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Evaluating Efficiency of Energy Conservation Measures in Energy Service Companies in China

Saina Zheng[1], Chor-Man Lam[2], Shu-Chien Hsu[3,*], and Jingzheng Ren[4]

Abstract

Energy service companies (ESCOs) in China have been adopting various energy conservation measures, thus playing a significant role in mitigating carbon dioxide emissions. The efficiencies of such measures vary across China, yet a comprehensive decision-supporting tool that guides the selection of measures according to geographical characteristics is lacking. This study aims to develop an efficiency evaluation framework using data envelopment analysis (DEA) to guide the selection of the most efficient ESCO measures in different parts of China. Data from 1,304 ESCO projects in six parts of Mainland China were examined using DEA to determine the efficiency of 15 energy-saving measures in the manufacturing and building sectors. The results indicate that reconstruction of Industrial Boiler Furnaces is the most energy-efficient measure in the manufacturing sector, while energy management systems are the most efficient measure in the building sector. The variation in the statuses of economic development and the climate conditions of the six areas of China are the major factors for the differences in efficiency. A decision-making tool for guiding the selection of the ESCO measures with the most efficient technologies for specific regions and end-uses is proposed to provide comprehensive information to both investors and the ESCOs.

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[1] Ph.D. candidate, Department of Civil and Environmental Engineering, The Hong Kong Polytechnic University.
[2] Ph.D. candidate, Department of Civil and Environmental Engineering, The Hong Kong Polytechnic University.
[3] *Corresponding author: Assistant Professor, Department of Civil and Environmental Engineering, The Hong Kong Polytechnic University.
E-mail: mark.hsu@polyu.edu.hk; Tel: +852-27666057
[4] Assistant Professor, Department of Industrial System and Engineering, The Hong Kong Polytechnic University.

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1 Introduction

Climate change is one of the most significant and urgent global issues because of its broad environmental, economic, and social impacts. The interrelationship between climate change and the energy industry has been established by the Intergovernmental Panel on Climate Change (IPCC): the energy sector contributes significantly to climate change, while the adverse effects of climate change will disrupt various processes in the energy industry (World Energy Council & University of Cambridge, 2014). The high potential of energy-saving through the implementation of energy-efficiency strategies has been recognized (World Energy Council & University of Cambridge, 2014). Policies on energy performance improvement are a vital tool in promoting efficient utilization of energy and reducing the impacts of climate change (Solangi, Islam, Saidur, Rahim, & Fayaz, 2011). Numerous energy-efficiency policies have been announced and implemented worldwide; these include the National Energy Conservation Policy Act in the United States, the Energy Act 2011 in the United Kingdom, and the Energy Conservation Law of the People's Republic of China (World Energy Council, 2017). Transport, industry, and building sectors have been revealed to be the three main sectors covered by the mandatory energy-efficiency policies in numerous countries (Figure 1), including China, presenting the huge potential for energy saving. The Paris Agreement, regarded as a milestone, recognized the importance of energy technology and innovation in meeting climate objectives. The implementation of mandatory policies and guidelines encouraged the development and application of numerous energy-saving technologies integrated with the application of renewable energy sources, such as photovoltaics (PV), combined heat and power systems, heat pumps, and motor system optimization (Tassou, Ge, Hadawey, & Marriott, 2011). Increasing numbers of energy-efficiency projects have been conducted, thus reducing the use of considerable amounts of energy sources and GHG emissions, leading to high financial savings (Painuly, Park, Lee, & Noh, 2003).

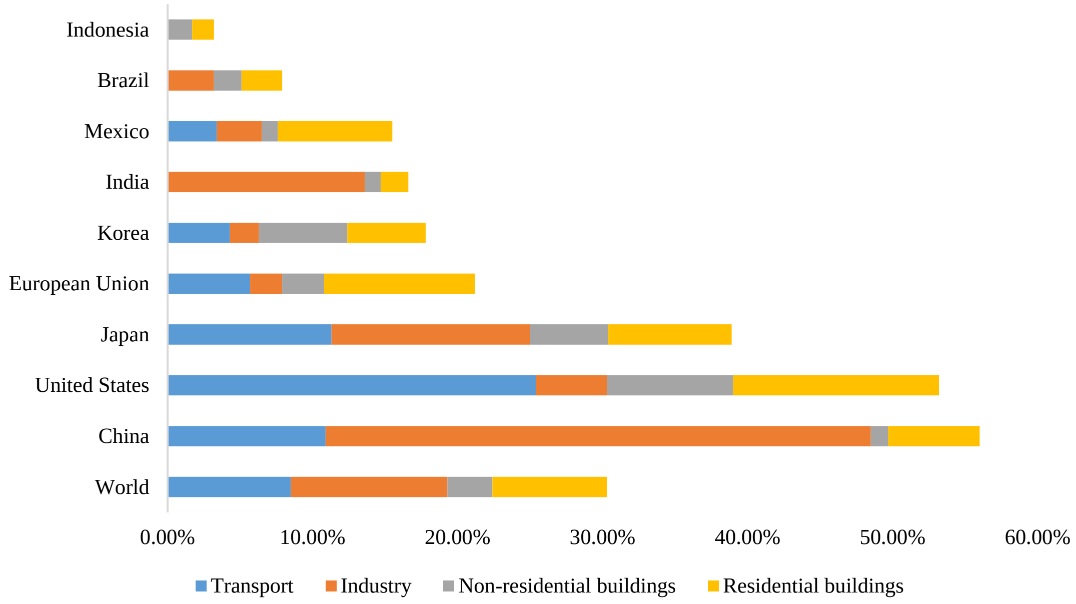


Figure 1: Share of energy consumption covered by mandatory energy efficiency policies (Source: Energy Efficiency Market Report 2016)

To encourage investment in energy efficiency projects, the energy performance contracting (EPC) approach has been used in some countries through energy service companies (ESCOs) that help implement energy-saving strategies with zero initial investment by ESCO customers. ESCOs are companies that conduct energy-efficiency projects by providing a package of energy services (e.g., guaranteed energy savings, and associated design and installation services) for customers (Xu & Chan, 2013; Xu, Chan, Visscher, Zhang, & Wu, 2015). The main drivers of the ESCO industry include technology, policy, and finance (Da-li, 2009; Goldman, Hopper, & Osborn, 2005; M.-K. Lee et al., 2003; Edward Vine, 2005). EPC is a market-oriented approach in which the ESCOs implement energy efficiency measures and are paid from the financial savings made by the customer as a result. Besides the avoidance of initial investment, another advantage of the EPC approach is that multiple aspects of improvements in energy efficiency can be bundled together and achieved through the application of numerous energy-saving skills in one comprehensive and complex project, thus enhancing the flexibility and savings of the projects (Bates, 2010; Xu, Chan, and Qian, 2011; Zheng et al., 2018). Multi-dimensional skills are essential for ESCOs to become successful in accommodating various end uses (E Vine et al., 1999). ESCO technologies have developed over the years, from partial replacement to complex improvement (M.-K. Lee et al., 2003). The integrated application of energy conservation technologies (referred to as energy conservation measures in this research study) is the core competitiveness of an ESCO.

