CEEP-BIT WORKING PAPER SERIES

CEEP-BIT

Efficiency assessment of hydroelectric power plants in Canada: A multi criteria decision making approach

Bing Wang, Ioan Nistor
Tad Murty, Yi-Ming Wei

The Center for Energy and Environmental Policy Research, Beijing Institute of Technology (CEEP-BIT), was established in 2009. CEEP-BIT conducts researches on energy economics, climate policy and environmental management to provide scientific basis for public and private decisions in strategy planning and management. CEEP-BIT serves as the platform for the international exchange in the area of energy and environmental policy.

Currently, CEEP-BIT Ranks 82, top 5% institutions in the field of Energy Economics at IDEAS（http://ideas.repec.org/top/top.ene.htm), and Ranks 104, top 5% institutions in the field of Environmental Economics at IDEAS (http://ideas.repec.org/ top/top.env.html).

Yi-Ming Wei
Director of Center for Energy and Environmental Policy Research, Beijing Institute of Technology

For more information, please contact the office:

Address:
Director of Center for Energy and Environmental Policy Research
Beijing Institute of Technology
No.5 Zhongguancun South Street
Haidian District, Beijing 100081, P.R. China

Access:
Tel: +86-10-6891-8551
Fax: +86-10-6891-8651
Email: ceeper@vip.163.com
Website: http://ceep.bit.edu.cn/english/index.htm

Efficiency assessment of hydroelectric power plants in Canada: A multi criteria decision making approach

Bing Wang [a,b,c], Ioan Nistor [c], Tad Murty [c] and Yi-Ming Wei [a,b]

[a] Center for Energy and Environmental Policy Research, Beijing Institute of Technology, Beijing 100081, China

[b] School of Management and Economics, Beijing Institute of Technology, Beijing 100081, China

[c] Department of Civil Engineering, University of Ottawa, Ottawa K1N6N5, Canada

Email addresses: bingwang_bit@163.com (B. Wang), inistor@uottawa.ca (I. Nistor), tadmurty@gmail.com (T.S. Murty), wei@bit.edu.cn (Y.M. Wei)

Highlights

- Modelling the overall hydropower efficiency from the viewpoints of the technical efficiency, profitability, environmental benefits and social responsibility

- The overall hydropower efficiency in Canada experienced a slight improvement in 2012, following an obvious downtrend from 2005 to 2011

- The paper outlines the pivotal roles of energy saving and social responsibility in the overall efficiency of hydropower corporations

- The lower hydropower generating efficiency occurs in some of the most important economic regions of Canada

- Hydropower efficiency improvement in Canada is driven by the technical efficiency, management factors and by the implementation of the energy saving plans.

Efficiency assessment of hydroelectric power plants in Canada: A multi criteria decision making approach

Abstract

Hydropower plays a major role in the Canadian electricity generation industry. Few attempts have been made, however, to assess the efficiency of hydropower generation in Canada. This paper analyzes the overall efficiency of hydropower generation in Canada from comprehensive viewpoints of electricity generating capability, its profitability, as well as environmental benefits and social responsibility using the TOPSIS (the Technique for Order Preference by Similarity to Ideal Solution) method. The factors that influence the efficiency of the hydropower generation are also presented to help to the sustainable hydropower production in Canada. The most important results of this study concern (1) the pivotal roles of energy saving and of the social responsibility in the overall efficiency of hydropower corporates and (2) the lower hydropower generation efficiency of some of the most important economic regions in Canada. Other results reveal that the overall efficiency of hydropower generation in Canada experienced an improvement in 2012 following a downtrend from 2005 to 2011. Amidst these influencing factors, energy saving and social responsibility are key factors in the overall efficiency scores while management (defined herein by the number of employees and hydropower stations of a corporation) has only a slightly negative impact on the overall efficiency score.

Keywords: Hydropower efficiency; TOPSIS; Social responsibility; Energy saving; Benchmarking management

1. Introduction

Renewable energy development plays a significant role in meeting energy demand, boosting energy security, addressing environmental issues and climate change as well as contributing to other aspects of social development (IEA, 2012; Flavin and Aeck, 2005). Total renewable power capacity worldwide exceeded 1,470 GW in 2012, up by 8.5% from 2011 (REN21, 2013). Out of this, renewable power capacity additions represented more than one third of global power capacity developments (GEA, 2012). Furthermore, hydropower rose worldwide by 3% to an estimated total installed power of 990 GW in 2012, accounting for 67 percent of renewable energy capacity. That is to suggest that

among renewable resources, hydropower occupies the dominant role in renewable energy market and leads the way for reliable, renewable and clean energy.

Hydropower plays a vital role in meeting Canada's growing electricity needs while reducing air pollutants and greenhouse gas emissions (Canadian Hydropower Association, 2008). While Canada's energy sector is the fourth largest contributor to Canada's GDP, Canada is the world's third largest hydropower generating country. And hydropower, as the largest primary source in 2012, accounted for 63.3% of the total electricity generation and totaled 376.4 million megawatt-hours in Canada. Furthermore, numerous provinces greatly depend on the use of hydropower for electricity, including Quebec (QC), Manitoba (MB), British Columbia (BC), Newfoundland and Labrador (NL) and Ontario (ON). Moreover, over 90 percent of the electricity consumed in the provinces of Quebec, British Columbia, Newfoundland and Labrador, Manitoba as well as in the Yukon Territory is from hydropower (Canadian Electricity Association, 2013a).

The significance of hydroelectric power in Canadian power generation industry shows that efficiency analysis is essential to the management of hydropower generation in Canada. This topic has received worldwide attention. However, few attempts have been made to analyze the efficiency of hydropower generation in Canada. Moeini and Afshar (2011) presented ant colony optimization algorithms to hydropower reservoir operation problems in Canada and concluded that this model is useful for optimal operation of hydropower reservoirs. Minville et al. (2009) combined the regional climate model with statistical tests to evaluate the impacts of climate change on hydropower production and power plant efficiency and further projected the trends of hydropower production from 2010 to 2099. Their hydropower generation efficiency analysis mainly considered technological efficiency by using a case study. With the increasing concern about environmental issues and corporate social responsibility, a comprehensive framework for hydropower efficiency analysis is needed. Furthermore, the efficiency of hydropower generation only at one plant or a river basin is not representative for the efficiency at regional level.

In the absence of research work about the efficiency of hydropower in Canada, the present study is a timely role and expands the research breadth in this field from a more sustainable and responsible perspectives. This study applies the decision method to deduce the overall efficiency of hydropower generation in Canada and analyzes the impact factors of hydropower efficiency through the use of a regression model. Benchmarking management is further employed to identify best practices and suggest improvements for the hydropower production sector in Canada. This decision analysis is performed by employing the general version of TOPSIS (the Technique for Order Preference by Similarity to Ideal Solution). Considering the lack of a comprehensive study on the overall efficiency of hydropower generation and that few studies have been conducted to investigate this topic from the aspects of climate change, other environmental aspects and corporate social responsibility, this paper attempts to address three issues:

(1) When considering the technical, environmental and social aspects of hydropower generation, what is the difference between various corporations? Why such differences occur?

(2) What are the changes of the hydropower efficiency in time? Why?

(3) What are the influence factors for hydropower generation efficiency? And what can one learn from those "best practices"?

