and military security"; Sovacool and Mukherjee (2011) propose that energy security should include five dimensions (availability, affordability, technology development, sustain ability, and regulation), and they break them into 20 components, 320 simple indicators, and 52 complex indicators.

Considering the purpose of this article, proposing our own generic conceptualization of energy security is inappropriate and may be counterproductive. We agree with Cherp and Jewell (2011) and Cherp (forthcoming) that when addressing the energy security challenges of a particular country—in our case, China—analysts should attempt prioritization and contextualization. In other words, we do not believe in the existence of a one-size-fits-all definition of such slippery concept as "energy security." This study loosely follows the definition of Yergin (1988) that energy security is not an endgame but a means to achieve a number of national objectives. The objective of energy security is "to assure adequate, reliable supplies of energy at reasonable prices and in ways that do not jeopardize major national values and objectives" (Yergin 1988, p. 112). Although this definition is not applicable to every country, we find it helpful in the case of China (see Leung 2011). The key domestic concern of the Communist Party of China (CPC) is "promoting China's economic development while maintaining political and social stability" (Sutter 2008, p. 2). The post-Mao China is a noncommunist nation, ruled by a communist party. Hence, unlike democratic regimes, the CPC cannot gain political legitimacy from election or constitutions. To maintain the CPC's political

Table 1 The primary fuel mix of China, 1996–2011

	Total (Mtce)	Coal (%)	Oil (%)	Electricity (%)	Natural gas (%)
1996	1,351.9	73.5	18.7	6.0	1.8
1997	1,359.1	71.4	20.4	6.4	1.8
1998	1,361.8	70.9	20.8	6.5	1.8
1999	1,405.7	70.6	21.5	5.9	2.0
2000	1,455.3	69.2	22.2	6.4	2.2
2001	1,504.1	68.3	21.8	7.5	2.4
2002	1,594.3	68.0	22.3	7.3	2.4
2003	1,837.9	69.8	21.2	6.5	2.5
2004	2,134.6	69.5	21.3	6.7	2.5
2005	2,360.0	70.8	19.8	6.8	2.6
2006	2,586.8	71.1	19.3	6.7	2.9
2007	2,805.1	71.1	18.8	6.8	3.3
2008	2,914.5	70.3	18.3	7.7	3.7
2009	3,066.5	70.4	17.9	7.8	3.9
2010	3,249.4	68.0	19.0	8.6	4.4
2011	3,480.0	–	–	–	–

Sources: National Bureau of Statistics (2011, 2012b)

legitimacy as a ruler, it needs to meet people's economic and nationalistic expectations: economic development, rise in quality of living, territorial integrity, as well as China's rise to super power status (Leung 2011). As political scientist Breslin (2005, p. 749) similarly argued, it is "an unwritten social contract between the party and the people whereby the people do not compete with the party for political power as long as the party looks after their economic fortunes." China's energy security traditionally focuses largely on oil security partly because oil is a strategic commodity that is globally sought-after. Given that the transport and military sectors lack economic substitutes for oil products, interrupted supplies of oil mean that the logistical system of the Chinese economy and society will derail, and the military power of the People's Liberation Army (PLA) will be degraded. These results, in turn, will compromise China's economic and military power that underpin the above four pillars of major national values and objectives (See Downs (2006) for an outstanding analysis on this issue).

3 Reconsidering External Dependence

Another reason why the Chinese leaders are particularly concerned about oil security is the fact that China lost her 30-year energy independence in 1993 when the country became a net importer of oil (Leung et al. 2011; Li and Leung 2011). Once a large supplier of crude oil in the 1980s, China's import dependency of oil now stands at 57.5 %, up from 7.6 % in 1993 (Leung 2010; China Daily 2012). Comparatively, the import dependency of natural gas and coal were merely 11.6 %

and 4.5 %, respectively, in 2010 (National Bureau of Statistics 2012a). In other words, in terms of external dependence levels, natural gas and coal currently remain a secondary concern to China's energy security. Although China will have to import increasingly more natural gas on a net basis (unless it finds a way to tap into its unconventional gas resources at the scale comparable to the USA), Beijing has successfully landed a number of long-term contracts, and the supplies secured are likely enough to fill the supply–demand gap in the near future (Higashi 2009). China currently aims to raise the share of natural gas in primary energy mix to 10 % by 2020, reportedly requiring 250 billion cubic meters (Bcm) of natural gas supply to realize the plan. Fortunately, by the end of 2011, the three national oil companies (NOCs) including CNPC, Sinopec, and CNOOC have already procured 37.6 Bcm per year of LNG supply over long-term contracts and 30–40 Bcm per year of pipeline gas from Turkmenistan. Chinese gas outputs amounted to 96.8 Bcm in 2010, meaning that the current levels of domestic gas supplies, plus the amount of gas imports having been secured, already fulfill ~70 % of the 250 Bcm requirement (Economist Intelligence Unit 2011, pp. 51–52, 55). China should thus have enough time to negotiate additional imports of gas with supply countries.

Chinese national leaders embrace the oil-centric view of energy security also because they are powerless in reversing the steadily rising trend of the country's oil dependency, given that the horizon on expansion in domestic production is limited whereas the room for oil demand growth is mammoth. On one hand, the complex geology and limited endowment of crude oil in China together have limited the efforts to expand output. There are now 22 large- and medium-sized oil bases in operation that are mostly located in eastern China. The Daqing, Shengli, and Liaohe oilfields together account for almost 90 % of the total output in eastern China, but these oilfields have been tapped heavily for several decades, and production is becoming increasingly difficult and costly—in fact, Shengli's output peaked in 1991, Liaohe's in 1995, and Daqing's in 1997. During 1996–2009, oil output in eastern China dropped from 108.2 to 88.6 million tons, offsetting the production growth in the rest of China, which increased from 49.1 to 99.9 million tons (Leung et al. 2011). On the other hand, China's oil market, already the world's second largest, has tremendous room for growth. Take road transport sector as an example: the sector has been the largest contributor to China's oil demand for the last two decades. Although China overtook the USA to possess the biggest stock of vehicles in 2010, the 2010 passenger car stock in China was only 45.7 per 1,000 persons, meaning that China's passenger car stock on a per capita basis in 2010 was equivalent to that of the USA in 1917, which stood at 45.8 per 1,000 persons (Leung et al. 2012). Kennedy (2010, 2011) holds that if present trends continue, China's import dependency may reach 80 % by 2030 and that even if China succeeds in rapidly deploying electric vehicles after 2015, it will still depend on imports to meet two-thirds of its oil demand in 2030. Yergin (2011) predicts that China's oil demand growth will slow, not stop, only when China's urbanization is largely completed sometime in the 2030s and 2040s. This implies that the Chinese government is hopeless when it comes to reducing China's oil import dependency [for in-depth analyses on China's oil sector, see also Leung (2009, 2010), Leung et al. (2011, 2012), Li and Leung (2011), Troner (2011), and Ma et al. (2012)].

According to a recent survey conducted by Bambawale and Sovacool (2011), among a range of energy security goals, "security of supply of fossil fuels" ranks as the most important in the mindsets of Chinese energy stakeholders and decision-makers. Unlike in the 1990s, the Chinese leaders no longer believe in the possibility of energy independence because limiting oil use will throttle economic growth and because China possesses the world's largest foreign currency reserves for any imports it needs. At the turn of the century, Chinese energy security measures have become much more noticeable outside its territory. Like many powerful energy-importing countries, including the USA [considering its continuing commitment to the Saudi Arabian monarchy, for example; see Klare (2004) and Newmyer (2009)], China does not fully trust the operation of the energy markets. The fact that most of China's oil imports are transported through sea lines of communication (SLOCs) that are seemingly controlled by foreign navies (most notably that of the US) fosters a sense of insecurity and a fear that these supplies can be threatened in the context of a conflict with the West, such as a Sino-American armed conflict over Taiwan (Dannreuther 2011). To hedge the actual and perceived risks, the country has adopted a range of energy security measures, some of which are seen by many Western observers as "nonmarket" or "mercantilist." Financially backed by state policy banks and politically supported by Beijing's energy diplomacy, the Chinese national oil companies (NOCs) have been avowedly carrying out what is known as their "going-out" strategy (Downs 2011; Kong 2011). This strategy includes acquiring foreign equity oil assets. By the first quarter of 2010, the Chinese NOCs have been operating in the upstream sector of 31 countries and have equity production in 20 countries (IEA 2011). The state and the NOCs also collaborate to establish international oil and gas pipelines. Currently, three international oil pipelines (Kazakhstan–China, Burma–China, and Russia–China) and two international gas pipelines (Turkmenistan–China and Burma–China) are in operation. These pipelines have two major functions. First, they help "lock in" and "open up" energy supplies—except the Burma–China oil pipeline as no indigenously produced oil will go through this pipeline. Second, they are perceived to able to circumvent the potential naval blockades by the West and the "Malacca Dilemma" (Zhang 2011; Andrews-speed and Dannreuther 2011). As Burma is an oil-barren country, the Burma–China oil pipeline is built solely to reduce China's reliance on the Malacca Strait, through which more than 80 % of Chinese oil imports sail.

However, we need to reconsider the actual effectiveness of these energy security measures. The Chinese leaders have overestimated the risk of externally induced supply disruptions of energy:

1. The so-called Malacca Dilemma seems overblown. When faced with nonmilitary disruptions on the Strait of Malacca, such as pirate attacks or crashes, oil tankers sailing towards China can always be diverted through alternative passages, e.g., the Sunda and Lombok straits at an additional cost of as little as one or two dollars per barrel. Considering that pipelines are far more expensive

than tankers in terms of what must be spent to move a given volume of oil over a given distance, the additional transport cost of taking alternative passages is negligible (Erickson and Collins 2010);
2. The USA appears not willing to impose any military oil blockade on China, because it harms China and allies alike, including Japan and South Korea, and also because it risks "mutually assured destruction" of the Chinese and American economies considering the close integration between the two economies.

On the other hand, Leung (2011) finds that the Chinese leaders have overestimated the effectiveness of these external energy security measures:

1. Equity oil cannot protect Chinese consumers from a price shock, although it is true that the purchase of equity interests in oil fields overseas enables the investors to predict exactly how much oil it will receive and at what cost over the life of the field.
2. If oil produced overseas by Chinese companies is shipped home, it will likely face the same transportation risks as oil purchased by a Chinese company on the spot market.
3. Most of China's equity oil produced is not shipped home. Whether China's NOCs sell their foreign equity oil to Chinese consumers or on the international market seems to be largely profit driven.
4. Even if a larger proportion of China's foreign equity oil is shipped back home, import dependency of oil (an indicator of energy security adopted by Chinese top leaders) will increase anyway. In this sense, import of equity oil and import of "normal" oil are no different—both can be blockaded militarily.
5. When small-scale armed conflicts occur between the USA and China, the US military will order complete blockades. We can assume that all possible channels, including the Malacca, Sunda and Lombok straits, and, of course, the seas in Myanmar will be completely sealed off. No oil tankers can reach Sittwe or Gwadar as they will be a concentrated target set, highly vulnerable to blockades or even precision strikes.
6. When all-out wars occur between the USA and China, some, if not all, of China's pipelines can be sabotaged or bombed, as pipelines are fixed and long objects, making them harder to defend geographically. In the scenario of all-out war between the USA and China, Kazakhstan or Russia may be asked by the USA to shut down their pipelines. As Burma is regarded by the USA as "pariah state," the American voters may not oppose the idea to bombard the Sittwe port and sabotage the Burma–China oil and gas pipelines.
7. Burma is politically unstable in the first place—see the 2009 Kokang incident, for example. In recent years, Washington has proclaimed its high-profile return to the Asia Pacific region by expanding its strategic deployments (political scientists call it the "offshore balancing" strategy) and been actively counterbalancing the influence of Beijing to Myanmar.
8. Unlike pipelines, tankers can often route around any points of disruptions—flexibility enhances security, not reduces it.

The above analysis does not suggest that China should not continue and expand her external energy security measures at all. Building pipelines diversifies routes and means of energy imports into China and, in some cases, opens up new sources of energy supplies to China. The "going-out" strategy of the NOCs improves China's knowledge of the nuanced networks of the global energy market, her access to technological know-how and the less codified tricks of the trade, and her global corporate networks. All these are pivotal in better preparing the Chinese political and corporate energy leaders for managing, and responding to, the risks of China's energy security. We advocate, however, that the internal dimension of China's energy security is at least equally remarkable but is seriously underplayed or neglected by policy-makers and analysts, especially those with military or international relations background.

4 Thinking Internally

As early as 2003, Chen Xinhua (2003, p. 5), a former program manager for China at the IEA, was discontented with the fact that increasingly more scholars and experts pay attention only to the scramble for the increasingly scarce energy resources among energy-consuming countries and stated clearly that "energy security must first be dealt with domestically." The erratic 2008 Chinese winter storms that affected large portions of Southern and Central China with unusual heavy snows, ice and cold temperatures caused severe power shortages in 19 provinces and widespread coal transportation disruption. Zha Daojiong (2008, p. 80), a distinguished energy security specialist in China, thereafter publicly reprimanded his colleagues for worrying too much about "wars, blockades, and embargoes" and pay too little attention to the numerous "domestic, nonwar/non-adversarial challenges" facing China's energy system.

Similarly, in November and December 2009, the cold weather hit both Central and Northern China again. Although the disruption to energy supplies was less serious than in 2008, a number of regions had to cut or reduce power and gas supplies to factories and offices, while the coal stocks at power plants dropped to as low as 8 days of requirement, down from the usual 15 days. Some power plants had to shut down due to a lack of coal (Andrews-speed 2010). This denotes the "resilience" side of China's internal energy insecurity—the capacity to keep energy supplies flowing despite the occurrence of a sudden and unexpected accident or keep the duration of any interruptions sufficiently short in order not to seriously affect the socioeconomic activities (Cherp and Jewell 2011). The factors lowering the resilience of China's power system include the deliverability problem of coal. After the restructuring of the coal industry in the 1990s (by shutting down the small-scale township and village coal mines), China's coal output have become remarkably concentrated in the northern Central provinces of Shanxi, Shaanxi, and Inner Mongolia (Leung et al. 2011), which are distant to the demand centers. As a result, coal delivery overloads the rail transportation system, leaving little room for boosting coal supplies in emergency.

If the above unpredictable, transient supply disruption of electricity is considered as "shock," the long-term, expectable shortage of electricity can be regarded as "stress," which has been remarkably pronounced roughly since 2003. As aforementioned, China has undergone a new round of heavy industrialization since 2003, jacking up the country's energy intensity for the first time in decades. The unexpected surge in power demand caused the power shortages throughout the country in 2004, leading to a sudden jump in diesel sales when factories employed their own diesel generators. This single unexpected event significantly sent the oil prices soaring, for few analysts had foreseen the subtle causality between China's power sector and the global oil market (Mathrani 2006; Leung 2010). Since then China has invested heavily in expanding the power generation capacity and the power shortage problem was largely solved, but the problem has come back and become worse in recent years.

As part of the economic stimulus package, the Chinese government has subsidized the residents living in small towns and rural areas to buy electric appliances. Since the start of 2009, these residents have bought more than 100 million air conditioners, washing machines, refrigerators, and other appliances, artificially creating more demand for electricity (Bradsher 2011). The later occurrence of power shortages partly discerns that China's social policy sometimes contradicts her electricity policy.

Amidst the rebound in the global economy, China's industrial demand for electricity has surged correspondently. In 2011, China suffered its worst power shortage in years, with the industrial centers of Guangdong and Zhejiang among 20 provinces and municipalities rationing electricity as economic growth outpaces power supply growth. For example, in Dongguan, an important production base in Guangdong, electricity had been cut off one in every 4 days in summer, forcing many businesses to use their backup power generators, increasing production costs (Chung 2011). The China Electricity Council (CEC) stated that China's power shortage will peak at 30 million kW in 2011 and brownouts afflicted 24 provincial grids during the peak (Wang 2012). The CEC warned that some parts of the country will experience severe blackouts in the summer of 2012 as the result of an electricity shortage of 30–40 million kW (Mu 2012).

The power shortages in China are caused partly by insufficient capacity and partly by the fact that power plants do not have the incentive supply electricity at full capacity. Since the onset of the deregulation reform in the coal market in 1993, China's coal price has been on a steady increase. However, the electricity price is still regulated strictly by the central government as a social stability measure (Zhao et al. 2012). This so-called market coal versus planned electricity (*shichang mei miandui jihua dian*) situation has led to the well-known coal-power conflict, and many power suppliers face financial losses when they supply power (Rui et al. 2010). Reportedly, China's top five thermal power companies had combined losses of 13.7 billion RMB for their thermal generation businesses (Chung 2011). This is called the "institutional shortage" of power supplies, which seems more common in Central and Western China, according to Dave Dai, a Hong Kong-based analyst at Daiwa Securities Capital Markets (Bloomberg 2012).

This "institutional shortage" is also evident in the case of oil. Li and Leung (2011) find that although China's crude oil prices have been linked to international markets, its domestic prices for oil products, such as diesel, are still largely regulated. Oil refineries pay high prices for crude oil and then sell the refined products at lower prices to end users (Andrews-speed 2008). When China sees a sudden surge in demand for, say, diesel and this cannot translate to higher prices automatically, wholesalers and refiners, state-owned or private, will choose to reduce their output, export their oil products, or store them betting on future price hikes (Hook 2010).

In addition to the internal interruptions of energy supplies, we argue that environmental degradation should be regarded as a critical aspect of China's energy insecurity. As we have argued, energy security should not be taken as a final goal but a crucial means to China's four pillars of national goals. If an energy security policy is effective in ensuring uninterrupted energy supplies for these national goals but is ineffective in avoiding the outcome of unconstrained energy consumption from compromising these national goal, this energy security policy defeats its purpose. Given that China has become the world's largest emitter of greenhouse gases, China is expected more fervently by the international community to contribute to the mitigation of climate change, and China agreed in Copenhagen to reduce the 2005 level carbon intensity of its economy by 40–45 % by 2020 (Moore 2009). This strategic plan calls for the decarbonization of the structure of energy consumption by replacing coal with renewable energies and natural gas and an increase in overall energy efficiency. It is in the greatest interest of China to pursue a low-carbon energy economy, and it has little to do with ethicality or the perceived threat of climate change.

Two strategic reasons hold that environmental degradation should be seen as an integral part of China's energy security policy. First, the Beijing regime also fears that emitting carbon irresponsibly may give the Western community an excuse to levy an export carbon tax on Chinese exports or to force the RMB to appreciate through the threat of carbon tax, unsettling China's economic well-being and compromising the four national goals. Second, subnational air pollution, largely due to extensive and intensive coal use, destabilizes the society and hence contradicts the national goals. According to the official figures, the Chinese government received 600,000 complaints about environmental degradation in 2004 and recorded 50,000 environment-related protests and riots in 2005 (Riley and Cai 2009). No newer official data have been published ever since, but on 20 December 2011, a major riot erupted in Haimen, a city of about 120,000 that is part of the major Pacific port of Shantou (in Guangdong province). Residents complained that existing coal-fired plants have already polluted the air, spurred a rise in cases of cancer, and damaged the local fishing industry. 30,000 angry citizens occupied a public highway and surrounded government offices in an attempt to block the project of a coal-fired power plant, claiming it is damaging their health (Simpson 2011). The energy security survey of Bambawale and Sovacool (2011) provides a strong support to this argument. They were surprised to find that local environmental factors, including "minimizing air pollution" came out as the most important dimension after security of energy supply in China. They commented, "since we did not anticipate this, it was an eye opener that Chinese priorities are clearly aligned towards local environmental issues" (p. 1956).

5 Concluding Remarks

This paper has deconstructed the traditional conceptualization of China's energy security and proposed the broader understanding of this concept that incorporates the internal dimension, including institutional energy shortages and inconsistent energy governance. It has also pointed out that energy security is a means but is not an end. Under this concept, the environmental degradation caused by energy production and consumption should be considered by China's energy security theorists as long as the environmental degradation contradicts the national goals of energy security. This paper also shows that Chinese energy leaders have overstated the threat of externally induced disruptions of energy supplies and the effectiveness of external energy security measures, such as acquisitions of foreign equity energy reserves and building international pipelines. At the same time, they have underplayed the significance of the internal energy security challenges, failing to recognize the fact that China has not experienced any disruptions of oil imports over the last decade but it has recurrently suffered from internal disruptions in oil, coal, and power supplies and distribution. The findings of this research call for a swing of the analytical pendulum—a shift from the narrow understanding that paint "energy security" and "security of oil imports" with the same brush to a broader understanding that "energy security" that takes into account both internal and external challenges.

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Guy C.K. Leung is a Doctoral Researcher, School of Environment and Development, University of Manchester, UK. He is also a Lecturer in the Master of Global Political Economy Programme at the Chinese University of Hong Kong. He can be reached at guyleung@gmail.com.

Raymond Li is a Teaching Fellow at the School of Accounting and Finance at the Hong Kong Polytechnic University. He also serves in the editorial board of the Journal of Emerging Trends in Economics and Management Sciences and the International Research Journal of Applied Finance. He can be reached at Ray.Li@polyu.edu.hk.

Maximilian Kuhn is the Chief Editor of the EUCERS Strategy Paper and a Visiting Research Associate with the European Centre for Energy and Resource Security (EUCERS) at the Department of War Studies, King's College London. He is also a Research Associate at the Center for Energy, Marine Transportation and Public Policy (CEMTPP), School of International Affairs (SIPA) at Columbia University, New York, where he coordinates the EURASIA GAS 2030 Scenario Project. He can be reached at maximilian.kuhn@kcl.ac.uk.

The Energy Efficiency Policy Initiatives and Energy Security: Experiences from India

Sivani Dhanalekshmy

Abstract Purpose This paper presents significant developments of energy efficiency sector in India from 1960 to present date. It also tries to reveal the importance of energy efficiency policies for energy security. The study also highlighted the major challenges faced during the implementation and effective compliance of these efficiency measures.
Methodology The study was conducted by desktop analysis using a wide variety of sources such as published books, research papers, regulations, polices, and roadmaps on energy in global and Indian context.
Findings The study shows that energy efficiency initiatives are integral part of the India's energy planning strategies. As its different domestic conventional sources of commercial energy sources are minimized with the increase of usage and the Government of India realized to adopt an energy efficiency strategy to go on a sustainable path of energy development.
Limitations In this paper an attempt has been made to analyze the changing importance of energy efficiency policy initiatives of India from 1960 to present date. This work can be considered as a stepping stone and further research is needed.
Originality/Value The paper provides a range of information about energy efficiency scenario in India. The methodology and results reported in this paper may be used for anyone who interesting to research in Indian energy sector.

Keywords Energy efficiency • Energy security • Energy policy • Sustainable energy

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S. Dhanalekshmy (✉)
Department of Applied Economics, Kannur University, Thalassery Campus, Palayad, Kerala, India 670661
e-mail: lekshmy2006@gmail.com

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1 Introduction

Energy is the life blood of the society. The prosperity of the community, industry, and economy depends up on safe, secure, sustainable, and affordable energy (European Union 2011). Access to energy is essential to addressing the problems that cause poverty. A life lived without energy is a life lived in poverty (World Coal Association 2012). Poverty reduction means increased energy consumption. Though the energy needs of people living in poverty are small, and small amounts of energy can make significant difference in their lives, millions of men, women, and children in the developing world do continue to live absolute poverty because they do not have access to modern energy services (Andrew Scott 2010).

According to International Energy Association's World Energy Outlook (2011), there are 1.3 billion people across the globe without access to electricity and 2.7 billion people who do not have clean cooking facilities. This problem is mainly spread across the developing world, considering sub-Saharan Africa and developing Asia which together account for 95 % of people in energy poverty.

While world energy demand has undoubtedly grown significantly over time, most of the low-income developing countries with high import dependency show a high vulnerability to energy price volatility (BP 2011). The world primary energy consumption pattern shows that this will increase in the coming years. Figure 1 shows the primary energy consumption of the world in 2011.

From 2000 to 2010 India's primary energy consumption increased at a CAGR of 5.9 %, while global consumption rose at a CAGR of 2.5 %. As a result, India transitioned from being the world's seventh largest energy consumer in 2000 to fourth largest within a decade. However India's per capita energy consumption is one of the lowest in the world (Earnst and Young 2012). The global average of per capita consumption is 1,747 kg of oil equivalent (kgoe), while India's per capita consumption is merely 447 kgoe (BP 2011). Over the next few years, the high growth in GDP is likely to further increase energy consumption in India. According to the International Energy Agency, the country's total primary energy demand is expected to increase to 897 million tons of oil equivalent by 2015, increasing at a CAGR of 3.7 % during the period 2009–2025 (IEA 2011). India's growing primary energy consumption is shown in Fig. 2 given below.

India's economic transformation after the early 1990s has put energy at the center of its economic agenda (Bastia 2006). The present and coming generations have a tremendous task to creating and implementing a road map for a reliable, affordable, and sustainable energy for all end users. The concept of "energy security" can be traced to the eve of World War I when the First Lord of Admiralty Winston Churchill made a historic decision to shift the power source of naval ships of the Great Britain from coal to oil (Yergin 2006). Energy security refers to a resilient energy system (Brown et al. 2003). Energy security essentially implies ensuring uninterrupted supplies of energy to support economic and commercial activities necessary for the sustained growth of the economy. The relevance for this concept for India emanates from the increasing imbalance between the demand for

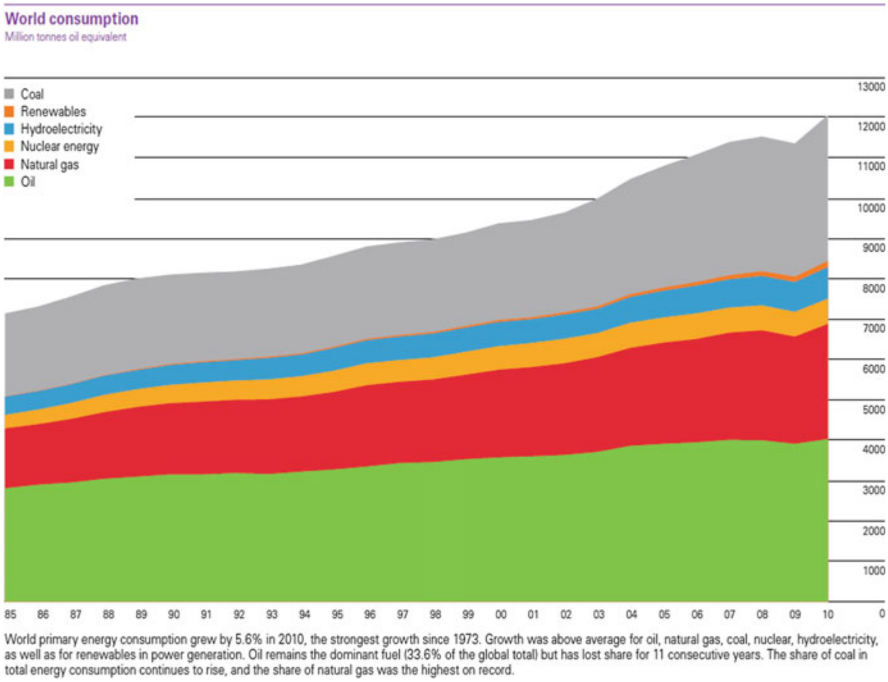

Fig. 1 World primary energy consumption. *Source*: BP Statstical Review 2011

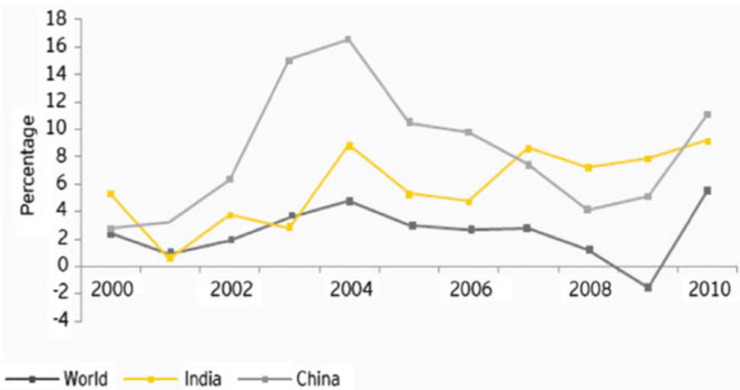

Fig. 2 Rising primary energy consumption of India (%y-o-growth). *Source*: BP statistical Review of World Energy 2011

energy and its supply from indigenous sources, implying thereby the growth import dependence for essential requirements of the nation (Singh 2010). With a growing GDP rate of 8 %, India is moving parallel to China in terms of development but the energy consumption is catching up as well. Today we have identified a myriad of energy sources from fossil fuel to nuclear energy. But our demands on energy due to changes in our lifestyles have also increased. According to IEA figures, the global demand on energy would increase by 60 % by 2030. In order to enhance energy security, it is necessary to consider policies which are reducing risks from both the supply and demand side. For this purpose, the governments of developing countries are advised to diversify their resources of imported energy, while seeking to reduce a reliance on imported energy (especially oil) over the long term. While considering on the demand side, policies aimed at increasing energy efficiency are often the easiest and lowest cost-effective method to achieve greater energy security (GNSED 2010). Therefore, after summing up all the energy issues, energy efficiency has been identified as the only tool to overcome the energy challenges facing the world today.

2 Background

The 1973 oil embargo raised the oil prices worldwide, but it was the developing countries which were the main victims of oil price hike. According to a World Bank study, the oil import bill for the developing countries in 1974 rose to around US$45 billion (Willrich 1975). In the twenty-first century, changes in energy supply or demand in one region will have repercussions across the globe (Foquet 2008). So the efforts in energy conservation or energy efficiency taken by a nation will attribute the global energy security. The World Summit on Sustainable Development (WSSD) held in Johannesburg, South Africa, in 2002 high lightened the importance of the energy efficiency and access to sustainable energy as key element to sustainable development (IIEC 2004). Energy efficiency can serve as a stepping stone for ensuring green growth, economic efficiency, and sustainable development (UN 2011).

Energy conservation and energy efficiency are related but separate concepts. Energy conservation is achieved when growth of energy consumption is reduced, measured in physical terms. Energy efficiency may be defined as a practice of judicious use of energy with an aim to reduce its economic cost and environmental impact. It has been in practice ever since after the first oil shock in 1973; now it has assumed even more importance because of being the most cost-effective and reliable means of mitigating the global climate change (Dey 2007).

The four primary energy sources are coal, oil, gas, and nuclear energy, and the energy efficiency was considered as fifth fuel (Don Hedley 1986). At present the energy efficiency became the first one and the world governments exploit energy efficiency as their energy resource of first choice because it is the least expensive and most readily scalable option to support sustainable economic growth, enhance national security, and reduce further damage to the climate system (ICLEI 2007).

The energy efficiency is a fundamental element in progress towards sustainable energy future. The concept of energy efficiency can be applied in energy extraction, transportation, conversion as well as in consumption. As global energy demand

Table 1 Key reasons for advocating energy efficiency

Market failures
Payback gap—consumers face higher interest rate than producers
• Differences of prices from marginal cost—with franchised monopolies or regulatory oversight, prices rarely reflect marginal cost
• Risk sheltering of the utility—monopoly franchise or regulatory oversight shields utility from risk
• Rate of return regulation—leads to an incentive to over invest
• Externalities—externalities are not seen by market actors
• Lack of information—consumers does not choose EE technologies because of lack of knowledge
• High transaction costs—consumers miss opportunities because of high transaction costs
• Disconnected decision makers are tenant/landlord relationships—consumers may not be able to influence EE decisions. This occurs, such as for instance, when one party, the landlord, pays for the equipment while the other party, the tenant, pays the energy bill
Other reasons
• Ensuring adequate energy supply
• Maintaining consumer price stability
• Promoting greater equity with respect to energy cost burdens

Source: Adapted from Pacuadan and Guzman (2002) in Reddy et al. (2009)

continues to grow to find the needs and aspirations of the population across the globe, actions to increase energy efficiency will be essential (ICC 2007). Many developing countries have also implemented major efficiency drives. Energy efficiency is a means to conserve natural resources, reduces environmental degradation, and not least to save money (Reddy et al. 2009). It is true that energy efficiency helps to reduce greenhouse gas (GHG) emissions that it is an essential part of an effective strategy to climate change. It is estimated that, by using the most advanced technologies, a CO_2 reduction of about 50 % is possible until the year 2050 (Martinot and Mac Doom 2000). Energy efficiency is a gold mine for CO_2 reduction and should not be overlooked in aiming for the Kyoto Protocol and beyond. Pacuadan and Guzman (2002) pointed out the key reasons for advocating energy efficiency which can be fulfills multiple objectives and they are compiled in the Table 1.

Energy efficiency improvements have multiple advantages, such as the efficient utilization of natural resources, reduction in air pollution levels, and lower spending by the consumer on energy-related expenditure. Investments in energy efficiency result in long-term benefits which are reduced energy consumption, local environmental enhancement, and overall economic development (Reddy et al. 2009). The short-term and long-term benefits are given in Table 2.

There are certain barriers or obstacles present while implementing energy efficiency technologies which are lack of information, transaction, institutional, and regulatory issues that make investment. The major key barriers that were identified by the International Energy Association are given in Table 3.