China, as the world's main energy consumer, has been improving its energy-efficiency and has become the world's energy-efficiency heavyweight over the last few decades. Although the global economy is becoming less energy intense, the progress in this direction needs to be accelerated for the world's energy system to become sustainable (IEA, 2016). Since 2015, the Chinese government has launched its 13th Five-year Plan, with an investment of USD 270 billion, aiming to save approximately 560 Mtoe annually by 2020 (IEA, 2016). The savings will come from two shifts in economic structure: (i) from industry to services and (ii) from high-intensity manufacturing to lighter manufacturing. Since EPC was introduced into China in 1996, the Chinese government has been advocating its development (Table 1). With policy support, EPC developed rapidly, with investment increasing from 0.85 billion Chinese Yuan (CNY) in 2003 to 103.96 billion CNY in 2015 and output increasing from 1.77 billion CNY in 2003 to 312.73 billion CNY in 2015. However, the lack of appropriate mechanisms for guiding financial investment in such projects has been identified as an important barrier to promoting energy-efficiency (Hannon & Bolton, 2015; M.-K. Lee, Park, Noh, & Painuly, 2003). A decision-making tool for guiding the selection of the ESCO measures, with technologies for specific regions and end-uses that save maximum energy for a given investment, is demanded to provide comprehensive information to investors and the ESCOs.

Although each ESCO project may adopt different energy-saving measures, they each serve the same purpose of achieving the highest level of energy savings and profits (outputs) with the least investment and shortest contract period (inputs). The efficiency of the energy-saving measures in ESCO projects can be measured by the input-output relationship (Blomberg, Henriksson, and Lundmark 2012; Guo et al., 2011). Determination of weights on the inputs and outputs with different units of measurement was compulsory in previous multifactor studies, which has led to subjectivity in the evaluation. This research suggests the use of Data Envelopment Analysis (DEA), which can assess the relative efficiency of the decision-making units (DMUs), based on their performance in different criteria, without the need for assigning subjective weighting. The DEA approach has been adapted for benchmarking the environmental and economic performance of different activities, such as transportation, wastewater treatment, farming, and regional eco-efficiency (Kuosmanen & Kortelainen, 2005; Lorenzo-Toja et al., 2015; Picazo-Tadeo, Gómez-Limón, & Reig-Martínez, 2011; Rybaczewska-Błażejowska & Masternak-Janus, 2018). The DMUs should have the same function and require the same types of inputs and outputs, yet the inputs and outputs should be able to be measured in different units, such as the amount of emissions and monetary values. Such characteristics give DEA the advantage and flexibility for wide application in different fields. Thus, DEA is identified as a suitable tool for evaluating the relative performance of different ESCO measures regarding investment costs, contract periods, energy saving, and profit.

This study aims to evaluate the efficiency of energy conservation measures in different regions of China. The aim can be achieved by the following three main steps: (i) sorting the common energy conservation measures provided by ESCOs; (ii) benchmarking the ESCO measures by determining the relative efficiency of each measure applied in the manufacturing and building industries; and (iii) developing a DEA framework to guide decision-making in the selection of the energy conservation measures provided by the ESCOs in different regions and, thus, optimize the efficiency of the investments in energy saving. The DEA framework will be demonstrated across China.

2 Related studies and data description

2.1 Related studies

The successfulness of ESCO projects is often evaluated by the amount of energy saved, which can be reflected by the financial profits achieved (E Vine, Nakagami, & Murakoshi, 1999). Scholars agree that the efficiency of technologies differs (Nassiri & Singh, 2009a; Sarıca & Or, 2007; Q. Wang, Zhao, Zhou, & Zhou, 2013). For a client who wants to adopt an ESCO for energy-efficiency improvement, it is crucial to choose the most efficient energy-saving measure, reducing energy consumption by more with least investment.

Previous studies have attempted to evaluate the efficiency of the energy-saving measures that use various methods to assist decision-making. Ouyang et al. (2009) utilized a life cycle costing method to evaluate the economic performance of energy-saving renovation measures for residential buildings in urban China. Nikolaidis et al. (2009) conducted an economic analysis and ranked the energy conservation measures in the building sector in Greece in terms of the Net Present Value, Internal Rate of Return, Savings to Investment Ratio, and Depreciated Payback Period.

Table 1: Related policies of either EPC or ESCO in China

Year	Key Policy	Contents regarding EPC or ESCOs
2000	Further Promotion of Energy Performance Contracting System Notice	The first document to promote EPC issued by national authorities
2001	Energy Conservation and Resources Comprehensive	Guiding technological retrofit, promoting EPC technical mechanism

	Utilization of the 10th Five-Year Plan	
2004	Notice of State Council on Resource Conservation Activities	Encouraging implementation of the EPC and giving energy financing guarantees
2005	Notice of State Council on Recent Focus on Construction of a Conservation-Oriented Society	Promoting EPC and energy conservation investment guarantee mechanism
2006	The 11thFive-Year Plan	Releasing technology support program: key building energy technology research and demonstration
2007	Comprehensive Energy Conservation Program of Work Notice Embodiments	Foster energy efficiency services market accelerate the implementation of EPC and ESCO
2010	Opinions on Accelerating the Implementation of EPC for the Development of the Energy Service Industry	Tax incentives of sales tax and free transfer of assets.
2010	Contract energy management Projects Financial Incentives Fund Management Interim Measures	Allocating awards funds to ESCOs of a certain size.
2013	Energy Development of the 12th Five-Year Plan	Promoting further policy support, improving management system of ESCOs.
2014	Program of Implementing the Greening Development in Industry	Integrate resources of ESCOs
2016	The People's Republic of China for National Economic and Social Development of the 13th Five-Year Plan	Promoting EPC mode
2017	Approved guidelines for energy-saving auditing of ESCOs in public buildings	Specific energy saving auditing and determine the acceptable criteria

These methods focus on the economic aspect and cannot achieve a general ranking due to the unidentified weight. Recently, more scholars have been focusing on the measures' efficiency using DEA (Korhonen & Luptacik, 2004; Meng, Su, Thomson, Zhou, & Zhou, 2016; Mousavi-Avval, Rafiee, Jafari, & Mohammadi, 2011b; Oggioni, Riccardi, & Toninelli, 2011; Zhou, Ang, & Poh, 2008). DEA does not need to specify either the production functional form or the weights on different inputs and outputs. It produces detailed information on the efficiency of the unit, relative not only to the efficiency frontier but also to specific efficient units that can be identified as either role models or comparators. DEA has been proven to be a reliable method for measuring the efficiency of different energy conservation measures with multiple inputs and outputs.