The remainder of this paper is structured as follows: in Section 2, the authors review the literatures, considering the aspects and methods used for hydropower efficiency assessment; in Section 3, the theoretical framework and data resources supporting the model TOPSIS used are explained while the results and discussion are presented in Section 4. Finally, Section 5 outlines the concluding remarks and policy implications. This last part also highlights the contributions that the present study seeks to make as well as further development of this research.

2. Literature review

2.1. Economic and technological efficiencies

Efficiency analysis in relation to electricity generating was historically concentrated on distribution networks (Inglesi-Lotz and Blignaut, 2014; Farsi and Filippini, 2004). Studies analyzing the efficiency of electricity generating plants include Çelen (2013); Kleit and Terrell (2001); Knittel (2002). Jamasb and Pollitt (2001) reviewed the frequency with which different input and output variables are used to model electricity distribution. The most widely-used inputs were number of employees, transformer capacity and network length while the most frequently-used outputs were units of energy delivered, number of customers and size of the service area. Kleit and Terrell (2001) used a Bayesian method to analyze the potential effects of deregulation on gains in electricity generation and found that deregulating electricity generation increases efficiency. Similar research by Knittel (2002) concluded that alternative regulatory programs provide firms with an incentive to increase efficiency. It can be seen that those variables generally represent good indicators which reflect the economic and technological efficiencies of electricity generation.

As for hydropower efficiency, Barros and Peypoch (2007) applied a random cost frontier method to demonstrate the role of competition and regulation in determining the technical efficiency of the hydroelectric generating plants in Portugal. Further analysis by Barros (2008) divided total productivity into technically efficient change and technological change and applied a DEA (Data Envelopment Analysis) model to analyze the hydropower efficiency of the Portugal Electricity Company. Using this model, Barros (2008) described the hydropower industry evolution, the inputs and outputs for efficiency assessment as well as best practices and benchmark management which were further applied to improve the efficiency of hydropower generation industry. Jha and Shrestha (2006) employed an Input-oriented DEA model to evaluate the performance of hydropower plants of the Nepal Electricity Authority and presented the difference in the efficiency scores between the studied hydropower plants.

2.2. Environmental efficiency and social responsibility

Recent research outlined that environmental efficiency and social responsibility are important aspects of the hydropower efficiency. A literature review by Jamasb et al. (2004) revealed the absence of a universally accepted set of input and output variables for modelling electricity units. Liu and Liu (2012) studied the social responsibility, especially for the employee development of the electricity sector in China from the perspective of human resource management. Harmsen et al. (2013) analyzed the electricity efficiency policies and identified the possible implications for the Indian electricity sector. Noailly (2012) researched empirically the impact of alternative environmental policy instruments on technological innovations and found that two types of environmental policies has a positive impact on the direction and rate of technological innovation aiming to improve the energy efficiency of buildings.

Hydropower facilities provide many societal and environmental benefits in addition to producing the much needed renewable electricity. Numerous energy companies provided their corporate social responsibility reports, including Vattenfall (2011) and Brookfield Renewable Power (2013). As the Canadian Hydropower Association (Canadian Hydropower Association, 2013) suggested, Canadian hydropower industry should promote the technical, economic, social and environmental advantages of hydropower and advocate a responsible development and use of hydropower to meet present and future electricity needs in a sustainable manner. Established by the Canadian Electricity Association (2013b) for utilities across Canada, the Sustainable Electricity Company designation requires energy utilities to commit to standards on environmental management systems and guidance on social responsibility. This represents a significant milestone in making the electricity sector and companies more environmentally, socially, and economically responsible in their activities. Almost every

Canadian hydropower company regularly presents their ongoing efforts in augmenting their corporate social responsibility. The changes observed in the energy market have obliged energy companies to react. However, strategic planning requires a sound and efficient basis if it is to yield successful results. Thus, efficiency analysis of hydropower generation at the level of the enterprise should consider the environmental benefits and social responsibility.

2.3. Methods for energy efficiency analysis

The literature review of a sample of recent publications on energy efficiency shows that they adopt one of three main complementary efficiency methodologies: DEA (Wang et al., 2012, 2013; Yuan et al., 2013), which is of particular relevance to the present research, the Stochastic Frontier Model (Mugisha, 2007; Stern, 2012; Filippini and Hunt, 2012) and TOPSIS (Çelen, 2012; Çelen and Yalçın, 2012). These three methods represent branches of multi criteria decision making models. Since the DEA model does not impose any functional form on the data nor make any distributional assumptions for the inefficiency term, the previously mentioned TOPSIS method is frequently used in decision making (Afshar, 2011; Khazaeni et al., 2012).

Stochastic frontier model can be divided into the heterogeneous and homogenous model. Because of the homogeneity assumption, this model is not comparable with DEA modelled research, since DEA models neither allow for clusters nor for statistically estimated parameters. Barros et al. (2013) applied the heterogeneous stochastic frontier model to analyze cost efficiency of the Chinese hydroelectric companies and concluded that dimension (the market share) is the main cause of heterogeneity in the case study. The most recent and comprehensive survey of research techniques on energy efficiency can be found in Çelen (2013). Apart from these techniques, another frequently used approach is index decomposition analysis (Ang, 2006; Liu and Ang, 2007; Ang and Xu, 2013).

3. Methodology

3.1. Conceptual framework for hydropower efficiency analysis

In this study, the TOPSIS model is introduced to analyze the overall hydropower efficiency in Canada from a technological, economic, environmental benefits and social responsibility points of view. Based on the literature reviews and data availability, nine indicators are chosen to represent the overall hydropower efficiency. The classic regression method is also employed to discuss the determinants of hydropower efficiency and to explore possible implications from the benchmarking analysis. By analyzing the results, the authors put forward several recommendations for sustainable development of the Canadian hydropower sector. Fig. 1 illustrates the conceptual framework of the methodology used in this study.
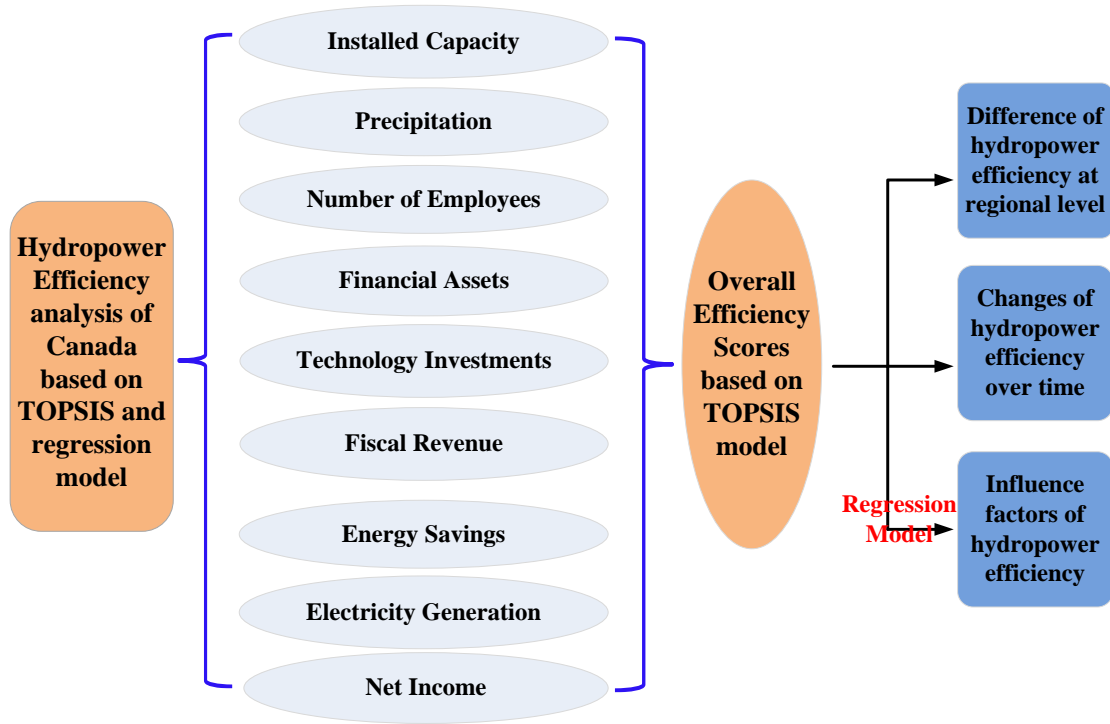
Fig. 1. Methodology framework for the hydropower efficiency analysis.