Table 2 Positive aspects of energy efficiency

Short-term benefits	Long-term benefits
Reduces load, peak demand, and energy use	Less oil wells, refineries, forests, land, water etc.
Reduces market prices for all consumers	Less subject to security risks and interruptions
Often less costly and more cost effective	Creates jobs and improves the economy
Less subject to market and fuel price volatility	Less subject to market and fuel price volatility
No transportation and distribution costs	Improve economic development
Short gestation periods	Less transport (fuels to the energy-generating places)
Fuel is saved	Less health impacts
Plantations are saved	Reduced environmental impacts
	(a) Local pollutants
	(b) Global pollutants
	(c) Water use
Reduces local pollutants	Increases energy security
Improved quality of service	

Source: Reddy et al. (2009)

Table 3 Barriers to energy efficiency

Barrier	Examples
Market	Market organization and price distortions that prevent customers from appraising the true value of energy efficiency
	The principal agent problem, in which the investor does not leap the rewards of improved efficiency (the classic case being landlord–tenant situation)
	Transactions costs (project development costs are high, relative to potential energy savings)
Financial	Lack of understanding of EE investments or to perceived risk in the part of financial institutions
Information and awareness	Lack of sufficient information and understanding in the part of consumers to make rational consumption and investment decisions
Regulatory and institutional	Energy tariffs that discourage EE investment (such as declining block prices)
	Incentive structures that encourage energy providers to sell energy rather than invest in cost-effective energy efficiency
	Institutional bias towards supply–side investments
Technical	Lack of affordable EE technologies suitable to local conditions
	Insufficient local capacities for identifying, developing, implementing, and maintaining EE investments

Source: IEA (2010)

3 Energy Efficiency Policies

Traditionally, economic development has been closely connected to the adequacy of energy. Countries pursuing economic growth are expected to resort to increasing levels of energy use. Achieving these levels of energy production and utilization through present technologies is not only difficult and expensive but also environmentally unsustainable. Various studies indicate that increased energy efficiency can bridge the gap between growing demand and reduced supply without affecting adversely the quality of service (Golove and Eto 1996; Reddy and Balachandra 2003; Reddy et al. 2009). According to IEA's World Energy Outlook, effective policy commitment to energy efficiency is necessary, which is still lacking in many developing countries. Without this policy commitment, international efforts to help and assist developing countries will not be able to fully succeed (Janssen 2010). Energy security is one of the main targets of energy policy (Winzer 2011).

Energy efficiency policies usually consist of instruments of governmental intervention into the energy market. These instruments aim to overcome barriers to investment in energy efficiency improvements. The role of governments in influencing energy markets has changed dramatically over the last 2,000 years, and historically, governments of agrarian and rural economies focused only marginally on modern forms of energy. Governments had other priorities (Jupp 2006). The transition away from biomass fuels that depended on land for production towards fossil fuels gradually led to an increased involvement of the governments in energy markets. The nineteenth and twentieth centuries saw the formation of a large number of large energy supply companies, first of coal and then oil (Fouquet 2009). Sustainable energy policies fell into four major categories such as climate change, energy efficiency, renewable energy, and transportations as shown in Fig. 3.

Actions undertaken in each category can be broadly classified into policy- and process-type initiatives. Policy-type initiatives are generally designated at the country level and comprise country strategies and national plans or programs targeting specific sectors or areas of the economy. Process-type initiatives comprise the actual tools used to apply the policy in practice. Other programs focus mostly on technologies promoting energy efficiency and cleaner, more energy-efficient ways of production. Another popular policy initiative is encouraging voluntary agreements by industry. Several countries have country strategies, national policies, or legislation in place to guide energy efficiency policy, devise strategies, and set targets and ways to monitor performance (IIEC 2004). Here in this paper made an attempt to analyze the changing pattern of energy efficiency policy initiatives of India from 1960 to till date and its contribution to the global energy security in a nutshell.

4 A Brief History of Energy Efficiency Initiatives in India

The Indian Electricity Act, 1910 provided the basic framework for electricity supply in India. The period immediately after independence saw the introduction of many new policies, legislation, and programs aimed at progress and development in India. Electricity was one of the sectors which received attention during this period. The primary concern was the supply of electricity, and also oil and coal, to

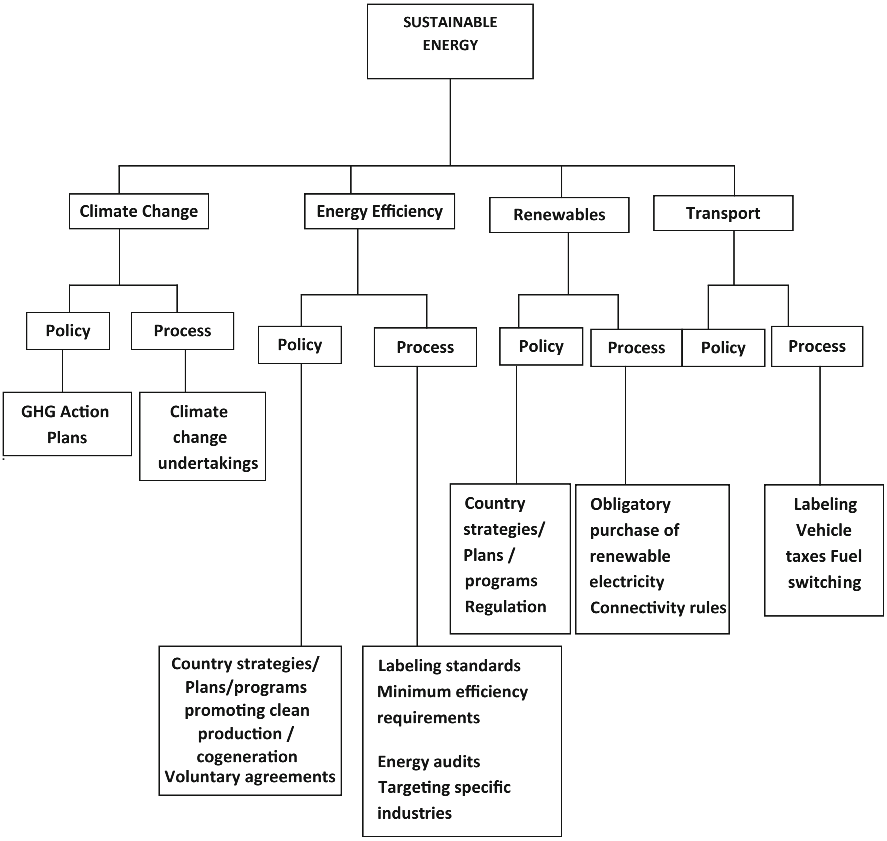

Fig. 3 Flow chart of effective and popular policy. *Source*: IIEC 2004

support growth; conservation of energy was not a matter of priority during the first 15–20 years after independence. The Planning Commission was set up in March 1950 and charged with the responsibility of assessing of all resources in the country, augmenting deficient resources, formulating plans for the most effective and balanced utilization of resources, and determining priorities. The first Five Year Plan (1951–1956) allocated 27 % of the budget outlay towards irrigation and power; multi-purpose river valley projects were given importance. The second and third Five Year Plans (1956–1961 and 1961–1966) gave impetus to interconnection between regional grids, allowing the grids of different states to be connected together. The third plan, for the first time, referred to increased efficiencies in large thermal boilers by using high temperatures and pressures. It also acknowledges that the overall efficiency of thermal stations had been very low, around 20 % until 1960, but improvements were expected in the future due to the operation of larger units (Vasudevan et al. 2011).

Integrated energy planning was recognized as an essential element of development planning in India since independence but with very little focus on Demand Side Management (DSM). The Energy Survey of India Committee (ESIC) was established in 1963 (GOI 1965) to study the demand and supply of energy on a national, regional, and sectoral basis. The study was to provide the government with a framework for energy development planning until 1981, with specific focus on rural energy requirements. The ESIC estimated energy demands for different growth scenarios and made recommendations for investments and pricing of different forms of energy.

The fourth Five Year Plan (1969–1974) for the first time decoupled power and irrigation and considered power as a separate area for development. Installed capacity increased to 14,290 MW at the end of 1969, from about 1,710 MW in 1950.

Although the power sector began with 40 % ownership of installed capacity by the public sector, a national push towards increasing public sector dominance in the power sector resulted in state electricity bodies (SEBs) owning 80 % of installed capacity by 1970. By the end of the 1960s, the government realized the need for understanding the supply–demand balances over the next two decades in order to plan for the energy requirements of the country. The Fuel Policy Committee was appointed by the Government of India in 1970 to prepare an outline of the national fuel policy for the next 15 years (GOI 1974). A comprehensive final report was submitted in 1974. It emphasized the necessity of substitution of oil by coal and that higher efficiency in electricity generation and transmission with special attention to hydel power developments. It also provided an outline for the energy policy of the country and suggested the setting up of an Energy Board to ensure the integration of the energy plan with the national plan.

The 1973 world oil crisis forced the Fuel Policy Committee to consider the implications of the crisis on the Indian economy. In the light of this development, the committee made a number of important recommendations on energy policy including several suggestions on substitution of oil by coal and electricity and on energy conservation in general. The committee adopted economic forecasting techniques and end-use analysis in arriving at sectoral energy demand estimates. However, the major thrust of this study, which was finalized in 1974, was more on supply side of energy than on sectoral demand analysis and demand management. With continued economic growth being of primary interest, the government aimed at promoting and enforcing a culture of energy conservation at all levels so that it became a permanent discipline at consumption points as well. After the first "oil shock" (1973), the government of India realized the need for conservation of energy and a "Petroleum Conservation Action Group" was formed in 1974 (Vasudevan et al. 2011).

The Working Group on Energy Policy (WGEP) was another expert group constituted by the Government of India in 1977. The WGEP was required to outline the national energy policy for the next 5, 10, and 15 years (GOI 1979). The report of WGEP was finalized in 1979. The WGEP made detailed projections of the demand for both commercial and noncommercial forms of energy up to the end of the century and suggested a number of corrective policy measures to manage the energy demand. The Reference Level Forecast (RLF) and Optimum Level Forecast (OLF) made by the working group highlighted the crucial issues of energy planning relevant to energy conservation and inter-fuel substitution. The methodology adopted by the WGEP was more or less similar to the one adopted by its preceding expert groups. The sectoral demand estimates in this report were, however, based on a more detailed analysis of the end-user requirements of energy. The recommendations of WGEP provided a broad framework for energy sector planning in the sixth Five Year Plan (Ramachandra 2009).

The Working Group on Energy Policy constituted by the Planning Commission in 1977 and submitted its report in 1979. The working group has analyzed the trends in the past energy consumption, reviewed the energy resources of the country, and estimated the future energy requirements (GOI 1979). The group has made a number of recommendations to future energy requirements in line with supply possibilities. The major thrust of these policy prescriptions was towards:

1. Curbing oil consumption to the minimum possible level
2. Increasing the efficiency of utilization of energy
3. Reducing overall energy demand by reducing intensity of energy consumption
4. Increased reliance on renewable energy sources, mostly hydropower

In the wake of the oil crisis and in recognition of the importance of energy conservation, the Petroleum Conservation Action Group (PCAG) was established in 1976 with initiative from NPC, IOC, and DGTD, which then evolved into the Petroleum Conservation Research Association (PCRA) in 1978, under the aegis of the Ministry of Petroleum and Natural Gas, to make oil conservation a national movement. They aimed to do this by creating awareness about the importance, methods, and benefits of conserving petroleum products and by promoting research and development in industry, transport, agriculture, and domestic consumers. They are especially on fuel efficient technologies by providing training and technical assistance for better economy and increased efficiency in the use of energy and also by promoting the substitution of petroleum products by alternative sources of energy.

An Inter-Ministerial Working Group on Energy Conservation (IMWG) was constituted in 1981 to develop policies to achieve energy savings targets, which submitted its report in 1984 and it stated that "Energy conservation requires lesser energy inputs for the same level of economic growth. In other words, an increase in energy productivity is the hallmark of energy conservation. Energy conservation also implies the substitution of costly imported energy by cheap energy; the harnessing of non-conventional energy resources to supplement conventional resources etc. In the hierarchy of importance, substitution of oil by coal occupies the major importance and challenge" (GOI 1984). The group proposed the creation of an apex body to initiate, coordinate, and monitor the progress and implementation of various energy conservation measures in India.

It was the sixth plan (1980–1985) that it was necessary to reduce dependence on energy imports. However, the plan noted that a country cannot be said to be dependent on other countries as long as it is able to pay for these imports and called for an all-out effort to accelerate growth of exports, and an *Advisory Board on Energy (ABE)* was set up in March 1983 (Ramachandra 1999). In addition to several important recommendations on the technical, financial, and institutional aspects of energy, ABE also made detailed projections of energy demand in different regions till 2004 under assumptions of different macroeconomic scenarios. These estimates were made based on both end-use and regression methods. Unlike the predecessor working group that provided policy guidelines for energy sector planning, owing to the complexity of the investment choices available in energy and energy-related sectors, ABE was set up to evaluate various options together with reference to the costs of energy resources involved. This was to provide a more precise indication of the optimum energy strategy to be adopted by the government. The seventh Planning Commission took up a long-term energy modeling to analyze the supply options available in coal, oil, natural gas, and electricity with reference to the economic resource costs involved (GOI 1983).

Up until the beginning of the 1990s, the Indian economy was protectionist in nature and largely closed to the outside world. A large public sector, a host of nationalized institutions, centrally designed policies and state intervention in markets characterized the economy. The economic crisis of 1991 forced the then government to adopt a policy of reforms including deregulation, privatization, and opening up the country to foreign investment. These reforms included the energy sector. Despite all the activities described earlier, there was no legislation on the conservation and efficiency activities. In 1994, the Ministry of Power constituted a working group of representatives from various ministries to formulate legislation on energy conservation. In 1997, it was decided to propose an enactment for energy conservation. A cabinet note for this proposal was approved in 1997, and a one-man committee was set up to review the proposed Energy Conservation Bill. The ninth plan (1997–2002) recognized the need to conserve natural resources and the need to encourage use of renewable sources of energy like the sun and wind. It states, “It is important that conservation of natural resources receives adequate priority, especially from the environmental angle. The danger of further deterioration in the quality of air and water is not unreal. Therefore, it is essential that these resources are used with utmost care so that growth is sustainable.” The plan also gave cognizance to the need for an appropriate technology base to tackle the issue of natural resource conservation. The 1990s also saw the beginning of some innovative initiatives targeting energy conservation (GOI 1997).

The Five year plans of India have already been realized the significance of the energy efficiency and conservation. The eleventh Five Year Plan has also emphasized the implementation and rectification of programs for agricultural pump sets for energy efficiency in the agricultural sector. The Working Group on Energy Conservation has recommended a comprehensive scheme for the Twelfth Five Year Plan period. This includes awareness programs, trainings, development, research, energy audit, and energy efficiency measures in various sectors providing subsidies to implementing agencies and covering other aspects as well (GOI 2011).

The first Oil Conservation Week (OCW) was organized in 1991, and its continued success led to its extension to the Oil Conservation Fortnight (OCF) from 1997; during this period, awareness and educational programs and various sectoral activities are undertaken. The government declared 14 December as the National Energy Conservation Day and the National Energy Conservation Awards were instituted to recognize organizations contributing to energy conservation in various sectors. (In 2010, awards were given away in 32 sectors.)

5 Latest Policies and Institutions of Energy Efficiency

1. India Hydrocarbon Vision: 2025

   Oil and natural gas play a vital role in the economic growth of the country. Thus, it is necessary to have a long-term policy for the hydrocarbon sector, which would facilitate meeting the country's future energy needs. The India Hydrocarbon Vision: 2025 lays down the framework, which would guide the policies relating the sector for the 25 years that it was declared in 2000 with the following objectives:

   (a) To assure energy security by achieving self-reliance through increased indigenous production and investment in equity oil abroad
   (b) To enhance the quality of life by progressively improving product standards to ensure a cleaner and greener India
   (c) To develop the hydrocarbon sector as a globally competitive industry which could be benchmarked against the best in the world through technology upgradation and capacity building in all facets of industry
   (d) To ensure oil security for the country keeping in view strategic and defense considerations (India Hydrocarbon Vision: 2025 Document, 2000)

2. The Energy Conservation Act 2001

   In February 2000, the Energy Conservation Bill was introduced in Parliament and The Energy Conservation Act (EC Act) was published in the Gazette of India in October 2011 (and effective from 1 March 2002) and is known as the Energy Conservation Act 2001. In 2002, the Energy Management Centre was reinstituted as the *Bureau of Energy Efficiency (BEE)*. The key objectives of the Act are:

   - To provide a policy framework and direction to the national energy conservation activities
   - To coordinate policies and programs on efficient use of energy with the stakeholders
   - To establish systems and procedures to verify, measure, and monitor energy efficiency improvements
   - To leverage multilateral, bilateral, and private sector support to implement the Act

- To demonstrate energy-efficient delivery systems through public–private partnerships

  The Energy Conservation Act lays down clear action plans and envisages the establishment of a specific organization to convert these plans into reality through various regulatory and promotional interventions. The thrust areas identified for the implementation of the Act are

  (a) Indian Industry Program for Energy Conservation
  (b) Demand Side Management
  (c) Standards and Labeling Program for notified equipment and appliances
  (d) Energy Efficiency in Buildings and Establishments
  (e) Energy Conservation Building Codes
  (f) Professional Certification and Accreditation
  (g) Manuals and Codes
  (h) Energy Efficiency Policy Research Program
  (i) School Education
  (j) Delivery Mechanisms for Energy Efficiency Services

  The Bureau of Energy Efficiency has a mission to institutionalize energy efficiency, to set up a delivery mechanism for energy efficiency services, and to provide leadership to implement a nationwide energy efficiency program, with a thrust on self-regulation and market principles and with the primary objective of reducing energy intensity of the Indian economy (The Energy Conservation Act 2001)

3. The Electricity Act 2003

   The Electricity Act 2003 was enacted to harmonize and rationalize provisions of existing laws and to reform legislation by promoting efficient and environmentally benign policies. The Act mandates efficiency in various forms in generation, transmission, and distribution. Under the provisions of Section 3(1) of the Act, the Central Government brought out the National Electricity Policy for the development of the country's power system based on optimal utilization of resources. The policy emphasizes higher efficiency levels of generating plants, stringent measures against electricity theft, energy conservation measures, and boosting renewable and nonconventional energy sources. The Act recognized the requirement of introducing newer concepts like power trading, open access, Appellate Tribunal, etc. and also emphasized special provision for rural areas (The Electricity Act 2003)
4. Integrated Energy Policy

   The Integrated Energy Policy aims to bridge the prevailing gap in the demand and supply of energy in short-, medium-, and long-term perspective. Recognizing the role of both private and public sector participation in meeting the energy needs of the country, the policy strikes a right balance by stating that "wherever possible energy market should be competitive. However, competition alone has been shown to have its limitation in a number of areas of the energy sector and independent regulation becomes even more critical in such instances." The approach of Integrated Energy Policy is summarized below

- Till market matures in independent regulation across the energy streams is a necessity
- Pricing a resource allocation to be determined by market forces under an effective and credible regulatory oversight
- Transparent and targeted subsidies
- Improved efficiencies across the chain
- Policies that reflect externalities of energy consumption
- Incentives/disincentives to regulate market and consumer behavior
- Management reforms to foster accountability and incentives for efficiency

The broad vision behind the Energy Policy is to reliably meet the demand for energy services of all sectors at competitive prices. The policy ensures India's energy security that at its broadest level and in primarily about ensuring the continuous availability of commercial energy at competitive prices to support its economic growth and meet the lifeline energy needs of its households with safe, clean, and convenient forms of energy even if that entails directed subsidies. Meeting this policy vision India pursues all available fuel options and forms of energy, both conventional and nonconventional. The policy also emphasizes to seek to expand its energy resource base and seek new and emerging energy sources and consider very important that to pursue technologies that maximize energy efficiency, demand side management, and conservation (GOI 2006).

Along with electricity demand, India's oil requirement is also growing rapidly. Today, India consumes about 3–6 million barrels of oil per day. The nation's crude oil imports are projected to reach five million barrels per day in 2020, which is more than 60 % of Saudi Arabian oil production currently. Power generation, industrial fuel, transport, fertilizers, and petro-chemicals firms are some of the major consumers of petroleum products. The government has initiated various steps to promote conservation of petroleum products in the transport, industrial, agriculture, and domestic sectors. Adoption of measures and practices which are conducive to increase fuel efficiency and training programs in the transport sector is one of them. Modernization of boilers, furnaces, and other oil-operated equipment with efficient ones and promotion of fuel-efficient practices and equipment in the industrial sector and standardization of fuel-efficient irrigation pump sets and rectification of existing pump sets to make them more energy efficient in the agricultural sector are also adopted by the government. Development and promotion of the use of fuel-efficient equipment and appliances like kerosene and LPG stoves in the household sector are other initiatives on the side of government.

The Working Group for the eleventh Plan (2007–2012) suggested an outlay of about USD 1.4 billion for energy conservation measures, but this is minuscule in relation to the budget for other elements of the power sector. One of the objectives of the eleventh plan is to reduce the energy intensity per unit of greenhouse gas (GHG) by 20 % from the period 2007–2008 to 2016–2017. India's objectives for GHG emission reduction were formally addressed when the Government of India launched the National Action Plan for Climate Change (NAPCC) in mid-2010. The NAPCC relies on eight missions where the National Mission for Enhanced Energy Efficiency (NMEEE) is a critical one. NMEEE aims to boost the programs under the EC Act through four major initiatives:

(a) Perform, Achieve and Trade (PAT) scheme, designed as a market-based mechanism to enhance efficiency in DCs (energy-intensive industries and facilities as specified by BEE) by setting goals, reducing energy intensity, and allowing those who exceed goals to receive energy permits that can be traded with other DCs
(b) Market Transformation on Energy (MTEE), which envisages an active shift to energy-efficient appliances and machinery in designated sectors through innovative measures
(c) Financing mechanisms to help finance Demand Side Management (DSM) programs
(d) Enhancing of energy efficiency in power plants

Since the enactment of the Energy Conservation Act 2001, the decade saw various policy initiatives for mobilizing public and private enterprises towards EE. The BEE was formed, under the Ministry of Power, as a vehicle for deploying the recommendations of the Energy Conservation Act. The BEE is also the legal entity for executing the initiatives under NMEEE and engages in public–private partnership in implementing various EE programs under it. The EE policy endorsements through the Electricity Act 2003 and NMEEE reinforce BEE's role as the central agency for developing and establishing systems and procedures necessary for achieving India's overarching energy efficiency goals. Since India is a quasi-federal polity, the planning process in the energy sector at the national level is very complex, and the national plan is an amalgam of central and state plans. The institutional structure of the energy efficiency sector in India is given in Fig. 4.

6 Schemes for Promoting Energy Efficiency in India

The conventional sources of energy such as thermal, hydro, and nuclear are major sources of generation of electricity in India. Conventional sources of energy are valuable because their formation takes millions of years whether it is oil or coal. Moreover, the conventional sources of energy are exhaustible. Energy prices may rise in the long run to reflect the relative scarcity and high cost of exploration and extraction. Hence, all initiation has to be taken to optimal use of the available resources so that they can continue for a long duration. Energy efficiency improvements not only reduce the energy consumed per unit products and services made available but also improve energy security of the country to ensure sustained availability of energy resources at affordable price. In order to promote the efficient use of energy and its conservation, the Ministry of Power through the Bureau of Energy Efficiency initiated a number of schemes which are as follows:

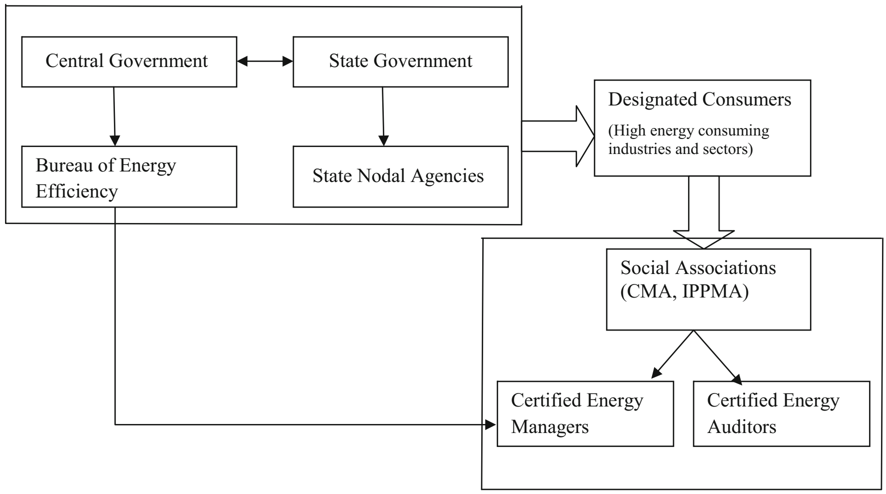

Fig. 4 Illustration of the institutional framework of the energy efficiency sector in India. *Source*: Mercados 2010

1. The *"Bachat Lamp Yojana"* aims at the large scale replacement of incandescent bulbs in households by CFLs. It seeks to provide CFLs to households at the price similar to that of incandescent bulbs and plans to utilize the Clean Development Mechanism (CDM) of the Kyoto Protocol to recover the cost differential between the market price of the CFLs and the price at which they are sold to households.
2. *Standards and labeling* is a scheme for energy efficiency labeling of an equipment under clause (a–d) of section 14 of the Energy Conservation Act, 2001 by the Government of India which has powers to:

   (a) Direct display of labels on specified appliances or equipment (14.d)
   (b) Enforce minimum efficiency standards by prohibiting manufacture, sale, and import of products not meeting the minimum standards (14.c)
   The standards and labeling program for end-use appliances and equipment provides for self-certification by the manufacturers based on the standards issued by BEE, STAR rating, ranging from 1 to 5 in the increasing order of energy efficiency. The scheme has been developed in collaboration with all the stakeholders and aims at providing information on energy performance so that consumers can make informed decisions while purchasing appliances.

3. *The Energy Conservation Building Code (ECBC)* was launched by the Government of India on 27 May 2007. The ECBC sets minimum energy standards for new commercial buildings having a connected load of 100 kw or contract demand of 120 KVA in terms of the amended EC Act, 2001. The ECBC defines norms of energy performance and takes into consideration the climatic regions of the country where the building is located. Energy Conservation Building

Code (ECBC) addresses the five climatic zones of the country (hot and dry, warm and humid, composite, temperate, and cold).

4. The objective of the *Agricultural and Municipal DSM* scheme is to create appropriate framework for market-based interventions in agricultural pumping sector by facilitating a policy environment to promote public–private partnership (PPP) to implement projects.
5. *State Designated Agencies (SDAs)* are statutory bodies set up by states to implement energy conservation measures at state level. SDAs are expected to play three major roles namely:
   - As a development agency
   - As a facilitator
   - As a regulator/enforcing body
     The main emphasis of the scheme is to build capacity necessary to enable them to discharge regulatory, facilitative, and enforcement functions under the Act, given that the institutional capacity is limited—both in terms of human and infrastructure resources.
6. Large number of *small and medium enterprises (SMEs)* like foundries, brass, textiles, refectories, brick, ceramics, glass, utensils, rice mills, and dairy units are said to have large potential for energy savings. Many of these units are in clusters located in various states of the countries. BEE has initiate diagnostic studies in 25 clusters to prepare cluster-specific energy efficiency manuals covering specific energy consumption norms, energy-efficient process and technologies, best practices, case studies etc. These studies would provide information on technology status, best operating practices, gaps in skills and knowledge, energy conservation opportunities, energy saving potential, etc., for each of the subsector in SMEs.
7. *Contribution to State Energy Conservation Fund (SECF)* is a statutory requirement under section 16 of the Energy Conservation Act 2001 and is one of the key elements of the Energy Conservation Action Plan (ECAP). The effort will be to create a pool of financially sustainable activities for SDAs (like training programs, fee for services, etc.) which can augment the fund. The Ministry of Power has approved the scheme "Contribution to SECF by the Bureau of Energy Efficiency" for which Rs.70.00 crores was sanctioned and to be disbursed during the last three financial years of the XI Five Year Plan, i.e., 2009–2010, 2010–2011, and 2011–2012 (GOI 2011).

6.1 Key Challenges in Securing Energy Efficiency Targets in India

India is a developing economy with a large agricultural base and a growing industrial infrastructure. The country is facing the critical challenge of meeting a rapidly increasing demand for energy. India's economy is projected to grow 7–8 %

over the next two decades and in its wake will be substantially increased in demand for oil to fuel land, sea, and air transportation (Sambamurti 1984; Bastia 2006). At present energy efficiency has been stated as a policy objective of most of the governments and it has become an integral part of the India's energy planning strategies. As in the case of any developing country, there are so many challenges to attain the energy efficiency targets to India. According to the Bureau of Energy Efficiency of India, nation's energy efficiency is the fifth lowest in the world. But there is a room for substantial energy savings. The industrial sector consumes about half of the total commercial energy available in India and 70 % of this by energy-intensive sectors like fertilizers, aluminum, textiles, cement and iron steel, and paper and 15–25 % of this is avoidable. One of the major challenges with regard to energy efficiency is that the energy-efficient technologies are often come at increased cost as to compare to their traditional counterparts. This leads the consumers to abstain from or unable to pay the premium for efficiency despite its long-term benefits. The distortion of the price included in subsidized pricing of energy (including that of electricity), particularly for agriculture. Low prices provide fewer incentives for people to regulate and/or reduce consumption. This also adds to the financial burden on the country's exchequer. The recent decontrol of petrol is, therefore, a step in the right direction. While lack of information was a barrier in the early years, the government's effective use of mass media, including the print and electronic media, has somewhat widened the reach of the energy efficiency message. However, these changes have benefited urban and semi-urban regions much more than others. Rural areas struggle with energy conservation issues in the agrarian sectors because of inefficient practices partially driven by an unreliable power supply. Nontechnical losses like energy theft have continued to be a concern. While small conservation projects in homes require little or no financial investment, such initiatives in the industrial, building, and other sectors usually require some investment due to the scale and nature of the related activities. There is a range of financial programs available at the central and state levels. While it is premature to comment on their effectiveness, there is a concern that information on these are not easily available to those who can benefit from it. Improving energy efficiency requires a comprehensive, long-term approach. There is a need for stable policy framework to encourage investment in the manufacturing and distribution of energy-efficient products and for consumers to develop the necessary confidence to deploy such products.

7 Conclusion

Conventional energy resources use which are based on oil, coal, and natural gas are undoubtedly catalyzing the economic progress, but it is too potentially damaging to the environment and human life and a key challenge to climate change. The potential of renewable energy sources is vast as they can meet many times the world's energy demand. The renewable energy resources such as biomass, wind, solar, hydropower, and geothermal energy can provide sustainable energy for the world. It is now imperative to consider that future energy scenario is primarily based on renewable energy and other energy-efficient technologies. The task of meeting the growing energy demand of India's development process is enormous. India is probably the only country fully fledged ministry dedicated to the energy production from renewable energy sources. India is emerging as a growing market for solar, wind, and hydroelectric power. India ranks fifth in the global wind energy production. The significant developments of the energy sector in the last five decades shows that India is running along with her counterparts of the world for realizing energy efficiency. A huge financial investment especially for energy efficiency initiatives is the need of the hour. India is moving ahead and in forefront of all developing nations. The CDM activities are also important to sustain the energy security. The new era of energy efficiency initiatives of India will play a vital role in the nation's target to be energy secured. The study shows that India is on a path of sustainable development along with all other developing nations, and these efforts not only contribute to the energy security of India but to a large extent to all set to play a pivotal role in global energy security also.

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Dhanalekshmy Sivani is a research scholar in development studies at the Department of Applied Economics, Thalassery Campus, Kannur University, Palayad. P.O., Thalassery, Kerala, India. Pin. 670661. She can be contacted at lekshmy2006@gmail.com.

Impact of Shocks on Australian Coal Mining

Svetlana Maslyuk and Dinusha Dharmaratna

Abstract Purpose and Methodology Coal has enormous importance for the Australian economy: Australia is one of the largest exporters of black coal in the world and the significant share of electricity generation in Australia is produced using brown coal. This study investigates whether shocks to Australian black and brown coal mining sector have permanent or temporary effects using Chow (1960) and Quandt–Andrews (Andrews, Econometrica 61(4):821–856, 1993; Andrews and Ploberger, Econometrica 62(6):1383–1414, 1994) tests for structural breaks and Zivot and Andrews (J Bus Econ Stat 10(3):251–270, 1992) and Clemente–Montanes–Reyes (Econ Lett 59(2):175–182, 1998) unit root tests with one and two structural breaks.
Findings Results indicate that impact of shocks on export of black coal is likely to be temporary and permanent for black and brown coal production.
Practical Implications This study has important implications for industrial and energy conservation policies and firm level strategies as well as for modeling and forecasting purposes. For instance, if shocks to coal production are persistent, this is likely to be transmitted to other sectors of the economy and the key macroeconomic variables such as employment levels.
Originality/Value This study found that proper modeling specifications for Australian black and brown coal production and black coal exports should include structural breaks. In addition, since exports of coal were found to be stationary, shocks to exports will result in a temporary deviation from the long-term growth

S. Maslyuk (✉)
Department of Economics, School of Business and Economics, Monash University, Northways Road, Churchill, VIC 3842, Australia
e-mail: svetlana.maslyuk@monash.edu

D. Dharmaratna
Department of Economics, Monash University, Wellington Road, Clayton, VIC 3800, Australia
e-mail: dinusha.dharmaratna@monash.edu

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trajectory. Stationarity of exports also implies that it is possible to forecast future export levels based on the past values, which will be of no use for brown and black coal production.

Keywords Coal • Australia • Structural breaks • Unit root tests with structural breaks

1 Introduction

Australia is ranked as one of the world's leading mining nations. It is rich in both black and brown coal and has approximately 6 and 25 %, respectively, of the world's total coal reserves. According to the Australian Bureau of Statistics (ABS 2007), total Australian estimated bituminous coal resources account to about 39.2 gigatonnes. Coal mining is the second largest exporting industry in Australia (ABARES 2011), and in terms of international coal exports, Australia ranks sixth behind the USA, Russia, China, India, and South Africa (ABS 2010). This chapter focuses on Australian black and brown coal mining because of its significant contribution to the Australian and world economy.