2.2 Data collection

The previous research did not explore the efficiency of different energy conservation measures due to the lack of sufficient data. This research contributes to collecting sufficient specific data regarding the inputs and outputs of all ESCO projects conducted from 2011 to 2015 in China. The collected data include a variety of energy conservation measures in the manufacturing and building industries, based on 3,225 projects from 2011 to 2015 in mainland China. The historical data were classified into eight categories in the manufacturing industry and seven categories in the building industry. DEA was adopted to evaluate the efficiency of each measure. The input data for the DEA in this paper were collected from the results of censuses conducted by the ESCO Committee of the China Energy Conservation Association. The collected data cover ESCO projects implemented in 30 provinces, distributed into six regions, in mainland China. As data of Tibet and Hainan are missing for some years, these two provinces were excluded from the analysis. Table 2 shows an example of the detailed information collected for each project, including the investment, the energy saving, the financial saving, and the contract period.

Among the collected data for the 3,225 projects, some projects were excluded from the DEA for the following three reasons: (i) data for either investment, energy saving, project location, or financial profit are missing; (ii) the type of energy saving measure cannot be recognized from the information provided; and (iii) more than one energy conservation measure was adopted. After the data sets were filtered, 1,304 projects were selected.

Table 2: Example of detailed information of DMU

Year	Name of ESCO	Region	Name of project	Investment (million CNY)	Contract period (year)	Energy saving (standard coal)(ton)	Financial profit (million CNY)	Measure
2011	Liaoning Nengfaweiye Energy Technology Co., Ltd.	Liaoning	Renovation of circulating water system	6.78	1	7100	8.81	Circulating water system

3 Examined energy conservation measures

More than half of the total delivered energy in the world has been consumed by the industrial sector, which comprises energy-intensive manufacturing, non-energy-intensive manufacturing, and non-manufacturing industries ("International Energy Outlook 2016-Executive Summary-Energy Information Administration," 2016). Energy-intensive manufacturing industries include petroleum refineries, iron and steel, and bulk chemical production; non-energy-intensive manufacturing industries include plastics, wood products, and transportation equipment manufacturing; while non-manufacturing industries consist of agriculture, forestry, fishing, mining, and construction industries. Because only one energy-saving measure is available for the transport sector, the replacement of conventional lights with light-emitting diode (LED) lights, selection for the most efficient measure in this sector using DEA is not necessary. The transport projects were excluded from the analysis; thus, this paper focuses on the manufacturing and building industries.

3.1 Manufacturing sector

As the largest consumer in most countries (including China), the manufacturing sector has significantly contributed to the increase of CO_2 emissions (Ang & Pandiyan, 1997). Advanced energy-saving technologies have been adopted to save energy in the manufacturing sector, including re-circulating cooling water systems, the use of residual industrial heat, frequency control, PV power generation, reconstruction of industrial boiler furnaces, heat pump technology, efficient electric motors, and energy management systems.

MM1 (Manufacturing Measure 1) - Re-circulating cooling water system: The function of the re-circulating water system is sending the cooling water to the condenser. The steam turbine is cooled, and the vacuum of the condenser is maintained. The re-circulating systems reduce the fresh water demand for cooling and alleviate thermal pollution through the usage of air heat (Panjeshahi, Ataei, Gharaie, & Parand, 2009). In such systems, water circulates in the cooling water network, where it absorbs heat from the system through heat exchangers and heat rejection in the cooling tower (Ponce-Ortega, Serna-González, & Jiménez-Gutiérrez, 2010). Water condensed in the cooling tower is then re-circulated and continues the heat transfer process. Re-circulating cooling water systems are widely adopted in electric-power generating stations, refrigeration and air conditioning plants, and steel mills.

MM2 - Use of residual industrial heat: The operation of industrial plants has contributed notably to aquatic and atmospheric heat pollution, which poses threats to the environment. The wastage of potentially recyclable thermal energy also increases the energy intensity of the industrial process, thus inflating the production costs (Nguyen, Slawnwhite, & Boulama, 2010). The engineering and scientific community has been searching for practical and efficient methods for recycling waste heat into a high-quality source of energy. Making use of residual heat pressure is both possible and advisable in certain economic and technical conditions. The residual industrial heat is commonly used by ESCOs for urban heating and generation of electric power.

MM3 - Inverter Technology: Inverter technology involves changing the power supply frequency, thus regulating the load, reducing power consumption, reducing losses, and extending service life. It has significant potential to increase the efficiency and flexibility of power distribution, with the abilities of reactive power control and voltage and frequency ride-through.

MM4 - PV power generation: As an unlimited renewable energy resource, solar energy has been recognized as the keystone of sustainable development programs (Dinçer, 2011; Frate & Brannstrom, 2017). Compared to other renewable energy systems, PV technology has the advantages of simple operation and maintenance, scalability, and quiet and carbon-free operation (Ho, Frunt, & Myrzik, 2009). The most dominant end-uses in China’s PV market include solar energy manufacturing and applications in remote villages.

MM5 - Reconstruction of boilers and industrial furnaces: Boilers and industrial furnaces (BIFs) are a special class of boilers or furnaces that recover energy and materials through the incineration of hazardous wastes. BIF efficiency is one of the key factors of heat recovery capability; thus, it has a direct impact on the energy-savings achieved. Approaches to improve BIF efficiency include maximizing the transfer of heat to water and minimizing the heat loss from boilers via various means, such as emissions of hot flue gas and radiation, and blowdown losses of steam boilers (Saidur, Ahamed, & Masjuki, 2010).