3.2. Hydropower generation efficiency assessment model based on TOPSIS

The TOPSIS method, first developed by Hwang and Yoon (1981), is a widely accepted multi criteria decision making (MCDM) technique based on the concept that the positive ideal alternative has the best level for all considered attributes, while the negative ideal is the one with all worst attribute values. Its basic principle assumes that the chosen alternative should simultaneously have the shortest distance from the positive-ideal solution and the farthest distance from the negative-ideal solution (Ertugrul and Karakasoglu, 2009). Figure 2 shows the analytical framework for TOPSIS method. In this illustration, X^* and X^o are the positive ideal and negative ideal solutions in the assessment, respectively, while f_1 and f_2 represent the benefit attributes. It is easy to evaluate the alternatives of x_1, x_2, x_3 and x_6 based on their distances with X^*. While x_4 and x_5 have the similar distance with X^*, another determinant-the distance between the alternative and the negative ideal solution X^o - is selected to arrive at the decision. This way, x_4 has a relatively efficient score than x_5 because of its relative longer distance with respect to X^o. Based on this algorithm, the problem of the units inconsistency brought by different criteria can also be evaluated. Due to its advantages in ranking and selecting a number of externally determined alternatives through a distance measure, this method has been widely applied in efficiency analysis and risk management.
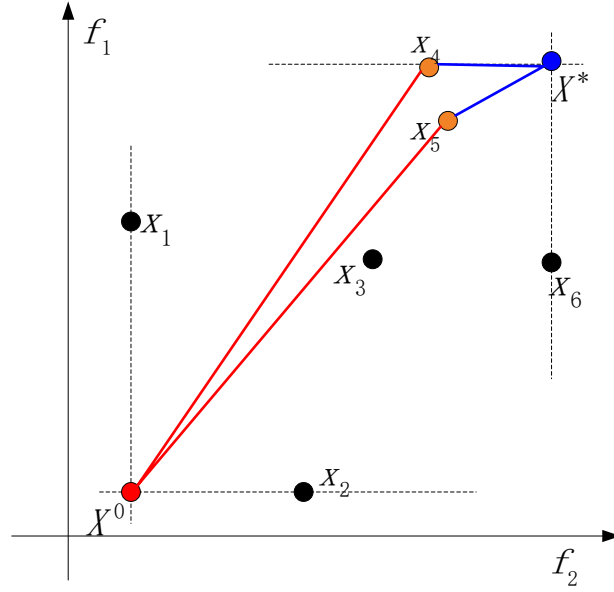
Fig. 2. Analytical framework for TOPSIS model.

In our research, the TOPSIS technique for efficiency analysis of the Canadian hydropower generation is carried out as follows:

Step 1: Let x_{it} be the original hydropower efficiency assessment sequence of province i in year t. There are nine evaluation criterions in this research. Thus, x_{it} can be presented as $x_{it} = (x_{it}^1, x_{it}^2, \cdots, x_{it}^9)$. An evaluation matrix consisting of five provinces and nine criteria from 2005 and 2012 is developed, with the intersection of each alternative in year t given as x_{it}. Therefore one obtains a matrix $(x_{it})_{40 \times 9}$.

Step 2: The original matrix $(x_{it})_{40 \times 9}$ is then normalized to form a Regulated matrix $R^* = (r_{it})_{40 \times 9}$ for our efficiency assessment by the vector normalization method as demonstrated in Equation (1). The time period t from 2005 to 2012 is presented as $t = 1, 2, \cdots, 8$.

[1] $\quad r_{it}^j = x_{it}^j \Big/ \sqrt{\sum_{i=1}^{5} \sum_{t=1}^{8} (x_{it}^j)^2}$, $\quad i = 1, 2, \cdots, 5$ and $j = 1, 2, \cdots, 9$

Step 3: Calculate the Weighted normalized decision matrix for hydropower efficiency assessment by Equation (2).

[2] $\quad W = (w_{ij})_{m \times n} = (w_j r_{it}^j)_{m \times n}$

where w_j is the weight given to the criteria j and $\sum_{j=1}^{n} w_j = 1$. In this study, nine attributes have been given the same weight with a fair consideration.

Step 4: Determine the most inefficient reference (the negative ideal assessment unit) A_a and the most efficient alternative (the positive ideal assessment unit) A_b by using Equation (3) and (4):

[3]

$A_a = \left\{ \left\langle \min(w_{ij} | i = 1, 2, \cdots, m) | j \in J_+ \right\rangle, \left\langle \max(w_{ij} | i = 1, 2, \cdots, m) | j \in J_- \right\rangle \right\} = \left\{ \alpha_{aj} | j = 1, 2, \cdots, n \right\}$ [4]

$A_b = \left\{ \left\langle \max(w_{ij} | i = 1, 2, \cdots, m) | j \in J_+ \right\rangle, \left\langle \min(w_{ij} | i = 1, 2, \cdots, m) | j \in J_- \right\rangle \right\} = \left\{ \alpha_{bj} | j = 1, 2, \cdots, n \right\}$ where

$J_+ = \left\{ j | j \in positive \right\}$ and $J_- = \left\{ j | j \in negative \right\}$, which are a set of positive (benefit) and negative (cost) attributes, respectively.

Step 5: Calculate the distance d_{ia} between the province i and the worst condition A_a by Equation (5);

$$[5]\, d_{ia} = \sqrt{\sum_{j=1}^{n}(w_{ij} - \alpha_{aj})^2}\,,\quad i = 1, 2, \cdots, m$$

and the distance d_{ib} between the province i and the best condition A_b by Equation (6).

$$[6]\quad d_{ib} = \sqrt{\sum_{j=1}^{n}(w_{ij} - \alpha_{bj})^2}\,,\quad i = 1, 2, \cdots, m$$

Where d_{ia} and d_{ib} are the Euclidean distances for the province i to the most efficient and inefficient conditions, respectively.

Step 6: Calculate the similarity of province i to the worst condition (the inefficient reference):

$$[7]\quad S_i = d_{ia}/(d_{ia} + d_{ib})$$

where $0 \leq S_i \leq 1$, $i = 1, 2, \cdots, m$.