The purpose of this chapter is to study the impact of shocks on Australian black and brown coal mining sector using Chow (1960) and Quandt–Andrews (Andrews 1993; Andrews and Ploberger 1994) tests for structural breaks and unit root tests with structural breaks. Structural change in time-series data can be loosely defined as sudden changes in government policies (introduction of a new tax) and man-made or natural disasters (civil war in Libya or Fukushima nuclear disaster) occurring at either the national or international scale. In this chapter we consider annual physical volumes of black and brown coal production and exports of black coal over the period 1966–2009. Unit root in production or export values would imply that shocks to coal production or exports will have permanent effects. This has important implications for the effectiveness of government policies (since mining is one of the top industries generating revenue) and companies, which have to operate in the uncertain economic conditions. If coal production has a unit root, according to Smyth and Inder (2004), government-initiated structural reform is likely to be of limited value, because the impact of such reform on the long-run growth path will be offset by other shocks. If coal output is instead trend stationary, this implies that only large shocks such as government policies aimed at changing the market fundamentals will have at least semipermanent effects on the growth path of the industry (Li 2000).

The contribution of this chapter is as follows. The majority of studies on Australian black and brown coal did not allow for the possible existence of structural breaks when testing for the unit root and relied on conventional unit root tests such as augmented Dickey–Fuller (ADF) (Dickey and Fuller 1981) and Phillips–Perron (1988). These conventional tests are very sensitive to the choice of lag in the model as well as the data frequency. In addition, these tests are typically criticized for their low power in rejecting the alternative hypothesis of stationarity in small samples (Pindyck 1999). Therefore, it is possible that findings of the early research could be misleading because structural breaks were not taken into account. Typically the problem of low power of these conventional tests can be approached by considering larger samples of data, by allowing for structural breaks or by applying panel-data tests. In this chapter, we use 44 years of coal data and allow for structural breaks when testing for stationarity.

Foreshadowing the main results, structural breaks are found to be significant for coal series, which indicates that proper unit root specification for the coal series should include structural breaks. Brown and black coal series were found to be nonstationary variables, while for coal exports unit root null hypothesis was rejected in favor of stationary behavior.

This chapter is structured as follows. Section 2 provides an overview of coal mining industry in Australia. Section 3 discusses the shocks which could have impacted the mining industry. Section 4 provides a brief literature overview. Sections 5 and 6 discuss data and methodology, respectively. Section 7 provides results and Sect. 8 concludes the chapter by discussing the policy implications.

2 Coal Mining Industry Overview

Coal was first discovered in Australia in the New South Wales (NSW) in 1791, and since then production of coal has occurred in all states except Northern Territory. Queensland is now the largest producer of coal in Australia. Black coal mining is heavily concentrated in the Sydney Basin in NSW and the Bowen Basin in Queensland, and the majority of brown coal reserves are located in Victoria. Together NSW and Queensland produce over 96 % of all Australian black coal, while Victorian Latrobe Valley mines of Yallourn, Hazelwood, and Loy Yang produce about 98 % of Australia's brown coal (ABS 2010). Table 1 shows Australian 2010 annual coal production by state and the type of coal.

Coal is produced from two types of mines: surface (open cut) and underground. Following Mudd (2009), approximately 70 % of all coal produced in Australia is produced by open-cut mining, while coal more than 70 m below is mined using underground methods. In Australia, anthracite, bituminous, and subbituminous types of coal are classified as black coal. Black coal can be defined as a solid rock formed from brown coal after greater heat and pressure have been applied (ABS 2010). Raw coal refers to coal produced at the mine site before washing and other methods of beneficiation. After washing and beneficiation, coal is then classified as the saleable black coal. Black coal that is used mainly for generating electricity in power stations is called as thermal (steaming) coal. Metallurgical (coking) coal is black coal that is suitable for making coke which is used in the production of pig iron. Metallurgical coal is usually rare and attracts a higher price than thermal coal. As compared to black coal, brown coal (lignite) has a lower

Table 1 Australian annual coal production by state and the type of coal

	Queensland	NSW	Victoria	Tasmania	South Australia	Western Australia
Coal type	Bituminous, subbituminous (black coal)	Bituminous, subbituminous (black coal)	Lignite (brown coal)	Bituminous (black coal)	Subbituminous (black coal)	Subbituminous (black coal)
2010 production	253.7 Mt	185.7 Mt	68.5 Mt	0.6 Mt	3.8 Mt	6.6 Mt

Source: Table obtained from Mudd (2009) energy and higher ash and water content. Therefore, the greenhouse gas emissions related to conversion of brown coal to energy are very high. Brown coal is usually unsuitable for export and is used in Australia for electricity generation in power stations located in close proximity to the mine (power stations in Victoria).

The black and brown coal mining industry at present contributes 8.4 % to the Australian GDP, and its share in Australian GDP has increased by more than 3 % over the past decade (ABS 2010). While brown coal is used solely for domestic purposes, black coal is one of the most valued Australian export commodities. The share of black coal in Australian exports has been steadily rising, and in 2009 Australia was the largest coal exporter (23 % of total Australian exports) in the world supplying 28 % of the world total (ABS 2010). Exports of black coal comprised of metallurgical coal and thermal coal, and among the other minerals, black coal (metallurgical and thermal) was the largest export earner (ABS 2010).

Overall Australian coal production (for domestic consumption and exports) has been increasing at an average annual rate of 3.3 % between 2000 and 2008. The domestic consumption of coal increased at an annual rate of 1.6 % over the same period. About 75 % of Australia's electricity is generated using black and brown coal. In addition to electricity generation, black coal is also used in production of coke, which is important for the making of iron and steel, cement, and food processing. Brown coal is also mined to produce soil conditioners, fertilizers, briquettes for industrial and domestic use and low ash and low sulfur char products.

At present, the overall coal industry employs approximately 135,000 people Australia wide (ABS 2010). Employment in the black coal industry peaked in 1986 and declined until 1997 due to closures of underground mines in the Australian state of NSW. Currently, black coal employee earnings are the highest when compared to average employee earnings in other industries. There are approximately 1,800 employees who are directly employed in the brown coal industry with around 1,000 contractors. The significant proportion of revenue generation and employment is concentrated in Gippsland Basin in Victoria. Australian coal industry includes a range of businesses in addition to coal mining including significant processing, transport, and support services related to the industry. Australian coal mines have diverse ownership structures including government, public-listed companies, and private firms. In addition, state governments are given wide control over planning, development, extraction, and sale of coal resources (Lucarelli 2011).

2.1 Exports

The value of Australia's coal exports over time has risen from $8.4 billion in 1999 to $39.4 billion in 2009, a rise of over 370 %. Both thermal and metallurgical coals have exhibited very strong growth over this time period. Thermal coal exports have risen from $3.2 billion to $14.4 billion (350 %), while metallurgical coal exports rose from $5.1 billion to $24.7 billion (380 %) (ABARES and Geoscience Australia

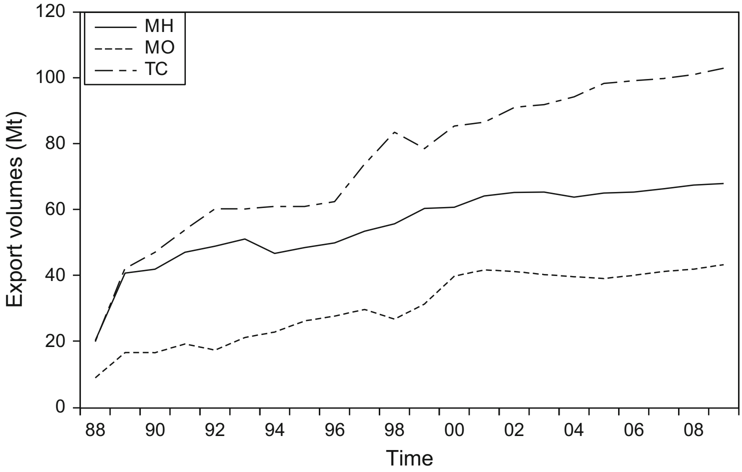

Fig. 1 Black coal exports: metallurgical and thermal coal. Note: MH, metallurgical coal, high quality; MO, metallurgical coal, other quality; TC, thermal coal

2010). Coal that is being exported is mainly used in the world electricity market and world steel market.

Thermal coal volumes have displayed steady growth from 1999 to 2009 (increased by 76.7 %). Export volumes and price of thermal coal moved quite closely up to 2007. However, over the period 2008–2009, the price tended to grow at a much stronger rate and the price of thermal coal finished up nearly 160 % higher in 2009 relative to 1999 (ABARES and Geoscience Australia 2010). The price effect on metallurgical coal exports over the period 1999 to 2009 was even more pronounced than for thermal coal. It started tracking higher about halfway through the period. The price for metallurgical coal finished at a point 230 % higher than in 1999. The volume of metallurgical coal exports was 46.3 % higher in 2009 relative to 1999 (ABARES and Geoscience Australia 2010).

In 2009 Australia was ranked as the second largest thermal coal exporter and accounted for about 19 % of the world thermal coal trade. Japan, Korea, Taiwan, and China were the standout buyers of Australian thermal coal over the period 1999–2009. Australia continued to rank as the number one in metallurgical coal trade and accounted to about 64 % of the total world trade. Japan, India, China, Korea, and European Union were the largest buyers of Australian metallurgical coal.

Figure 1 decomposes coal exports into exports of metallurgical coal of high-quality (MH), metallurgical coal of other quality (MO) and thermal coal (TC). It shows that from 1988 to 2009 exports of all coal types were increasing with total exports of metallurgical coal (coal of high and other quality) being greater than export volumes of thermal coal.

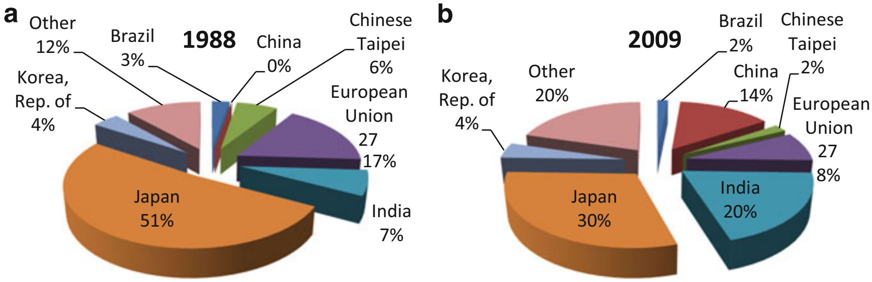

Fig. 2 Metallurgical coal exports by country: 1988 versus 2009. (**a**) Metallurgical coal exports in 1988. (**b**) Metallurgical coal exports in 2009

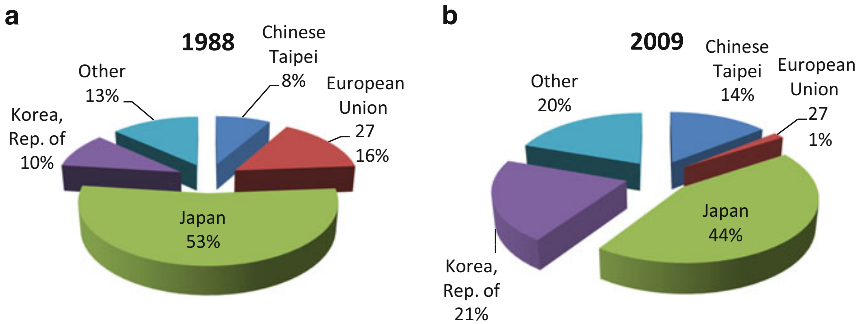

Fig. 3 Thermal coal exports by country: 1988 versus 2009. (**a**) Thermal coal exports in 1988. (**b**) Thermal coal exports in 2009

Figures 2 and 3 show changes in the export of Australian black coal based on major export destinations. For instance, the shares of Japan in both thermal and metallurgical coal have declined. China's exports have risen from almost 0 to 14 % in 20 years.

3 Internal and External Shocks

In this section we will discuss various events that could have an impact on Australian coal mining industry. Since the NSW and Queensland together are the major producers of recoverable black coal and Victoria is the only producer of brown coal, the focus of this discussion will be on these three states.

3.1 1960–1986

The Australian black coal industry achieved an uninterrupted rapid growth from 1960 to 1986. This strong growth was largely due to improvements in the mining technology and expansion in the Japanese export market for coking coal (Lucarelli 2011). While the open-cut mining has increased relative to underground mining, manual mining technologies were phased out during this period (Lucarelli 2011). Whereas the growth in the black coal mining industry was largely export driven, the domestic market slowed down because of the significant shift out of coal into natural gas and petroleum products. Domestically black coal was mostly used by the power, steel, and iron industries (Lucarelli 2011). During this time, Japan was the dominant exporter of black coal during 1960 to 1986, and the top concern of the Japanese buyers was security if supply and price appeared to be of a secondary concern (Lucarelli 2011). Japan and Australia have long-term contracts (10–15 years) with the provisions for price adjustments over the term of the contract. Initially exports of Australian coal were dominated by Japan (90 % of exports in 1960); later South Korea, Taiwan, and Europe also obtained a larger share of Australian black coal exports.

Australia’s black coal industry completely relied on coking coal in the early 1960s. From 1960 to 1975, black coal industry exports shifted from total reliance on coking coal to a combination of coking and steaming coal (Lucarelli 2011). In 1973, 1975 and 1978, Organization of the Petroleum Exporting Countries (OPEC) increased oil price leading to crisis in Asia’s power system. As a result of oil price shocks, large Asian economies started to rely on steam coal and uranium as sources of power generation, which led to increase in demand for Australian coal. In fact, during 1980 to 1995 many coal-fired power plants were built in several Asian countries.

Australian black coal prices were low and stable from 1960 to 1973, which was supported by the stable American dollar to Australian dollar exchange rate. From 1972 to 1974, significant depreciation of American dollar against the Australian dollar made Australian black coal exports more expensive. However, this did not have a much impact on the export levels because of large increase in crude oil prices, which were a significant factor in driving the expansion of Australian black coal exports.

Although the labor productivity improved over the period, on several occasions, there were strikes over wages. This is because, although nominal wages have increased steadily, real wages continued to increase from 1960 to 1975 and then started decreasing due to higher inflation. In addition, there were major improvements of coal-handling ports in NSW and Queensland accompanied by the construction of extensive interstate rail networks to transport coal from inland mines to coastal ports. Within the states, the railway tracks were built to transport coal to specific power stations (Lucarelli 2011).

Similar to black coal, brown coal industry showed a clear progression during this period. The construction of the aluminum smelter near Geelong in the 1960s led to the major development of the Anglesea brown coal mine and the power station complex to provide electricity. In 1970s a few more new power plants came into operation after completing the construction work, which led to a further expansion in the Victorian brown coal industry (Vines 2008). The production of brown coal in Victoria has increased over the long run with minor fluctuations in the production in the short run.

3.2 1987–2003

During 1987 to 1996, Australian black coal producers experienced a 16 % drop in the average real price of black coal exports (Lucarelli 2011). In 1997, the Australian black coal industry struggled due to adverse impacts faced by Asia during the Asian financial crisis. Inefficient labor practices, less efficient technologies and government-imposed fees on users were some critical factors that have affected the international competitiveness of the black coal industry (Productivity Commission 1998).

A massive decline in the oil prices in 1980s after the oil price shocks and the emergence of Indonesia as a major supplier of steam coal have led to a decrease in Australia's export competitiveness. During 1995 to 2003, when Indonesian coal suppliers were primary sellers of coal to power companies in North and Southeast Asia, Australian coal producers had hard times of competing with their Indonesian counterparts. Despite this, changes in American dollar to Australian dollar exchange rate did not have much effect on Australian black coal prices during 1987–2003 (except for the period during the Asian financial crisis). During this period, there was successful privatization by the Governments of NSW and Queensland of their ports and rail systems (Lucarelli 2011).

Brown coal industry showed a steady increase in production during this period. In mid- and late 1980s until mid-1990, Loy Yang open-cut mine extended its mining operations and power generation (Vines 2008). In addition, the expansion of infrastructure and transport systems in Victoria, especially in the locality of brown coal mines, have substantially supported the growth of the industry.

3.3 2004 to Date

After 2003, there were two major tendencies developed in the international coal market, first, price differential developed to favor coking coal and second, an increase in volatility of steam coal prices. The possible causes of the above tendencies were sudden increase in steam coal imports by China, shutting down of nuclear power plants in Japan and energy supply shortfalls in China, Indonesia, South Africa, and Australia (Lucarelli 2011). Although Japan remained the largest single export customer of Australian black coal, there was significant growth in demand for black coal by Taiwan and Korea in 2008 and by China and India in 2009. Both India and China have relied on Australia for coking coal. While Chinese imports of coal from Australia were not significant prior to 2009, India had been consistently increasing its share of coking coal exports from 2004 to 2009. At the same time, India's steam coal imports from Australia have been declining since 2004.

The prices of both steaming and coking coal increased from 2007 to July 2008 but then followed a rapid decline due to the global financial crisis and stayed low until a slow recovery in mid-2009. In addition to the above tendencies, Governments of NSW and Queensland could not keep up with the rapid expansion of rail system and this contributed to the increased coal price volatility in the region.

In the brown coal industry, there was a fire accident in a briquette factory in 2004 which imposed extensive damages and huge restoration costs on the damaged factory. However, there were further expansions in brown coal excavation using highly mechanized technologies. Government increased their research spending on brown coal industry particularly on Latrobe Valley (Vines 2008).

4 Literature Review

Literature on Australian coal mining is rapidly growing. Due to importance of mining to Australian economy, a vast body of literature tends to focus on the impact of mining on other macroeconomic variables, such as gross domestic product (GDP) and employment levels. However, there are only a few researches that examine the impact of other variables on mining. For example, Ali and Rahman (2012) investigated the impact of Australian coal exports on the Australian dollar to American dollar exchange rate. They found that the Australian coal export had a positive relationship with the exchange rate of Australian dollar to American dollar and that Australian coal exports contributed about 8 % to the exchange rate from 1992 to 2009.

Using input–output modeling, experimental workshops, stakeholder analysis, and the choice modeling survey, Ivanova et al. (2007) examined social and economic impacts associated with changes in the life cycle of coal mining operations in the Queensland's Bowen Basin. They suggested positive impact of mining on employment and economic growth on the regional level. In a recent report to the Minerals Council of Australia, Davidson and de Silva (2011) investigated the impact of phasing out of coal mining in the near future in Australia. Based on the time-series analysis, they found that due to high integration of coal mining in the Australian economy, the employment consequences of the loss in mining jobs were likely to be significant. According to their findings, for each job lost in the coal mining industry, 6.5 jobs will be lost in the economy as a whole.

There are not many studies which investigate structural breaks and the impact of various shocks on the Australian coal mining. For example, Higgs (1986) modeled the short-run effects of exogenous shocks (cut in real wages, introduction of protection of mining industries, changes in taxation mix, movements in the exchange rate) on Australian mining sector using computable general equilibrium ORANI model. He found that in the mid-1980s all of the shocks analyzed were projected to bring detrimental impact on Australian mining. Clarke and Waschik (2012) studied the implications of Australia's carbon pricing policy on the energy-intensive, trade-exposed industries of which coal mining is the example. Based on the computable general equilibrium (CGE) model of the Australian economy, they argued that the competitiveness of Australian coal mining and energy-intensive, trade-exposed industries in general will be adversely affected by carbon pricing policies. Barrett et al. (2012) studied the short-run impact of Carbon tax on brown coal mining and electricity generation in the Victorian Latrobe Valley. They found that introduction of a Carbon tax would lead to a decline in regional GDP and a small decline in national GDP, accompanied by a decline in regional employment levels.

Barnett (1994) provided a brief overview of Australian coal mining and outlined major actors which affected the industry in 1980s. According to him, strikes were one of the important factors affecting the industry between 1981 and 1992. During this time, the coal mining industry suffered between 3 and 16 days lost per employee due to industrial disputes. Using rational expectations model, Harvie and Hoa (1994) analyzed macroeconomic consequences arising from volatile terms of trade shocks in Australia's mineral resources sector in 1980s. They considered the adjustment process during three distinct study periods: sharp decline in terms of trade (1983–1986), sharp improvement in terms of trade (1987–1988) and gradual decline in terms of trade (1989–1992), which corresponded to sustained increase in GDP in the first two periods and deteriorating GDP in the third period.

Swan et al. (1998) studied structural changes in price–quality relationships in the Australia–Japan coking coal trade using the Quandt's exogenous regime switching model. They found that the structure of price–quality relationships for the Australia–Japan coking coal trade changed fundamentally for semisoft coking coal with the merging of the soft coking coal category into the semisoft coking coal category after the 1994 Japan financial year and for hard coking coal with the subsequent adoption of the fair treatment system in 1996 Japan financial year.

In relation to stationarity testing, there is no consensus in the literature of whether coal production, consumption, or export series are stationary. As suggested by Yang (2000) and Sari et al. (2008), this is because different countries or even industries depend differently on a particular energy source such as coal. If early literature applied univariate conventional unit root tests, now the trend is towards panel unit root tests. Yoo (2006) applied conventional unit root tests to South Korean coal consumption and found that coal consumption in South Korea is a nonstationary variable. Apergis and Payne (2010) applied panel unit root tests for coal consumption from 15 emerging market economies and found that coal consumption series were nonstationary. The contribution of this chapter to the literature is the application of unit root tests with structural breaks, which has not yet been done in the literature with respect to the Australian coal data series.

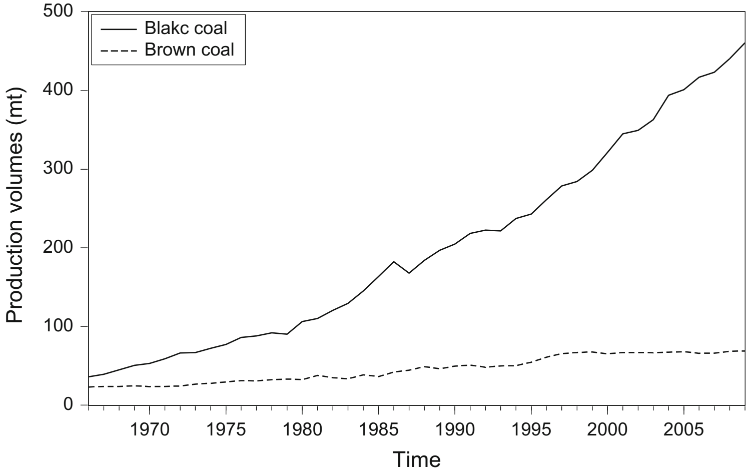

Fig. 4 Black and brown coal production: 1966–2009

5 Data

In this study we use data from the Australian Bureau of Agriculture and Resource Economics (ABARE) on production and export volumes of black coal and production volumes of brown coal. We use the above-mentioned data for the sample period from 1966 to 2009. Our choice of sample period and periodicity reflects the limitations in the availability of time-series data on coal production.

Figure 4 below shows the dynamics in annual black and brown coal production (in million tonnes) in Australia. From Fig. 4, we can clearly see that in contrast to brown coal, black coal production was on a sharp upward trend throughout the sample period with production volumes being consistently higher than volumes of brown coal production.

Figure 5 illustrates the production volumes of coal (both brown and black coal) by state. As stated earlier, the majority of coal is produced in Queensland, followed by NSW and Victoria. In other states, volumes of production have traditionally been very low reflecting low deposits. The only state which has been producing brown coal is Victoria.

Figure 6 shows the dynamics in black coal exports and domestic consumption of black coal (in million tonnes) over the period 1966–2009. Both domestic consumption and export volumes have been growing with observable short-run fluctuations. However, export volumes have overtaken domestic consumption in 1983, and the gap between them has been widening throughout the sample period being the largest in 2009.

Table 2 shows descriptive statistics. All data (brown coal domestic consumption, black coal domestic consumption, black coal exports) were transformed into natural logs prior to undertaking the analysis. The coefficient of standard deviation

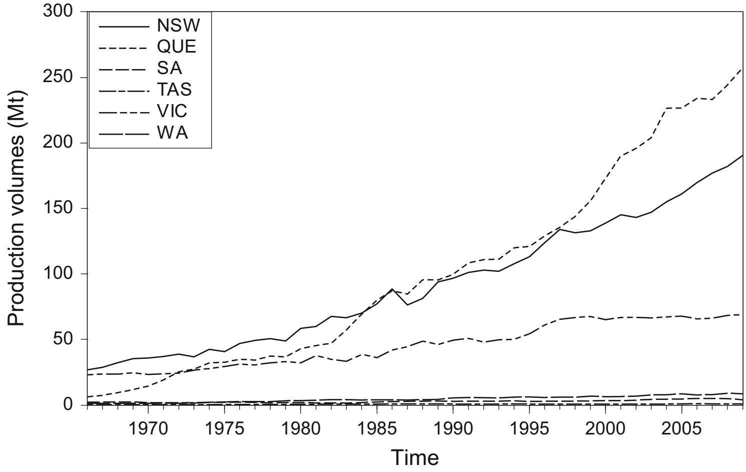

Fig. 5 Black and brown coal: production levels by state. Note: *NSW* New South Wales, *QUE* Queensland, *SA* South Australia, *TAS* Tasmania, *VIC* Victoria, *WA* Western Australia

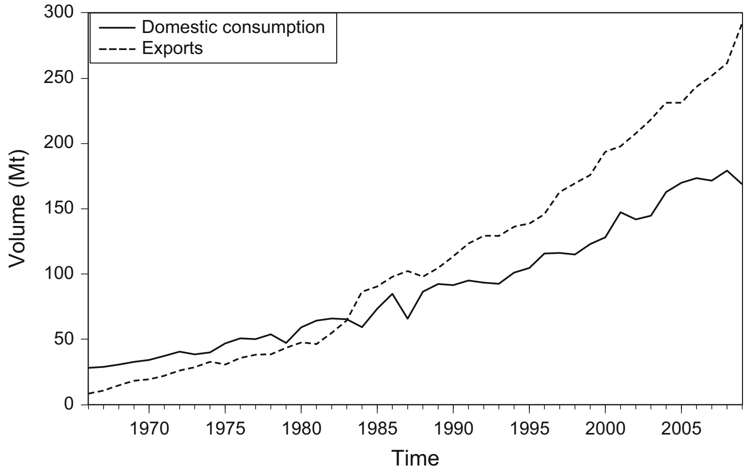

Fig. 6 Black coal: domestic consumption and exports: 1966–2009

indicates that the natural log of exports has the highest volatility, followed by the logged black coal production and brown coal production. The mean of all three variables is positive indicating that production has been on a positive level (growth) over the entire sample period. The Jarque–Bera (JB) statistics for normality indicate that all variables are normally distributed. Log coal series are negatively skewed and show low kurtosis.

Table 2 Descriptive statistics

	LN_BLACK	LN_BROWN	LN_EXPORT
Mean	4.3386	3.7439	4.3475
Median	4.4492	3.8093	4.6039
Maximum	5.1886	4.2297	5.6776
Minimum	3.3290	3.1298	2.0844
Std. dev.	0.5656	0.3905	0.9687
Skewness	−0.1658	−0.1778	−0.5544
Kurtosis	1.8565	1.5928	2.2511
JB	2.5989 (0.2727)	3.8622 (0.1450)	3.282 (0.1938)

6 Methodology

Glynn et al. (2007) define structural break as the change in time series due to some unique economic event, which may reflect institutional, legislative, or technical changes, changes in economic policies or large economic shocks. If a series is nonstationary (I(1)) or has a unit root, the impact of a structural break will have a permanent impact on the series. There are several advantages of using unit root tests with structural breaks over the conventional tests such as ADF or Phillips–Perron. These conventional unit root tests have very little power when having a near unit root process and in small samples. Therefore, if the visual inspection of the series inclines the possibility of a structural break, unit root tests that allow for structural breaks should be used instead of these above-mentioned conventional tests. In addition, unit root tests with structural breaks help to identify when the breaks have occurred. The existence of structural breaks has been confirmed for the coal data series used in the chapter by the Chow (1960) breakpoint test for exogenously determined structural change and the Quandt–Andrews test for unknown breakpoint; the use of unit root tests with structural breaks is justified (Andrews 1993; Andrews and Ploberger 1994).

Chow test uses F-statistic to test whether the coefficients in two linear regressions are equal after diving the data series into two subsamples (Chow 1960). In contrast to Chow test, the Quandt–Andrews test does not assume a priori knowledge of the exact point of the structural break. This point is determined by the maximum Wald F-statistic. Quandt–Andrews test performs a single Chow test at every observation between the two dates and computes the corresponding test statistic (Andrews 1993; Andrews and Ploberger 1994). Then these statistics from individual Chow tests are summarized into one test statistic for a test against the null hypothesis of no breakpoints.

Currently, literature recognizes two types of unit root tests with structural breaks depending on whether the break was endogenously (Lee and Strazicich 2001; Lumsdaine and Papell 1997; Zivot and Andrews 1992) or exogenously (Perron 1989) estimated. Exogenous (is known and pretested) break tests assume that breakpoint is known to the researcher. However, what the researcher might suspect to be a break will not necessarily have a power to change the direction of the data.

Endogenous break tests permit the break to be determined by the data and not to be given from outside to the model. These tests are superior to exogenous-based tests because they allow the data to speak for itself. Although these tests identify the break date, these dates are likely to be imprecise because the tests are not as efficient in determining the break date as the break estimators (Allaro et al. 2011). However, both types of tests are sensitive to the number of breaks both under alternative and null hypotheses as well as the number of lags in the analysis. In the essence, all endogenous tests used in this chapter are based on the modified ADF and will be summarized below.

6.1 Zivot and Andrews (ZA) (1992) Unit Root Test with One Structural Break

Building on Perron's (1989) unit root test with one exogenous structural break, Zivot and Andrews (1992) proposed a unit root test that allows for one break to be endogenously determined within the data series. Several testable models were proposed: Model A, which allows a one-time shift in the intercept of the series, and Model C, which is a combination of a one-time shift in the intercept and the slope of the trend function. In each of these two models, the null hypothesis is a unit root without a structural break and the alternative hypothesis is trend stationarity with a possible one-time break at some unknown point of time.

Let series y_t be the series to be tested for the unit root properties. A shift in the intercept of the series (Model A) can be tested through Eq. (1a):

$$y_t = \hat{\mu}_A + \hat{\theta}^A \mathrm{DU}_t(\hat{\lambda}) + \hat{\beta}^A t + \hat{a}^A y_{t-1} + \sum_{J=1}^{k} \hat{c}_j{}^A \Delta y_{t-1} + \hat{e}_t, \tag{1a}$$

where $\hat{\mu}_A$ is the mean, $\mathrm{DU}_t(\hat{\lambda})$ is the dummy variable for the break where $\mathrm{DU}_t(\hat{\lambda}) = 1$ if $t > T\lambda$ and zero otherwise and $\hat{\lambda}$ is the estimated location of the break fraction. The break fraction can be computed as $\lambda = \frac{T_\mathrm{b}}{T}$, where T_b is the time of the break.

Model C, which allows the possibility of a one-time change in the intercept and the trend break, is given in (1b) below:

$$y_t = \hat{\mu}^C + \hat{\theta}^C \mathrm{DU}_t(\hat{\lambda}) + \hat{\beta}^C t + \hat{\gamma}^C \mathrm{DT}^*{}_t(\hat{\lambda}) + \hat{a}^C y_{t-1} + \sum_{J=1}^{k} \hat{c}_j{}^C \Delta y_{t-1} + \hat{e}_t. \tag{1b}$$

Here, $\hat{\gamma}^C \mathrm{DT}^*{}_t(\lambda)$ is the break in the trend function and $\mathrm{DT}^*{}_t(\hat{\lambda}) = 1 - T\lambda$ if $t > T\lambda$ and zero otherwise. As compared to Model A, Model C is less restrictive.

In these models, the location of the break λ is chosen so that the one-sided t-statistic for testing the hypothesis $\hat{a}^i = 1, i = A, B, C$, is minimized. The decision rule is to reject the null of a unit root in favor of trend stationarity. Zivot and Andrews (1992) reported that this test is not prone to size distortions. However, the power of these tests is low when the magnitude of the break in the trend function is small or moderate (Zivot and Andrews 1992).

6.2 Clemente–Montanes–Reyes (1998) Unit Root with Two Structural Breaks

Second unit root test that we use in this chapter is the Clemente–Montanes–Reyes (CMR) (1998) unit root test which allows for two structural shifts in the mean of the series. In the CMR test the null hypothesis [Eq. (2a)] of a unit root with structural break(s) is tested against alternative of stationary series with structural breaks [Eq. (2b)]:

$$Ho : y_t = y_{t-1} + \delta_1 \mathrm{DTB}_{1t} + \delta_2 \mathrm{DTB}_{2t} + u_t, \tag{2a}$$

$$Ha : y_t = \mu + d_1 \mathrm{DU}_{1t} + d_2 \mathrm{DTB}_{2t} + e_t, \tag{2b}$$

where DTB_{it} represents the pulse variable that takes the value 1 if $t = \mathrm{TB}_i + 1$ $(i = 1,\ 2)$ and 0 otherwise and $\mathrm{DU}_{it} = 1$ if $t > \mathrm{TB}_i$ $(i = 1,\ 2)$ and 0 otherwise. TB_1 and TB_2 are the time periods when the change in the mean has occurred (Clemente et al. 1998).

Similar to ZA tests, CMR does not require a priori knowledge of the dates of structural breaks, which represents an advantage over unit root tests with exogenously determined breaks. Building on Perron and Vogelsang (1992) and Perron (1997) tests, CMR allows estimating two models, an additive outliers (AO) model and an innovational outliers (IO) model depending on whether a change in the mean of the series was sudden (AO model) or gradual (IO model). This is the advantage of CMR over ZA which uses the innovational outlier model and assumes gradual changes in the series.