MM6 - Heat pump technology: Heat pumps are devices that are capable of absorbing a small amount of heat from renewable sources, such as ground, air, water and waste heat, and transferring it to places with colder temperatures. The characteristics of heat pump technology make it particularly suitable for applications in heating, ventilation, and air conditioning (HVAC) systems, as well as in water and district heating.

MM7 - Efficient electric motors: Efficient electric motors are the power drivers for the machines and are widely used in the manufacturing industries, in which mechanical energy is needed. Efficient electric motors can achieve greater efficiency by reducing energy losses, including stator power losses, rotor power losses, magnetic core losses, friction and windage losses, and stray load losses (Emadi, 2004).

MM8 - Energy management system: An energy management system is an information management system. It facilitates the optimized use of energy in industry. The energy management system collects energy consumption data from smart devices inserted in the equipment for analysis. Through various means, such as energy planning, energy monitoring, energy statistics, energy consumption analysis, key energy consumption equipment management, and energy metering equipment management, business managers can accurately grasp both the breakdown and the trend of the company expenses on energy consumption. With such information, specific energy conservation policies could be implemented in different production departments. Thus, both economic benefits and energy-efficiency could be increased.

3.2 Building sector

Building energy consumption in China has contributed to more than 33% of the national energy consumption and has been increasing by more than 10% annually for the past two decades (Cai, Wu, Zhong, & Ren, 2009; Chan, Qian, & Lam, 2009). The 56.1 billion m^2 building area in 2014 is expected to reach 70 billion m^2 by 2020 (Beijing energy research center. Tsinghua University, 2016). More than 90% of the existing buildings are energy intensive, causing the building energy consumption per unit area in China to be approximately double that of developed countries with similar environmental conditions (Wu, Liu, Liu, & Qu, 2007). A series of policies, including technology innovation and selection, have been implemented to reduce building energy consumption (Kong, Lu, & Wu, 2012). The energy conservation measures can be divided into several sectors: miscellaneous building system, central air conditioning, inverter technology, indoor lighting, heating systems, energy management systems, and building-integrated PV.

BM1 (Building Measure 1) - Miscellaneous building system: Miscellaneous building system involves renovation of buildings, building function improvement, and utilization of renewable energy.

BM2 - Central air conditioning: The improving economic and living standards in China have caused the increasing use of air conditioning (Lu, 2007). Energy consumption by air conditioning accounts for approximately 20% of the total global energy consumption. To reduce the energy consumption for air conditioning, devices that facilitate energy saving, such as programmable logic controllers, inverters, digital-analog conversion modules, temperature sensors, and temperature modules, have been widely promoted.

BM3 - Inverter technology: By changing the power supply frequency, inverter technology can regulate the load, lower the power consumption, reduce losses, and extend the service life of the systems. Such technology is applied most commonly in HVAC systems in buildings. Inverter technology maintains a steady indoor temperature by subtly adjusting its output, thus avoiding the need in conventional systems to switch the motors on and off to achieve the same purpose. This approach improves the operational efficiency of HVAC systems.

BM4 - Indoor lighting: Energy consumption for lighting contributes 5% of the energy budget of the average households. Therefore, replacement of conventional lighting devices with energy-efficient ones would be an effective and efficient way to achieve energy-savings. Advancements in semiconductor technology have favored the replacement of traditional light sources by LED lights (Tsuei, Pen, & Sun, 2008). Other options include the adoption of halogen incandescent lighting and compact fluorescent lamps.

BM5 - Heating system: Upgrades of heating systems could be achieved by changing the types of fuels used and installing control systems. The use of clean fuels, such as natural gas, could improve the environmental and economic performance of the system. The installation of automatic temperature control systems could promote efficient energy consumption by maintaining the optimal temperature in buildings (Nikolaidis et al., 2009).

BM6 - Building energy management system: A building energy management system (BEMS) is a sophisticated method to monitor and control the energy demand in both commercial and residential buildings. It can optimize the building operations, provide energy management information, remotely monitor and control the services and functions, and monitor the building status and environmental conditions. BEMS can improve energy efficiency in two ways: (i) providing real-time and extensive data on energy consumption to the facility operator to increase the energy-efficiency of the overall system, and (ii) streamlining the operation of the machinery monitored and controlled by the BEMS.

BM7 - Building-integrated Photovoltaics: Building-integrated photovoltaics (BIPV) are gaining wider application in new buildings for supplying either principal or ancillary sources of electricity. BIPV involves the integration of PV panels into the envelope, including the roof and facades, of buildings; thus, the large surface area of high-rise buildings could be utilized to promote energy-efficiency (Petter Jelle, Breivik, & Drolsum Røkenes, 2012).

4 Evaluation method and research scope

4.1 Evaluation method: Data envelopment analysis

DEA applies linear programming to measure the performance of organizational units, which are defined as the DMUs in DEA. It has been successfully employed for accessing the relative performance of a set of firms that use multiple identical inputs to produce multiple identical outputs (Azadeh, Ghaderi, & Maghsoudi, 2008; Ramanathan, 2003). Compared to other approaches that measure efficiency, DEA has the following advantages: firstly, identification of the functional relationships between inputs and outputs is not required (Bian, He, & Xu, 2013; Seiford & Zhu, 2002); secondly, only the physical quantities of inputs and outputs are required to evaluate the relative efficiency (Abbott, 2006). Nassiri and Singh (2009a) evaluated the efficiency of energy use by paddy producers in Punjab state (India) with the aid of DEA. Other researches have also utilized DEA to focus on energy-efficiency evaluation (Chauhan, Mohapatra, & Pandey, 2006; Korhonen & Luptacik, 2004; W.-S. Lee, 2008; Mousavi-Avval, Rafiee, Jafari, & Mohammadi, 2011a). An increasing number of researchers apply DEA to study energy efficiency in different regions and countries (Meng et al., 2016; K. Wang, Yu, & Zhang, 2013a).