$S_i = 0$, if and only if the province i is the most inefficient condition.

$S_i = 1$, if and only if the province i is the most efficient condition.

Step 7: Rank the efficiency scores of the five provinces according to S_i, where a higher value of S_i indicates a better solution with higher hydropower efficiency.

Using this method, the total efficiency of five provincially-owned hydropower corporations is further evaluated and the development trend of hydroelectric efficiency is obtained.

3.3. Indicators and Data resources

Combined with the indicators of electricity generating efficiency and profitability, the indicators of environmental benefit and social responsibility have been selected to formulate the aspects of efficiency assessment in this study.

The general paucity of the data on the environmental performance of hydroelectric generation means that this information must be gathered through a combination of available data sources. In this study, data on energy saving has been collected for the aspect of environmental benefit, but whenever unavailable, an estimate was made on the basis of pre-existing data. Apart from these indices mainly selected from the literature (labeled in Section 2), other indicators are also chosen according to data availability and based on their universal acceptability in literature. Table 1 demonstrates descriptive statistics for these indices and their values are divided by the number of hydropower stations. For example, Installed Capacity (IC) represents the installed capacity per hydropower station in each province.

Table 1

Characteristics of the indicators of hydropower efficiency analysis, 2005-2012.

	Minimum	Maximum	Average	Standard Deviation
Installed capacity	106.83	599.51	355.27	2444.71
Precipitation	455.57	981.54	727.57	4708.93
Employee	51.64	449.93	253.19	1821.25
Financial Asset	101.51	767.16	365.98	2639.63
Technology Investment	4.11	210.00	52.07	450.70
Fiscal Revenue	16.88	216.25	104.24	793.44
Energy Saving	0.55	243.43	60.12	647.71

Electricity Generation	0.47	3.48	1.97	13.83
Net Income	0.46	38.89	12.39	109.61

As outlined in the BC-hydro annual report 2006, the following statement "*Our largely hydroelectric generating system is heavily dependent on precipitation and reservoir levels to meet our financial targets*" reinforces that the multi-annual amount of precipitation is a key factor for hydropower generation. In this sense, an important issue is to determine the multi-annual volume of precipitation for each Canadian province. The website of Environment Canada, an institution under the jurisdiction of the Federal Government of Canada (http://climate.weather.gc.ca/) provides, among other climate parameters, historical data for precipitation across the entire country. In this study, based on the locations of hydropower generating plants and the annual reports of five hydropower companies, nineteen (19) sub-regions in five of the Canadian provinces which generate an important percentage of hydropower (4 in Quebec, 5 in Ontario, 4 in British Columbia, 4 in Manitoba and 2 in Newfoundland and Labrador) and 112 weather stations (Quebec 30, Ontario 28, British Columbia 27, Manitoba 17 and Newfoundland and Labrador 10) have been selected. Equation 8 describes the calculation of the precipitation factor for each of the selected provinces at one year.

$$[8] \quad R = \sum_{i=1}^{N} percentage_i \times r_i$$

where R is the precipitation of each province and the province can be divided into N regions. The $percentage_i$ represents the percentage of the total installed capacity of hydropower plants in the i region among the total installed capacity of this province. r_i is the annual average value of precipitation of those selected weather stations in i region. Taking the province of Manitoba for example, Figure 3 presents the selection of hydropower plants for hydropower efficiency analysis. Four sub-regions (N =4 for the calculation of precipitation in Manitoba) have been classified according to the location of hydropower plants and the river basin. Based on the classification in Figure 3, Table 2 describes the weather stations chosen for the data of precipitation, which is determined by data availability and the percentage of hydropower installed capacity of each region.
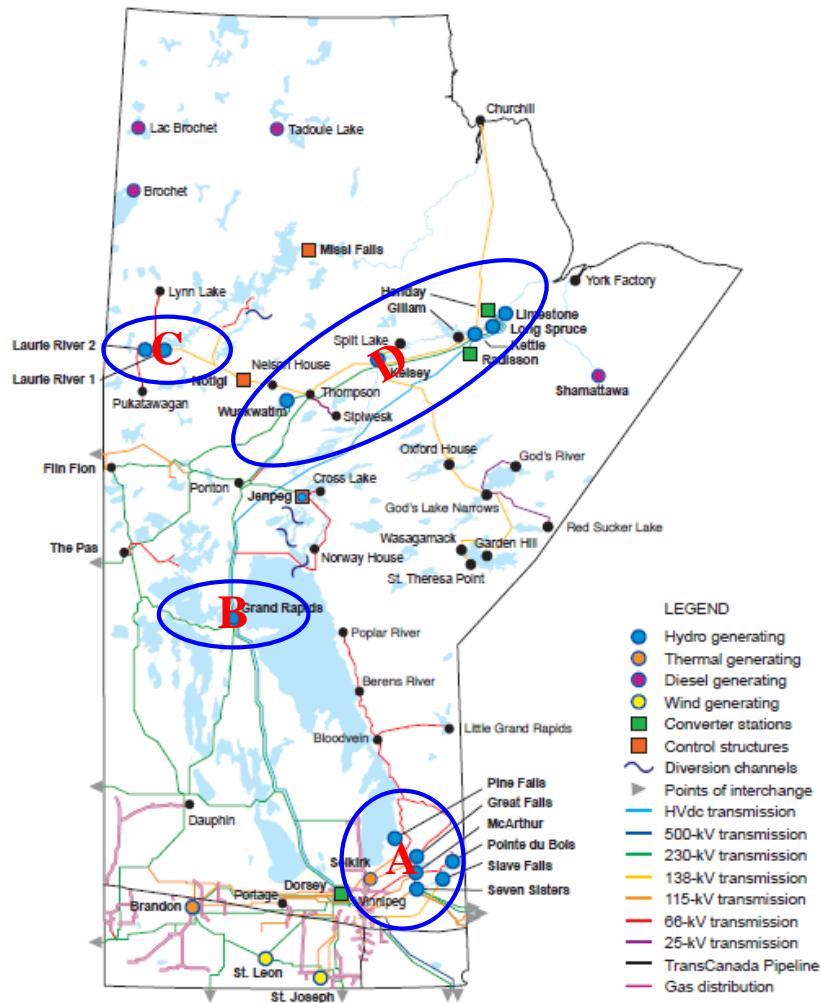
Fig. 3. Selection of hydropower plants and their weather stations (Manitoba). Data resource: Manitoba Hydro, 2013.

Table 2

Selection of weather stations for hydropower efficiency analysis in Manitoba.