Unit root hypothesis in the IO model can be tested by estimating the following model [Eq. (3)] and then obtaining the minimum value of the pseudo t-ratio for testing whether the autoregressive parameter ρ is equal to 1 for all break combinations (Clemente et al. 1998):

$$y_t = \mu + \rho y_{t-1} + \delta_1 \mathrm{DTB}_{1t} + \delta_2 \mathrm{DTB}_{2t} + d_1 \mathrm{DU}_{1t} + d_2 \mathrm{DU}_{2t} + \sum_{i=1}^{k} c_i \Delta y_{t-1} + e_t. \tag{3}$$

Testing for unit root with two breaks in the mean in the AO model requires two-step procedure. First, the deterministic part of the model had to be removed by estimating Eq. (4a) and then carry out the test by searching for the minimal t-ratio for the $\rho = 1$ hypothesis in the following model (Clemente et al. 1998):

$$y_t = \mu + d_1 \mathrm{DU}_{1t} + d_2 \mathrm{DU}_{2t} + \tilde{y}_t, \tag{4a}$$

$$\tilde{y}_t = \sum_{i=0}^{k} \omega_{1i} \mathrm{DTB}_{1t-i} + \sum_{i=0}^{k} \omega_{2i} \mathrm{DTB}_{2t-i} + \rho \tilde{y}_{t-1} + \sum_{i=1}^{k} c_i \Delta \tilde{y}_{t-1} + e_t. \tag{4b}$$

7 Results and Discussion

In this section we will discuss the results of our estimations. Table 3 shows results of the Chow test for exogenously chosen structural break. These results are in accordance with Swan et al. (1998), who also found 1995 as the break date for Australian exports of coking coal to Japan.

Results of Quandt–Andrews are shown in Table 4 below. The null hypothesis of no breakpoints could not be rejected within the time period considered for all series under the examination.

As seen in Tables 3 and 4, breakpoints estimated using the tests above reveal structural breaks exist in all series. Quandt–Andrews test suggested a single break in the series compared to Chow test. For black coal, both Quandt–Andrews and Chow tests suggest 1980 as the break date. This can be a reflection of massive increase in black coal production due to the oil price shocks experienced since 1978. As a result of these oil price shocks, Asian economies (Japan, Taiwan, and Korea) increased their demand for Australian coal. During the period 1980 to 1995, many new coal-fired power stations were built in these countries and increased the exports of coal. This explains the structural break in exports in 1982. According to Chow test, there are two structural breaks in exports in 1981 (can be explained by the world oil crisis) and 1995. During 1987 to 1991, Australian black coal industry was expanding, and there were no major competitive threats in the international coal market. However, there was increasing competition by Indonesia in the international coal market in 1995. Australian black coal industry managed to continue expansion due to past investments in transportation, infrastructure, and mine capacity. This was further enhanced by the government subsidies for diesel which kept the cash cost of production of coal very low. However, over the time Indonesia captured the thermal coal market and became the largest producer in 2006.

Chow test suggested two structural breaks in brown coal. The first break in brown coal occurred in 1984 which corresponds to an increase in domestic consumption. Brown coal power stations located in Latrobe Valley, Victoria, were built in the 1970s. These power stations operated in full capacity during early and mid-1980s. The second break occurred in 1995 according to the Chow test and

Table 3 Chow breakpoint test

Variable	Estimated breakpoint	F-statistic	Log likelihood ratio	Wald statistic
Brown coal	1984	3.0252 (0.0601)	6.2014 (0.0450)	3.4554 (0.1777)
	1995	2.6464 (0.0836)	5.4722 (0.0648)	4.7818 (0.0915)
Black coal	1980	3.2249 (0.0506)	6.5811 (0.0372)	6.4499 (0.0398)
Exports	1981	4.5925 (0.0162)	9.0939 (0.0106)	8.2515 (0.0162)
	1995	1.1689 (0.3214)	2.5032 (0.2860)	12.2785 (0.0022)

Table 4 Quandt–Andrews unknown breakpoint test

Variable	Estimated breakpoint	Value	Probability
Brown coal	Maximum Wald F-statistic: 1996	83.4135	0.0000
Black coal	Maximum Wald F-statistic: 1980	14.3021	0.0422
Exports	Maximum Wald F-statistic: 1982	15.8294	0.0079

Note: Null hypothesis denotes no breakpoints within 15 % trimming (Hansen 1997)

1996 according to the Quandt–Andrews test. These events could reflect two factors; first is privatization of the state electricity commission of Victoria which was held between 1995 and 1999. Privatization separated the brown coal industry both vertically and horizontally and introduced more competition at the generation and distribution levels. The second factor is the increase in research and development expenditures as well as expenditures on mining licences.

Tables 5 and 6 show results of ZA tests, Models A (one-time break in intercept) and C (one-time break in intercept and trend). Results of the ZA test show that for brown coal and black coal production for domestic consumption, the null hypothesis of a unit root cannot be rejected at all with 1 % significance level. This means that the impact of shocks on production will be permanent in nature. Since coefficient dummies are significant, the tests reveal a one-time break in the intercept. However, the break dates are different for brown and black coal. In terms of exports of black coal, the null hypothesis of a unit root has to be rejected in favor of trend-stationary alternative with one break in intercept in 1981.

Table 6 shows that exports are stationary I(0) series at 1 % level of significance, since the unit root null was rejected in favor of the trend-stationary hypothesis with one-time break in the level and the trend function. At the same time, unit root null can be rejected for brown and black coal production at 5 and 10 %, respectively. Therefore, we conclude that provided one-time break in both intercept and trend function, all series were found to be trend-stationary variables with a structural break.

Table 5 Results of ZA test with one break in intercept

Variable	Estimated break	Dummy coefficient on intercept	Minimum test statistic	Decision
Brown coal	2002	1.5172*** (3.793)	−3.7276	I(1)
Black coal	1979	1.0673*** (4.120)	−3.7797	I(1)
Exports	1981	0.8914*** (7.655)	−6.357***	I(0)

Notes: Critical values are 0.01 = −5.34, 0.05 = −4.8, and 0.1 = −4.58
***Indicates (1) rejection of the null hypothesis of a unit root at 1 % level and (2) that the structural breaks were significant at 1 % level. Tests have been performed using R12 econometric software

Table 6 Results of ZA test with one break in intercept and trend

Variable	Estimated break	Dummy coefficient on intercept	Dummy coefficient on trend	Minimum test statistic	Decision
Brown coal	1995	2.0986*** (5.225)	0.0227*** (5.136)	−5.1727**	I(0)
Black coal	1983	2.2339*** (5.202)	0.0406*** (4.600)	−4.9743*	I(0)
Exports	1983	1.28940*** (7.329)	0.0406*** (4.821)	−6.1942***	I(0)

Notes: Critical values are 0.01 = −5.57, 0.05 = −5.08, and 0.1 = −4.82
***Indicates (1) rejection of the null hypothesis of a unit root at 1 % level and (2) that the structural breaks were significant at 1 % level
** and *indicate rejection of the null hypothesis of a unit root at 5 and 10 % level. Tests have been performed using R12 econometric software

Table 7 Results of CMR (1998) unit root with double break in the mean

	Additive outlier (AO)			Innovative outlier (IO)		
Variable	Minimum *t**	Optimal breakpoints	Decision	Minimum *t**	Optimal breakpoints	Decision
Brown coal	−3.560	1981*, 1993*	I(1)	−3.254	1971, 1984	I(1)
Black coal	−3.128	1982*, 1997*	I(1)	−3.621	1978, 1995	I(1)
Exports	−3.539	1982*, 1997*	I(1)	−6.364*	1981, 1995	I(0)

Note: 5 % critical value is −5.490. Optimal breakpoints denote the structural break dates suggested by the CMR tests
*Indicates (1) rejection of the null hypothesis of a unit root at 5 % level and (2) that the structural breaks were significant at 5 % level. Tests have been performed using Stata 11 econometric software

CMR tests show that at 5 % significance level, the null of a unit root with structural breaks in the mean cannot be rejected for brown and black coal. These results are presented in Table 7 and hold for both AO and IO models, although the estimated break dates are not identical. For exports, IO model suggests that a unit root null cannot be rejected at 5 % of significance, which is in line with the findings of the ZA test. However, the AO model suggests that exports are nonstationary I (1) series meaning that the impact of shocks on exports is likely to have a permanent effect.

Comparing structural break tests and unit root tests, one can observe that the estimated break dates are not identical but very close in time. For an example, for brown and black coal, all the tests identify late 1970s of early 1980s as breaks reflecting the impacts of the international oil crisis on coal market. In contrast to other tests, only CMR model suggested 1995 and 1997 as break dates for black coal. During 1995 and 1997 the growth rate of black coal was high due to increase in energy consumption in Australia. Similar structural breaks are estimated for black coal exports. As discussed before, these breaks are due to increased competition in the world market, government subsidy programs, and continuous reaping of the benefits from past investments.

The second break in the brown coal according to the CMR model occurred in 1993 (AO model) and 1984 (IO model). In 1993, Morwell Briquette and power division in Victoria was split from the State Electricity Commission of Victoria, and this has led to increase in production of Briquettes using brown coal. In 1984, there was an increase in brown coal production as a result of international oil price shocks.

It should also be noted that coal and crude oil are substitutes in energy consumption. Therefore, changes in the price of crude oil due to uncertainty in oil-producing countries, such as oil price shocks of late 1970s or the recent Arab Spring events, should have an impact on the demand for Australian coal. According to Australian Competition and Consumer Commission (ACCC), Brent, the international crude oil benchmark, or Tapis, the regional crude oil benchmark, is more relevant to the prices that Australian refiner's pay for crude oil than other international crude oil prices (ACCC 2011). Australia has very limited resources of crude oil with most of the domestic crude oil coming from two areas: the North West Shelf (Western Australia) and the Southeast Gippsland Basin (Victoria). The majority of crude oil imports are from Southeast Asia, in particular Vietnam, Malaysia, and Indonesia. In addition, approximately a quarter of Australia's petrol is imported, primarily from Singapore, and the most appropriate benchmark for the refined petrol that is sold to Australian consumers is the price of Singapore Mogas 95 Unleaded (Mogas 95) (ACCC 2011).

Figure 7 shows annual exports of black coal and annual Brent crude oil price in USD from 1986 to 2009 with structural breaks highlighted by dashed lines. Some of the breaks (1987, 1997, and 2008) in the series appear to coincide as shown in Fig. 7. However, Chow test did not identify any of these break dates as significant. The CMR (additive outlier) model suggested a structural break in 1997 for black coal exports which was significant at 5 % level. This suggests that Asian financial crisis had a significant impact on coal.

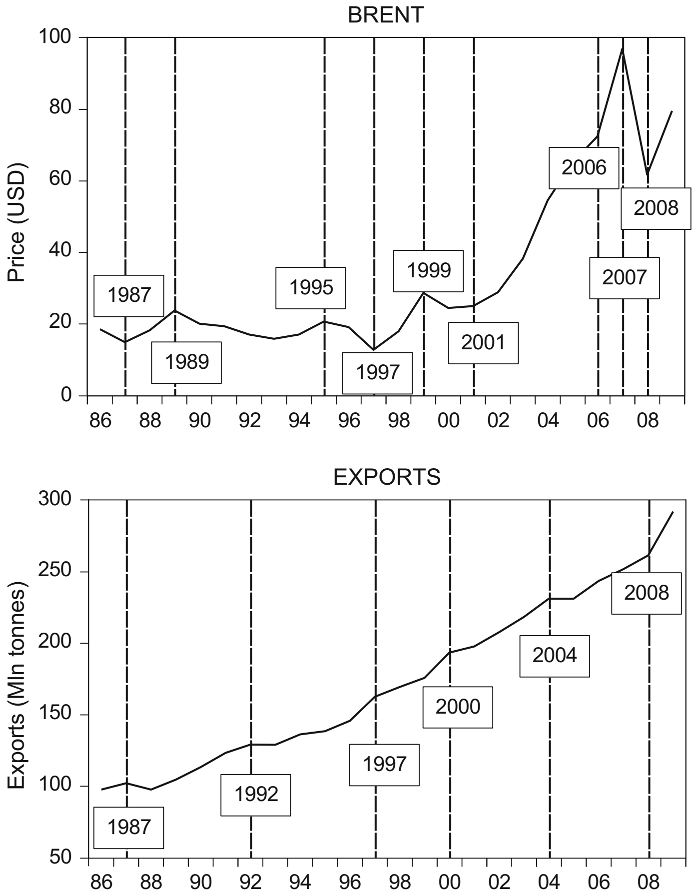

Fig. 7 Annual exports of black coal and annual Brent crude oil price. Note: Source of Brent data is Thomson Reuters

8 Policy Implications and Conclusions

Brown and black coals are among the most important commodities in the world. Following BP Statistical Review (2012), the share of coal production has been increasing in the world's energy mix, making it the fastest growing form of energy outside the renewables. Changes in coal production are likely to have significant implications for the general macroeconomic variables.

The focus of this chapter was on investigating the existence of structural breaks in the Australian coal mining and studying stationarity properties of coal production and exports. Based on ZA Model A and CMR tests, we have found evidence of black and brown production for domestic purposes being nonstationary variables, while black coal exports were found to be stationary mean-reverting process with structural breaks. At the same time, ZA Model C which considered a one-time break in both trend function and intercept suggested that all coal series were stationary. Additional tests are required to study stationarity properties of black and brown coal production (unit root tests allowing multiple structural shifts in data); exports of black coal were found to be stationary by majority of the tests that we performed in this chapter. This means that impact of the shocks on export volumes is likely to be transitory in nature.

This is particularly important for the new Carbon tax policy introduced in Australia on July 1, 2012. The Australian Government Climate Change Plan 2011 fixed the value of a tax at AUD 23 per tonne of carbon dioxide (CO_2) emitted in the first year of operation and adjusts the tax according to the targeted inflation level of 2.5 % in the next two consecutive years. From July 2015, the government is planning to introduce a national emissions trading scheme designed based on the cap-and-trade principle. Given that exports of coal are stationary, introduction of a tax is likely to cause temporary decline in exports because the price of Australian export coal will be higher. However, since coal is an input with few substitutes, in a medium term, exports are likely to revert back to their trajectory.

The issue of whether energy production is stationary has important implications for industrial policies and firm level strategies as well as for modeling and forecasting purposes (Apergis and Tsoumas 2012). For instance, significant structural break, such as environmental tax, which permanently affects the series, is likely to substantially modify behavior of the firm and firm strategy as well as the long-term planning. Also, it is important for formulating energy conservation policies with a long-term goal of reducing green house gas emissions, which require knowing time-series properties of a particular energy resource. Energy conservation policies would require fewer and more efficient use of coal and would put a higher price on coal production. If coal production is stationary, the energy conservation policies will be transitory in nature and will not have a permanent impact on the coal trend path, which in fact will be observed if coal production is nonstationary I(1) variable.

Another reason why the issue of stationarity is important lies in the degree to which the energy sector is connected to other sectors of the economy (Apergis and Tsoumas 2012).This is because permanent shocks to coal industry may be transmitted to other sectors of the economy as well as the macroeconomic variables (Lean and Smyth 2009). For an example, since ZA test finds that brown coal production is nonstationary, shocks to brown coal production such as newly introduced Carbon tax or Mineral Resource Rent Tax (MRRT) could have a permanent impact not only brown coal mining industry but also on electricity generation, prices, and consumption as well as regional and national employment and GDP. MRRT was introduced on July 1, 2012, and a 30 % tax is payable by coal mining companies whose annual profits are AUD 75 million and above.

In relation to structural breaks in the coal data, both Chow and Quandt–Andrews tests and unit root tests show that such events as September 11, 2001, or war in Iraq in March 2003 did not affect either the domestic production or exports of coal, while oil crisis in the late 1970s did. This could be because of the duration of the impact. While oil price shocks of late 1970s were of longer duration and hence higher uncertainty, much shorter Iraq war did cause temporary increase in oil prices in March 2003, but prices returned to around American dollar 25 for a barrel of crude oil in late April. CMR additive outlier model suggested 1982 and 1997 as break dates for black coal production and exports. Breaks observed in 1997 correspond to Asian financial crisis. Based on the estimated break dates, we can conclude that only large international events have a noticeable impact on Australian coal data. Financial crisis, shocks in the international oil market and oil prices are the likely events that affect Australian coal export volumes.

There are several areas for future research. For instance, future research should consider panel-data unit root tests with multiple structural breaks in coal production grouped by the state of origin or by the export destination. This will help to formulate appropriate regional policies as well as provide a better understanding on export markets for Australian coal.

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Dr. Svetlana Maslyuk is a Lecturer in economics in the School of Business and Economics, Monash University. Her research interests include energy and natural resource economics, economic development and sustainable energy consumption and applied time-series econometrics. She holds a PhD in Economics from Monash University. Her recent publications are in energy economics and energy policy.

Dr. Dinusha Dharmaratna is a Lecturer in the Department of Economics, Monash University. Dinusha completed her PhD in economics in 2009 at the Monash University. Her research interests are in the fields of environmental economics with a special focus on renewable resource management, climate change issues, and agricultural and urban water management. Her recent publications are in WHO Bulletin, Journal of the Asia Pacific Economy, Asia Pacific Journal of Economics and Business and Water Resources Research.

An Assessment of the Impacts of Government Energy Policy on Energy Technology, Innovation, and Security: The Case of Renewable Technologies in the US Electricity Sector

Edwin Garces and Tugrul Daim

Abstract **Purpose** The reduction of using natural gas and coal and the necessity of having different sources of energy are essential for the energy security in the USA. Renewable energy technologies are considered as the alternative, but these technologies are not yet reliable and cost effective. The objective of this paper is to identify the factors that results in technological change and to analyze the direction and effects of energy policies in the electricity sector.
Design/Methodology/Approach Based on the induced technological change theory, a co-integration analysis is done to evaluate the short- and long-run effects of the factors on renewable technology change by, focusing on the analysis of energy policies. An ex post quantitative policy evaluation is applied.
Findings The results of the empirical analysis show that the variables are associated in the long run, while the relationship between renewable energy technologies and the electricity market is not significant.
Practical Implications The federal and state energy policies, R&D investment, knowledge stock, and knowledge accumulation are not entirely connected to electrical market variables. These results indicate the importance of energy policies aiming at accomplishing the energy security objectives.
Originality/Value This paper focuses on understanding how policies impact the renewable energy technology and analyzing the relationships and directions of the effects among the variables. The empirical and quantitative analysis, focusing on a theoretical model and the practical analysis, aims to understand the long- and short-run policy effects to develop better technology plans and achieve the energy security objectives.

E. Garces (✉) • T. Daim
Department of Engineering and Technology Management, Portland State University,
P.O. Box 751, ETM, Portland, OR 97207-0751, USA
e-mail: edwing@pdx.edu; tugrul@etm.pdx.edu

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1 Introduction

Recently, high conventional energy prices and the political and economic instability show the necessity of having different sources of energy. In this context, renewable energy technologies will contribute to achieve the government objectives of reducing foreign energy dependency and reduction of contaminant emissions.

The development of renewable energy power technologies is important for energy security as a part of national security. Energy security, defined by Bielecki (2002), implies the "reliable and adequate supply of energy at reasonable prices" (p. 237). In the US electricity sector, the major sources of energy come from natural gas and coal. However, these two sources are linked to concerns of foreign dependency and environmental pollution. In the case of coal, the source is abundant, inexpensive, and will last for a long time. However, since coal is associated with over-emission, replacing coal by clean sources for generating electricity is necessary (Wirth et al. 2003). In the case of natural gas, as Bielecki (2002) indicates, the problem is not availability but that concentration of the major reserves is outside the USA and is related to the complexity of distribution and transport of natural gas to markets (Bielecki 2002).

In order to reduce dependency on natural gas and reduce the risk associated with coal pollution, it is the objective of the government to promote renewable energy production and to eliminate imports of oil and gas by 2030 (Spector 2009; The White House 2002). However, the elimination or reduction of natural gas and coal use is complex since in the electricity market, supply levels need to be adjusted according to the demand levels. Accordingly, diversification is one of the options to reduce the foreign energy dependency, and all the options need to be considered with long-term programs that promote the improvement of efficiency (Bielecki 2002).

The new alternative source of energy comes from renewable resources. In the specific case of the electricity sector, electricity can be generated by renewable resources, such as wind, sun, tidal waves, and marine currents. However, renewable energy technologies are not taken as an integral part of the electrical grid system, because they are economically inefficient and technically unstable compared with conventional energy technologies. Considering reliability and price, the use of renewable energy on a large scale, like wind turbines, has many concerns. These renewable energy technologies are intermittent and their costs are not yet competitive with nonrenewable sources.

At present, electricity from renewable energy technologies does not represent a significant fraction of total production (Deutch et al. 2006). For example, in the "Economic Dispatch in the Electrical Power System," electrical plants using renewable resources are not included as base or marginal units. This concern is much more serious because energy scarcity and new environmental restrictions have appeared. Generating alternatives present challenges to be more reliable and capable to generate electricity in a large scale in a cost-efficient way, and increasing the reliability of these new generation alternatives presents challenges.

The US electrical market has changed during the last 10 years, showing that policy makers have given more priority to renewable energy. However, even as the use of renewable energy sources has been increasing, the penetration in the market is limited (Johnstone et al. 2010). One of the reasons for the limited adoption is the higher cost of renewable technologies, compared to substitute fossil fuel products (Johnstone et al. 2010).

The market adoption or diffusion of renewable technologies is associated with market failure, since the electricity market has the characteristics of a natural monopoly. This market failure in the electricity industry implies that investors do not adopt renewable technology, despite high electricity prices. Renewable technologies are not adopted because the amount and type that firms invest in knowledge is driven by private profit incentives from appropriate innovations (Loschel 2002).

Due to the market failure, the government has been applying and restructuring national and state policies in order to find an energy source that is clean and cost competitive, specifically in the electric industry. Since policy interventions affect the process of technological change (Kerr and Newell 2003) and to accelerate the adoption and diffusion of renewable energy technologies in the electricity market, the government has been applying different types of policies. The policies, such as certificates, feed-in tariffs, production quotas, and tax credits, aim at reducing production costs of using renewable energy (Johnstone et al. 2010). At present, the policies appear to have failed because renewable technologies are believed to be a second option in technology selection. The failure of policies is associated with controversial practices for promoting technologies such as the Energy Independence and Security Act of 2007 which does not include the Renewable Energy Portfolio Standard (RPS) (CRS 2007).

It is clear that policies lack comprehension of technological change and diffusion of technologies for renewable energy technologies. However, energy independence and environmental restrictions are factors that can be considered as the determinants of using and promoting renewable energy in the electricity sector (Bielecki 2002). Therefore, the necessity of generating electricity from clean resources is a government priority (Mignone 2007).

Unlike other studies analyzing only environmental or renewable policies, this paper examines the relationship between renewable technological change and policies associated with the electrical sector, including federal and state regulations.

Modeling technological change is an important issue for formulating policies regarding the environment and energy (Gillingham et al. 2007). Therefore, this paper will find answers for the following questions:

- How have government policies been affecting renewable technology change?
- What are effective policies that promote renewable energy technology change?
- What are the main factors causing technological change and causal relationships between them?

Considering the challenges of renewable technologies and policies in the electrical sector, the main objectives of this paper are:

- To identify the factors that results in technological change and to describe the effects of technology policies related to renewable technology innovation in the electricity sector.
- To analyze the direction and effects of energy policies in the electricity sector for inducing the change and adoption of renewable technologies by applying ex post quantitative policy evaluation.

It is important to understand how policies affect the renewable energy technology. Modeling technological change is essential to analyze the policies and their final effects, in order to develop optimal policies and economic models (Grubb et al. 2000). However, previous analyses had been focused on environmental strategies and environmental policy analysis as mentioned by Popp (1998). There are few studies specifically about renewable energy technology change and adoption in the electricity sector.

Finally, it is crucial to have empirical and quantitative analysis to understand the long- and short-run policy effects in order to formulate better technology plans. Empirical analysis is needed, because theories, such as the induced technology theory, explain how factors affect technological change; however, theories do not explain how new knowledge is developed (Popp 1998). Applying the endogenous growth theory gives an opportunity to analyze knowledge formation and accumulation as well as how the factors explain the knowledge accumulation and the direction of technological change. Therefore, understanding endogenous technological change is important since policies affect the evolution of technologies, costs, and outcomes (Weyant and Olavson 1999).

2 Theory and Literature Review

As cited by Loschel (2002) "Schumpeter (1942) distinguishes three stages in the process of technological change": Invention, innovation, and diffusion (p. 1). In the frame of induced innovation, technological change is explained by different methods and theories. Due to the motivation and objectives of this paper, technological change has been associated with the "induced technological change theory," which can be divided into the following theories:

2.1 Exogenous Technological Change

Using the Solow (1956) theory, in the energy and environmental field, technological change has been considered as an exogenous variable which implies an autonomous function of time. Technology follows two functions of time: a Hicks-neutral productivity following economic progress and the energy-saver approach (Gillingham et al. 2007). In this context, autonomous technological change depends on autonomous trends and government R&D. This differs from endogenous technological change, which considers technological change as dependent on corporate R&D in response to market conditions (Grubb et al. 2000).

2.2 Endogenous Technological Change

This model considers R&D investments as one of the main reasons for technological innovation which is a product of profit maximization. Endogenous technological change (ETC) incorporates the feedback of policies that alters the state and direction of technological change (Gillingham et al. 2007). Feedback takes the form of information from prices, research and development (R&D) or learning by doing (LBD).

The three most common models of endogenous technological change are the following: "direct price-induced, R&D-induced, and learning-induced" (Gillingham et al. 2007, p. 2738). Direct price-induced technological change implies that the changes of relative prices cause innovation because of the reduction of more expensive technologies (this is concordant with Hicks-induced innovation). R&D-induced technological change explains the change in rate and the direction produced by changes in R&D investments. Learning by doing (LBD) uses a unit cost of a technology as a decreasing function of cumulative output.

In the analysis of the relationship between energy, technology, and environment, there are two approaches: bottom-up and top-down models. Bottom-up models integrate the new technologies considering their cost and performance. In this context, technological change is a product of substitution of one technology for other technologies with better cost-efficiency performance (Loschel 2002). Since energy and price are regarded as exogenous, this analysis "may overestimate the potential penetration" (McFarland et al. 2004, p. 686).

Top-down models describe the energy sector in aggregate way by neoclassical theory. These models do not describe technologies (Loschel 2002), but represent technology in the aggregate production function.

The research associated with the theories described above focuses on environmental analysis. In this context, induced technological change has been explained by addressing environmental policies. Goulder and Mathai (2000) studied changes of technology (related to avoid CO_2 emissions—avoided cost) affected or induced by carbon-abatement policies. Their paper considers the R&D and learning by doing (LBD) approaches of knowledge accumulation. Using analytical and numerical models, the main conclusion is under the presence of induced technological change, the time profile of optimal taxes is lower.

There is a lot of research analyzing the relationship between policies and technological innovation focused on environmental policies. For example, Johnstone et al. (2010) use panel data patents among 25 countries to analyze the effects of environmental policies on technological innovation. This study uses a linear model where patents represent technological change as a dependent variable and policies, price, R&D, and consumption are the exogenous variables. Johnstone et al. (2010) conclude that there has been an increase in technological innovation among the 25 countries, and this improvement has been significant and positively affected by different environmental policies.

A theoretical review about induced technological change associated with energy, environment, and policy was made by Weyant and Olavson (1999). Also, Bosetti et al. (2006) use an endogenous model that emphasizes on learning by researching and learning by doing. Endogenizing technological change was empirically modeled by Pizer and Popp (2007) who focus on R&D process, learning by doing, and diffusion.

Theoretical analysis and empirical (statistical and econometrical) analysis have demonstrated that the government policies affect technological change following the endogenous theory. The empirical studies use the demand side and the supply side in order to explain technological change. In this context, empirical studies combine market analysis considering supply. Popp (1998) studies the impact of energy prices on technological innovation, specifically energy-efficiency innovation. Popp (1998) uses the number of patent citations in the USA to measure the state of knowledge and investigate market effects (demand- and supply-side factors). Additionally, Popp (1998) uses demand- and supply-side theories implying that technological change (energy-saving research) depends on the energy prices and the "usefulness of the existing stock of scientific knowledge" (p. 3). In this case, a linear relationship is used where the relative number of patent application is the dependent variable and the price of energy, marginal productivity, R&D investment, and other variables are determinant variables. The results show that energy price and the marginal productivity of R&D play an important role in technological innovation. Using the demand and supply side, Tsoutsos and Stamboulis (2005) argue that systematic innovation processes for diffusion of renewable technologies depend on successful policies.

Moreover, many researchers focused on the innovation of some specific technologies as the effect of renewable energy policies. For instance, Adelaja et al. (2010) analyze the case of the wind industry by using an empirical approach and focusing on state policies such as Renewable Portfolio Standards (RPSs). The results show that RPSs are not important drivers of wind technological change.

3 Methodology

In this chapter, an econometrical model, based on the induced endogenous technological innovation theory, has been developed. The empirical analysis is based on a theoretical model and then a co-integration analysis is done in order to analyze the short- and long-run patterns.

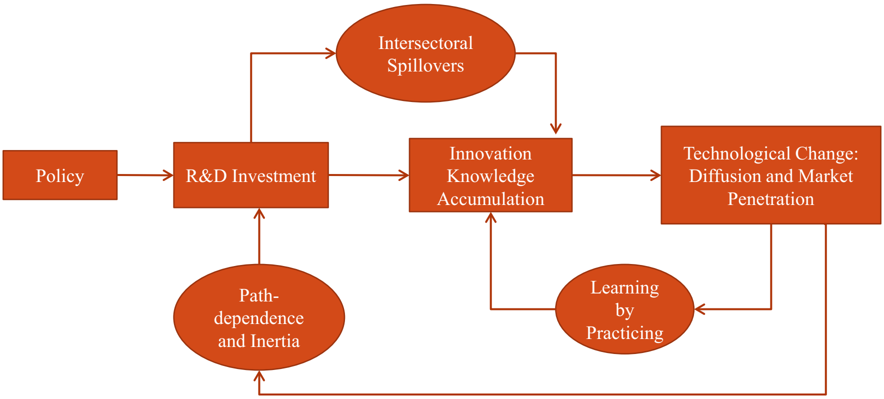

Fig. 1 Endogenous technological change. *Source*: Adapted from Weyant and Olavson (1999)

3.1 Theoretical Analysis

Formulated and based on induced endogenous technology change, there are indications that technological change is not exogenous but endogenous (Loschel 2002). In this context, the effects of policy and other variables are endogenously associated. The reason for not adopting an exogenous model is that exogenous assumptions of technological change are unresponsive to policy (Gillingham et al. 2007). Following an endogenous analysis, knowledge accumulation, research, and development expenditure are emphasized in the analysis, applying an additional endogenous function as shown below.

A top-down analysis is adopted since this model is appropriate for a long-run innovation analysis and gives important framework for knowledge accumulation and spillovers (Loschel 2002).

The dynamic process of technological change is shown by Weyant and Olavson (1999) as presented in Fig. 1.

Figure 1 shows that the technological change and market diffusion are preceded by knowledge accumulation, which interacts with the market by LBD. Policies and R&D investment affect knowledge accumulation first and then the technological change and technology adoption.

Adopting an endogenous analysis, R&D investment and policies play an important role in the knowledge accumulation, because R&D is an intangible asset to the firms' knowledge capital (Loschel 2002). In addition, electricity price is included in the model to analyze the relationship of this variable with technological change and knowledge accumulation. The main idea of the adoption of this variable is to analyze and prove the connection of this variable with endogenous modeling. Even though Gillingham et al. (2007) indicate that technological change does not follow an endogenous approach since policies and prices are historic, considering knowledge accumulation under different policies and market scenarios is important since there are retrofit effects.

Following the model of Goulder and Mathai (2000), the objective, as it is applied by Goulder and Mathai (2000), is to minimize the cost, choosing optimal patterns of abatement cost and R&D investment depending on knowledge accumulation. The objective function is represented as

$$\underset{A_t I_t}{\text{Min}} \int_0^a [C(A_t, H_t) + p(I_t) I_t) \mathrm{e}^{-rt} dt. \tag{1}$$

C represents the cost, A_t abatement, H_t knowledge stock, $p(.)$ real price of investment, I_t R&D investment, r interest rate, and t time.

The objective function depends on knowledge accumulation and it is subject to

$$\dot{H} = a_t H_t + k\varphi(I_t, H_t). \tag{2}$$

$\dot{H}$ is the knowledge accumulation and a_t and k the parameters.

This constraint is the function to focus on. Endogenous human knowledge capital accumulation is represented by the function φ and the autonomous part by αH_t.

H_t, the state of knowledge, can be represented by the number of patent applications. $\dot{H}$, the accumulation of knowledge or experience, can be represented by the cumulative number of applications of patents.

Therefore, the analysis is concentrated on (2). This Eq. (2) explains the transmission function where H and I determine the accumulation of knowledge through the function φ as represented below:

$$H, I \rightarrow \varphi \rightarrow \dot{H}$$

The function (2) is transformed and represented by a Cobb–Douglas function:

$$\dot{H} = H_t^a \, \varphi(I_t, H_t, Z)^k \tag{3}$$

Notice that the variable Z is added and represents other exogenous variables that can affect the knowledge change, such as policies or prices.

Applying natural logarithms to the function (3),

$$\text{In } \dot{H} = a_t \ln H_t + k \ln \varphi(I_t, H_t, Z) \tag{4}$$

Assuming that φ can be represented as Cobb–Douglas function as follows,

$$\varphi = M I_t^a H_t^b, Z_t^c \tag{5}$$

M is a parameter. Applying natural logarithms to (5),

$$\ln \varphi = \ln M + aI_{\mathrm{t}} + bH_t + Z_t \tag{6}$$

Replacing (6) in (4),

$$\ln \dot{H} = \propto \ln(H_t + k[\ln M + a\ln I_t +) b \ln H_t + c\ln Z_t]$$

Finally, grouping and renaming the parameters,

$$\ln \dot{H} = A\ln H_t + B\ln I_t + C\ln Z_t \tag{7}$$

It is important to notice that the parameters A, B, and C have different meaning comparing to the initial function. In this case, the knowledge accumulation depends on the stock of knowledge and R&D investment. This last relationship is linear and a co-integration analysis is recommended.