The basic definition of efficiency in DEA is the ratio of total outputs to total inputs (equation 4-1-1).

$$\text{Efficiency} = \frac{output}{input} \qquad (4\text{-}1\text{-}1)$$

DEA estimates the relative efficiencies of DMUs concerning the best-performing DMU (or DMUs, if there are more than one best-performing DMUs). An efficiency frontier is obtained, in a simplified graphical method considering the trade-offs between two inputs for producing the output, by identifying and joining the best-performing DMUs. The frontier represents a standard of the best performance (100% efficiency) using the existing technologies, and the DMUs that are not on the frontier are considered inefficient. The DEA model has various extensions considering the returns to scale and multiplier settings (Ramanathan, 2003). The most common DEA models are the CCR model (developed by Charnes, Cooper, and Rhodes) and the BCC model (developed by Banker, Charnes, and Cooper). These two models have been used for measuring overall efficiency and pure technical efficiency (C.-C. Lee, 2009; Nassiri & Singh, 2009b; Z. Xu, 2011). The CCR model takes Constant Return to Scale (CRS) and estimates the overall efficiency of a DMU, which comprises pure technical efficiency and scale efficiency. Pure technical efficiency describes the efficiency in converting the inputs into outputs, while scale efficiency identifies whether the scales of production are optimal, where any changes in the scales will not further increase the productivity. The BCC model modified the CCR model with the assumption of variable returns to scale (VRS), thus breaking down the overall efficiency into pure technical efficiency and scale efficiency. It takes into account the variation of efficiency concerning the scale of operation and, hence, measures the pure technical efficiency (Banker, Charnes, & Cooper, 1984).

When considering a greater number of inputs and outputs, a general mathematical formulation is used. Multiple inputs and outputs are linearly aggregated using weights in DEA. Inputs and outputs are represented by x and y, respectively. Subscripts i and j represent particular inputs and outputs, respectively. Thus, x_i represents the i^{th} input, while y_j represents the j^{th} output, of a DMU. v_j is the weight assigned to output y_j, and u_i is the weight assigned to input x_i. Let the total number of inputs and outputs be represented by I and J, respectively, where $\mathrm{I}, \mathrm{J} > 0$. The efficiency of a DMU in converting the inputs to outputs can be defined using equation 4-1-2.

$$\text{Efficiency} = \frac{\sum_{j=1}^{J} v_j y_j}{\sum_{i=1}^{I} u_i x_i} \qquad \text{(4-1-2)}$$

The overall efficiency OE_m of the m^{th} DMU can be determined by solving the following CCR model (Charnes, Cooper, & Rhodes, 1978):

$$\text{Max } OE_m = \frac{\sum_{j=1}^{J} v_{jm} y_{jm}}{\sum_{i=1}^{I} u_{im} x_{im}}$$

$$\text{Subject to } 0 \leq \frac{\sum_{j=1}^{J} v_{jm} y_{jm}}{\sum_{i=1}^{I} u_{im} x_{im}} \leq 1; m = 1{,}2, k, M$$

$$v_{jm}, u_{im} \geq 0; i = 1{,}2, K, I; j = 1{,}2, K, J$$

The pure technical efficiency TE_m of the m^{th} DMU can be determined by solving the following BCC model (Charnes et al., 1978):

$$\text{Max } z = y_j \sum_{j=1}^{J} v_j - v_j$$

$$\text{Subject to } u_i x_i = 1$$

$$-\sum_{i=1}^{I} u_{im} x_{im} + \sum_{j=1}^{J} v_{jm} y_{jm} - u_0 e \leq 0$$

$$v_{jm}, u_{im} \geq 0; i = 1,2,K,I; j = 1,2,K,J$$

where z and u_0 are scalar and free in sign, and u_0 is free of sign.

4.2 Descriptions of the regions and areas of China

The data sets were divided into six groups according to their geographical locations in the six parts of mainland China (Table 3); i.e., North China (NC), Northeast China (NEC), East China (EC), South Central China (SCC), Southwest China (SWC), and Northwest China (NWC) (Wu & Li, 1995).

Table 3: List of six geographical regions in China

North China (NC)	Beijing, Tianjin, Hebei, Shanxi, Inner Mongolia
Northeast China (NEC)	Liaoning, Jilin, Heilongjiang
East China (EC)	Shanghai, Jiangsu, Zhejiang, Anhui, Fujian, Jiangxi, Shandong
South Central China (SCC)	Henan, Hubei, Hunan, Guangdong, Guangxi, Hainan, Hong Kong, Macau
Southwest China (SC)	Chongqing, Sichuan, Guizhou, Yunnan, Tibet
Northwest China (NWC)	Shaanxi, Gansu, Qinghai, Ningxia, Xinjiang

North China consists of five regions: Beijing, Tianjin, Hebei, Shanxi, and Inner Mongolia. Beijing and Tianjin are municipalities that have experienced the most rapid economic growth in China. The development of Hebei, Shanxi, and Inner Mongolia relies mainly on heavy industry and energy industry, which are considered as energy-consuming and highly-polluting industries. Such industries produce and export millions of tonnes of coal and steel to other regions and countries every year. Northeast China, which consists of the regions of Liaoning, Jilin, and Heilongjiang, is an area with many heavy industries; thus, it is known as the industrial center of China. East China, comprising Shanghai, Jiangsu, Zhejiang, Anhui, Fujian, Jiangxi, and Shandong, is the area where most of the light industries and service industries are located in China (K. Wang et al., 2013a). Because of its convenient transportation system and maturely developed infrastructures, this area has also attracted the most foreign investments and technologies. Shanghai, Jiangsu, and Zhejiang are considered to be the most economically and socially developed regions in China. South Central China consists of Henan, Hubei, Hunan, Guangdong, Guangxi, Hainan, Hong Kong, and Macau. Henan has a large population and relies heavily on agricultural industries. Hubei and Hunan are known as another industrial center of China. Southwest China includes Chongqing, Sichuan, Guizhou, Yunnan, and Tibet, while Northwest China comprises Shaanxi, Gansu, Qinghai, Ningxia, and Xinjiang. These two regions have relatively low population density and high reserves of resources, including coal, oil, natural gas, and minerals. The Northwest area is the least developed area in China, and it is mainly supported by basic industries and lacks modern industries.

4.3 Data classification and processing

In this research, Hong Kong and Macau were excluded due to the absence of data. The ESCO projects were divided into 15 categories based on the types of measures adopted. Each category was further divided into six subcategories according to the regions. Figure 3 shows the quantity distribution of the ESCO energy conservation measures' implementation and reveals that more than half of the projects adopted the techniques of either MM1, MM2, or MM3. Figure 4 presents the distribution of the energy conservation measures in 1,304 projects in the six regions of China. Most projects were located in NC (23.01%), EC (33.36%) and SCC (21.93%). According to the type and region of the energy conservation measures, the collected data of the ESCO projects were generalized, as shown in Table 4.