Region	Station Name	Latitude	Longitude	Station ID
Falls (Part A)	Stony Mountain	50.117	-97.167	5022791
	Arborg	50.933	-97.083	5030080
	Fisher Branch (AUT)	51.083	-97.555	50309J6
	Gimli Harbour CS	50.631	-96.982	5031041
	Great Falls Climate	50.522	-95.977	5031201
	Pinawa Canwarn	50.148	-95.89	5032161
	Victoria Beach (AUT)	50.7	-96.567	5032951
Grand Rapids	Grand Rapids Hydro	53.158	-99.283	5031111

(Part B)	Grand Rapids (AUT)	53.186	-99.268	5031A10
	Cowan	52.033	-100.65	5040FJ3
	Cross Lake Jenpeg	54.533	-98.033	5060623
Laurie River (Part C)	Flin Flon	54.683	-101.683	5050919
	Lynn Lake	56.864	-101.076	5061648
	Lynn Lake RCS	56.85	-101.067	5061649
Nelson River and Wuskwatim (Part D)	Gillam A	56.358	-94.711	5061001
	Thompson A	55.803	-97.863	5062922
	Thompson Zoo	55.752	-97.866	5062926

The provinces of Quebec, British Columbia, Newfoundland and Labrador, Ontarioand Manitoba play a pivotal role in Canada's hydropower development (Canadian Hydropower Association, 2008). The proportion of hydropower capacity of these five provinces accounts for about 95% of the national hydropower, specifically 97.02% in 2012 and 96.79% in 2011 (Canadian Electricity Association, 2013a). This confirms that the five selected provinces in this model are representative for the overall hydropower efficiency analysis of Canada. Therefore, except for the data on precipitation, the data resources for other indicators are obtained from the Key Canadian Electricity Statistics (Canadian Electricity Association, 2013a) and from the Annual Reports of BC hydro, Newfoundland and Labrador Hydro, Manitoba Hydro, Ontario Power Generation and Hydro-Quebec (Manitoba Hydro, 2013; BC Hydro, 2013; Nalcor Energy, 2012; Ontario Power Generation, 2013 and Hydro-Quebec, 2013). The period of this study covers the period from 2005 to 2012. Thus, there are 40 samples that the authors used in this study.

4. Results and Discussions

4.1. Differences between the hydropower generation efficiency at provincial level

Based on the efficiency scores of the five provincial hydropower corporations for the period between 2005 and 2012, the average value for each province could be calculated. The average TOPSIS scores for Quebec, Manitoba, Newfoundland and Labrador, British Columbia and Ontario are 0.6478, 0.5172, 0.5129, 0.5041 and 0.3383, respectively. Hydro-Quebec seems to have the highest generation efficiency while Ontario has the lowest one among the five provinces.

Coincidentally, these two provinces (Quebec and Ontario) share some similarities, such as the geographic location, climate features, as well as the number of hydropower stations. The hydroelectric efficiency of each province, however, shows major difference. The reason may be the fact that even though Ontario and Quebec have comparable number of hydropower stations (65 and 59, respectively), Ontario's hydropower efficiency per station is significantly lower than that of Quebec. The installed capacity of each generating unit in Ontario is generally smaller comparing to those in Quebec: this implies a higher consumption of human resources and financial investment per energy output. Among its 65 hydropower plants, Ontario has only 19 plants with an installed capacity over 100 MW and 28 plants with installed capacity of less than 10 MW. This indicates that scale of the hydropower production is of great significance in the level of hydropower efficiency and a large number of hydropower plants with a lower installed capacity may work against efficiency improvement.
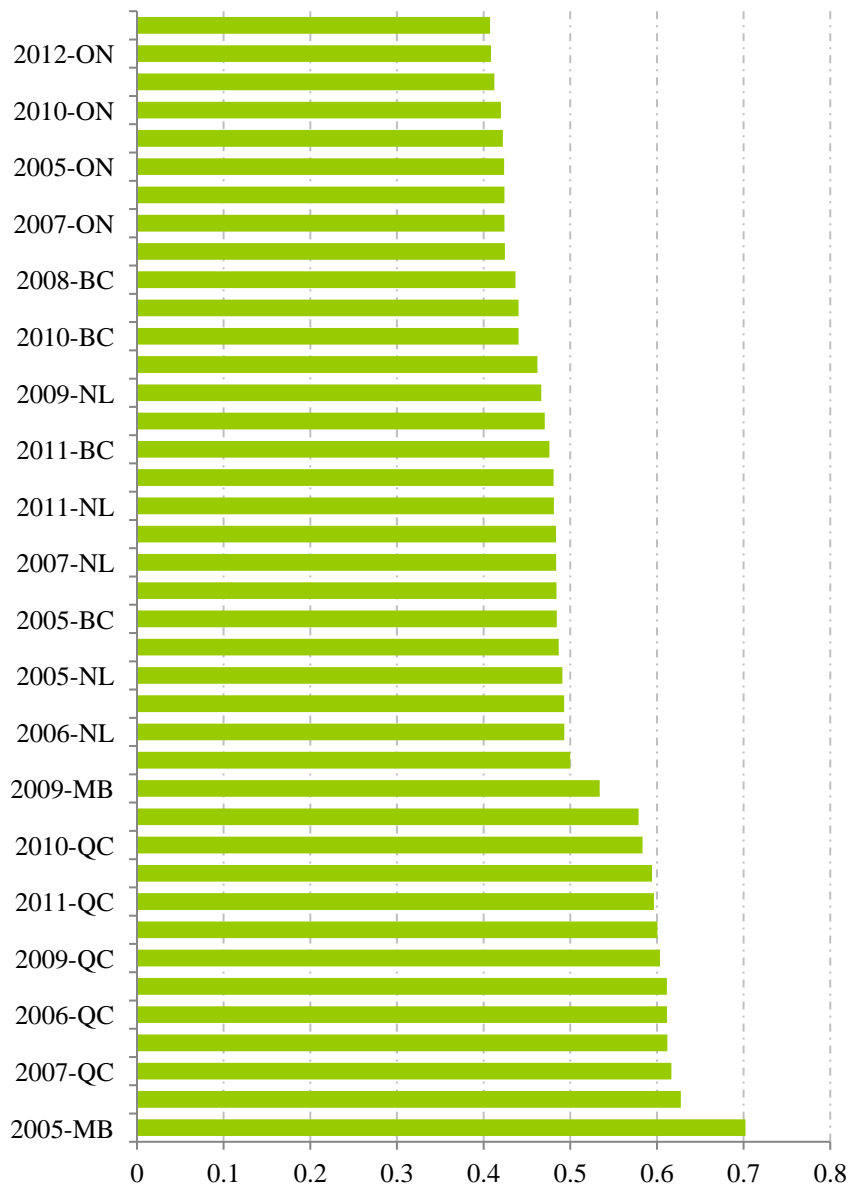
Fig. 4. Hydropower efficiency of different Canadian provinces from 2005 to 2012.

Figure 4 depicts the overall efficiency scores for the five studied Canadian provinces from 2005 to 2012. It can be seen that Quebec and Manitoba have higher efficiency scores while Ontario's scores are generally lowest. This indicates similar results as those obtained from an analysis on the average efficiency scores, which shows that efficiency could be validated using both average scores and each single score.