The variable Z_t represents other exogenous variables as price. Price-induced innovation is a theory which has been used to explain that changes in relative factor prices induce technology change, because of avoiding the use of more expensive inputs. This theory has microeconomic foundations explaining that there is a dynamic change in the production function caused by the changes in relative prices (Liu and Shumway 2009). The influence of prices is also explained by the demand-pull theories of innovation, for example, Popp (1998) mentioned that energy price makes new technology in energy efficiency more valuable. Therefore, higher energy prices from an efficient point of view will motivate to create or invent new technologies, which include renewable energy technologies.

3.2 Model Specification: Empirical Model

Modeling-induced endogenous technological change is complex because of the nonlinear characteristics and path dependency (Grubb et al. 2000). Therefore, a time-series econometric approach appears to be appropriate for this analysis. A time-series approach and properties presented by Liu and Shumway (2009), who recall the work of Thirtle et al. (2002), have been used. Therefore, the following arguments of the analysis are:

- The variables are not stable time series and co-integrated in the first order.
- There is co-integration among the variables.
- The positive and negative relationships among the variables following the hypothesis established above.
- There is a transmission effect from policies, R&D, and knowledge accumulation to the technology change and market adoption.
- The causalities are unidirectional and between variables.

Introducing the endogenous part into the model has been done in different ways. Most of the models include the endogenous term as a knowledge accumulation function. Also, other models, such as Schmidt et al. (2010), add lags in the explanatory variables.

The price of electricity is a variable that is considered in this analysis. The inclusion is important since market price plays an import role in technology adoption and diffusion. The variable price has been used by many scholars, especially in empirical analysis, like Johnstone et al. (2010), in the econometrical model.

The time-series modeling consists of the following analysis:

- Unit root test to see the stationality of the variables. The variables, as it will be shown below, are not stationary and first-order integrated.
- Co-integration analysis. Since each variable is not stationary in the first difference, along with the assumption of the long-run relationship among the variables, a co-integration analysis is made.
- Vector error correction model (VECM). The variables appear to be co-integrated and a VECM can be obtained in order to see the effects of these variables in the short and long run. Since policy dummy variables are used, the VECM considers these variables as exogenous variables.
- In addition to these analyses, transmission channel in VECM is used and coefficient test: Wald test is performed to see the causality among variables.

The policy analysis is performed by using dummy variables that represent the main federal and state policies regarding the electricity sectors. This is an ex post policy evaluation, but was not performed a structural test of the models to see if the policies have affected significantly the change in direction of technological change and adoption. Instead, the VECM and inclusion and significance in the model of the dummy variables will show if these polices have been affecting the dependent variables.

3.3 Limitations of the Study

The major limitation associated with the present analysis is associated with the data. Because renewable technology does not have long history, the size of data is constrained to 33 data points which can be considered a small sample size in a time-series analysis. The data availability is another factor associated with different variables. At the same time, the source or restriction of using the information is restricted or does not exist for public use. As a consequence, it is necessary to consider only the most representative government policies to be analyzed. Important policies, such as the National Energy Act of 1878 and Public Utility Regulatory Policies Act of 1978, could not be considered for mathematical econometrical reasons, because these Acts were enacted in 1978 and the data started in 1977 (considering the dynamic analysis and lag of variables).

Table 1 Variables and names

Variable	Name	Name (after taking natural logarithm)
Cumulative of number of patent applications	ACUMPATENTS	ACUM1
Number of patent applications (PCT applications)	PATENTS	PAT1
R&D investment in electrical renewable in million USD (2010 prices and exch. rates)	RDRENEW	RD1
Electricity generation from renewable (1,000 kWh)	RENEWGEN	GEN1
Average price of electricity (¢/kWh)	PRICEELECT	PRICE1
Energy Policy Act 1992	EPA1992	
Energy Policy Act 2005	EPA2005	
The American Recovery and Reinvestment Act 2009	ARRA2009	
Renewable Energy Certificates	REC	
Renewable Portfolio Standard	RPS	

Table 2 Main statistics of the variables

Variable	Mean	Median	Maximum	Minimum	Std. dev.
ACUMPATENTS	868.50	370.70	5,133.00	8.00	1,233.04
PATENTS	155.55	41.50	950.20	6.00	263.98
RDRENEW	510.60	305.96	2,228.14	166.66	483.47
RENEWGEN	668,948.20	915,837.00	1,468,394.00	34,349.00	471,374.60
PRICEELECT	13.41	13.26	16.72	10.79	1.94

3.4 Data and Variables

The definition and nomenclature of the variables used in the model are shown in Table 1:

The main statistics of the variables are shown below in Table 2.

The policies are dummy variables with one after each policy was enacted.

The federal policies considered in this paper are:

- ESA = Energy Security Act 1980
- EPA1992 = Energy Policy Act 1992
- EPA2005 = Energy Policy Act 2005

The state policies are:

- REC = Renewable Energy Certificates
- RPS = Renewable Portfolio Standard

Based on Fig. 2, there is no clear evidence of co-integration; however, a co-integration is conducted and the results were positive as the co-integration analysis shows. In the case of the price, the pattern has a negative relationship.

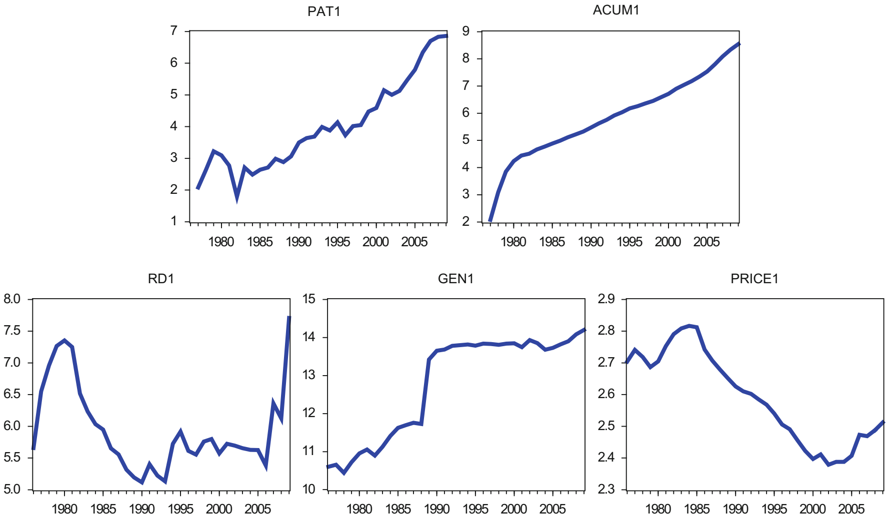

Fig. 2 Trends of variables (natural logarithms)

For the data of the number of patent applications, PCT number of patent applications from the OECD database was used. The PCT were preferred because of the availability of more years. The analysis is for US areas and the data size is considered from 1977 to 2009. The sources of data are OECD, IEA, and EIA.

4 Co-integration Analysis and Results

Applying the Granger causality test, as shown in Table 3, all expected causation direction among the variables were proved, except the relationship between the generation of electricity by renewable and R&D investment. In addition, the causation between price and generation is weak since the results are contradictory using different lags in the analysis.

By applying the augmented Dickey–Fuller test statistic, it is proved that all the variables are not stationary in the initial level and present unit root. At the same time, all the variables are stable and do not present unit root after their first difference. These results suggest a co-integration analysis (Table 4).

The results of the co-integration analysis based on the Trace statistics and Max-Eigen statistic are shown below. Both tests confirm that variables are co-integrated and have two co-integrating equations. Therefore, there is a relationship among the variables in the long run (Tables 5 and 6).

Based on the results, a vector error correction model is obtained. As is shown in the co-integration analysis, two co-integrated equations are considered. The results are shown in Table 7.

Table 3 Summary of causal test (pairwise Granger causality tests)

Variables	Hypothesis	Number of lags	*F* statistics	Prob.
ACUM1–PAT1	ACUM1 does not Granger cause PAT1	4	4.65	0.008
	PAT1 does not Granger cause ACUM1	4	1.35	0.287
RD1–PAT1	RD1 does not Granger cause PAT1	4	3.97	0.016
	PAT1 does not Granger cause RD1	4	2.29	0.096
GEN1–PAT1	GEN1 does not Granger cause PAT1	4	0.58	0.679
	PAT1 does not Granger cause GEN1	4	0.17	0.950
PRICE1–PAT1	PRICE1 does not Granger cause PAT1	4	0.40	0.806
	PAT1 does not Granger cause PRICE1	4	0.87	0.502
GEN1–RD1	GEN1 does not Granger cause RD1	4	0.55	0.698
	RD1 does not Granger cause GEN1	4	2.06	0.121
PRICE1–RD1	PRICE1 does not Granger cause RD1	4	2.78	0.053
	RD1 does not Granger cause PRICE1	4	2.20	0.104
PRICE1–GEN1	PRICE1 does not Granger cause GEN1	4	0.84	0.515
	GEN1 does not Granger cause PRICE1	4	2.65	0.062
PRICE1–GEN1	PRICE1 does not Granger cause GEN1	1	0.15	0.700
	GEN1 does not Granger cause PRICE1	1	6.42	0.016

The three equations indicate that there exist long-run effects. The R&D investment, electricity generated from renewable technologies, and price affect positively the number of patents. Meanwhile, analyzing the first error correction term (knowledge accumulation is not considered), the adjustment effects or feedback effects show that 72.6 % of the adjustment takes place in each period to go back to equilibrium levels. In the second error correction term (considering the knowledge accumulation), the adjustment is 18.8 % in each period. In the short run, the change in the number of patents is affected positively by all the variables including the policies.

In (9), there are long-run effects of the variables. Knowledge accumulation is positive, and the adjustment terms are at 21.7 % and 18.8 % levels. The variation of all the variables has positive effects on the variation of knowledge accumulation, except the variation of the number of patents.

The long-run relationship part in (10) shows that knowledge accumulation and price have not contributed positively to the generation of electricity using renewable technologies. However, R&D investments and number of patents affect positively the use of renewable technologies in the long run. It is important to notice that the adjustment speed to the equilibrium in this equation is 12.5 %, and it is slower than the other equations. Unlike the number of patents and knowledge accumulation, in this case, the policies have multiple results. The federal policy ESA and state RPS programs contribute to generation by using renewable technologies; however, the EPA1992, EPA2005, and REC show negative effects.

Using the equations above and the statistical significance and Walt coefficient significance, the following relation flow has been built:

All variables are not related to energy price. In addition, the relationship from R&D to generation is weak and only statistically significant at 10 %. However,

Table 4 Stationary test results: unit root summary

Variable[a]	Levels	Model	Augmented Dickey–Fuller test statistic		Durbin–Watson stat	Result
			t-Statistic	Prob[b]		
PAT1	Level	Trend and intercept	−1.853	0.655	2.075	Patents is not stationary, has unit root
	First difference	Trend and intercept	−6.929	0.000	2.063	Patents is stationary, no unit root
ACUM1	Level	Trend and intercept	−2.445	0.351	1.872	ACUMPATENTS is not stationary, has unit root
	First difference	Trend and intercept	−7.879	0.000	2.116	ACUMPATENTS is stationary, no unit root
RD1	Level	Only intercept	−2.136	0.233	1.743	RDRENEW is not stationary, has unit root
	First difference	Trend and intercept	−4.675	0.004	1.833	RDRENEW is stationary, no unit root
GEN1	Level	Trend and intercept	−1.262	0.880	1.857	RENEWGEN is not stationary, has unit root
	First difference	Trend and intercept	5.358	0.001	1.981	RENEWGEN is stationary, no unit root
PRICE1	Level	No intercept, no trend	−0.940	0.302	1.865	PRICEELECT is not stationary, has unit root
	First difference	Only intercept	−3.438	0.017	1.863	PRICEELECT is stationary, no unit root

[a]Natural logarithms of variable
[b]Null hypothesis rejected at 5 % significance

Table 5 Summary of co-integration test: unrestricted co-integration rank test (Trace)

Hypothesized number of co-integrated equations	Eigenvalue	Trace statistic	Critical value (0.05)	Prob.
None*	0.821	116.670	69.819	0.000
At most 1*	0.734	63.344	47.856	0.001
At most 2	0.360	22.330	29.797	0.281
At most 3	0.216	8.511	15.495	0.413
At most 4	0.031	0.975	3.842	0.324

* Significant at 5 % level
Trace test indicates 2 co-integrating equations at the 0.05 level
Rejection of the hypothesis at the 0.05 level

Table 6 Summary of co-integration test: unrestricted co-integration rank test (maximum eigenvalue)

Hypothesized number of co-integrated equations	Eigenvalue	Max-Eigen statistic	Critical value (0.05)	Prob.
None*	0.821	53.345	33.877	0.000
At most 1*	0.734	41.014	27.584	0.001
At most 2	0.360	13.820	21.132	0.380
At most 3	0.216	7.537	14.265	0.428
At most 4	0.031	0.975	3.842	0.324

* Significant at 5 % level
Max-Eigenvalue test indicates 2 co-integrating equations at the 0.05 level
Rejection of the hypothesis at the 0.05 level

technology accumulation and technology change do not have any relationship with the levels of generation (market). Therefore, technology diffusion appears to be disconnected from the entire system process and is only directly connected to the policies. These results can be explained because some policies are imposed directly to the market. The connection between federal and state policies and technology change is proven but federal policies does not affected yet to the process of knowledge accumulation. The results are shown in Fig. 3.

As Liu and Shumway (2009) say, the reason for some conflicting results could be explained by the data limitations. Furthermore, the gap between technology change and policies can be explained by the higher renewable costs, since external costs are taken into account (Tsoutsos and Stamboulis 2005). Another reason for no connection with the market is that the effects of energy prices on energy supply technologies are fast (Popp 1998), and the diffusion of new technology is not instantaneous and follows a learning process (Loschel 2002).

Another explanation of the lack of successful market penetration is explained by Nordhaus (2002) mentioning that in the market economies, the private sector determines the allocation of inventive activities. However, as Bielecki (2002) suggests, the possible effects of the improving competitiveness of renewable energy technologies may be seen after 2020.

Table 7 Vector error correction estimates (VEC)

Model 1

$\Delta(PAT1) = \beta1*(PAT1(-1) + 0.124*RD1(-1) + 0.237*GEN1(-1) + 5.216*PRICE1(-1) - 21.220) + \beta2*(ACUM1(-1) - 0.133*RD1(-1) + 0.238*GEN1(-1) + 5.901*PRICE1(-1) - 23.415) + \beta3*\Delta(PAT1(-1)) + \beta4*\Delta(ACUM1(-1)) + \beta5*\Delta(RD1(-1)) + \beta6*\Delta(GEN1(-1)) + \beta7*\Delta(PRICE1(-1)) + \beta8 + \beta9*ESA + \beta10*EPA1992 + \beta11*EPA2005 + \beta12*REC + \beta13*RPS$

	Coefficient	Std. Error	*t*-Statistic	Prob.
$\beta1$	−0.727	0.404	−1.801	0.089
$\beta2$	0.378	0.486	0.778	0.447
$\beta3$	−0.429	0.151	−2.847	0.011
$\beta4$	3.404	1.095	3.109	0.006
$\beta5$	0.025	0.176	0.140	0.890
$\beta6$	0.255	0.135	1.885	0.076
$\beta7$	0.843	1.749	0.482	0.636
$\beta8$	−2.208	0.803	−2.749	0.013
$\beta9$	0.490	0.541	0.906	0.377
$\beta10$	0.183	0.126	1.447	0.165
$\beta11$	0.517	0.203	2.548	0.020
$\beta12$	1.105	0.521	2.122	0.0479
$\beta13$	0.284	0.155	1.833	0.083

R-squared = 0.819; DW = 2.622

Model 2

$\Delta(ACUM1) = \beta14*(PAT1(-1) + 0.124*RD1(-1) + 0.237*GEN1(-1) + 5.216*PRICE1(-1) - 21.220) + \beta15*(ACUM1(-1) - 0.133*RD1(-1) + 0.238*GEN1(-1) + 5.901*PRICE1(-1) - 23.415) + \beta16*\Delta(PAT1(-1)) + \beta17*\Delta(ACUM1(-1)) + \beta18*\Delta(RD1(-1)) + \beta19*\Delta(GEN1(-1)) + \beta20*\Delta(PRICE1(-1)) + \beta21 + \beta22*ESA + \beta23*EPA1992 + \beta24*EPA2005 + \beta25*REC + \beta26*RPS$

	Coefficient	Std. Error	*t*-Statistic	Prob.
$\beta14$	−0.218	0.047	−4.638	0.000
$\beta15$	0.188	0.057	3.335	0.004
$\beta16$	−0.014	0.018	−0.808	0.430
$\beta17$	1.483	0.127	11.65	0.000
$\beta18$	0.024	0.020	1.156	0.263
$\beta19$	0.018	0.016	1.116	0.279
$\beta20$	0.289	0.203	1.419	0.173
$\beta21$	−0.453	0.093	−4.848	0.000
$\beta22$	0.268	0.063	4.266	0.000
$\beta23$	0.027	0.015	1.863	0.079
$\beta24$	0.074	0.023	3.130	0.006
$\beta25$	0.037	0.061	0.607	0.552
$\beta26$	0.066	0.018	3.689	0.002

R-squared = 0.981; DW = 2.622

Model 3

$\Delta(GEN1) = \beta27*(GEN1(-1) + 23.393*PAT1(-1) - 23.858*ACUM1(-1) + 7.239*RD1(-1) - 5.424*PRICE1(-1) + 7.647) + \beta28*\Delta(GEN1(-1)) + \beta29*\Delta(GEN1(-2)) + \beta30*\Delta(PAT1(-1)) + \beta31*\Delta(PAT1(-2)) + \beta32*\Delta(ACUM1(-1)) + \beta33*\Delta(ACUM1(-2)) + \beta34*\Delta(RD1(-1)) + \beta35*\Delta(RD1(-2)) + \beta36*\Delta(PRICE1(-1)) + \beta37*\Delta(PRICE1(-2)) + \beta38 + \beta39*ESA + \beta40*EPA\ 1992 + \beta41*EPA2005 + \beta42*REC + \beta43*RPS$

	Coefficient	Std. Error	*t*-Statistic	Prob.
$\beta27$	−0.125	0.057	−2.179	0.048
$\beta28$	−0.392	0.232	−1.690	0.115
$\beta29$	−0.460	0.239	−1.920	0.077
$\beta30$	0.548	0.768	0.714	0.488
$\beta31$	0.092	0.273	0.335	0.743
$\beta32$	11.900	7.871	1.511	0.155
$\beta33$	−0.421	3.384	−0.124	0.903
$\beta34$	0.833	0.468	1.780	0.099
$\beta35$	0.789	0.451	1.749	0.104
$\beta36$	4.664	4.336	1.076	0.302
$\beta37$	3.158	4.067	0.777	0.451
$\beta38$	−4.102	2.485	−1.650	0.123
$\beta39$	3.520	2.003	1.758	0.102
$\beta40$	−0.690	0.258	−2.671	0.019
$\beta41$	−0.142	0.330	−0.429	0.675
$\beta42$	−0.839	0.881	−0.952	0.359
$\beta43$	0.3321	0.286	1.161	0.267

R-squared = 0.519; DW = 2.075

The results for the long and short run are shown below:

Equation (8)

$$\begin{aligned}\Delta(PAT1) = & -0.726 * [PAT1(-1) + 0.124 * RD1(-1) + 0.236 * GEN1(-1) + 5.215 * PRICE1(-1) - 21.220] \\ & + 0.377 * [ACUM1(-1) - 0.132 * RD1(-1) + 0.23 * GEN1(-1) + 5.900 * PRICE1(-1) - 23.415] \\ & - 0.428 * \Delta(PAT1(-1)) + 3.403 * \Delta(ACUM1(-1)) + 0.024 * \Delta(RD1(-1)) + 0.254 * \Delta(GEN1(-1)) \\ & + 0.843 * \Delta(PRICE1(-1)) - 2.208 + 0.490 * ESA + 0.182 * EPA1992 + 0.516 * EPA2005 + 1.104 * REC \\ & + 0.283 * RPS\end{aligned}$$

Equation (9)

$$\Delta(\mathrm{ACUM1}) = -0.217 * [\mathrm{PAT1}(-1) + 0.124 * \mathrm{RD1}(-1) + 0.236 * \mathrm{GEN1}(-1) + 5.215 * \mathrm{PRICE1}(-1) - 21.220] \\ + 0.188 * [\mathrm{ACUM1}(-1) - 0.132 * \mathrm{RD1}(-1) + 0.237 * \mathrm{GEN1}(-1) + 5.900 * \mathrm{PRICE1}(-1) - 23.415] \\ - 0.014 * \Delta(\mathrm{PAT1}(-1)) + 1.482 * \Delta(\mathrm{ACUM1}(-1)) + 0.023 * \Delta(\mathrm{RD1}(-1)) + 0.017 * \Delta(\mathrm{GEN1}(-1)) \\ + 0.288 * \Delta(\mathrm{PRICE1}(-1)) - 0.452 + 0.268 * \mathrm{ESA} + 0.027 * \mathrm{EPA1992} + 0.073 * \mathrm{EPA2005} \\ + 0.036 * \mathrm{REC} + 0.066 * \mathrm{RPS}$$

Equation (10)

$$\Delta(\mathrm{GEN1}) = -0.125 * [\mathrm{GEN1}(-1) + 23.392 * \mathrm{PAT1}(-1) - 23.857 * \mathrm{ACUM1}(-1) + 7.239 * \mathrm{RD1}(-1) \\ - 5.424130477 * \mathrm{PRICE1}(-1) + 7.64] - 0.391 * \Delta(\mathrm{GEN1}(-1)) - 0.459 * \Delta(\mathrm{GEN1}(-2)) \\ + 0.548 * \Delta(\mathrm{PAT1}(-1)) + 0.091 * \Delta(\mathrm{PAT1}(-2)) + 11.895 * \Delta(\mathrm{ACUM1}(-1)) - 0.420 * \Delta(\mathrm{ACUM1}(-2)) \\ + 0.832 * \Delta(\mathrm{RD1}(-1)) + 0.789 * \Delta(\mathrm{RD1}(-2)) + 4.66 * \Delta(\mathrm{PRICE1}(-1)) + 3.157713962 * \Delta(\mathrm{PRICE1}(-2)) \\ - 4.101 + 3.519 * \mathrm{ESA} - 0.690 * \mathrm{EPA1992} - 0.141 * \mathrm{EPA2005} - 0.838 * \mathrm{REC} + 0.332 * \mathrm{RPS}$$

*The negative values in parenthesis are lags of the respective variable

Δ denotes the variation of the variable

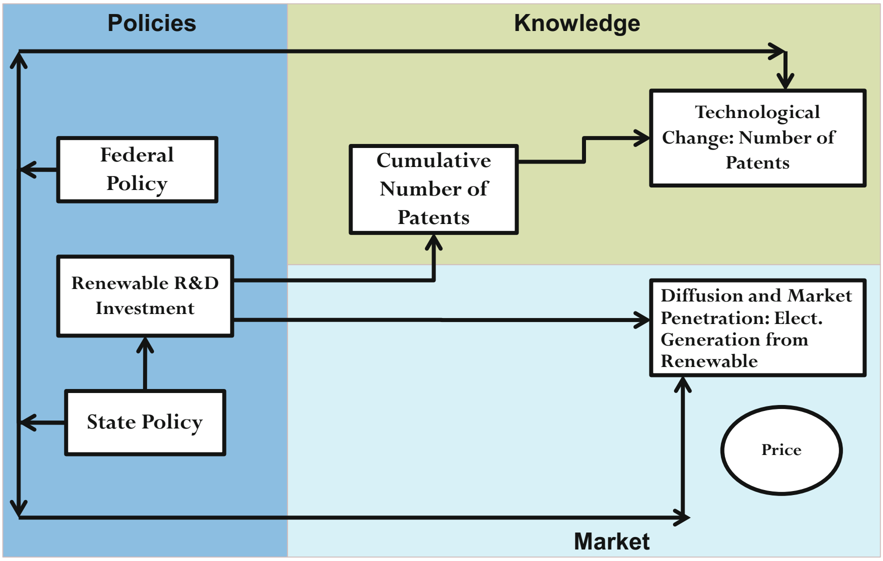

Fig. 3 Relationships in the dynamic process of technological change

5 Conclusions and Recommendations

Following an induced endogenous technological change model, a time-series analysis has been done. After the statistical analysis, it was found that the variables are stable in their first differences and co-integrated. Then three vector error correction models were obtained.

Because it is necessary to reduce energy security risk, the elimination of natural gas and coal in the electricity sector is important. The US government needs to promote new energy alternatives including incentives to switch the production of electricity from carbon plants to carbon-free technologies (Wirth et al. 2003). Diversification of technologies, such as renewable energy technologies, represents the government strategy; however, as the statistical analysis shows, renewable energy technologies are not yet competitive and not able to replace conventional energy sources.

The lack of significance and connection of the market variables to technological change and accumulation show that renewable energy technologies are not massively used in the electricity market in the USA. Despite the long-run relationship among variables showing the association of the patterns of variables, the short-run effects show problems that renewable energy technologies have entering the electricity market. There are many reasons for having this result which include high energy cost from renewable sources, dynamic of the diffusion phase and learning process, and decisions of the market sector for allocating investments.

The existence of a long-run relationship and the market disconnection are indicators (according to the statistical analysis) that the role of the US government is essential to promote technological innovation, especially related to commercialization. The government role is important to solve the problem of renewable energy technologies as well as the improvement of energy security. In the long and short run, policies should address oil substitutes, including electricity, when the market does not ensure the national security (Deutch et al. 2006).

Federal policies affect technological change and diffusion of technology through the market. However, they do not affect knowledge accumulation. This is congruent with what Johnstone et al. (2010) mention that environmental policies positively affect the improvement of renewable energy technologies. State policies have been affecting knowledge accumulation, technological change, and technology diffusion. To ensure more effective policies and to improve energy security, federal policies need to focus on integrating technological change. The knowledge stock needs to be used and be promoted by the federal and state policies simultaneously, connecting to knowledge accumulation and market incentives.

An important aspect in energy security is to apply the right policy and choose the optimal mechanism to promote renewable energy technologies. In this context, R&D investment needs to receive special attention, since R&D expenditures directly influence knowledge accumulation and technology diffusion. Therefore, state policies and R&D investments appear to be more crucial to improve renewable technologies.

As Tsoutsos and Stamboulis (2005) suggest, focusing on specific policies should be limited to niches and then integrated with the diffusion of renewable energy technologies and policies. Therefore, in order to eliminate the gap between technology and market, it is important to have specific policies about the market. The dissociation between the market and technological change does not depend only on policies, but other technological barriers – as indicated by Tsoutsos and Stamboulis (2005).

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Edwin Garces is a PhD student at the Department of Engineering and Technology Management at Portland State University. His interests are in the intersection of technology and economics for energy.

Tugrul Daim is an Associate Professor at the Department of Engineering and Technology Management at Portland State University. His research interests are in management of energy technologies.

An Overview of Energy Policy and Security in the Pacific Region

Shivneel Prasad, Veronika Schulte, and Pritika Bijay

Abstract Purpose The Pacific Island Countries (PICs) are especially vulnerable to problems associated with energy security as some of them are small island nations and some of them have no energy access. For this reason, energy security is extremely important for the Pacific region in order to improve the quality of life and welfare of people there. As a basis one option would be to adapt an energy policy in these countries at the same time as providing alternative sources of energy to meet energy needs, such as renewable energy sources.

Methodology This paper will give an overview of the existing energy policies in certain PICs and will highlight examples concerning energy security in the different PICs. It will also look into some of the ways that PICs are currently trying to increase energy security by highlighting examples of alternative sources of energy in the PICs.

Findings The present paper is a result of cooperation during the "Small Developing Island Renewable Energy Knowledge and Technology Transfer Network (DIREKT)," which is a cooperation scheme involving universities from Germany, Fiji, Mauritius, Barbados, and Trinidad and Tobago. The aim of this project is to strengthen science and technology capacity in the field of RE in certain African, Caribbean, and Pacific (ACP) small island developing states by means of

S. Prasad (✉)
Faculty of Science, Technology and Environment, College of Foundation Studies, The University of the South Pacific, Laucala Campus, Suva, Fiji
e-mail: prasad_sv@usp.ac.fj

V. Schulte
Faculty of Life Sciences, Research and Transfer Centre "Applications of Life Sciences", Hamburg University of Applied Sciences, Lohbruegger Kirchstraße 65, Sector 4S, Room 0.33, Hamburg 21033, Germany
e-mail: veronika.schulte@haw-hamburg.de

P. Bijay
Faculty of Science, Technology and Environment, School of Engineering and Physics, The University of the South Pacific, Laucala Campus, Suva, Fiji
e-mail: pritika_m@usp.ac.fj

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technology transfer, information exchange, and networking. The project is funded by the ACP Science and Technology Programme, an EU program for cooperation between the European Union and the ACP region.

Keywords Pacific island countries • Energy policy • Energy security

1 Introduction

The term Pacific Island Countries (PICs) describes many islands scattered widely across a large area of ocean, 1.8 % land and 98.2 % water (see Fig. 1) (Fifita 2012). The remoteness and diverse geographical nature of these countries combined with their heavy reliance on fossil fuels to meet their energy need make energy security a big concern for PICs. Lack of fuel diversity and indigenous fuel indicate the heavy reliance of PICs on fossil fuels (Singh 2012a).

Majority of the fossil fuel usage is in the transportation sector (~75 %); hence, reduction of fossil fuel reliance would have to target the transport sector. However, only a small portion (10 %) of the funding is provided for this sector (IRENA 2012). Lack of proper policies and regulations to guide the power generation by Independent Power Producers (IPPs) hinder progress (IRENA 2012).

PICs share many common socio-economic challenges which include lack of indigenous fossil fuel leading to poor fuel diversity. Limitations in technological infrastructure mechanisms provide a barrier in the development of their own renewable energy resources. Apart from technological challenges, lack of clear or non-existent energy policies in majority of the PICs also hinder advancements in renewable energy (RE). A good example of this is the policy of net metering, which has been largely successful in Cook Islands, Palau, and other PICs (IRENA 2012).

This paper gives an overview of the existing energy policies in various PICs demonstrating examples concerning the energy security in the different PICs. It will also look into some of the ways that PICS are currently trying to increase energy security by highlighting examples of alternative sources of energy in the PICs. In order to ensure that the PICs play their part in preserving their environment and, at the same time, ensuring energy security, most of the PICs have started to modify or, if they did not already have them, to introduce energy policies.

2 Energy Mix and Supply in Pacific Island Countries

PICs are heavily reliant on imports of fossil fuels to meet their energy demands, with ~25 % being used to meet power demands, while the remaining 75 % is used for transportation (Gielen 2012). Currently, more than 90 % (Table 1) of overall energy needs are met by fossil fuels. A study carried out by Asia Development Bank (ADB) indicated that the energy supply grew by a rate of around 4 % from 1990 to 2006 (SPC 2011). In 2009, the mix of fossil fuels (Table 1) comprised diesel, petrol, and kerosene, with the additional introduction of liquid petroleum gas (LPG).

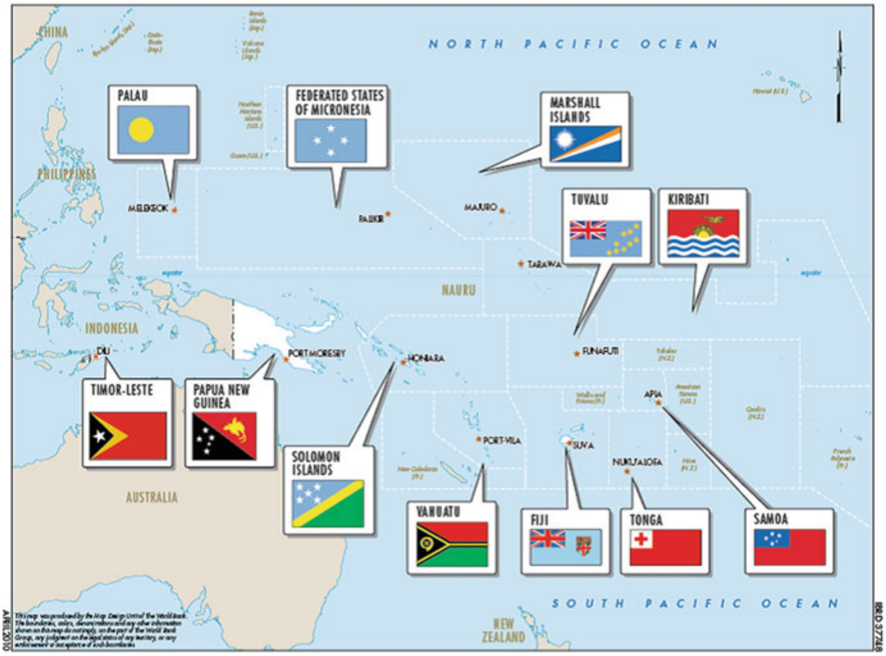

Fig. 1 Pacific Island Countries' geographical location (*Source*: http://www.theprif.org/)

More than one-third of Fiji's total import bill at the end of 2008 was accounted for by fossil fuels alone (Singh 2012b) and other PICs also spend similar amounts. Renewable energy (RE) currently accounts for 10 % of energy needs in PICs with most of them having less than 1 % of energy contributed by RE. The majority of RE contribution comes from the energy industry, so if one looks at the energy sector then RE contribution looks more significant. Figure 2 shows the major RE contributors in some PICs; the countries which are not represented have either an insignificant amount of RE contribution or no data is available for them.

The majority of the RE contribution for Fiji, FSM, and Samoa is from hydro with the rest of the contribution from solar, wind, and biomass when considering the PICs as a whole (Bijay et al. 2012).