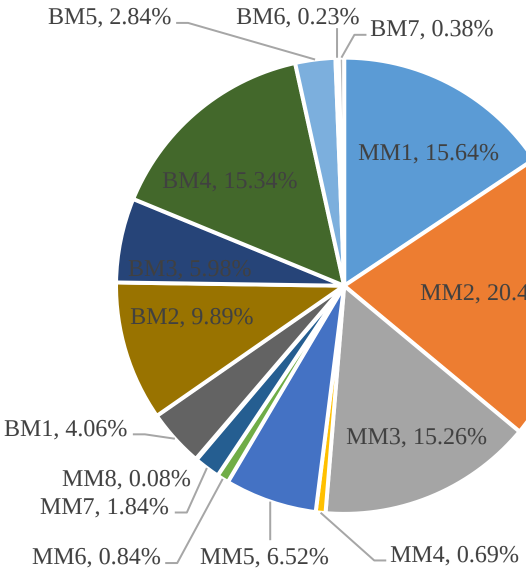


Figure 2: Percentage of 15 energy conservation measures

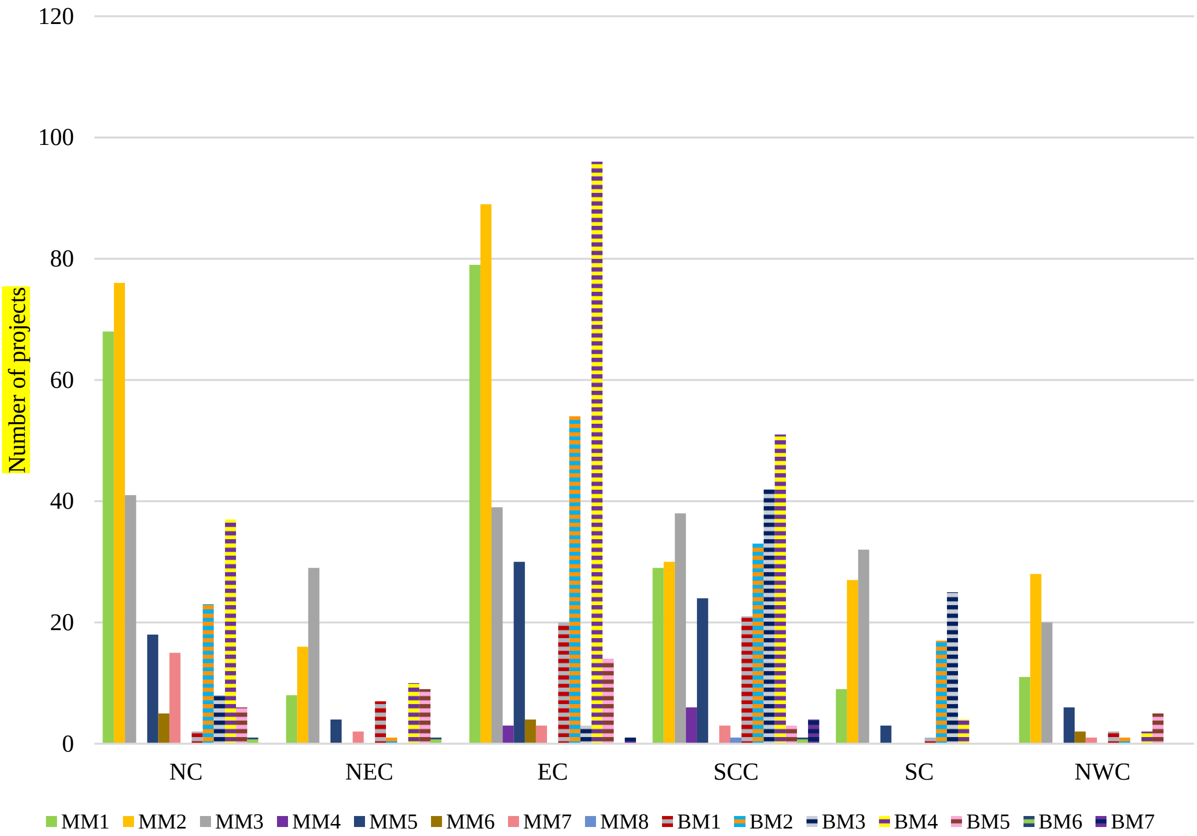


Figure 3: Distribution of energy conservation measures in six regions in China

Table 4: Example of generalized information of ESCO projects

Measure	Region	Investment (million CNY)	Energy saving (ton)	Financial profit (million CNY)	Contract period (year)
MM1	NEC	6.78	7100	8.81	1
MM1	NC	0.0168	6	0.02	2
MM1	EC	5.10	5355	7.65	3
MM1	NC	96.53	510000	425.7	15

The data sets were named by the types of measures used and the locations. For example, the project in the first row in Table 4 was named MM1NEC. After sorting the projects, 67 combinations of measures and locations were obtained.

The investment of measure ($\mathrm{I}Measure_{\alpha}$) was calculated as equation 4-3-1:

$$\mathrm{I}Measure_{\alpha} = \frac{\sum IMeasure_{\alpha,\beta}}{n} \ (\mathrm{i} = 1{,}2 \dots 67;\ \mathrm{j} = 1{,}2 \dots \mathrm{n}) \qquad (4\text{-}3\text{-}1)$$

where α represents one of the 67 measures, n is the number of projects using measure α, and β denotes one of the projects.

Similarly, the energy saving ($\mathrm{E}Measure_{\alpha}$), energy saving profit ($\mathrm{P}Measure_{\alpha}$) and contract period ($\mathrm{CP}Measure_{\alpha}$) can be calculated as equation 4-3-2, 4-3-3, and 4-3-4, respectively.

$$\mathrm{E}Measure_{\alpha} = \frac{\sum EMeasure_{\alpha,\beta}}{n} \ (\alpha = 1{,}2 \dots 67;\ \beta = 1{,}2 \dots \mathrm{n}) \qquad (4\text{-}3\text{-}2)$$

$$\mathrm{P}Measure_{\alpha} = \frac{\sum PMeasure_{\alpha,\beta}}{n} \ (\alpha = 1{,}2 \dots 67;\ \beta = 1{,}2 \dots \mathrm{n}) \qquad (4\text{-}3\text{-}3)$$

$$\mathrm{CP}Measure_{\alpha} = \frac{\sum CPMeasure_{\alpha,\beta}}{n} \ (\alpha = 1{,}2 \dots 67;\ \beta = 1{,}2 \dots \mathrm{n}) \qquad (4\text{-}3\text{-}4)$$

The inputs and outputs of each measure in DEA are shown in Table 5.