4.2. Differences between hydropower generation efficiency for different years

With the overall efficiency scores for the five Canadian provinces, the authors can obtain the variation of efficiency scores from 2005 to 2012 and the volatility of the efficiency scores for each region, as shown in Figure 5. Results from the standard deviation analysis show that the hydropower efficiency scores in Manitoba has the highest level of volatility, British Columbia, Newfoundland and Labrador, Quebec show the moderate levels while the changes of Ontario's efficiency are relatively small. This fact is also supported by Figure 5 which shows that efficiency scores for the province of Manitoba has an obvious downtrend whilst those of all other four provinces fluctuate around an average value. The reason for the decrease of Manitoba's hydropower efficiency is related to the

negative influence of the lower electricity prices in export markets and to the decrease of electricity production per installed capacity caused by a colder than usual winter season (Manitoba Hydro, 2013).
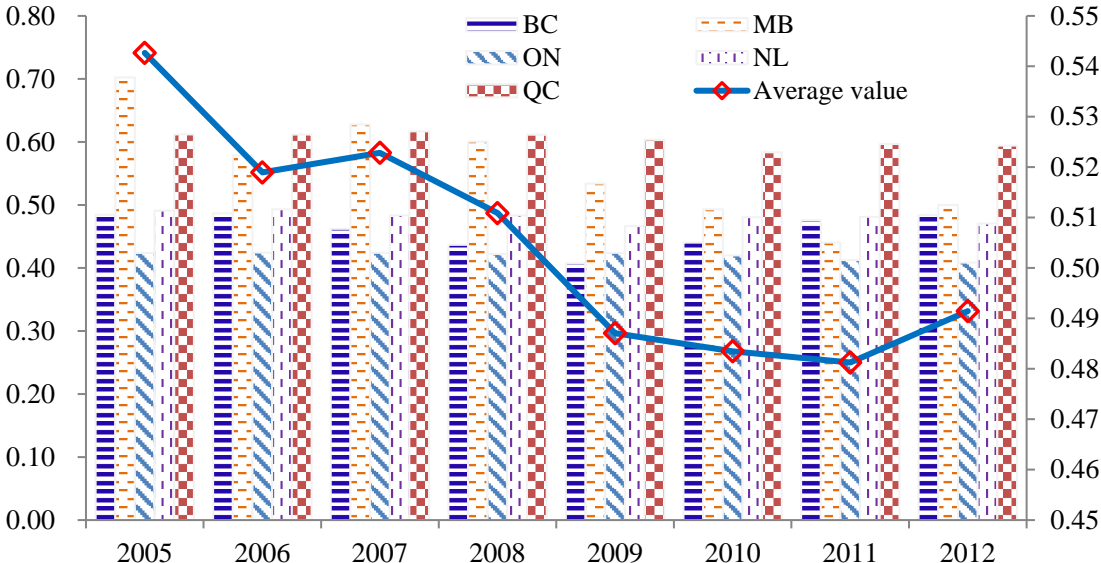

Fig. 5. Changes in hydropower efficiency of five Canadian provinces from 2005 to 2012.

The trend of the hydropower efficiency during the analyzed period is also presented in Figure 5. The annual average values of hydropower efficiency, represented by the blue line in Figure 5, demonstrates that the efficiency of all hydropower enterprises decreased from 2005 to 2011, followed by a slight increase in 2012. Significant declines occurred between 2006 and 2009. The reason for the former is due to extreme weather events as inferred also by the following statement from BC hydro: "*A year of extreme weather events provided challenges in managing the BC Hydro water system*" (BC Hydro, 2013). Manitoba Hydro's declaration - "*The reduced water flows resulted in reduced hydraulic generation and lower surplus energy available for sale in export markets*" (Manitoba Hydro, 2013) - also support this assumption. The second reduction may be attributed to poor economic conditions and milder than normal winter weather conditions, which are discussed in the Management Discussion and Analysis section of the annual report of each provincially-owned power corporation.

4.3. Influence factors for hydropower efficiency

In order to examine the determinants of hydropower efficiency, this study performs a classic regression analysis, estimating the coefficient between overall hydropower efficiency and its drivers. It is recognized that the efficiency scores obtained in the first stage of this research (TOPSIS model) are correlated with the explanatory variables - impact factors - used in the second stage (regression model). While data resources of TOPSIS are selected from the balance sheets of each company, variables in the regression model are independent of these, establishing a separation between efficiency drivers and balance sheet variables that characterize the management practices of the hydroelectric plant.

Table 3

Variables for impact factor analysis of hydropower efficiency.

	Definition	Calculation
y	Overall efficiency of hydropower generation	Efficiency Score
x_1	Generating efficiency	Electricity/IC
x_2	Profitability	Net income/IC
x_3	Environmental benefit	Energy saving/Technology investment

x_4	Climate change	Precipitation
x_5	Management	Job/IC and the number of stations
x_6	Social responsibility	Revenue/Finance Assets

Notes: IC and TI is the abbreviation of Installed Capacity and Technology investment, respectively.

This study chooses six possible drivers for hydropower efficiency, which are all presented in Table 3. Each parameter has its own specific meaning in the organization of efficient hydropower generation unit. The regression results are shown in Table 4. It can be seen that the model appears to fit the data well, with a statistically high R^2 coefficient (adjusted R^2=0.947). The F-value and the degrees of freedom of the regression analysis are 117.248 and 6, respectively.

Table 4

Regression coefficients for the determinants of hydroelectric efficiency.

Predictor variables	Unstandardised Coefficients	Standard errors	Standardised Coefficients	F-value	Degree of freedom	
					Total	Regression
Constant	1.351***	0.295	-			
x_1	0.504***	0.082	0.488			
x_2	0.166***	0.022	0.417	117.248***	39	6
x_3	0.179***	0.039	0.263			
x_4	0.013	0.039	0.027			
x_5	-0.033	0.034	-0.092			
x_6	0.193***	0.035	0.326			

Notes: ***$p < 0.001$, **$p < 0.05$, *$p < 0.10$

Results show that apart from the parameter x_5 (the indicator of management), other factors are positively associated with overall hydropower efficiency. These results support also the assertion that the total number of hydropower plants and the number of employees has a slightly negative effect on hydropower efficiency, suggesting that the hydropower corporation should carefully decide on the proper number of hydropower plants and too many hydropower plants and a large number of employees beyond the threshold will reduce the efficiency of hydropower plants. Amidst all other factors, the hydropower generating efficiency has the most important role in the overall efficiency score, while profitability follows. Even though the factors of generating efficiency and profitability in many provinces are often regarded as relatively important comparing to the environmental benefit and social responsibility, the gap is not very big, which indicates that, as a responsible hydropower generation company, other than the vital role of electricity generation and profit-making, the environment impact and social responsibility are also of considerable interest to the sustainable development of each hydropower generating unit.

4.4. Benchmarking management for efficiency improvement

Benchmarking theory is used to find outstanding examples in order to learn its advantages (Bogan and English 1994) and has applications in the performance assessment of wind farms (Barros and Antunes 2011). In the present research, the authors use this theory to analyze the possible pathways to enhance the hydropower efficiency.

The hydropower efficiency analysis at provincial level shows that Quebec and Manitoba set good examples in this industry. As Barros et al. (2013) concluded that regulation must be applied in accordance with clusters, benchmarking management should consider the similarity for Quebec and Manitoba. As for Ontario, efficiency may be reduced due to (1) too many hydropower generation stations with a lower installed capacity (when compared, for instance, with Quebec) and (2) a high ratio of financial investment to net income (compared with the hydropower projects in Manitoba). As

for British Columbia, efficiency problems are related to (1) technology investment with reduced energy saving (compared to Manitoba) and (2) a high ratio of financial investment to net income (compared with Manitoba and Quebec). For the case of Newfoundland and Labrador, hydropower efficiency could be improved by using a potent energy saving plan similar to that of Quebec.

5. Conclusions and policy implications

5.1. Conclusions

From the analysis conducted in this study, the authors can draw the following conclusions.