3 Energy Security

Energy security is essential in ensuring economic and social stability as energy is required for almost all basic everyday needs such as transportation, education, and health care. Out of all of the PICs, only PNG has access to indigenous fossil fuels and exports oil (Fifita 2012). The rest of the PICS have zero fuel supply diversity and thus rely on imported fossil fuels to meet their energy demands (Fernstein et al. 2010). This can be better pictured by the percentage of GDP that PICs spend on fossil fuels (Fig. 3).

Table 1 Fossil fuel contribution to PICs' energy needs (Bijay et al. 2012; SPC 2012e, f)

Country	% of demand met by fossil fuels	Fuel mix
Cook Islands	99	12.7 million liters of diesel (7.2 million liters for electricity generation alone), 4.2 million liters of petrol, and 9.7 L of kerosene
Fiji	91	259 million liters of diesel, 58 million liters of petrol, 191 million liters of kerosene, and 16 kilotonnes of LPG
FSM	85	
Kiribati	75	
Nauru	99.95	11.7 million liters of diesel, 2.2 million liters of petrol, and 9.45 tonnes of liquid petroleum gas (LPG)
Niue	99	1.2 million liters of diesel (60 % used for electricity generation), 532 thousand liters of petrol, and 25.8 tonnes of LPG
Palau	99.95	25.6 million liters of diesel, 14.3 million liters of petrol, and 11.7 million liters of kerosene
Tonga	75	

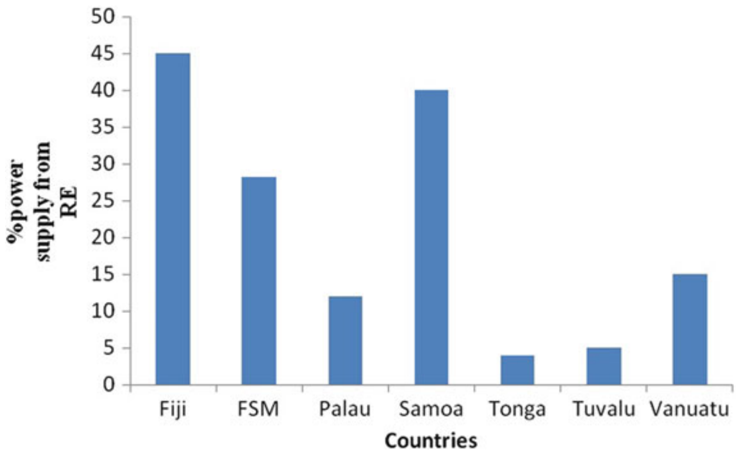

Fig. 2 Percentage electricity production from RE (according to Dornan 2012)

Figure 3 indicates that most PICs spend a considerable amount of their GDP on fossil fuels, from a minimum of 0 % spent by PNG to a maximum of ~70 % spent by Kiribati. The rest of the PICs spend between 5 % and 30 % of GDP on fossil fuels. The percentage of GDP spent on fossil fuels indicates the vulnerability of the PICs to fuel price increases and the negative effect this could have on them. This was noted in 2008 when the fuel price shot to over US$140 per barrel (Fernstein et al. 2010). Currently, the fuel price fluctuates around US$100 to US$140 per barrel (Fifita 2012).

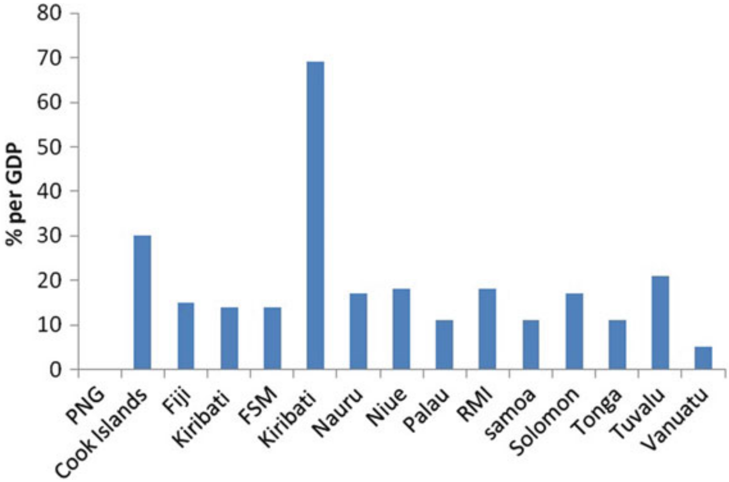

Fig. 3 Fuel import as a percentage of GDP (according to Fifita 2012)

Fuel imports contribute to a substantial proportion of the PICs' national imports and considerably outweigh exports, making them heavily reliant on external sources of financing, such as foreign investment or loans, in order to cope with fossil fuel price increase. If external financing is not available, then foreign reserves have to be drawn in order to cover the shortfall. PICs mostly keep 3–4 months of reserves to cover imports which if depleted will make international payment obligation difficult. Asian Development Bank (ADB) estimated that price increase of 30 %, from $61.8 per barrel to $80, would result in a loss of over 1 month's worth foreign reserves in most of the PICs (Davies and Sugden 2010).

Added to this, one should also consider the fuel supply chain and the remoteness of the PICs. Singapore is the main supply hub for New Zealand, Guam, Palau, and Fiji (Kumar 2010; SPC 2012f). Fiji and Nauru also import some of their fuel from South Korea (SPC 2012b, c). Palau obtains its fuel from Guam and Singapore, the Cook Islands from Fiji and New Zealand, Niue from New Zealand, and Kiribati from Fiji (SPC 2012a, b, c, d, e, f).

With this long supply route, the cost of fuel is further escalated when fuel is distributed amongst the PICs. The geographical nature of these island nations only adds further to the price of fuel due to the additional transportation costs in these countries. This not only adds to the increase in fuel prices but increases the prices of all products that have to be shipped out to the islands, making energy security not only related to fuel but to other basic needs as well (IRENA 2012).

In order to ensure an uninterrupted fuel supply, PICs have to store fuel. Each PIC has a different level of fuel supply security (Fig. 4), averaging at around 160 days, with Nauru accounting for the highest level of fuel supply security at ~650 days. The rest of the PICs apart from RMI and Palau are well below the average mark having fuel supply security of less than 3 months. This low level of fuel supply security indicates low energy security due to the fossil fuel dependency of PICs.

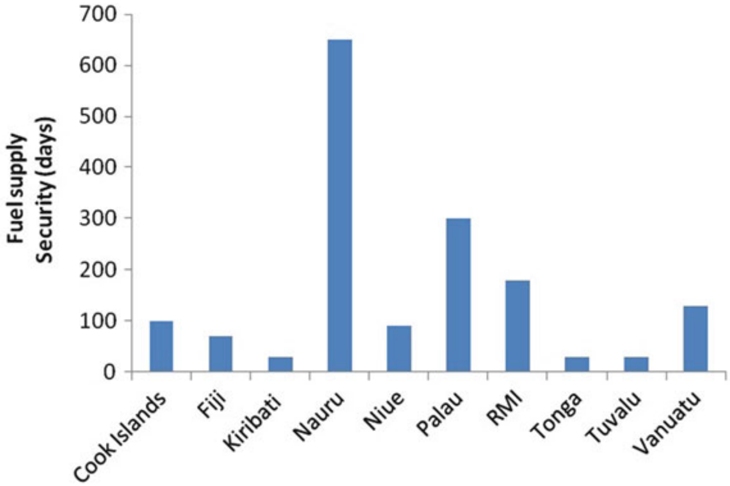

Fig. 4 Fuel supply security for the PICS (according to Fifita 2012)

This could cause a major problem if the fuel supply chain were to be disrupted by a natural disaster or other unforeseen circumstance.

Fernstein et al. (2010) stated that many PICs remained vulnerable due to no mitigation measures, such as petroleum supply contracts, which might limit risks and allow the PICs to take advantage of oil prices. Estimation by Asian Development Bank in 2009 using the United Nations Development Programme (UNDP) oil-price vulnerability index (OPVI) indicated that PICs were amongst the most vulnerable to oil-price volatility (Dornan and Jotzo 2012). The OPVI, reflecting local petroleum resources and oil-use intensity taking into account economic strength and resistance, were high amongst the PICs (UNDP 2007). The rises in fuel prices directly influence inflation in the PICs and tend to slow economic growth at the same time, hindering progress of the Millennium Development Goals (MDGs). It directly impacts the livelihoods of the Pacific islanders in the sense that increased fuel prices would not only affect energy but also increase the cost of food and other basic needs due to increased transportation costs (Davies and Sugden 2010).

Fuel supply is one part of energy security in PICs; energy access is another. Energy production in terms of electricity reaching the people is also another issue to be looked at. Electrification rates in PICs range from 100 % in the Cook Islands, Nauru, Niue, Palau, Samoa, and Tuvalu to a low of around 10 % in the Solomon Islands (Fifita 2012).

Thus, in order to tackle these issues, PICs need to diversify their energy production and reduce their dependency on fossil fuels.

4 Energy Policy in PICs

The first step PICs need to look into, in order to ensure energy security, is to modify or develop energy policies that address energy issues (Singh 2012b). The first regional energy policy developed in 2002 was the Pacific Islands Energy Policy and Plan (PIEPP) (Singh et al. 2012). PIEPP was to act as a guideline for the development of national energy policies as well as a means of coordinating energy programs for each PIC. It was reviewed in 2004 by the developers' Council of Regional Organizations of the Pacific (CROP) energy working group (EWG) and PICs and split into Pacific Islands Energy Policy (PIEP) and Pacific Islands Energy and Strategic Action Plan (PIESAP) (Wade et al. 2005).

It is acknowledged that, at a national level, many PICs have some form of national energy policy (NEP), a roadmap or energy documentation, which acts as a national energy guideline (Singh et al. 2012). The NEPs of the individual countries vary, with little modifications being made to factor in current initiatives to focus on energy security at regional levels as well as on the introduction of RE into the energy mix (Singh et al. 2012).

A NEP for PICs was developed with the help of PIESAP for 11 PICs with cabinet endorsement from only Fiji, Nauru, Niue, Samoa, the Solomon Islands, Tonga, Tuvalu, and Vanuatu (Zieroth 2008).

The first draft of the NEP for Fiji was drawn up in 2004. The document provided a view of Fiji's potential energy future (National Energy Policy Document 2004) by

- Identifying energy challenges and opportunities facing Fiji as a PIC
- Clarifying the government's strategic direction in energy policy
- Explaining how energy policies are to work in that strategic direction
- Identifying possible future initiatives for policy improvement

The NEP for Fiji was approved by the Fijian Cabinet in 2006, providing a common framework for all energy sectors, both private and public, to move forward in the direction of achieving overall growth and development of the economy by optimum use of energy resources (Fiji National Assessment Report 2010). It focused on

- Energy Planning—development and review of a regulatory framework. Coordination and consultation amongst energy and other sectors and management of energy information.
- Energy Security—ensure stable and adequate energy supplies to be achieved through the diversification of the energy base, in turn to be achieved by developing indigenous alternative energy and RE resources and encouraging energy efficiency.
- Power Sector—ensure a 100 % electrification rate by extending the local grid, stand-alone systems, and involvement of the private sector in energy production.
- Renewable Energy—focus on promoting the use of appropriate RE technologies by providing incentives, researching local RE resources, and adapting RE standards for local use.

Singh (2012b) stated that as a result of the NEP, Fiji had embarked upon developing its own biofuel industry, establishing its own biofuel standards in line with the Worldwide Fuel Charter and the International Fuel Quality Center's recommendations. In addition, phase one of getting an accredited lab has been completed, and guidelines for biofuel transportation and storage have been established (Singh 2012b).

A draft NEP for Palau was written in October 2009 and implemented in August 2010 (http://www.reeep.com, 2012). The vision of this policy was to encourage the

- Improvement of institutional arrangements for energy sector management and creation of an energy administration to implement measures in the NEP and its related strategic action plan
- Use of energy efficiency in order to reduce national energy consumption
- Use of RE technologies and simultaneous reduction in Palau's dependency on fossils

A similar structure to PIESAP was followed by PICs in drafting their NEPs, providing broad policy frameworks, supporting large grids, supplying urban areas and rural electrification policies, and providing small-grid or stand-alone electrification schemes (Singh 2012a). It has been made clear that the PIEEP had several underlying flaws which presented serious barriers to the successful implantation of the plan (Singh et al. 2012). The PIEEP was largely unsuccessful in delivering its objective of coordinating regional energy sector planning and programs of regional organizations due to lack of clear vision for regional energy programs and the uncertainty of the role of Secretariat of the Pacific Community Applied Geoscience and Technology Division (SOPAC) as the lead agency (Singh et al. 2012).

By 2009, there was a need to replace PIEP since it was not properly addressing the energy issues or the vulnerability of PICs due to rising oil prices. An urgent need to increase energy security and efficiency led to the development of the Framework for Action on Energy Security in the Pacific (FAESP) at the 40th Pacific Islands Forum in Cairns, 2009 (Singh 2012a). A whole-of-sector approach (WOSA) was adopted by FAESP recognizing the need for continued dependency on fossil fuel in the future as well as highlighting and paving a way for developing NEP in PICs (SPC 2011). FASEP was formulated, keeping in mind the various stakeholders that contribute to energy security, and is based on 11 guiding principles which allow stakeholders to work together and with the PICs. The guidelines take into account sustainable livelihoods, climate change, and gender and cultural issues as well as the need for improved planning, capacity development, and energy efficiency. It embodies seven themes to help improve energy security (SPC 2011):

1. Leadership, governance, coordination, and partnerships

    - The "many partners, one team" approach, highlighting the need for cooperation between energy providers and for facilitators in the government and private sector to work together.

2. Capacity development, planning, policy, and regulatory frameworks
   - The importance of vision and planning provided by an effective policy to help create an energy-secure Pacific, as well as building capacity in terms of human resources.
3. Energy production and supply
   - Energy supply will come from fossil fuels as well as RE sources. Thus emphasizing that energy security can be improved by proper management and availability of indigenous and imported sources, making it affordable for all.
4. Energy conversion
   - FASEP acknowledges electric power as a significant secondary source of energy and the importance of reliable and efficient generation and supply of electricity from various sources.
5. End-use energy consumption
   - FASEP acknowledges the need for proper use and effective conversion of energy, especially in transport, which includes drafting standards, labeling appliances, and drafting building codes.
6. Energy data and information
   - The need for collaborative collection of data on energy and the need for a regional energy databank based on a common set of indicators to assess the energy sector.
7. Financing, monitoring, and evaluation
   - The importance of proper financing in the energy sector.

FASEP is associated with the Implementation Plan for Energy Security in the Pacific (IPESP) which links directly to the implementation of FASEP, helping it achieve its long-term objectives and key priorities. IPESP includes indicators, set targets, and milestones for specific regional strategies for each theme in order to enable the impact and effectiveness of measured regional responses with the desired outcome of providing a strengthened contribution to energy security at a national and regional level (SPC 2011).

The WOSA has been used to formulate the Tonga Energy Road Map (TERM), the new national energy policy for Tonga, which identifies several development partners: the Government of Tonga (GoT), Tonga Power Limited (TPL), and other partners. These partners come together with other stakeholders around a common agenda (Singh et al. 2012; Fernstein et al. 2010; TERM 2010). TERM is aimed at reducing Tonga's vulnerability to oil-price fluctuations and reducing its reliability on fossil fuels. It identifies policy gaps and, at the same time, overlaps into Tonga's existing energy policies, legislation, and energy industry regulations whilst also serving as a guideline for the GoT, TPL, and other stakeholders (TERM 2010).

5 What Are PICs Doing to Ensure Energy Security?

To ensure energy security and that the PICs are in line with energy policy, both at a regional level as well as national level, PICs are trying to increase the use of RE in the energy mix as well as improve energy efficiency to reduce energy consumption. RE resources and technologies, such as solar, wind, or hydropower, have the potential to reduce dependency on fossil fuels and are thus a way for PICs to increase their energy security by integrating them into their energy mix. Most PICs possess RE resources in abundance as seen in Table 2, with the RE sources of the most interest to PICs being solar, hydro, wind, biomass, and biofuel (Syngellakis 2012).

Currently, most PICs use RE in electricity generation and as such are ensuring a more energy-secure future. Targets have been set to increase the contribution of RE in the area of electricity generation (Table 3). Targets range from a low of 20 % to a maximum of 100 % to be met by PICs by 2020.

Hydropower is a proven RE source and is being readily implemented by countries with hydro potential. Hydropower has been providing diversity in the electricity sectors of Fiji, French Polynesia, New Caledonia, Papua New Guinea (PNG), Samoa, the Solomon Islands, and Vanuatu (Marconnet 2007).

Use of solar power is increasing due to the geographical nature of the PICs, with solar thermal mostly being used for water heating. Considering power generation, use of solar photovoltaic (PV) is increasing due to the decline in the cost of PV technology and rising fuel prices. Home solar systems are being used in Kiribati, Tuvalu, Fiji, French Polynesia, PNG, the Solomon Islands, and Micronesia to provide electricity to remote locations, offsetting the use of fossil fuels (Weir and Prasad 2012). Grid-connected PV has also been introduced in PICs, with the largest PV system, with a rated peak power of 1.3 MW, being commissioned in Tonga in July 2012 (Bijay et al. 2012). Fiji has two grid-connected systems which became operational in 2011 and 2012 with rated capacities of 12 kW and 45 kW respectively (Nanjangud 2012). Grid-connected systems were also implemented in FSM, Nauru, Niue, Palau, and the Marshall Islands as part of the REP-5 program (REP-5 2010).

The use of wind power is also on the increase in PICs, with systems being installed in the Cook Islands, Fiji, Vanuatu, New Caledonia, French Polynesia, Hawaii, and PNG (Marconnet 2007; Andrieu and Pesnel 2006). Butoni Wind Farm, commissioned in 2007, was Fiji's first wind farm, has a total installed capacity of 10 MW, and has already provided total savings of approximately FJD 2.13 million for Fiji (FEA 2012) (Fig. 5).

Biofuels can be used for electricity generation or transportation and show great potential in providing fuel diversity to PICs. Singh (2012b) and Woodruff (2007) highlighted how the use of coconut oil and ethanol could help diversify fuel usage in PICs.

Apart from RE, energy efficiency (EE) is also playing a major role in reducing fossil fuel imports. EE measures were implemented by the Pacific Islands Forum

Table 2 Resource potential in the PIC (Syngellakis 2012)

Country	Solar	Wind	Biomass	Hydro	Geothermal	OTEC	Wave
Cook Islands	✓✓✓	✓✓	✓✓			✓✓	✓
Fiji	✓✓	✓✓	✓✓✓	✓✓✓	✓✓✓	✓✓	✓✓
FSM	✓✓	✓	✓✓	✓✓	✓✓	?	?
Kiribati	✓✓✓	Unlikely	✓			✓✓	?
Marshall Island	✓✓✓	✓	✓			✓✓	?
Nauru	✓✓✓	Unlikely	✓			✓✓	?
Niue	✓✓✓	✓✓	✓			?	?
Palau	✓✓✓	✓	✓✓			?	?
PNG	✓✓	✓✓	✓✓✓	✓✓✓	✓✓✓	?	?
Samoa	✓✓	✓✓	✓✓	✓✓	✓✓	?	?
Solomon Islands	✓✓	✓✓	✓✓✓	✓✓✓	✓	?	?
Tonga	✓✓✓	✓✓	✓			?	✓✓
Tuvalu	✓✓	Unlikely	✓✓			?	?
Vanuatu	✓✓	✓✓	✓✓✓	✓✓✓	✓✓✓	?	?

Note: ? means no data available

Table 3 Current and projected targets for RE electricity generation in PICs (*Source*: Gielen 2012)

Countries, territories, and associated states	Current RE electricity generation (% of total)	RE targets (% of total)	Year
Cook Islands	<1	50	2015
		100	2020
Fiji	75	90	2015
FSM		Urban 10 and rural 50	2020
Kiribati	<1	10	ND
Marshall Islands	1	20	2020
Nauru	<1	50	2015
Niue	3	100	2020
Palau	3	20	2020
PNG	46	No target set	
Samoa	42	+20	2030
Solomon Islands		50	2015
Tokelau	1	100	2012
Tonga	<1	50	2012
Tuvalu	25	100	2020
Vanuatu	19	25	2012

Secretariat (PIFS) and funded by the 9th European Development Fund (EDF9) as part of the REP-5 (2010) program in Nauru, Niue, the Republic of the Marshall Islands, the Federated States of Micronesia, and Palau. EE awareness campaigns have also been conducted with some PICs including EE in their NEP. EE is also acknowledged in the fourth and fifth themes of FASEP to improve energy security in PICs.

A number of other organizations are also actively engaged in the PICs in order to assist in the transition of RE developments. One of these organizations is

Fig. 5 Butoni wind farm in Fiji

International Renewable Energy Agency (IRENA). A meeting of Pacific Island leaders, in Abu Dhabi last January 2012, led to the endorsement of proposed IRENA activities for the Pacific region. Some of these activities included (IRENA 2012)

- Mapping the RE readiness of the PICs
- Creation of a repository of knowledge of relevant technologies
- Assessment of grid-stability issues
- Integration of the activities into a coherent roadmap for PICs

Another such initiative is the United Nations "Sustainable Energy for All" (SE4ALL) which has aims to ensure universal access to modern energy services, doubling the global rate of energy efficiency improvements and share of RE into the global energy mix. SE4ALL initiative has been joined by more than 50 developing countries with these countries initiating or already having completed rapid assessments to help the determination of opportunities and challenges to fulfill the three aims (http://www.sustainableenergyforall.org).

6 Conclusion

Currently, more than 90 % of energy demands are met by fossil fuels alone, with RE playing a very minor part, mostly in electricity generation. A large percentage of the PICs' GDP is spent on importing fossil fuels, which indicates the vulnerability of PICs to rises in the price of fossil fuels as well as the negative effects these could have on their economies.

Energy security is a major concern for PICs due to their remoteness from the fuel supply chain as well the PICs' dependency on fossil fuels to meet their energy needs. The long supply chain only adds to the cost of fuel, which is further escalated when fuel has to be transported internally within the countries. Also most of the

PICs have fuel supply security of less than 3 months which, if supply were disrupted, would cause a huge energy disaster for these PICs.

Added to this is the geographical nature of PICs, making it hard to provide 100 % electrification in all PICs, with some PICs having low electrification of around 10 %.

In order to combat energy security issues, PIEEP, the first regional energy policy, was developed in 2002. PIEEP was split into PIEP and PIESAP in 2004, with the NEPs for eleven PICs being developed with the help of PIESAP. However, Cabinet endorsement was only received in eight of these countries. The NEPs of most PICs followed a similar structure to PIESAP and provided broad policy frameworks supporting large grids as well as schemes for rural electrification policies. However, PIEEP was largely unsuccessful in meeting some of its goals due to a lack of clear vision and leadership. FASEP, which employed a WOSA, was developed after the 40th Pacific Islands Forum in Cairns, 2009. It acknowledges the extension of the dependency on fossil fuels into the future as well as paving a way for the development of better energy security in NEP. It has 11 guiding principles and embodies seven themes to improve energy security. The themes embrace the WOSA and highlight the need for stakeholders in the public and private sectors to work together. This WOSA was used to formulate the TERM, which saw several stakeholders come together around a common agenda: energy security.

Energy policy is one step towards an energy secure future for PICs. Included within this is the need for RE to play a part in diversifying the energy mix, with this being clearly highlighted in FASEP and most of the PICs' NEPs. This has been recognized by the PICs, with them setting RE targets to be met in the future, from as low as 20 % to a maximum of 100 %, to be met by 2020. To reach these goals, the PICs are increasing the use of RE in the electricity generation mix. Solar and wind are the new, upcoming RE technologies that are making their mark in PICs. EE also plays a role in reducing the use of fossil fuels to increase fuel supply security.

Properly formulated NEPs and escalated use of RE and EE would see the energy security of the PICs increase in the near future. Together with this, initiatives and organizations such as SE4ALL and IRENA, respectively, with their continued engagement in PICs in development of RE and EE could lead to a more energy-secure future.

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Shivneel Prasad holds a Master of Science in Physics and Bachelor of Science Degree in Physics and Mathematics from the University of the South Pacific (USP) in Fiji. Currently, he is the Acting Subject Coordinator for Foundation Physics at the College of Foundation Studies, USP. His research interest includes renewable energy, energy efficiency, and climate change.

Pritika Bijay holds a Master of Science in Physics and Bachelor of Science Degree in Physics and Mathematics from the University of the South Pacific (USP) in Fiji. She is also working as Project Manager for an ACP-EU-funded project called Small Developing Island Renewable Energy Knowledge and Technology Transfer Network (DIREKT). Her research interest includes renewable energy, energy efficiency, and climate change.

Veronika Schulte is a Biologist and works at the Hamburg University of Applied Science in Germany in the Research and Transfer Centre “Applications of Life Sciences.” She is coordinating several EU-funded projects on technology transfer and development cooperation in the renewable energy sector in Latin America as well as African, Pacific, and Caribbean small island development states.

The Evolution of the Spanish Energy System in the Context of Energy Security: Current Trends, Future Developments

Rocio Valdivielso del Real

Abstract **Purpose** The aim of this chapter is to examine the main challenges that the Spanish energy system is facing in the context of energy security regarding the reduction in dependence toward foreign sources of energy and the development of a sustainable strategy with a view to suggest recommendations regarding the design of future energy policies.
Design/Methodology/Approach This chapter provides an analytical overview of the evolution of the Spanish energy system during the last decade. It also presents the results of a prospective analysis of the evolution of the Spanish energy system until 2030. The findings are presented and classified according to sources of energy, role of governmental policies, and their impact on the dependency of Spain on foreign sources. The data for this study was collected from a wide variety of sources: research reports, regulations, European Union documents, position papers, press reports about the energy policy in Spain, and companies' documents—i.e., annual reports and other public documentary sources.
Findings The findings reveal the presence of changes in the importance over time of different sources of energy in Spain. The overview of different scenarios highlights the role of state regulation in the evolution of the Spanish energy system in regard to foreign dependency and the achievement of a better path toward energy security and sustainability in the future.
Practical Implications The analysis of the Spanish energy sector highlights the presence of policy shortcomings in regard to dependence on foreign sources of energy and its consequences for energy security as well as the sustainable character of the Spanish energy system. This chapter provides insights on the trade-offs confronted by domestic policymakers that represent a starting point for further research.

R. Valdivielso del Real (✉)
Centre for the Study of Globalisation and Regionalisation (CGRS), University of Warwick, Coventry CV4 7AL, UK
e-mail: R.Valdivielso@warwick.ac.uk

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Originality/Value This chapter provides a comprehensive overview that illustrates the characteristics of the different components of the energy sector in Spain. It generates suggestions regarding the problems that the Spanish energy model must confront to satisfy current needs without compromising options for future generations in energy security. The analysis presented in this chapter could be used for exploring alternative views in the current public policy debates on energy policy and security in Spain.

Keywords Spain • Energy policy • Energy security • European Union • Environmental impact • Climate change • Sustainability

1 Introduction

The adequate supply of energy constitutes an important element for the proper functioning of the economy and society as well as being an intrinsic component of overall security across countries. The importance of energy security covers many different energetic sources as it is no longer limited to oil (IEA 2011c, 2012; Labandeira and Manzano 2012; Winzer 2012). While the negative implications associated with potential gaps between energy demand and supply are not new, the uncertainties regarding the ability of governments and companies to ensure the provision of energy at reasonable prices have increased in recent years (see Goldthau and Martin Witte (2009) for a critical overview). The current equilibrium between demand and supply of energy at the world level is increasingly difficult to sustain in the medium and long term. Both the guarantee of fossil fuel supply and its price could be exposed to significant tensions in the coming decades. Contributing factors to this situation include the high demand from emerging economies, such as China, and the concentration of oil and gas deposits in politically unstable areas such as the Middle East. Moreover, environmental factors are also important in the strategic analysis of the equilibrium between energy demand and supply, such as the risk of disasters while extracting reserves that are difficult to access and the need to reduce greenhouse gas emissions.

This situation is a serious concern for countries with a high degree of energy dependence such as Spain where oil accounts for almost half of consumed energy and natural gas accounts for nearly one-fourth (Ministerio de Industria, Energía y Comercio 2011). The Spanish energy dependency has serious implications for security. Any major disruption of supply—i.e., due to a serious international geopolitical event—could have repercussions in strategic sectors (Gobierno de España 2011). Moreover, the Spanish case is also interesting in regard to energy security given the presence of unresolved issues with domestic sources of energy production. First, the use of coal as a source of energy is increasingly challenged on grounds of environmental damages (Rabanal 2009). The continuing use of coal could lessen Spanish energy dependence but requires the implementation of technological innovations in order to reduce its polluting emissions. Second, the Spanish economy is experiencing an important economic slowdown after a decade of rapid economic growth. Growth slowed from 3.7 % in 2007 to 1.2 % in 2008 and the economy has contracted by several percentage points 0.1 % in 2010 (OECD 2010). Unemployment has increased from 9 % in 2007 to more than 23 % in 2012. The implication of the changing macroeconomic situation is that the Spanish state is financially constrained, thereby potentially limiting its ability to provide monetary incentives for energy companies.

The aim of this study is to provide insights and generate suggestions regarding the problems faced by the Spanish energy model in order to satisfy current needs without compromising options for future generations in energy security. The overview presented in this chapter could serve as an analytical tool for exploring alternative views in the current public policy debates on energy policy and security in Spain. Therefore, this paper builds upon the insights of previous studies about the prospective scenarios of energy security and sustainability in Spain (see Foidart et al. 2010; IEA 2009; Linares et al. 2008; Linares 2012; López-Peña et al. 2011; Németh et al. 2009).

This chapter examines the main challenges that the Spanish energy system is facing for the development of a domestic-based sustainable strategy with the provision of insights regarding the development of future energy policies. This chapter is divided into three parts. The first one consists of a brief overview of the energy challenges faced by member states at the EU level. The second part provides a diagnosis of the Spanish energy context. The energy security and sustainability problems of the current energy model are addressed, and the results of recent prospective analysis are introduced. The final part is devoted to a review of a prospective analysis of the Spanish electricity sector with an understanding of some of the mechanisms of response that are available in order to build a more secure and sustainable future in the energy context in Spain.

2 Background: The European Energy Context

Security concerns are increasingly important in the formulation of the energy policy of advanced industrialized countries. All aspects of daily and corporate life are shaped by the importance of energy issues. The levels of anxieties and uncertainties regarding the ability of governments (and companies) to guarantee the provision of energy at reasonable costs have experienced an upward trend in recent years.

European energy policy, in the overall context of global energy, confronts several coexisting challenges: the security of energy supply, the continuing access to an extensive freedom of choice for consumers at affordable prices, efficiency in energy production, the sustainability of the environmental impact associated with the production of energy, and the maintenance of the competitive position of the EU without the presence of market failures (Pérez-Arriaga and Barguin 2009).

The achievement of these objectives in the long term, however, is contingent upon their sustainable character—i.e., dependable access to primary energy sources, adequate infrastructures to produce and transport electricity in a reliable way, energy production without irreparable environmental damage, and fair/universal access to modern forms of energy supply in Europe and worldwide. In other words, the objective is to deal with security and competitiveness concerns over energy supply via the development of a more sustainable, efficient, and diverse energy mix (European Commission 2006a). The latter originates from secure and low carbon energy sources through innovation policies—a strategy reflecting that some of the world's most successful renewable energy companies and research institutions are in Europe (European Commission 2006b). Furthermore, the Energy Roadmap 2050 designed by the European Commission goes further by investigating the challenges that arise from the EU's 2050 decarbonization objective while at the same time ensuring security of energy supply and competitiveness (European Commission 2011).

Prospective studies are providing interesting insights into the workings and future of the European energy model (see Capros and Mantzos 2009; IEA 2011a). In Capros and Mantzos (2009), the reference situation is provided by a "Business as Usual" (BaU) or baseline scenario. The latter is characterized by a continuation of current trends and policies in regard to present and expected demand growth without additional measures of energy saving and efficiency, the unequal world distribution of energy sources, and inadequate effort in research and development (R&D) in energy, a continued rate of depletion of fossil fuel resources, the potential for insufficient investment in generation of electricity and network capacity, and inadequate efforts to curb climate change.

There are some informative aspects associated with the BaU scenario. First, important improvements in energy efficiency (demand and supply sides) are likely to lead to an annual decrease of 1.7 % in energy intensity of the EU 25. This scenario is seen as credible due to changes in the structure of the EU industry and the saturation of the demand for some important energy needs that result from policies already in place. Second, the absence of severe energy shortages has been forecasted for the next 20 years. The situation at a later date, in contrast, is characterized by greater uncertainties regarding the magnitude of fuel reserves. In the specific case of oil, peak production forecasts roughly extend to 2030. The growth in the consumption of oil will be made possible by an increase in imports, namely, from 47.2 % in 2000 to a forecasted value of 67.3 % in 2030. Concerns about security of supply have been driven by the concentration of oil and gas production in a small number of countries characterized by significant political uncertainty and risk. Third, improvements in environmental sustainability are likely to increase with the exception of carbon emissions.

To summarize, the main challenges of the EU energy policy in the short term are:

- The security of energy supply that reflects a high degree of dependence on imports of natural gas and oil (high volumes of imports from unstable regions) and the needed investments in infrastructures in order to ensure the adequacy of electricity supply
- The crucial role of electricity generation and transportation in tackling the problem of carbon emissions to meet climate change policy objectives

- The inability of existing policies to fully support the development of renewable energies
- The presence of high degrees of uncertainties in the future of nuclear energy after 2020

Alternative scenarios could be conceptualized in the event of the implementation of policies that would provide greater support to renewable energy, higher efficiency in final uses, greater public legitimacy toward nuclear energy, higher rates of taxation on carbon, and greater financial support for the development of new technologies (such as a carbon sequestration or hydrogen-based devices) (Pérez-Arriaga and Barguin 2009). According to Capros and Mantzos (2009), the implementation of the above policies could lead in a drop of more than 25 % of carbon emissions by 2030 as compared with 1990, one-third of the energy produced would come from carbon-free sources, and the import dependency ratio could be maintained at 55 % instead of 70 % or more in the business-as-usual scenario.