Table 5: Examples of Input and output of energy efficiency measures in China

Measure	Inputs		Outputs	
	Investment (million CNY)	Contract period (year)	Energy saving (ton)	Financial profit (million CNY)
MM1NC	547.11	3.61	13210.28862	1496.57

MM1NEC	594.29	3.50	9834.939024	1327.00
MM1EC	131.06	3.18	3352.597561	582.24
MM1SCC	88.96	3.05	2356.121951	690.56
MM1SC	193.17	4.11	8595.207317	1374.28
MM1NWC	169.00	4.91	2642.426829	576.16

5 Results and discussions

5.1 Regional energy conservation measures' efficiency

DEA programs incorporating the additional convexity constraint to take into account variable returns to scale called either BCC DEA models or VRS DEA models. In contrast, CCR DEA models are also called CRS DEA models. According to Cook (2001), there exists a relationship between the overall efficiency and the pure technical efficiency:

$$\text{overall efficiency} = \text{pure technical efficiency} \times \text{scale efficiency}$$

The results are given in Table 6. The columns of CRS and VRS show the efficiency results of the CCR model and the BCC model, respectively, while scale efficiency captures the impact of scale size on the productivity of the DMU concerned (Thanassoulis, 2001). The types of return to scale were identified based on the comparison between the radial increase in input levels and the proportionate radial increase in output levels. If the radial increase in output levels was less than the proportionate increase in input levels, the DMU was identified as having decreasing return to scale (DRS); if the radial increase in output levels was more than the proportionate increase in input levels, the DMU was identified as having increasing returns to scale, and, if the level of increases in the inputs and outputs are equal, the DMU was identified as having CRS.

Table 6: Efficiencies of different energy conservation measures in six regions in China

Region	DMU	Overall efficiency score	Pure technical efficiency score	Scale efficiency	Return to scale

North China (NC)	MM1NC	0.218349	0.310757	0.70263582	Increasing
	MM2NC	0.547973	0.598293	0.91589405	Increasing
	MM3NC	0.225646	0.308772	0.73078517	Increasing
	MM5NC	0.346363	0.502222	0.68966115	Increasing
	MM6NC	0.192461	0.218543	0.88065507	Increasing
	MM7NC	0.282281	0.38812	0.72730341	Increasing
	BM1NC	0.171892	0.232223	0.74020231	Increasing
	BM2NC	0.148743	0.291566	0.51015208	Increasing
	BM3NC	0.305777	0.623346	0.49054137	Increasing
	BM4NC	0.159801	0.243012	0.65758481	Increasing
	BM5NC	0.492055	0.493213	0.99765213	Increasing
	BM6NC	0.696998	0.787388	0.88520272	Increasing
Northeast China (NEC)	MM1NEC	0.169641	0.282895	0.59966065	Increasing
	MM2NEC	0.420106	0.530272	0.79224624	Increasing
	MM3NEC	0.188148	0.269097	0.69918282	Increasing
	MM5NEC	0.510449	0.520031	0.98157418	Increasing
	MM7NEC	0.366871	0.458236	0.80061584	Increasing
	BM1NEC	0.045658	0.112607	0.40546325	Increasing
	BM2NEC	0.756784	1	0.756784	Increasing
	BM4NEC	0.168777	0.332559	0.50750995	Increasing
	BM5NEC	0.229548	0.292906	0.7836917	Increasing
	BM6NEC	1	1	1	Constant
East China (EC)	MM1EC	0.293031	0.508947	0.57575936	Increasing
	MM2EC	0.404828	0.437783	0.92472298	Increasing
	MM3EC	0.223875	0.309389	0.72360362	Increasing
	MM4EC	0.157844	0.174866	0.90265689	Increasing
	MM5EC	0.401726	0.541255	0.74221208	Increasing
	MM6EC	0.15224	0.276336	0.55092351	Increasing
	MM7EC	0.086036	0.701545	0.12263789	Increasing
	BM1EC	0.107619	0.162805	0.66103007	Increasing
	BM2EC	0.138278	0.259536	0.53278929	Increasing
	BM3EC	0.271862	0.322542	0.84287318	Increasing
	BM4EC	0.232031	0.315314	0.73587281	Increasing
	BM5EC	0.169428	0.220401	0.76872609	Increasing
	BM7EC	0.236139	0.2504	0.94304712	***Decreasing***
South Central China (SCC)	MM1SCC	0.512032	0.800092	0.6399664	Increasing
	MM2SCC	0.495873	0.567684	0.87350181	Increasing
	MM3SCC	0.416454	0.502386	0.82895224	Increasing
	MM4SCC	0.235479	0.309415	0.76104584	***Decreasing***
	MM5SCC	0.177185	0.293741	0.60320146	Increasing
	MM7SCC	0.392437	0.625642	0.62725488	Increasing
	MM8SCC	0.436	0.546167	0.79829063	Increasing

	BM1SCC	0.14764	0.202097	0.73054029	Increasing
	BM2SCC	0.145428	0.258564	0.56244489	Increasing
	BM3SCC	0.064869	0.854462	0.07591795	Increasing
	BM4SCC	0.133504	0.237088	0.56309893	Increasing
	BM5SCC	0.397019	0.426012	0.93194323	Increasing
	BM6SCC	0.131922	0.309083	0.42681739	Increasing
	BM7SCC	0.28968	0.389209	0.74427878	***Decreasing***
Southwest China (SC)	MM1SC	0.469277	0.574581	0.81672906	Increasing
	MM2SC	0.332695	0.376878	0.88276578	Increasing
	MM3SC	0.241989	0.29574	0.81824914	Increasing
	MM5SC	0.755389	0.851033	0.88761423	Increasing
	BM1SC	0.161711	0.326137	0.49583764	Increasing
	BM2SC	0.118701	0.328933	0.3608668	Increasing
	BM3SC	0.06404	1	0.06404	Increasing
	BM4SC	0.136031	0.245009	0.55520818	Increasing
Northwest China (NWC)	MM1NWC	0.224877	0.346624	0.6487635	Increasing
	MM2NWC	0.762	0.799301	0.95333297	Increasing
	MM3NWC	0.273541	0.336329	0.81331375	Increasing
	MM5NWC	1	1	1	Constant
	MM6NWC	0.106792	0.204691	0.52172299	Increasing
	MM7NWC	0.923453	0.952553	0.96945052	Increasing
	BM1NWC	0.246216	0.249543	0.98666763	Increasing
	BM2NWC	0.099339	1	0.099339	Increasing
	BM4NWC	0.141029	0.186456	0.75636611	Increasing
	BM5NWC	0.192473	0.350307	0.54944092	Increasing

Source: Calculations based on MaxDEA software. DMUs with decreasing returns to scale (RTS) are in bold and italics.