(1) Differences in hydropower efficiency at provincial level show that the lower efficient hydropower generation units are located in Provinces with higher GDP, such as Ontario or British Columbia in the current reference set. Results reveal that hydropower efficiency in Quebec and Manitoba is higher than the average whilst that of Ontario and British Columbia is lower among the five provinces investigated. Ontario, however, ranked the first place in terms of economic output and final energy demand in Canada (2010) while British Columbia has the leading role in the western part of Canada. The fact that the lowest hydropower efficiency units were found to occur in the most developed economic provinces of Canada is a stark reminder of the significance of efficiency improvement in those provinces.

(2) The trend in the average hydropower efficiency from 2005 to 2012 demonstrates that the hydroelectric efficiency experienced two noticeable downturns in 2006 and 2009, respectively, and a slight increase in 2012. As for the efficiency scores at provincial level, the score of Manitoba present an obvious downtrend whilst those of all the other four provinces investigated fluctuate around the average value. Further, the hydropower efficiency score in Manitoba has the highest level of volatility. British Columbia, Newfoundland and Labrador, Quebec show the moderate levels while the changes of Ontario's efficiency are relatively small. The two downturns could be attributed to the frequent unfavorable extreme climate events and to the worse economic conditions. The reason for the changes in the overall hydropower efficiency could be found evidence in the annual report of these electricity utilities.

(3) Influence factors of hydroelectric generation reveal that generating efficiency has the most important role in the overall efficiency score, followed by the profitability. While the factors of generating efficiency and profitability are often considered more important than the environmental benefits and social responsibility, the gap, however, is not very significant. This indicates that as a responsible hydropower generation company, other than the vital role of electricity generation and gaining profit, it is of utmost importance to consider the environment benefits and social responsibility for the sustainable development of one generating corporation.

5.2. Policy implications

According to the results of the TOPSIS model and the analysis of the impact factors, some important implications for hydropower generation efficiency for Canada in the future are presented below

(1) Environmental benefits and social responsibility are essential in the overall hydroelectric efficiency assessment. Almost every hydropower corporation expressed their plan to become an electric utility operating in a safe, open and environmentally-responsible manner. However, this objective should be further implemented in the operation of hydropower generation. After all, sustainability is the main priority of renewable electricity. Some valuable practices are well

implemented with a good environmental outcome, such as the demand side management by BC Hydro and Manitoba Hydro, the Environmental Management Systems by Nalcor Energy (Newfoundland and Labrador) and Power Smart program by Manitoba Hydro.

(2) Hydropower generation companies in Ontario and British Columbia should strengthen the management of hydropower plants with lower efficiency and choose a proper number of generating units for units to be developed and/or retrofitted. Meanwhile, the results of benchmark management show different strategies for efficiency improvements of different corporations. Even though hydroelectricity only represents about 36% of the electricity generation in the operation of Ontario Power Generation (entirely owned by the Province of Ontario), its 65 hydroelectric generation stations with a lower average installed capacity (especially most of those with a less than 10 MW installed capacity) have a negative impact on the efficiency of hydroelectric generation. Remarkably, the Board of Ontario Power Generation is focusing on identifying and assessing alternative strategies for the company to achieve long-term financial sustainability. For the hydropower generation in the Province of Newfoundland and Labrador, the improvement may come from better energy saving plans.

Given the important role of the hydropower generation in Canada, the efficiency assessment of hydropower generation has received limited attention in Canada. The present work is the first attempt to fill in the gaps in the knowledge of this subject by using a comprehensive viewpoint and by addressing the impact factors of hydropower generation efficiency in Canada. The results of this research are expected to contribute to an efficient decision making for sustainable development of hydropower generation in Canada. Unlike the work Barros et al. (2013), the present reference set include almost 90 percent of hydropower generation in Canada. While electricity generating capability and its profitability were generally considered in the traditional efficiency assessment on energy systems (Jha and Shrestha, 2006; Barros and Peypoch, 2007; Barros, 2008), this study pays further attentions to the environmental benefits and social responsibility of one electric utility.

Even though this study is a first attempt to research the overall hydropower generation efficiency in Canada, there are some limitations to this research work. Though the authors considered energy saving as an environmental benefit, other indicators could also be used, such as the data on greenhouse gas reduction. Additionally, benchmarking analysis provides crude pathways for efficiency improvement. Also, under the availability of enough data resources, the conclusions from the DEA model could reveal a more precise projection for further improvement.

The determinants of hydroelectric efficiency indicate that changes in the precipitation regime will impact the efficiency of hydropower generation. The ongoing vulnerability of hydropower generation due to climate change may jeopardize the availability and reliability of hydropower (Wang et al. 2014a, b). Therefore, its influences and vulnerability of hydropower generation from extreme climate events should be considered in future study.

Acknowledgements

References

Afshar, A., Mariño, M.A., Saadatpour, M., Afshar, A., 2011. Fuzzy TOPSIS multi-criteria decision analysis applied to Karun reservoirs system. Water Resour. Manag. 25(2), 545-563.

Ang, B.W., 2006. Monitoring changes in economy-wide energy efficiency: from energy-GDP ratio to composite energy efficiency index. Energy Policy 34, 574–582.

Ang, B.W., Xu, X.Y., 2013. Tracking industrial energy efficiency trends using index decomposition analysis. Energy Econ. 40, 1014-1021.

Barros, C.P. 2008. Efficiency analysis of hydroelectric generating plants: A case study for Portugal. Energy Econ. 30(1), 59-75.

Barros, C.P., Antunes, O., 2011. Performance assessment of Portuguese wind farms: ownership and managerial efficiency. Energy Policy 39, 3055–3063.

Barros, C.P., Chen, Z.F., Managi, S., Antunes, O.S. 2013. Examining the cost efficiency of Chinese hydroelectric companies using a finite mixture model. Energy Econ. 36, 511-517.

Barros, C.P., Peypoch, N., 2007. The determinants of cost efficiency of hydroelectric generating plants: A random frontier approach. Energy Policy 35(9), 4463-4470.

BC Hydro, 2013. BC Hydro Annual Report 2013 [online]. Available from http://www.bchydro.com/about/accountability_reports/financial_reports/annual_reports.html [cited 18 January 2014].

Bogan, C.E., English, M.J., 1994. Benchmarking for Best Practices: Winning through Innovative Adaptation. New York: McGraw-Hill.

Brookfield Renewable Power. 2013. Corporate and Social Responsibility Report. Available from http://brookfieldrenewable.com/_Global/44/documents/relatedlinks/4076.pdf [accessed 18 January 2014].

Canadian Electricity Association, 2013a. Key Canadian Electricity Statistics 2013. Available from http://www.electricity.ca/media/IndustryData/KeyCanadianElectricityStatistics21May2013.pdf [accessed 18 January 2014].

Canadian Electricity Association, 2013b. Sustainable Electricity 2013 Annual Report: Innovating for a Sustainable Future. Available from http://www.sustainableelectricity.ca/media/AnnualReport2013/2013SustainableElectricityAnnualReport.pdf [accessed 18 January 2014].

Canadian Hydropower Association, 2008. Hydropower in Canada: Past, Present and Future. Ottawa. Available from https://canadahydro.ca/pages/cha-reports-and-publications [accessed 18 January 2014].

