Journal of Cleaner Production 69 (2014) 143–152

Contents lists available at ScienceDirect

Journal of Cleaner Production

journal homepage: www.elsevier.com/locate/jclepro

Quantitative modelling of electricity consumption using computational intelligence aided design

Yi Chen [a,*], Guangfeng Zhang [b], Tongdan Jin [c], Shaomin Wu [d], Bei Peng [e]

[a] School of Engineering and Built Environment, Glasgow Caledonian University, Glasgow G4 0BA, UK
[b] GREQAM, School of Economics, Aix-Marseille University, Marseille 13236, France
[c] Ingram School of Engineering, Texas State University, San Marcos, TX 78666, USA
[d] Kent Business School, University of Kent, Canterbury CT2 7PE, UK
[e] School of Mechatronics Engineering, University of Electronic Science and Technology of China, Chengdu 611731, China

ARTICLE INFO

Article history:
Received 22 August 2013
Received in revised form
14 January 2014
Accepted 14 January 2014
Available online 29 January 2014

Keywords:
CIAD
Electricity consumption
Energy price
Gross domestic product
Efficiency
Economic structure

ABSTRACT

High electricity consumption is of concern to the world for a variety of reasons, including its social-economic-environmental coupled impacts on well-being of individuals, social life and the federal energy policies. This paper proposes a quantitative model to examine the long-term relationship between annual electricity consumption and its major macroeconomic variables, including gross domestic product, electricity price, efficiency, economic structure, and carbon dioxide emission, using computational intelligence aided design (CIAD). It develops a firefly algorithm with variable population (FAVP) to obtain the parameters of the electricity consumption model through optimising two proposed trend indices: moving mean of the average precision (mmAP) and moving mean of standard derivation (mmSTD). The model is validated with empirical electricity consumption data in China between 1980 and 2012, based on which the error of approximations between 1980 and 2009 is ±15% and the error of predictions between 2010 and 2012 is [−8%, −5%]. The main contributions of this research are to develop: (1) a novel quantitative model that can accurately predict the social, economic and environmental coupled impacts on the annual electricity demands; (2) the conceptual CIAD framework; (3) FAVP algorithm; and (4) two new trend indices of mmAP and mmSTD. The findings of this research can assist the decision makers in resolving the conflict between energy consumption growth and carbon emission reduction without dooming the economic prosperity in the long run.

1. Introduction

The causality relationship between energy consumption (EC) and social or economic factors is one of the central themes in energy research. In the last decade, there has been an increasing research interest in studying the interactions among energy consumption, economic growth, and the sustainable energy policies. The UK, for example, strives to reduce its greenhouse gas emissions by at least 80% (from the 1990 baseline) by 2050, which reflects a reorientation away from specific technological solutions and moves towards structural transformation. The rapid development in China has contributed to the global prosperity in which electricity is the lifeblood of its economic sectors. However, economic growth also creates social-environmental problems such as pollution, global warming, and depletion of natural resources. This is because the majority of today's electricity is generated from fossil fuel fired power plants that release large amounts of greenhouse gas and pollutants. In addition to China and the UK, other countries (USA, New Zealand, Australia, India, Indonesia, Philippines and Thailand, etc.) will be also included in the following literature review section.

In the literature, three major areas have been investigated pertaining to energy consumption, as reviewed in the following paragraphs, which are, area (1): the causal relationship between economic growth and EC, area (2): the correlation between carbon dioxide (CO_2) emission and EC, and area (3): the modelling of EC and relative techniques.

The first research area is interested in the causal relationship between economic growth and EC. Ghosh (2002) examined the Granger causality between ELC per capita and GDP for India. Fatai et al. (2004) examined the causal relationship between GDP and various types of energy, including coal, natural gas, electricity and oil, and concluded that energy conservation policies do not have significant impacts on GDP growth in industrialised nations in New Zealand, Australia, India, Indonesia, Philippines and Thailand. Lee

* Corresponding author. Tel.: +44 (0)141 273 1988; fax: +44 (0)141 331 3690.
E-mail addresses: leo.chen@gcu.ac.uk, leo.chen.yi@live.co.uk (Y. Chen).

0959-6526/$ – see front matter © 2014 Elsevier Ltd. All rights reserved.
http://dx.doi.org/10.1016/j.jclepro.2014.01.058

(2005) conducted a study on a long-run co-integration relationship by considering the heterogeneity effects of nations and the causality relationship between energy consumption and GDP in 18 developing countries using a full-modified ordinary least squares (FMOLS) model. Zhang and Cheng (2009) investigated the existence and direction of Granger causality between economic growth, energy consumption, and carbon emissions in China from 1960 to 2007. Ozturk (2010) provided a survey on EC-economic growth and electricity consumption (ELC)-economic growth causality nexus. Wesseh and Zoumara (2012) investigated the causal dependency between energy consumption and economic in Liberia. Abbas and Choudhary (2013) performed an empirical study to determine the causality between ELC and economic growth in India and Pakistan, at aggregated and disaggregated level in the agricultural sector. By combining error-correction technique co-integration, Asafu-Adjaye (2000) estimated the causal relationships between the energy consumption and the incomes in India, Indonesia, the Philippines and Thailand. Soytas and Sari (2003) explored the causality relationship between the energy consumption and the income based on the time series models in the top 10 emerging markets and the G7 countries: USA, UK, France, Germany, Italy, Canada and Japan. Narayan and Smyth (2005) examined the relationships between EC, employment, and real income in Australia which indicated a long-run employment and real income Granger causality to EC. Sari and Soytas (2007) investigated the inter-temporal link between EC and income in six developing countries using generalised variance decompositions and generalised impulse response. Ajmi et al. (2013) tested the real causal links between EC and national income of G7 countries for policy decision making.