3 The Spanish Energy Context

3.1 Spain Before the Financial Crisis

The Spanish economy has enjoyed relatively high economic growth rates before the global financial crisis. Gross domestic product (GDP) grew at a 3.7 % cumulative annual rate, higher than the EU average. Moreover, total population in Spain increased by almost five million between 1996 and 2006. As a result of these factors, domestic energy consumption grew at a 3 % cumulative annual rate between 1995 and 2006 (Németh et al. 2009).

Energy intensity in Spain has increased since 1990 and has been relatively higher than the rest of the EU-15 member states (EU-15). Mendiluce et al. (2010) highlight that this aspect was driven by strong transport growth, the increase of activities linked to the construction boom, and the convergence to EU levels of household energy demand. Nonetheless, the overall level of energy consumption in Spain was still around 20 % lower than in Europe during the period 1995–2006 (IEA 2006).

In terms of greenhouse gas (GHG) emissions, the fast rate of economic growth in Spain resulted in a strong increase in emissions since 1990. The emissions increased by 52.6 % in the period 1990–2006 in the context of the Kyoto target for Spain being at 15 %. Nonetheless, the GHG emissions per capita in Spain remained 7 % lower than the EU-15 average in 2006 (EEA 2007).

Another distinctive feature of the Spanish energy system has been the increased share of domestic consumption of natural gas. It rose from 8 % to 22 % in the period 1995–2006, thereby reflecting a cumulative annual growth rate of 13 % in natural gas consumption (Németh et al. 2009). In particular, gas consumption has been important for electricity generation.

Spain is one of the European countries endowed with low fossil energy resources. Domestic energy sources are relatively scarce with the notable exception of coal and nuclear energy which has been produced domestically in significant amounts. For instance, the primary energy demand amounted to 145 million tonnes of oil equivalent (Mtoe) in 2005 (129.9 in 2009), of which merely 32 Mtoe (28.9 in 2009) were domestically produced (almost half nuclear, a fifth coal, 7 % hydraulic, and 14 % other renewables). As a result, the combination of growing energy demand and limited energy domestic production meant that imports increased 53 % between 1995 and 2005, a figure amounting to 4 % of GDP. Gas imports experienced the highest growth (284 %), followed by coal (60 %), and oil (24 %). In 2005 the degree of dependency on energy supply was 80 %, which constitutes an increase of 10 % points from 1995 (IDAE 2006).

Furthermore, the most important source of primary energy consumed in Spain is oil which is almost totally imported (IEA 2011b). Spain is highly reliant on imports of both crude and its products. Key oil providers for Spain are Mexico and Russia (around 15 % of the supply for each of them) and Nigeria, Saudi Arabia, and Libya (around 10 % for each of them). The gas supply structure is even less diversified with Algeria providing around 45 % of imports, followed by Nigeria and Qatar (15 % for each of them). The gas supply structure relies almost entirely on non-European countries (Németh et al. 2009).

3.2 *The Current Situation of the Spanish Energy System*

The Spanish case is interesting in regard to its energy mix as witnessed by the presence of some important changes. Spain produced 28.9 ktep (thousands of equivalent tonnes of oil) of primary energy, from different sources in 2009 (Eurostat 2012). Figure 1 shows the proportion of primary energy production in Spain during the year 2010. The first feature is the importance of nuclear energy which accounted for almost half of total primary energy produced (47 %). The second important feature is the low production of oil in Spain—only 0.4 % of the total primary energy produced in the year 2010. Biomass and waste constituted 20 % of production, while wind and solar energy accounted for the 14 % of energy produced (Fig. 1). Coal is still an important fuel in the electricity sector but it is overall declining in Spain (9 %). These figures will take even more importance when compared with consumption figures.

The overarching feature of Spanish energy is the important gap between production and consumption. The total production of primary energy was 28.6 ktep, while the total consumed was approximately 132.6 ktep in 2009. As a result, Spain imports the 78.3 % of the primary energy consumed. Approximately half (47 %) of the primary energy consumed in Spain was oil based in 2010. Coal and gas represented 6 and 23 %, respectively, of the primary energy consumption. A large percentage of imports consist of oil and gas, covering 70 % of the total imported energy (see Fig. 2). Thus, the Spanish economy is still characterized by

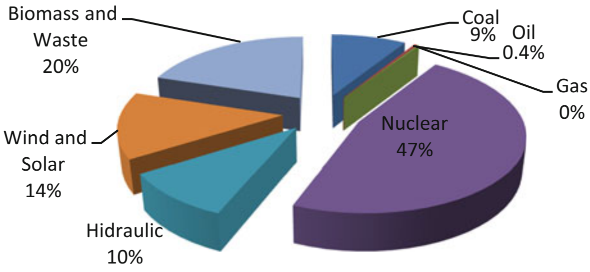

Fig. 1 Primary energy production in Spain 2010. *Source*: Adapted from Ministerio de Industria, Energía y Comercio (2011) own calculations

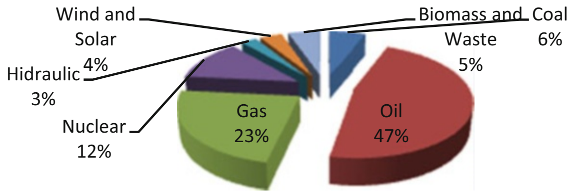

Fig. 2 Primary energy consumption in Spain 2010. *Source*: Adapted from Ministerio de Industria, Energía y Comercio (2011) own calculations

a high dependency on energy imports (Eurostat 2012). Spain is scarce in domestic energy sources since only coal and nuclear energy has been produced domestically in significant amounts, although the production of coal is itself declining since its extraction is becoming more expensive (Rabanal 2009).

Furthermore, the participation of wind and solar energy in the mix is becoming more important with their use almost totally concentrated in electricity generation. The growth of renewable energies in Spain has been driven by security and diversity concerns as well as local economy development objectives (jobs and support to economically depressed rural areas) (Labriet et al. 2010). Renewable energy sources (RES) have received different types of state aids (premium prices for electricity production, fiscal support of investments, and tax exemptions) to facilitate their market penetration. As a result, Spain has become the world's second largest producer of wind energy (16.7 GW installed at the end of 2008) behind Germany, but ahead of the United States.

Biomass sources of energy production have not been developed as fast as initially expected—in both electricity and heating purposes. The production of biomass sources of energy production is disappointing in the light of Spain being the first European country to enforce the compulsory implementation of solar thermal energy in new and refurbished buildings. In regard to the two components of biofuels (bioethanol and biodiesel), Spain is the second producer of bioethanol in Europe and remains way behind the two large European biodiesel producers (Germany and France), although its installed capacity is increasing slowly (Ciarreta et al. 2011; Labriet et al. 2010).

Finally, the future of nuclear energy remains uncertain in Spain. Although there is no nuclear moratorium in Spain, the current government does not support the installation of new nuclear plants. As a result, investments in nuclear energy are perceived as a high-risk venture by energy sector companies. The debate on the extension of the technical life of the existing nuclear power plants is currently ongoing given the completion of the 40-year lifespan of one plant in 2011. Spain's seven other remaining nuclear plants will not reach their lifespan deadline until at least 2020.

4 Spanish Energy Scenarios to 2030

4.1 Introduction

Concerns about energy security have been particularly important in Spain given its long-standing high degree of dependency on energy imports and, increasingly, by the environmental impact of its energy policy (Linares 2012). This section provides an overview of a prospective analysis of the Spanish energy system with 2030 as the target date (see Németh et al. 2009). The POLES (Prospective Outlook for the Long-term Energy System)-Spain is a one-country version of the POLES global energy system simulation model jointly designed and developed by the French Centre Nationale de la Research Scientifique in Grenoble and the Institute for Prospective Technological Studies in Seville. The POLES model simulates energy demand and supply in order to elaborate long-term scenarios for 57 regions, of which 45 correspond to countries (including the 27 EU member states). The model covers 13 energy sectors mainly in the areas of industry, transport, residential, and service sectors.

The methodological features of the POLES model are the following. First, the POLES model is one of partial equilibrium characterized by yearly simulation based on price-induced behavioral equations and performance effects associated with the use of different energy-related technologies. The main exogenous variables are the gross domestic product and population for each country or region (Hidalgo 2005).

Second, the key endogenous variables are the international prices of oil, gas and coal. The estimation of import demand and export capacities of the different regions builds from changes in the international prices of oil, gas, and coal. The price simulation for these sources of energy incorporates the Gulf capacity utilization rate for oil, the reserve on production ratio for oil and gas, and the trend in productivity and production costs for coal.

Third, the model is operating at three levels of analysis: international energy markets, regional energy balances, and national energy demand—the latter including new technologies, electricity production, primary energy production systems, and greenhouse gas emissions. Data for oil and gas supplies are derived from the production of the main reserve countries based on a simulation of current drilling activities and discovery of new reserves. The price simulation for these sources of energy incorporates the Gulf capacity utilization rate for oil, the reserve on production ratio for oil and gas, and the trend in productivity and production costs for coal.

Table 1 Basic assumptions in the baseline scenario (BaU) and energy efficiency scenario (EEF)

(1) Socioeconomic assumptions

Terms/years	Absolute terms				Annual growth rate		
	2005	2010	2020	2030	2005/2010	2010/2020	2020/2030
GDP (MEUR in PPP)	863	1,019	1,302	1,587	3.3 %	2.4 %	2.0 %
Population (Mcap)	43	45	46	46	0.8 %	0.3 %	0.0 %
GDP per capita (EUR/cap)	20,107	22,787	28,275	34,452	2.5 %	2.1 %	2.0 %
Number of dwellings (1,000)	15,247	17,083	19,388	20,247	2.2 %	1.3 %	0.4 %

(2) Binding legislative and policy representation

BaU	EEF
2.BaU.A. Energy efficiency targets set down[a]	**2.EEF.A.** Increased AEEIs to 1.5 % + primary energy saving of 20 % by 2020 with respect to BaU
	2.EEF.B. Additional increases in world oil (94 €/bbl) and natural gas (75 €/bbl) prices by 2030 (more constrained supply)

Notes: [a]The energy efficiency targets are set down in the Strategy for Energy Saving and Efficiency Strategy for Spain, Action Plan 2005–2007 and 2008–2012
Source: Adapted from Németh et al. (2009: 13)
AEEI autonomous energy efficiency improvement

The POLES model has been used in many forecasting studies, at both national and EU supranational levels (European Commission 2003a, b; World Energy Council 2007). The main results of two scenarios from the POLES-Spain study are presented in this section. The first scenario follows the historical trends of the energy system without the incorporation of any additional developments, i.e., the business-as-usual (BaU) or baseline scenario. The second scenario with high international energy prices is also presented, i.e., energy efficiency (EEF) scenario. This second scenario leads to a very different result for the Spanish energy system by 2030. It is characterized by three features, namely, lower energy intensity, increasing role of renewable energies, and lower dependency on external energy resources. The main drivers in this second scenario are major energy efficiency improvements and substantially higher prices for oil and natural gas.

The main socioeconomic assumptions common to both scenarios are presented at the top of Table 1. GDP is assumed to grow at high rates, namely, around two percent, thereby gradually converging to the long-term growth rate of the EU. The rate of population growth is assumed to be slower than that of the 1995–2005 decade. The peak should be reached at 46 million by 2010–2020. The number of dwellings, on the other hand, should increase at a lower rate than the GDP and reach around 20 million by 2030.

The assumptions regarding energy efficiency and the international energy prices appear at the bottom part of Table 1. The BaU scenario assumes that the targets of the current energy efficiency policies are achieved and that no major improvements are forthcoming (European Commission 2006b; International Energy Agency 2005). Energy efficiency was modelled in the POLES-Spain through two channels

(Németh et al. 2009: 12). First, the autonomous energy efficiency improvement parameter (AEEI) was designed to capture the efficiency gains associated with the implementation of specific energy technologies. Second, another mechanism of energy efficiency gains was designed with endogenous changes in the prices of resources, investments, and income incorporated in the model. In the BaU scenario, the sector-specific values for the AEEI parameter were applied in the −0.5 % to +0.5 % range. These were gradually increased from −0.5 % to −1.5 % in the EEF scenario for the period of 2008–2020. These AEEI values reflect the process of increased harmonization with the EU trends in the long term and the commitment of Spain to save 20 % on primary energy consumption with respect to the BaU scenario by 2020 (IDAE 2011). The underlying assumption for the energy efficiency scenario is that actors display a capacity of adaptation to changes in the production of energy that results from efficiency gains. Concerning international energy prices, a significant difference sets apart the BaU and the efficiency scenarios. While under the BaU oil prices are 51 €/bbl in 2020 and 74 €/bbl in 2030, they reach 61 €/bbl and 94 €/bbl in 2020 and 2030 under the efficiency scenario. The natural gas prices follow a similar evolution.

Moreover, there is a set of common assumptions in both scenarios (Németh et al. 2009: 13). First, the economic lifespan of current nuclear plants was extended to 2030. Second, the production of the renewable energy is largely driven by EU requirements and the commitments of Spanish policymakers as regards the fuel mix (20 % of all primary resources should come from renewable by 2020) and the low-temperature solar panels in buildings and the biofuel target (10 % of total fuel consumption should be covered by bio-combustion fuel and 5.75 % of all road transport should come from biofuel). Third, carbon-abatement commitments were modelled through an application of 18 €/tC carbon value for all EU member states. Finally, the existing structure of subsidies to electricity generation with renewable energies in place in Spain is taking the form of “feed-in” tariffs, but has been discontinued by the Rajoy government in early 2012.

4.2 *The Evolution of Energy Demand and Security of Supply in the Future Spanish Energy System*

In both scenarios, the energy-GDP intensity reverses its previously stable evolution in the decade prior to the economic crisis and starts to experience a marked decrease since primary energy consumption is currently growing at a rate that is inferior to that of the economy. The efficiency improvement in the case of the EEF scenario is more pronounced with gross domestic consumption to GDP expecting to fall by 40 % between 2005 and 2030, while it would fall by 27 % under the BaU scenario.

Figure 3 presents the evolution of primary energy consumption by fuels from 2005 to 2030. An interesting feature is that the growth of natural gas in the energy system is practically completed by 2020 under the BaU scenario, while coal and

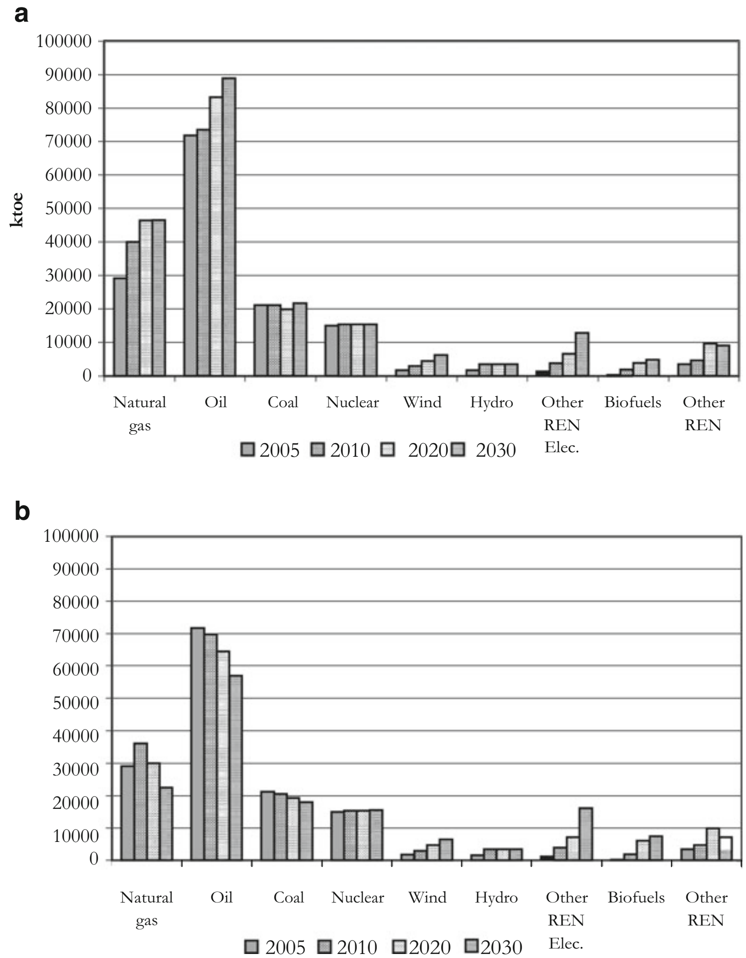

Fig. 3 Gross inland primary energy consumption. (**a**) Primary energy consumption in BaU. (**b**) Primary energy consumption in EEF. *Source*: Adapted from Németh et al. (2009, p. 15)

nuclear consumption remain approximately constant over the whole period. The empirical results of the BaU scenario are largely consistent with observed trends in recent years regarding both renewable energy resources and natural gas increasing their importance in the Spanish energy mix at the expense of oil and coal. In both scenarios, the presence of renewable resources in the Spanish energy mix exhibits a substantial increase, namely, more than tripling over the 25-year period. Under the EEF scenario, consumption of all fossil fuels decreases in the 2010–2030 period.

The significant expansion of renewable sources contributes to account for the drop in the energy dependency ratio, even if the overall energy demand also experiences an upward trend. In particular, the dependency ratio improves with respect to the current situation (76.69 %) under both the EEF scenario (59 % by 2030) and the BaU scenario (72 % by 2030) (Németh et al. 2009: 16).

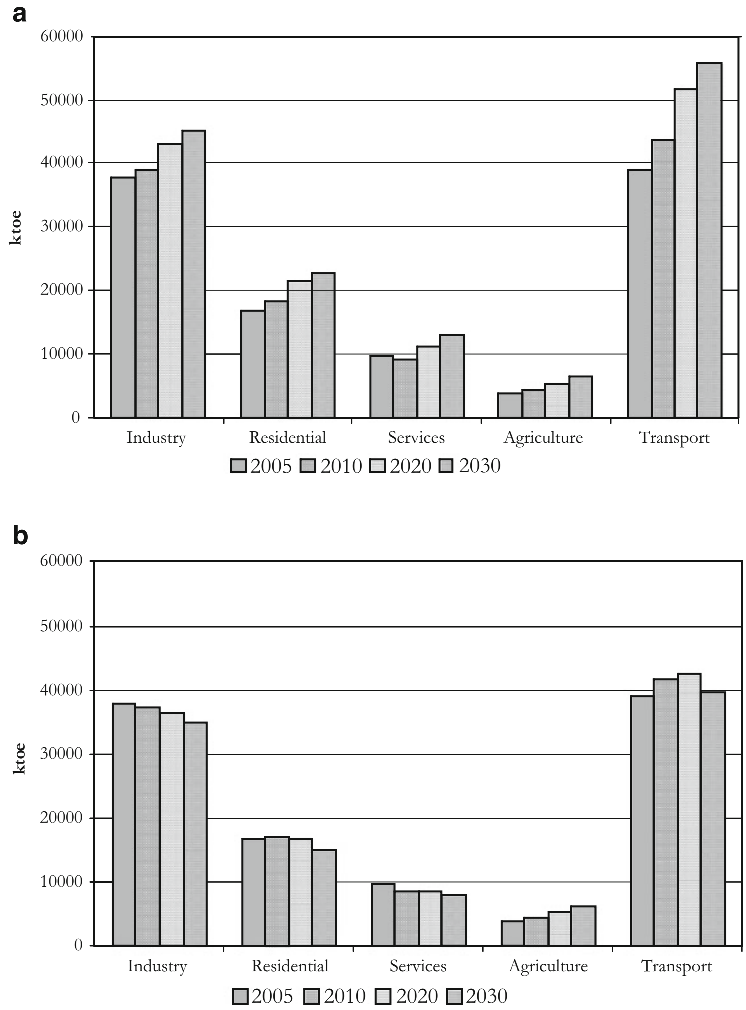

Fig. 4 Final energy consumption by sector. (**a**) Final energy consumption in BaU. (**b**) Final energy consumption in EEF. *Source*: Adapted from Németh et al. (2009, p. 17)

With respect to overall consumption by sector (Fig. 4), the BaU scenario is associated with an annual increase of slightly above 1 % from 2005 throughout 2030 in energy demand in transport, industry, residential, and service sectors. In contrast, the EEF scenario is associated with decreases in the energy consumption of industry, residential sector, and services for the whole period (at annual rates of 0.3 %, 0.5 %, and 0.8 %, respectively).

Furthermore, greenhouse gas (GHG) emissions are assumed to continue growing significantly in the BaU scenario—80 % higher in 2030 than in 1990. However, they will fall under the EEF scenario (Ibid: 23). Energy efficiency improvements are expected to bring results in the long term since they are usually connected to longer term investment cycles (Capros et al. 1999). The improvements achieved in the EEF scenario reflect both assumed efficiency gains and higher fossil fuel prices. This outcome shows that the Spanish economy has the potential of reducing GHG emission in the long term.

4.3 The Electricity Sector in the BaU and EEF Scenarios

The POLES-Spain model projects an annual increase in electricity consumption of 1.6 % under the BaU scenario from 2020 to 2030 and of 0.7 % under the EEF scenario for the same period (Németh et al. 2009: 18). By 2030, electricity demand is almost 25 % lower under the EFF scenario than in the BaU scenario.

The new demand will be met in great part by increased natural gas capacities in the electricity sector. This "dash-for-gas" process is expected to peak around 2020 as a result of high prices for natural gas. In 2030, gas-generated capacity is expected to reach 23 GW under the EFF scenario and 30 GW under the BaU. The relatively larger expansion under BaU reflects the different behavior of natural gas price that is assumed in the two scenarios—it is significantly higher in the EEF scenario. Power generation is expected to account for more than two-thirds of natural gas consumption by 2030 in both scenarios. More than a third of electricity could be generated from Combined Cycle Gas Turbine (CCGT) by 2030.

Such development entails the risk that the gas-fired capacity accumulation will be very concentrated in time, thereby disturbing later investment (replacement) cycles. The development of gas production facilities requires substantial investments and is characterized by a short lifetime (20–25 years). This would leave such investments vulnerable to cyclical shifts in the sector.

Coal has played a significant role in the Spanish electricity system. It has accounted for 25 % of production in recent years (Linares et al. 2008; Németh et al. 2009). However, recent government regulation, the adoption of Emissions Trading Schemes (ETS), and the enactment of subsidy cuts are militating to marginalize the role of coal-based technologies (Foidart et al. 2010). Nonetheless, the POLES-Spain model forecasts an increase in the use of coal from 2015 onward albeit in a new form, namely, in the pressurized fluidized-bed reactors and coal gasification technologies.

Hydro and wind constituted more than 40 % of the existing overall electricity capacity in recent years (Németh et al. 2009: 19). The high shares of hydro brought uncertainty into the electricity system because water serves three different uses: drinking water, irrigation for agriculture, and electricity generation. The latter use is less important as compared to drinking water and agricultural uses. Additionally, as most of the potential sites are already in use, no significant increase in capacities is foreseen in the future for this technology (European Commission 2009; Rübbelke and Vögele 2011).

The POLES-Spain model also forecasts that wind technology would maintain strong growth rates in the mid-/long term, while solar energy is expected to expand substantially from 2010 onward around the use of solar thermal power plants. This assumption was made with the expectation of the continuing operation of an attractive subsidy system (Ciarreta et al. 2011; Del Río González 2008). Another important feature is the biomass source of renewable energy which is also expected to exhibit a relatively strong growth through the whole period (close to 50 % increase by 2030). These developments are important for the evolution of electricity generation in Spain. A high share of electricity is projected to be generated from renewable sources (33 % under the BaU scenario, 46 % under the EEF scenario), of which more than half is solar and wind. Nevertheless, it is important to point out that Spain's new conservative government imposed a moratorium on power sale subsidies for renewable energy to be effective in 2013 (Royal Decree-Law—RDL 1/2012).

To sum up, the assumed efficiency improvements and the high fossil fuel prices associated with natural gas price constitute an important influence on the evolution of the Spanish electricity sector by reducing the total demand for electricity—approximately around 20 % by 2030. This scenario illustrates the prospects for reduced dependency on foreign sources of energy as well as for a more constrained role for gas. Nonetheless, the strict character of the assumptions in the POLES-Spain model—e.g., keeping nuclear capacities and interconnection lines constant—insightfully reminds us that these scenarios should be treated as such rather than being definitive and accurate forecasts (Németh et al. 2009).

5 Conclusions and Policy Recommendations

This chapter has highlighted the presence of several important challenges faced by the Spanish energy sector in the coming decades. First, the energy-GDP intensity remains high. The POLES-Spain model, a simulation energy model, has been run to assess two possible future scenarios of the Spanish energy system on this issue. Under the BaU scenario, some positive progress are noted in regard to the external energy dependency rate (decline from 76.69 % in 2010 to 72 % in 2030) and the energy-GDP intensity (expected to fall as a result of the decrease in the rate of growth of both electricity and transport demand). However, GHG emissions are expected to remain high, namely, at 80 % above 1990 levels by 2030. Under the energy efficiency scenario, a general improvement in all the indicators is expected to occur.

Second, both the EEF and the BaU scenarios highlight the risks associated with the rapid development of CCGT capacities. This technology constituted, until recently, two-thirds of the new investments in the power sector. Volatility of natural gas prices could result in significant high sunk costs. Issues associated with natural gas are further complicated by the high dependence on foreign sources.

Third, the aim for a greater share of renewable energy in the energy mix (46 % in 2030) requires massive investments in order to enlarge the capacity of interconnection lines of the Spanish electricity system. Moreover, electricity generation in Spain faces financial problems related to the issue of the accumulated tariff deficit—a long-standing problem associated with the maintenance of consumer prices at below electricity costs. This issue also connects to the question of renewable energy, namely, how to set tariff levels attractive enough to preserve the high level of investments in renewables without putting unsustainable pressure on the cost side.

Consequently, we can observe that anticipating the future of the Spanish energy system is a difficult task. However, long-term forecasts based on complex and well-conceptualized simulations of the Spanish energy contexts under a variety of circumstances—i.e., predefined scenarios—provided insights on the trade-offs and choices faced by policymakers.

This chapter closes with several recommendations for managing challenges in the evolution of the Spanish energy model with concerns of energy security and sustainability being prominent.

First, energy issues should be at the top of the political agenda. The anxieties over security supply at affordable costs could be reduced with appropriate sets of policies that shape the market incentives of companies. A key precondition for the successful contribution of market forces to public policy strategies is the reduction of uncertainties regarding the soundness of private investments in energy facilities. Part of the solution lies in the credible commitment of governments and regulators to long-term guidelines and targets. The credibility of government commitment would be facilitated by integrating Spain's energy policies as much as possible into the European and national legislative framework.

The removal of legal uncertainties regarding the use of specific types of energy and the provision of financial incentives constitute clear instances where public policy can be effective in closing the gap between energy demand and supply. The extensive investments in renewable sources of energy by some of Spain's largest energy company, particularly Gamesa and Iberdrola, illustrate how state policies can successfully incentivize domestic actors.

Second, the promotion of renewable energies should be strengthened by tackling some of the inefficiencies associated with current arrangements. As previously mentioned, Spain has been overall successful in promoting renewable energy development. Nonetheless, there are several shortcomings associated with the feed-in-tariff system for renewable energy. The feed-in-tariff system is partly tied to the government budget and tax system with the resulting consequence of lack of flexibility to make quick pricing adjustments—especially when Spain was hit hard by the global recession that began in 2008. Germany, in contrast, has embedded the feed-in-tariff system entirely on the ratepayer system, thereby allowing for quicker responses to the need for price adjustment.

Third, Spanish policymakers should clarify their long-term nuclear energy policy (up to 2030) in order to provide economic actors adequate guidance for making technology choices in the energy sector and, if a phase-out of nuclear energy is confirmed, develop a strategy for replacing nuclear units.

Finally, the implementation of more stringent carbon emissions regulations should be introduced since GHG emissions are assumed to continue growing significantly despite energy efficiency improvements. The creation of a tax on CO_2 could serve to reduce emissions and influence behavior related to large-scale energy consumption.

This chapter concludes by highlighting that significant advances toward energy security and sustainability in Spain are possible. This requires determined actions on energy policy. Some of these measures have been already initiated, therefore highlighting how government policies can provide attractive incentives for companies to increase supply and invest in renewable sources of energy. Therefore, it seems convenient to advance in this direction if a more secure and sustainable energy system is to be achieved.

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Dr. Rocío Valdivielso del Real is currently a Visiting Fellow at the Centre for the Study of Globalisation and Regionalisation (CSGR), University of Warwick. She is also a Research Associate at the London Centre for Corporate Governance and Business Ethics, Birkbeck College (University of London), and a Research Associate at ABM Analytics London. She holds a PhD in Management and Business, obtained at the University of London (thesis title: "The Evolution of the Spanish and British Electricity Sectors: An Analysis of the Market for Corporate Control and Human Resource Management Practices in a Liberalised Environment"). She also holds a PhD in Political Science from the Complutense University, Madrid. Her research interests are comparative political economy of advanced capitalist economies, corporate governance, energy policy in Europe, reregulation, and governance.

Energy, Development, and Economic Growth in Colombia

Clara Inés Pardo Martínez and Alexander Cotte Poveda

Abstract Purpose The aim of this study is to describe the causal relationships between energy use, development, and productivity in Colombia.

Design/Methodology/Approach The study was conducted by application of several econometric techniques. The time-series methodology used in this is based on the Granger causality test, which has been found appropriate by using the cointegration technique.

Findings This study shows that economic growth and development drive total energy consumption. The results regarding the relationship among energy, poverty, and inequality indicate that increases in gross domestic product and energy supply per capita contribute to decrease poverty. The results also confirm that access to modern energy services helps to decrease poverty. Moreover, the improvements in energy efficiency and decreases in CO_2 emissions have contributed to development and growth.

Practical Implications The results of this study showed the importance of the formulation and adoption of good policies and strategies that encourage sustainable energy use to improve growth and development, especially in developing countries.

C.I. Pardo Martínez (✉)
Energy and Climate Studies, Department of Energy Technology,
Royal Institute of Technology, KTH, Brinellvägen 68, 100 44 Stockholm, Sweden

Faculty of Administration, Universidad del Rosario, Calle 12C No. 6-25, Bogotá, Colombia
e-mail: cipmusa@yahoo.com

A. Cotte Poveda
Department of Economics, University of Göttingen, Platz der Göttinger Sieben 3,
37073 Göttingen, Germany

Faculty of Accounting and Administration, Universidad de La Salle, Cra 5 No. 59A-44,
Bogotá, Colombia

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Originality/Value This chapter provides an empirical approach for finding the causal relationship between development, productivity, and energy consumption in Colombia. The methodology and the results used in this study could be used for exploring the importance of energy in the productivity and economic development.

Keywords Energy • Economic development • Productivity • Poverty

1 Introduction

In developing countries, economic and household sectors require a modern and reliable energy supply at a reasonable price to increase economic growth, productivity, and standards of living. Energy consumption and gross domestic product are not adequate indicators from the approach of sustainability development where other approximations as human development index or indicators per capita are more suitable and reliable (Despotis 2005; Dutt 2009; Cotte and Pardo 2011). Several studies have evaluated the relationship between development and energy (Kemmler and Spreng 2007; Nguyen 2008) or economic growth and energy (Soytas and Sari 2003; Lee 2005; Hanesson 2009).

Among empirical studies, however, there is no consensus about the direction of causality. For example, Lee (2005, 2006) analyzes the causal relationship between energy consumption and the gross domestic product (GDP) in developed and developing countries. The studies find evidence that long-run and short-run causalities run from energy consumption to GDP in developing countries. The evidence and recent results show that there are different causal relationships, so, for example, between GDP and energy consumption for the USA is bidirectional causality, while for countries like the Netherlands, Canada, Switzerland, and Belgium, the causality is unidirectional.

The evidence for Colombia reveals that energy consumption does not play an important and clear role in productivity and that economic growth is almost completely dependent on capital (Castillo 1997). Other studies have suggested a relationship between energy and GDP. This relationship has shown a trend change from 2003 that has primarily been marked by greater efficiency in the process, change in the fuel used from low to high quality (i.e., from oil to natural gas), an increase in the process of the auto-generation of energy, and a greater contribution in the GDP of other activities with lower energy consumption such as construction activity (UPME 2007; ISA 2009; Pardo 2010).

Moreover, there exist different strategies used to resolve Colombian societal problems such as high levels of poverty and an increasing number of people whose basic needs are not satisfied. One strategy suggests that through economic expansion with the contribution of a solid energy sector, the government will have the means to create a fair, equalitarian, and unified society (UPME 2007). However, studies on the relationships among energy, productivity, and poverty are limited in the Colombian context.

With this background, the objective of this chapter is to examine the issue of causality among energy use, productivity, and poverty for Colombia for the period 1975–2008. This study contributes to the existing literature in the following manner. First, the authors intend to analyze the role of energy in productivity and poverty. Second, this study includes variables of energy consumption by economic sector and standards of living with the aim to understand the role of these variables in productivity and development. Third, the authors analyze the influence of energy services in poverty.

The order of the study is as follows: Energy trends and economy in Colombia are discussed in Sect. 2; Sect. 3 outlines the model, methodology, and data issues; the results are presented in Sect. 4; and conclusions and policy implications of the results and the future directions for research are briefly discussed in Sect. 5.

2 Energy, Economy, and Poverty in Colombia

Colombian energy policies are established almost entirely on direct regulation. Apart from some small exemptions to VAT taxes for environmental investments, the principal use of economic incentives in energy policies involves the pricing of fuels and agreements with specific manufacturing industrial sector that have high potentials to improve energy efficiency or to carry out changes in technology and renewable energy.

The main energy sources in Colombia in 2009 as primary energy are oil (43.2 %), natural gas (22.6 %), and hydropower (11.3 %) and as secondary energy, electricity (24 %), diesel oil (17.4 %), and gasoline (21.1 %). In the last years, fossil fuels have decreased their participation in the energy matrix of Colombia (UPME 2010).