Canadian Hydropower Association, 2013. Report of Activities 2012-2013. Available from https://canadahydro.ca/reportsreference/cha-reports-and-publications [accessed 18 January 2014].

Çelen, A., 2012. Performance evaluation of Turkish electricity distribution market using a combined FAHP/TOPSIS method. Energy Educ. Sci. Tech. Part A: Energy Sci. Res. 29(2), 1263-1276.

Çelen, A., Yalçın, N., 2012. Performance assessment of Turkish electricity distribution utilities: an application of combined FAHP/TOPSIS/DEA methodology to Incorporate equality of service. Utilities Policy 23, 59-71.

Çelen, A., 2013. Efficiency and productivity (TFP) of the Turkish electricity distribution companies: An application of two-stage (DEA&Tobit) analysis. Energy Policy 63, 300-310.

Ertugrul, I., Karakasoglu, N., 2009. Performance evaluation of Turkish cement firms with fuzzy analytic hierarchy process and TOPSIS methods. Expert Syst. Appl. 36(1), 702-715.

Farsi, M., Filippini, M., 2004. Regulation and measuring cost-efficiency with panel data models: application to electricity distribution utilities. Rev. Ind. Organ. 25(1), 1-19.

Filippini, M., Hunt, L.C., 2012. US residential energy demand and energy efficiency: A stochastic demand frontier approach. Energy Econ. 34(5), 1484-1491.

Flavin, C., Aeck, M.H., 2005. Energy for development: The Potential Role of Renewable Energy in Meeting the Millennium Development Goals. Worldwatch Institute, New York.

GEA, 2012. Global Energy Assessment-Toward a Sustainable Future, Cambridge University Press, Cambridge UK and New York, NY, USA and the International Institute for Applied Systems Analysis, Laxenburg, Austria.

Harmsen, R., Moth, L., Kumar, A., 2014. Applicability of Energy Saving Obligations to Indian electricity efficiency efforts. Energy Strategy Rev. 2: 298-306.

Hwang, C.L., Yoon, K., 1981. Multiple attribute decision making: methods and applications, A state of the art survey. Springer-Verlag, New York.

Hydro-Quebec, 2013. Hydro-Quebec Annual Report 2013 [online]. Available from http://www.hydroquebec.com/publications/en/annual_report/pdf/annual-report-2013.pdf [cited 18 January 2014].

IEA, 2012. World energy outlook 2012. Paris, France.

Inglesi-Lotz, R., Blignaut, J.N., 2014. Improving the electricity efficiency in South Africa through a benchmark-and-trade system. Renew. Sust. Energy Rev. 30, 833-840.

Jamasb, T., Pollitt, M., 2001. Benchmarking and regulation: international electric experience. Utilities Policy 9(3), 107-130.

Jamasb, T., Nillesen, P., Pollitt, M., 2004. Strategic behaviour under regulatory benchmarking. Energy Econ. 26(5), 825-843.

Jha, D.K., Shrestha, R., 2006. Measuring Efficiency of Hydropower Plants in Nepal Using Data Envelopment Analysis. IEEE T. Power Syst. 21(4), 1502-1511.

Khazaeni, G., Khanzadi, M., Afshar A., 2012. Optimum risk allocation model for construction contracts: fuzzy TOPSIS approach. Can. J. Civil Eng. 39(7), 789-800.

Kleit, A.N., Terrell, D., 2001. Measuring potential efficiency gains from deregulation of electricity generation: a Bayesian approach. Rev. Econ. Stat. 83(3), 523-530.

Knittel, C.R., 2002. Alternative regulatory methods and firm efficiency: stochastic frontier evidence the US electricity industry. Rev. Econ. Stat. 84(3), 530-540.

Liu, C., Liu, L.W., 2012. Research of Corporate Social Responsibility in Electricity Sector: A Perspective of Human Resource Management. In IEEE International Conference on Management of Innovation and Technology, Sanur Bali, 11-13 June 2012. doi:10.1109/ICMIT.2012.6225864.

Liu, N., Ang, B.W., 2007. Factors shaping aggregate energy intensity trend for industry: energy intensity versus product mix. Energy Econ. 29(4), 609-635.

Manitoba Hydro, 2013. Manitoba Hydro-Electric Board 62nd Annual Report [online]. Available from http://hydro.mb.ca/corporate/ar/2012/publish/index.html [cited 18 January 2014].

Minville, M., Brissette, F., Krau, S., Leconte, R., 2009. Adaptation to Climate Change in the Management of a Canadian Water-Resources System Exploited for Hydropower. Water Resour. Manag. 23(14), 2965-2986.

Moeini, R., Afshar, M.H., 2011. Arc-based constrained ant colony optimization algorithms for the optimal solution of hydropower reservoir operation problems. Can. J. Civil Eng. 38(7), 811-824.

Mugisha, S., 2007. Effects of incentive applications on technical efficiencies: Empirical evidence from Ugandan water utilities. Utilities Policy 15(4), 225-233.

Nalcor Energy, 2012. 2012 Business and Financial Report [online]. Available from http://www.nlh.nl.ca/HydroWeb/NLHydroWeb.nsf/0/32AC7A12BCF09B93A3257B870051A8C C/$File/Nalcor2012AnnualReport.pdf [cited 18 January 2014].

Noailly, J., 2012. Improving the energy efficiency of buildings: The impact of environmental policy on technological innovation. Energy Econ. 34(3), 795-806.

Ontario Power Generation, 2013. 2013 Ontario Power Generation Annual Report [online]. Available from http://www.opg.com/news-and-media/News%20and%20Media%20%20Reports/2013AnnualReport.pdf [cited 18 January 2014].

REN21. 2013. Renewables 2013 Global Status Report. REN21 Secretariat, Paris.

Stern, D.I., 2012. Modeling international trends in energy efficiency. Energy Econ. 34(6), 2200-2208.

Vattenfall, 2011. Towards sustainable energy: Corporate Social Responsibility Report 2011 Performance report. Available from http://corporate.vattenfall.com/Global/corporate/sustainability/Reports/corporate_social_responsibility_report_2011_performance_report.pdf [accessed 18 January 2014].

Wang, B., Liang, X.J., Zhang, H., Wang, L., Wei, Y.M., 2014a. Vulnerability of hydropower generation to climate change in China: Results based on Grey forecasting model. Energy Policy 65, 701-707.

Wang, B., Pan, S.Y., Ke, R.Y., Wang, K., Wei Y.M., 2014b. An overview of climate change vulnerability: a bibliometric analysis based on Web of Science database. Nat Hazards. Doi. 10.1007/s11069-014-1260-y.Wang, K., Wei, Y.M., Zhang, X., 2012. A comparative analysis of China's regional energy and emission performance: Which is the better way to deal with undesirable outputs? Energy Policy 46, 576-584.

Wang, K., Wei, Y.M., Zhang, X., 2013. Energy and emissions efficiency patterns of Chinese regions: A multi-directional efficiency analysis. Appl. Energ. 104, 105-116.

Yuan, X.C., Wang, Q., Wang, K., Wang, B., Jin, J.L., Wei, Y.M., 2013. China's regional vulnerability to drought and its mitigation strategies under climate change: data envelopment analysis and analytic hierarchy process integrated approach. Mitigation Adaptation Strategies Global Change. doi: 10.1007/s11027-013-9494-7.