In the second research area, the aim is to investigate how EC influences the CO_2 emission and renewable policy making. Ramanathan (2005, 2006) investigated the relationship between the energy consumption and CO_2 emission from 17 countries in the Middle East and North Africa using data envelopment analysis. Martiskainen (2007) reported different household consuming behaviours and the goal of reducing energy use and CO_2 emissions in the UK. Soytas et al. (2007) and Soytas and Sari (2009) studied the effect of energy consumption and the release of CO_2 in the US and Turkey. Chang (2010) utilised the multivariate co-integration Granger causality tests to investigate the correlations between carbon emissions, energy consumption and economic growth in China using ordinary least squares and vector error correction model.

The third research area focuses on the modelling of energy consumption by accommodating different factors using a variety of quantitative or analytical methods. Saab et al. (2001) investigated three univariate models: the autoregressive, the autoregressive integrated moving average, the autoregressive with a high-pass filter, then the case of electricity in Lebanon was studied for electrical EC forecasting. Swan and Ugursal (2009) conducted a literature review on various modelling techniques for residential energy consumption. Bianco et al. (2009) investigated the influence of economic and demographic variables on the annual electricity consumption in Italy with the intention of developing a long-term forecasting model. Payne (2010) published a survey on the empirical prediction models, and discussed various hypotheses on the causal relationship between electricity consumption and economic growth. Kiran et al. (2012) proposed two electricity energy estimation models based on artificial bee colony and particle swarm optimisation techniques to estimate electricity demand in Turkey. In this paper, we propose a quantitative model taking into account social, economic and environmental coupled impacts, which has not been adequately addressed in prior studies.

Albeit the large bulk of publications, existing literature on energy consumption models fail to address one of the following concerns: (1), they do not capture the coupling effects on energy consumption due to the interactions among social, economic, and environmental factors; (2), few effective methods are developed that allow for quantitative analysis, model verification, and parameter optimisation; (3), there is no any general quantitative modelling framework or platform has been mentioned. In response to the three concerns mentioned above, this paper proposes a computational intelligence aided design (CIAD) framework to construct and optimise the electricity consumption model. The model has been validated based on a 33-year data set collected from China.

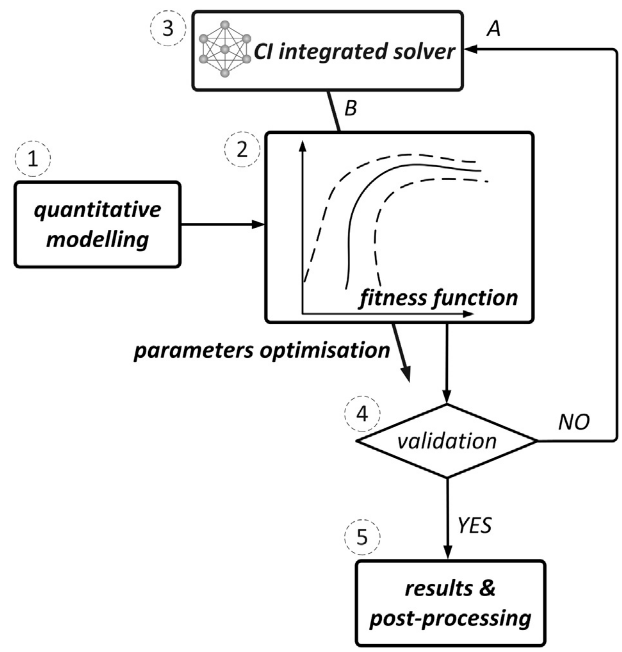

Fig. 1. Framework of computational intelligence aided design.

The contributions can be highlighted in three aspects. First, our model can effectively assess the impact of multiple factors on energy consumption by considering the correlations among social, economic, and environmental factors. Second, a swarm intelligence method-a variable population based firefly algorithm is devised as the search engine to optimise the model parameters. Third, two new metrics, the index of moving mean of the average precision (mmAP) and the index of moving mean of standard derivation (mmSTD) are introduced to characterise the dynamic behaviours of the evolutionary searching process.

The remainder of the paper is organised as follow. Section 2 describes the conceptual framework of CIAD. Section 3 proposes a quantitative approach to modelling national electricity consumption. Section 4 describes the solver for the CI optimisation which is built upon firefly algorithm. Section 5 defines two trend indices for evolutionary optimisation. Section 6 defines the fitness function to approximate the electricity consumption using the proposed model in Section 3. Section 7 provides the empirical results and further verifies the optimal design. Section 8 concludes the paper.

2. Computational intelligence aided design

Computational intelligence (CI) is a set of nature-inspired approaches which offers a wealth of capability for complex problem solving. Compared to the traditional optimisation methods, CI does not need to reformulate the problem in order to search a non-linear or non-differentiable space. Another advantage of the CI is its flexibility in formulating the fitness function which can be