To analyze the trends in energy, economy, and poverty, it uses spatial interpolation[1] to generate intuitive answers on how to understand different sets of coefficients from a linear regression and complex nonlinear ones. A trilateral analysis with spatial interpolation can help to determine the trends among the following selected variables: energy consumption, electricity consumption, energy supply per capita, poverty, and GDP taking into account that the system dimensionality adjusts with these variables. Moreover, it uses the robust plane to obtain nonplanar three-dimensional surface structures from the relationship of defined variables.

Figure 1 shows different relationships of several variables of energy, economy, and poverty. The first relationship among energy and electricity consumption and

[1] The natural neighbor algorithm (Watson 1994) uses a circular areal-based procedure for interpolation. This approach determines the growth rate trends that could get in the continuum of possible combinations between several decision variables through the regression planes and nonplanar surface.

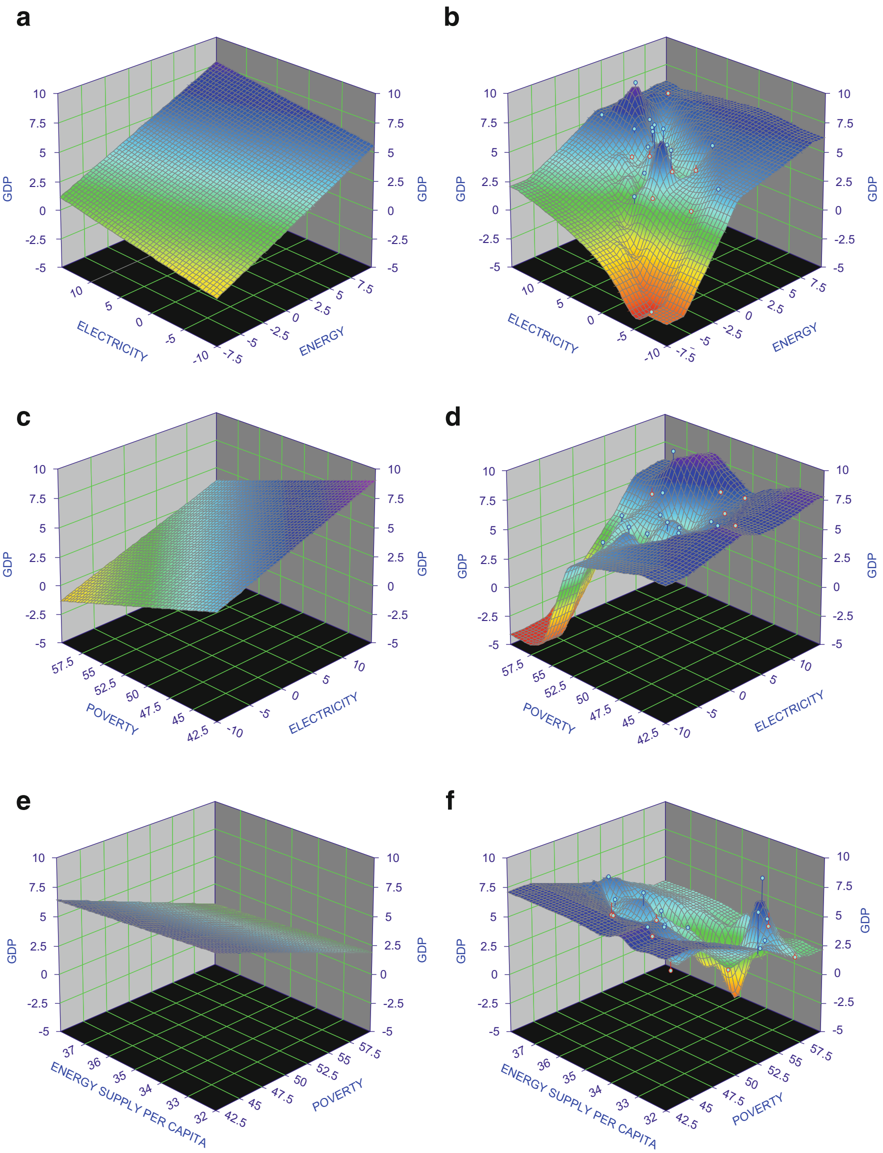

Fig. 1 Energy consumption, electricity consumption, energy supply per capita, poverty, and GDP (a trilateral analysis with spatial interpolation). (**a**, **b**) Energy, electricity and GDP in Colombia. (**c**, **d**) Energy, poverty and GDP in Colombia. (**e**, **f**) Poverty, energy supply per capita and GDP in Colombia

GDP indicates that these variables are associated positively, implying that a higher energy and electricity consumption higher economic growth measured as GDP. The second relationship among electricity consumption, poverty, and GDP shows that an increase in electricity consumption leads to a decrease in poverty and an increase in GDP. Finally, the third relationship between poverty, energy supply per capita, and GDP indicates that a higher energy supply per capita associates positively with GDP and negatively with poverty.

3 Methodology

An analysis on energy, development, and economic growth is important in the context of energy policy and security to determine good strategies and instruments that allow to improve the sustainability energy of a country. Several researchers have contributed with analysis of energy. However, few studies have analyzed the relationship between energy, development, and economic growth, especially in developing countries from an empirical approach. Therefore, this chapter tries to analyze this relationship with the aim to determine the important role of energy in the development and growth as a productive factor from the application of quantitative methods, which is a singular feature of this analysis as it is explained in the methods and discussion.

3.1 Model

The effects of energy use on development and economic growth have become important after the energy shocks in 1970s, and there has been recent emphasis on the use of sustainable energy resources as well as a search for energy-efficient production technologies and equipment. The roles of energy in development and economic growth are highlighted in a number of studies (see, e.g., Moroney 1991; Castillo 1997; Stern and Cleveland 2004; Paul and Bhattacharya 2008; Stresing et al. 2008; Cotte 2010; Cotte and Pardo 2011). Following Kummel et al. (1985) and Ayres (2008, 2010), the model assumes a production function of the following form:

$$Y_t = K_t^{\alpha} E_t^{\gamma} X_t^{\beta} \tag{1}$$

where Y_t is the total amount of production of the final good at time t, K_t is the capital stock, E_t is consumption of energy (energy sources used in this study are natural gas and biomass measured as firewood or charcoal consumption), and X_t is exports.

The first model is productivity, where the authors focus on the relationship between the energy use per unit of labor and the output per unit of labor. For this purpose, the model in (1) is expressed in terms of labor. Moreover, in this model, it includes other variable determinants of productivity such as better energy use measured as energy intensity (EI), pollution measured as CO_2 emissions (CO), and poverty (Pov). It can write (1) as

$$\frac{\ln Y_t}{L_t} = \frac{\alpha \ln K_t}{L_t} + \frac{\gamma \ln E_t}{L_t} + \frac{\beta \ln X_t}{L_t} - \varphi \ln \mathrm{EI}_t - \partial \ln \mathrm{CO}_t - \delta \ln \mathrm{Pov}_t \tag{2}$$

The relationship between poverty and energy is analyzed with the aim of determining the effects of energy consumption on poverty. For this purpose, the model of (1), poverty, is defined as a dependent variable.

$$\begin{aligned} \ln \mathrm{POV}_t = & -\vartheta \ln \mathrm{GDP}_t + \delta \ln \mathrm{GINI}_t + \varphi \ln \mathrm{IND}_t - \tau \ln E_t + \varepsilon \ln \mathrm{CO}_t \\ & + \partial \ln \mathrm{BM}_t \end{aligned} \tag{3}$$

where POV_t is the poverty at time t, GDP_t is the gross domestic product, GINI_t is coefficient of inequality, IND_t is indigence, E_t is energy supply per capita (where energy sources are electricity, natural gas, petroleum products, and other fuels), CO_t is CO_2 emissions, and BM_t is biomass measured as firewood and charcoal consumption.

In conventional economic theory, the production factor energy is either underestimated or given minor importance. The reason for this is that energy's share in the total factor cost is small in comparison to other production factors such as labor or capital. However, after the energy crises in 1973–1974 and 1979–1981, the role of energy in economic growth became an important production factor due to its large economic impact. Different studies have shown the role of energy in development and economic growth. For example, Moroney (1991) shows that energy consumption has played an important and clear role in productivity in the US economy. Lee (2005) demonstrates that in developing countries energy consumption and GDP could show long- and short-run causalities. Moreover, the energy-growth-development relationship is also affected due to the application of better and efficient technologies and fuels (Cleveland et al. 1984; Jollands and Aulkah 1997; Wing and Eckaus 2004; Fleay 2005). Therefore, energy is categorized as a critical factor for sustainable development and economic growth.

In order to examine the causality among energy use, development, and economic growth during the sample period (between 1975 and 2008) in Colombia, the authors have divided the analysis into two parts: (I) productivity analysis, where it focuses on the relationship between the energy use per unit of labor and the output per unit of labor [Eq. (2)], and (II) the relationship between poverty and energy is analyzed with the aim of determining the effects of energy consumption on poverty [Eq. (3)].

3.2 Estimation

Time-series model estimation involved the following steps.

(a) Test for Data Stationarity

In order to test the stationarity of each series, the authors first apply the unit root test. The authors have selected the Augmented Dickey–Fuller (Fuller 1976;

Dickey and Fuller 1979) test (ADF), Phillips and Perron (1988) test (PP), and Portmanteau and Bartlett (Bartlett's test Newton 1988; Bartlett 1955) test for white noise for this study. The tests are applied to the data at level and at first difference to determine the degree of integration in each of the series analyzed.

(b) Cointegration Analysis

This analysis will consider the potential long-run relation for the variables by applying cointegration analysis. The tests of cointegration chosen are based on testing the stationary of the error terms, the Cointegrating Regression Durbin-Watson (CRDW) statistic. This test requests the data series in each asset class to be integrated to the same order and the existence of a linear combination of the series which is integrated to a lower order than the individual series, that is, the number of times that the series must be differenced to perform stationarity is the same across all the data (Perman 1991). Finally, it uses a third test from approach of Johansen (1988) and Johansen and Juselius (1990) to test for the number of cointegrating relationships.

(c) Granger Causality Tests

After testing for the stationarity of each series and cointegration, it applies causality tests through the Granger approach with first-differenced VARs for each of the two pairs. In the case of the two variables *X* and *Y*, the Granger causality approach is different from the common use of the term, as it measures precedence and information specified by *X* in explaining current value of *Y*. According to this view, *Y* is said to be Granger caused by *X* if *X* helps in the prediction of *Y* or if lagged values of *X* are statistically significant (Engle and Granger 1987; Granger 1988).

d. Estimation of the Model

In this section, it estimates the casual relationship among energy, development, and poverty controlling for changes in capital, labor, human capital, exports, standards of living, and other energy features. The authors select ordinary least squares (OLS) for estimating the regression model, which provides certain advantages in this study. First, this model is flexible and easy to estimate, and it usually gives a good fit in the analysis time series. Second, this model takes into account the equations combination of long-run and short-run information in the data by exploiting the cointegration property.

3.3 Data

The model is estimated using time-series data for the period 1975–2008. The main sources of data are various issues of Energy Balances and Colombian Economic Survey.[2] The variables are defined as follows:

[2] Both are published by different entities of the Government of Colombia.

- Gross domestic product (GDP) coming from CEPAL is used as the measure of output. The data series is at 2000 price.
- The data on primary factors of production and other sources of economic growth include capital stock and labor force, which came from the DNP (the Department of National Planning). Capital stock is calculated in dollars at 2000 prices. The labor force is measured as persons in the work force.
- Exports of goods and services, in millions of dollars, at current FOB prices, are included as a proxy for the openness of the economy.
- The information about poverty, GINI and indigence principally comes from CEPAL, DNP, and the DANE (National Department of Statistics).
- The energy is measured in terajoules (TJ). Energy data were taken from energy balances made by the International Energy Agency (IEA) and by the Unidad de Planeación Minero Energética (Unit of Mining and Energetic Planning, UPME). Moreover, it included a variable to measure the impact of industrial energy consumption as a share of total energy consumption by industrial sector.
- Energy supply per capita was calculated as energy supply per person in Colombia from energy balances of the Unidad de Planeación Minero Energética (Unit of Mining and Energetic Planning, UPME).
- An energy intensity variable was included as a measurement of better energy use. This variable was calculated as energy consumption per unit of output.
- A CO_2 emissions variable was included to measure the effects of contamination. This variable was calculated using the following IPCC carbon emission factors: natural gas 56.1 tCO_2/TJ, petroleum products 73.0 tCO_2/TJ, other fuel 81.8 tCO_2/TJ, and electricity by Colombia, according to Resolution 181401/2004.

4 Results

4.1 Productivity Model

In the first part, the authors estimate the productivity model. The results for the unit root test are reported in Table 1. The tests are applied to level and first difference of the data series. The model is estimated in levels.

4.1.1 Estimation Results

Long-Run Relationship and Short-Run Relationship

Table 2 shows results of the long-run relationship and short-run dynamics. The equation of productivity is estimated for Colombia using annual data covering the period of 1975–2008. The selected model fulfills the standard diagnostic tests: serial correlation, functional form, normality, and heteroscedasticity.

Table 1 Results for stationarity—unit root test. Productivity model

	Portmanteau test		Bartlett's test		Dickey–Fuller test		Phillip–Perron test	
	Level	First difference	Level	First difference	Level	First difference	Level	First difference
Energy consumption	113.9 (0.00)	12.38 (0.57)	2.718 (0.00)	0.395 (0.99)	−1.743 (0.409)	−3.678 (0.004)	−2.579 (0.09)	−5.547 (0.00)
Natural gas	83.20 (0.00)	10.69 (0.710)	2.413 (0.00)	0.474 (0.978)	0.217 (0.973)	−3.665 (0.004)	−0.822 (0.812)	−6.228 (0.00)
Industrial energy consumption	94.13 (0.00)	21.846 (0.081)	2.663 (0.00)	1.143 (0.146)	−1.788 (0.386)	−8.476 (0.00)	−2.480 (0.120)	−8.887 (0.00)
CO_2 emissions	144.82 (0.00)	16.03 (0.311)	2.842 (0.00)	0.885 (0.413)	−2.537 (0.106)	−4.992 (0.00)	−2.403 (0.140)	−5.083 (0.00)
Energy intensity	96.17 (0.00)	10.84 (0.698)	2.375 (0.00)	1.069 (0.202)	1.414 (0.997)	−3.969 (0.00)	2.091 (0.998)	−4.031 (0.00)
Poverty	42.94 (0.00)	9.356 (0.807)	2.216 (0.00)	0.657 (0.780)	−2.481 (0.120)	−3.465 (0.008)	−2.095 (0.246)	−5.982 (0.00)
Gross domestic product	117.5 (0.00)	20.82 (0.106)	3.380 (0.00)	1.698 (0.006)	−1.558 (0.504)	−3.115 (0.025)	−1.440 (0.563)	−3.067 (0.029)
Capital	63.59 (0.00)	32.82 (0.003)	2.938 (0.00)	1.597 (0.012)	−1.935 (0.316)	−3.518 (0.007)	−1.618 (0.473)	−3.303 (0.014)
Exports	93.83 (0.00)	8.37 (0.868)	2.130 (0.00)	0.442 (0.989)	−0.224 (0.935)	−0.507 (0.890)	−0.114 (0.948)	−5.538 (0.00)
Critical value (at 5 %)	*P*-value ≤0.05	*P*-value ≥0.05	*P*-value ≤0.05	*P*-value ≥0.05	(−2.980)	(−2.980)	(−2.980)	(−2.980)

Table 2 Estimated regression model—estimates of the long-run coefficients and estimates of the error correction representation. Productivity model Dependent variable: productivity

Parameter	[1]	[2]	[3]	[4]
Constant	−1.862[a] (0.331)	0.003 (0.004)	−0.006 (0.077)	−0.001 (0.001)
Capital	0.140[a] (0.024)	0.092[a] (0.028)		
Exports	0.091[a] (0.025)	0.055[b] (0.028)	0.010 (0.008)	0.020[a] (0.007)
Energy consumption	0.616[a] (0.059)	0.482[a] (0.138)	0.940[a] (0.029)	0.904[a] (0.041)
Natural gas	0.175[a] (0.032)	0.059[c] (0.034)		
Industrial energy consumption	0.308[a] (0.075)	0.174[a] (0.065)		
CO_2 emissions			−0.030[c] (0.017)	−0.040 (0.036)
Energy intensity			−0.949[a] (0.027)	−0.954[a] (0.044)
Poverty			−0.000 (0.018)	−0.032 (0.023)
Residual		−0.500[a] (0.157)		−1.143[a] (0.189)
Ad R-squared	0.896	0.565	0.9950	0. 9680
F-value	58.08	7.950	1553.8	162.88

Note: Figures in parentheses are standard errors
[a]Significant at the 1 % level
[b]Significant at the 5 % level
[c]Significant at the 10 % level

The results show that the effect of capital output is positive and significant at the 1 % level. The estimate of the coefficient of exports is positive and marginally significant at 1 and 10 %, respectively. The estimate of the energy consumption and industrial energy consumption bears a positive sign and is significant at the 1 % level. This confirms the predictions of the importance of the energy for productivity. Natural gas consumption affects positively the productivity in Colombia. The estimated coefficients are highly significant. Finally, CO_2 emissions and the poverty, the estimated coefficients have a negative impact on the productivity.

Table 3 reports the results of the unit root tests applied to the residuals of the cointegration equations. The absolute values of the assessed test statistics for all the residuals are less than its critical value at the 5 % level. Moreover, the results of Johansen likelihood ratio test ($r = 0$) are all well below the 5 % significance level values indicating the acceptance of the null hypothesis. Therefore, neither of the series is cointegrated and the standard Granger test (Granger 1969) is appropriate.

The results show that the variables in the model are cointegrated providing evidence for the application of an error correction model mechanism (ECM) representation to evaluate the short-run dynamics (see Table 4).

Table 3 Cointegration tests. Productivity

	Dickey–Fuller test	Phillip–Perron test	CRDW	Johansen trace static
Productivity—energy	−1.432	−0.707	0.108	9.384
Productivity—natural gas	−1.559	−1.482	0.107	9.555
Productivity—industrial energy consumption	−1.561	−1.789	0.310	13.118
Productivity—energy intensity	−1.568	−1.527	0.106	8.123
Productivity—poverty	−1.579	−1.354	0.115	8.441
Productivity—capital	−1.617	−1.806	0.204	10.884
Productivity—exports	−1.635	−1.519	0.104	10.902
Critical value (at 5 %)	(−2.980)	(−2.980)	(0.38)	15.41
Maximum rank				0

Table 4 Test residuals

Variable	Dickey–Fuller test	Lags	Bartlett's test	Portmanteau test
Residual model [1]	−4.529 (0.000)	0	1.18 (0.123)	9.713 (0.837)
Residual model [3]	−6.680 (0.000)	0	0.64 (0.812)	14.33 (0.500)

Table 5 Granger test for causality

Null hypothesis	F-value	Probability	Decision
Growth in energy—labor does not cause productivity growth	14.485	0.0000	Rejected
Growth in natural gas—labor does not cause productivity growth	8.420	0.0013	Rejected
Growth in industrial energy consumption does not cause productivity growth	5.834	0.0074	Rejected
Growth in CO_2 emissions does not cause productivity growth	5.698	0.0082	Rejected
Growth in energy intensity does not cause productivity growth	9.088	0.0009	Rejected
Growth in poverty does not cause productivity growth	7.075	0.0031	Rejected
Growth in capital—labor does not cause productivity growth	8.161	0.0015	Rejected
Growth in exports—labor force does not cause productivity growth	9.315	0.0008	Rejected

Estimation results are presented in Table 2 models [2] and [4]. The Adj-R^2 is 0.56 and 0.96, respectively, suggesting that such error correction model fits the data reasonably well. More meaningfully, the error correction coefficient shows the expected negative sign and is highly significant. This demonstrates again a long-run relationship among the variables in the productivity model.

Table 5 shows the results for causality indicating that there is a long-run relationship between growth in terms of capital per worker and productivity growth. The variables are important and statistically significant determinants of productivity growth and development.

4.1.2 Discussion of Results

The estimated productivity model shows that the capital-labor ratio and exports-labor ratio are determinants of productivity. Energy and natural gas consumption used per worker also significantly contributes to productivity. Poverty variable shows a negative effect on productivity. Note that CO_2 emissions and energy intensity are significant and negatively affect productivity. The increase of industrial energy consumption positively affects productivity (see Table 2).

The results of variables of standards of living could indicate that productivity plays a substantial role in reducing poverty, which concurs with the bidirectional relationship between poverty and productivity and enables the conclusion that fighting poverty could improve productivity and that improving productivity could help fight poverty (Hayes et al. 1994; Dagdeviren et al. 2002).

The energy per worker positively affects the productivity. These results concur with the increasing trend in recent years of energy efficiency as a determinant of productivity. Improvements on energy efficiency are important to lead a dynamic productive economy with a high "quality of life," whereas a low "quality of life" is joined with low economic productivity and energy inefficiency. Encouraging efficiency in all factors of production will result in a higher "quality of life" and enable the authors to fund the transition to "sustainable development" (Herring 1998).

The results of natural gas consumption could demonstrate a relationship between productivity and inter-fuel substitution, where productivity improvements could be the result of a shift in the structure of energy sources from fuels with lower end-use efficiency such as coal and petroleum products to fuels with greater end-use efficiency such as gas and electricity (UNEP 1976). In the Colombian case, especially in the last decade, there has been inter-fuel substitution (from petroleum products to natural gas), which concurs with the results. Moreover, the results regarding energy intensity suggest that energy and labor productivity are complementary rather than substitutable and that they invest in new capital goods in order to increase productivity and simultaneously achieve improvements in energy efficiency (Mulder and Groot 2004).

4.2 Poverty and Energy Model

In this section, a model of poverty and energy is estimated. Table 6 shows the results of the unit root test. The model is estimated in levels, where the dependent variable is poverty.

4.2.1 Estimation Results

Long-Run Relationship and Short-Run Dynamics

Table 7 shows results of the energy and poverty model for Colombia using annual data covering the period of 1975–2008. The model fulfills the standard tests, functional form, serial correlation, normality, and heteroscedasticity.

Table 6 Results for stationarity—unit root tests. Poverty-energy model

	Portmanteau test		Bartlett's test		Dickey–Fuller test		Phillip–Perron test	
	Level	First difference	Level	First difference	Level	First difference	Level	First difference
Energy supply per capita	128.9 (0.00)	5.035 (0.985)	2.975 (0.00)	0.292 (1.00)	−1.666 (0.448)	−5.590 (0.00)	−1.780 (0.390)	−5.593 (0.00)
Biomass consumption[a]	129.43 (0.00)	9.243 (0.815)	2.92 (0.00)	0.632 (0.818)	0.344 (0.979)	−4.877 (0.00)	0.325 (0.978)	−4.917 (0.00)
CO_2 emissions	144.83 (0.00)	16.03 (0.311)	2.843 (0.00)	0.885 (0.413)	−2.537 (0.106)	−4.992 (0.00)	−2.403 (0.140)	−5.083 (0.00)
Indigence	40.57 (0.00)	9.807 (0.776)	2.361 (0.00)	0.874 (0.429)	−1.419 (0.573)	−4.877 (0.00)	−1.253 (0.650)	−7.749 (0.00)
Poverty	42.94 (0.00)	9.356 (0.807)	2.216 (0.00)	0.657 (0.780)	−2.481 (0.120)	−3.465 (0.008)	−2.095 (0.246)	−5.982 (0.00)
Gross domestic product	129.65 (0.00)	21.68 (0.085)	2.581 (0.00)	1.520 (0.019)	−0.517 (0.888)	−3.518 (0.0075)	−0.500 (0.892)	−3.569 (0.006)
Critical value (at 5 %)	P-value ≤ 0.05	P-value ≥ 0.05	P-value ≤ 0.05	P-value ≥ 0.05	(−2.980)	(−2.980)	(−2.980)	(−2.980)

[a]Biomass consumption is measured as firewood or charcoal consumption

Table 7 Estimated regression model—estimates of the long-run coefficients and estimates of the error correction representation. Poverty model Dependent variable: poverty

Parameter	[1]	[2]	[3]	[4]
Constant	5.167[a] (1.236)	0.017[b] (0.007)	4.590[a] (0.469)	−0.002 (0.005)
Gross domestic product	−0.051 (0.105)	−0.588[a] (0.211)		
GINI	0.057 (0.099)	0.180[b] (0.078)	0.015 (0.092)	0.146[c] (0.087)
Indigence	0.294[a] (0.048)	0.236[a] (0.038)	0.321[a] (0.036)	0.273[a] (0.043)
Energy supply per capita	−0.445[a] (0.154)	−0.191 (0.165)	−0.457[a] (0.114)	−0.244 (0.180)
CO_2 emissions	0.040 (0.132)	0.025 (0.178)		
Biomass			0.005 (0.028)	0.013 (0.160)
Residual		−0.737[a] (0.180)		−0.635[a] (0.198)
Ad R-squared	0.811	0.719	0.813	0.644
F-value	29.46	14.70	36.87	12.60

Notes: Figures in parentheses are standard errors
[a]Significant at the 1 % level
[b]Significant at the 5 % level
[c]significant at the 10 % level

Table 8 Cointegration tests. Poverty

	Dickey–Fuller test	Phillip–Perron test	CRDW	Johansen trace static
Poverty—energy supply per capita	−2.525	−1.987	0.377	8.676
Poverty—biomass consumption	−1.019	−1.103	0.173	6.446
Poverty—CO_2 emissions	−1.538	−1.533	0.192	12.930
Poverty—GINI	−2.680	−2.248	0.447	6.413
Poverty—indigence	−2.709	−2.718	0.717	8.742
Poverty—gross domestic product	−2.775	−2.576	0.252	6.556
Critical value (at 5 %)	(−2.980)	(−2.980)	(0.38)	15.41
Maximum rank				0

The results show that the impact of gross domestic product GDP is negative (−0.588) and marginally significant at the 1 % level. The estimate of the coefficient of GINI is positive and marginally significant at the 10 % level in the error correction representation model. The indigence variable affects positively the poverty in Colombia. The estimated coefficient is highly significant. The estimate of the energy supply per capita shows an inverse relationship and is significant at the 1 % level in some estimates of the long run. Finally, the CO_2 emissions and biomass are positive and statistically insignificant.

Table 8 reports the results of the unit root tests applied to the residuals of the cointegration equations. The absolute values of the calculated test statistics

Table 9 Test residuals

Variable	Dickey–Fuller test	Lags	Bartlett's test	Portmanteau test
Residual model [1]	−4.235 (0.000)	0	1.27 (0.078)	12.109 (0.670)
Residual model [3]	−4.713 (0.000)	0	1.12 (0.164)	10.530 (0.785)

Table 10 Granger test for causality. Poverty-energy model

Null hypothesis	*F*-value	Probability	Decision
Growth in biomass does not cause poverty	0.258	0.8544	Not rejected
Growth in CO_2 emissions does not cause poverty	1.140	0.3506	Not rejected
Growth in GINI does not cause poverty	2.253	0.1050	Not rejected
Growth in indigence does not cause poverty	11.17	0.0001	Rejected

for all the residuals are less than its critical value at the 5 % level. Moreover, the results of Johansen likelihood ratio test ($r = 0$) are all well below the 5 % significance level values indicating the acceptance of the null hypothesis. Therefore, neither of the series is cointegrated and the standard Granger test (Granger 1969) is appropriate.

The absolute values of the calculated test statistics for all the residuals and CRDW are less than its critical value at the 5 % level, and the Johansen likelihood ratio test indicates that the likelihood statistics are all well below the 5 % significance level (see Table 8). These results indicate that neither of the series is cointegrated. Therefore, the standard Granger test (Granger 1969) is appropriate.

Since in the model the variables are cointegrated, it is necessary to implement the mechanism of the error correction model (ECM) that allows the authors to investigate the dynamics of short term (see Table 9).

Estimation results are presented in Table 7 models [2] and [4]. The $Adj\text{-}R^2$ is 0.719 and 0.644, respectively, suggesting that such error correction model fits the data reasonably well. More significantly, the error correction coefficient shows negative and significant sign. Therefore, the variables of energy and poverty model have a long-run relationship.

Table 10 shows the results for causality where GINI, indigence, and biomass consumption affect poverty, meaning that increases in these variables also generate an increase in poverty, whereas increases in GDP and the energy supply per capita generate a decrease in poverty. These results concur with the fact that a country in modern times has substantially decreased poverty without growing its use of energy with better, cleaner, and efficiency energy services. This is manifested in the strong correlation observed between energy consumption and the national income (World Bank 2006).

4.2.2 Discussion of Results

The estimated results of the long-run relationship and short-run dynamics model for poverty and energy (see Table 7) show that GDP and the energy supply per capita have an inverse relationship with poverty indicating that better access to sustainable reliable and affordable supply of energy services and increase economic growth are pivotal in decreasing poverty because these variables contribute to improve income, welfare, and development in rural and urban communities (European Commission 2006).

The GINI and indigence variables have a positive and significant influence on poverty, indicating that an increase in these variables generates higher poverty. The persistence of poverty is clearly related to the distribution pattern, which is characterized by a high level of inequality, undermining the ability of economic growth to reduce poverty (Alonso 2004).

The biomass consumption variable has a positive influence on poverty. This means that increases in firewood or charcoal consumption contribute to higher poverty. Generally, people living in extreme poverty predominantly use fuels such as firewood or charcoal, which are considered to be the lowest rungs on the energy ladder, and in developing countries, restricted access to energy services and heavy dependence on traditional biomass are characteristic of poverty (European Commission 2006). Moreover, these results concur with the fact that lack of an adequate energy services exacerbates poverty and contributes to its perpetuation, as it precludes most industrial activities and the jobs they create. Experience in different countries has demonstrated how governments can help expand access to modern sources of energy as strategy to decrease poverty. However, electrification and access to modern energy services do not necessarily guarantee the alleviation of poverty (IEA 2005).

The relationship between poverty and CO_2 emissions is positive. Therefore, unsustainable, inefficient, and unclean energy use is widely recognized as a characteristic of poverty in most developing countries, and there is thus an emerging consensus among policy-makers and international organizations that the provision of modern energy services represents a major challenge to decrease poverty and guarantee sustainable development.

5 Conclusions

In this chapter, the authors attempted to find the direction of the causal relationship between productivity, poverty, and energy consumption in Colombia. It analyzes the impact of other variables such as exports, standard of living (GINI), better energy use (energy intensity), and environmental contamination (CO_2 emissions) on development and productivity. The methodology was based on the Granger causality test, which has been found appropriate by using the cointegration technique and discovering there is no cointegration between the variables concerned indicating that in energy analysis, empirical approaches are determinant to improve knowledge and formulation of energy policies.

The results of the long-run relationship and short-run dynamics infer that the capital-labor ratio and the exports-labor ratio are determinants of productivity. The results of exports show the dynamic of this variable in Colombia that during the sample period was characterized by growth, deceleration, and diversification. The poverty variable has a negative effect on productivity, indicating the importance of this variable for development and growth. Energy consumption positively affects development and productivity demonstrating that in the development of a country, energy, productivity, and exports are key factors and improvements in energy efficiency increase productivity and the decrease of the contamination also increases productivity.

The results of the relationship between energy and poverty indicate that GDP and the energy supply per capita are key factors helping to decrease poverty; the GINI and indigence variables have a direct relationship with poverty; and the access to modern energy services helps decrease poverty, which demonstrates that energy quality and security are key factors to decrease poverty and increase development and prosperity of population.

In future research, it is important to determine specific strategies to improve energy security and formulate adequate energy policies, especially in developing countries, where must encourage energy policies that integrate sustainability development and economic growth to improve welfare and quality of life.

6 Policy Recommendations

From the above analysis, it generates several policy strategies and can see that energy is a critical determinant of economic growth, development, and poverty in a country as Colombia. In order to achieve high economic growth, development, and decrease poverty, multidimensional policies are required. These policies should not ignore the energy sector or sustainable development.

In Colombia, the poverty reduction strategy should have a clear goal for the energy sector. However, poverty reduction strategies should emphasize the expansion of access to energy, improve reliability and achieve fiscal sustainability by reduction of the sector's budgetary specifications, decrease fiscal risk due to the energy sector, enhance governance, and ensure environmental sustainability. These efforts should be supported by a set of monitoring indicators such as the availability and affordability of energy-related equipment, fiscal discipline for energy utilities, and a regulatory framework.

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Clara Inés Pardo Martínez has 12-year professional experience working as professor in several Colombian Universities as consultant in different private and public sectors in topics related to HSEQ management systems with the International Standards ISO 9001, ISO 14001, and OHSAS 18001, energy management systems (ISO 50001), and clean production (this includes the design, development, implementation, and audit of the management system, development of training in management systems) and as researcher in the Wuppertal Institute (with research focus on energy efficiency in the manufacturing industries using econometric analysis with the following software: Eviews, Stata, SPSS, and EMS). She joined the Energy and Climate Studies program as a researcher postdoctoral in the field of energy policy, and she is currently professor and researcher of University of La Salle in Bogotá. Her research interests are the following: energy efficiency, energy economics, climate change, empirical analysis, productivity, industrial sector, HSEQ management systems, energy management systems, and economic growth and development.

Alexander Cotte Poveda Alexander Cotte Poveda is professor of Development Economics, Economic Theory, and Economic Growth at La Salle University in Bogotá, Colombia. He has published numerous articles in refereed journals, among them the Journal Oxford Development Studies; Journal of International Development; Socio-Economic Planning Sciences; Journal Peace Economics, Peace Science and Public Policy; Journal Quality and Quantity; Journal Energy Systems; and Journal Social Indicators Research. He is member of Editorial Board of the Emerging Markets Case Studies. Most of his current research is in the field of political economy, development politics, economic and violence, poverty, inequality, economic growth, energy, and human capital.