Taking the first row (MM1NC) as an example, it has an overall efficiency of only 0.218349, which can be broadly be interpreted as showing that the MM1NC could have supported its activity level with only 21.8349% of its resources. If the MM1NC can expand its production scale, it should be able to improve its overall operational efficiency. The pure technical efficiency shows the efficiency if inputs are not wasted. The increasing return to scale indicates that, if the MM1NC can expand its production scale, it can improve its overall efficiency. The values of overall efficiency, pure technical efficiency, and scale efficiency for BM6NEC and MM5NWC are 1, indicating that the resource utilization of these two measures, whether in technique or scale, has achieved the highest efficiency. Three DMUs—BM7EC, BM4SCC, and BM7SCC—showed characteristics of DRS. The results suggested a decrease in their inputs and production scales to improve their overall operational efficiency. PV power generation and building-integrated PV rely on the availability of solar energy, which is related to the duration of sunshine. As reported by the China Meteorological Administration, SCC and SC have the fewest hours of sunshine. The solar energy in SCC is insufficient, thus constraining the development of PV. In EC, where the duration of sunshine is greatest across China, PV technology has been developed to a mature level, leaving the minor potential for further improvement. Apart from BM3NC, BM2NEC, MM7EC, MM1SCC, BM3SCC, BM3SC, and BM2NWC, whose scale efficiency is lower than is their pure technical efficiency, all the other measures report scale efficiency values higher than pure technical efficiency values. It is suggested that these seven measures should first improve the allocation of input and output factors to improve pure technical efficiency and then expand operational scale to upgrade scale efficiency and, thus, boost the overall efficiency.

Figure 5 gives a clearer look at the efficiencies of these 67 measures in various parts of China. In NC, BM6 and MM2 were the most efficient measures. In NEC, BM6, BM2, and MM5, showed the most efficient performance. In EC, frequency control in both the manufacturing and the building sector showed significantly high efficiency. In SCC, MM1 and BM5 were the most efficient energy conservation measures in the manufacturing and building sectors, respectively. In SWC and NWC, MM5 showed the highest efficiency in the manufacturing sector, while BM1 showed the highest efficiency in the building sector.

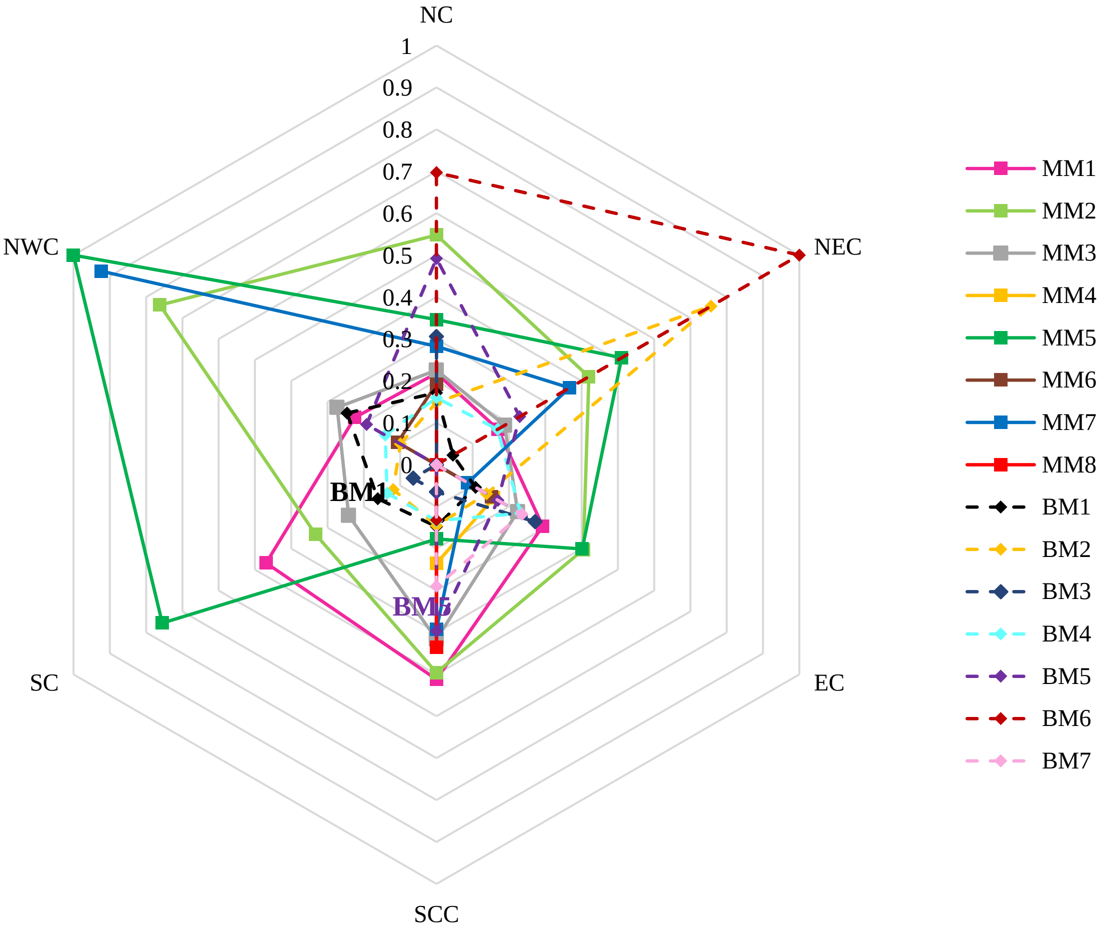


Figure 4: Efficiency of 15 energy conservation measures applied in 6 regions in China

The average efficiencies of the 15 energy conservation measures are shown in Figure 6, indicating that MM5 and BM6 showed the most efficient performance in the manufacturing sector and the building sector, respectively. Most industrial systems contain major steam systems, which use boilers to produce electricity (Saidur et al., 2010). The boiler efficiency, therefore, has great influence on the energy-saving potential. BEMSs ensure that operational needs can be fulfilled with the minimum energy cost and minimum environmental impact. Such systems contribute to the continuous energy management applied to the control of active systems in buildings, saving up to 15% of the utility supply costs (Defence Estates, 2001; Doukas, Patlitzianas, Iatropoulos, & Psarras, 2007).

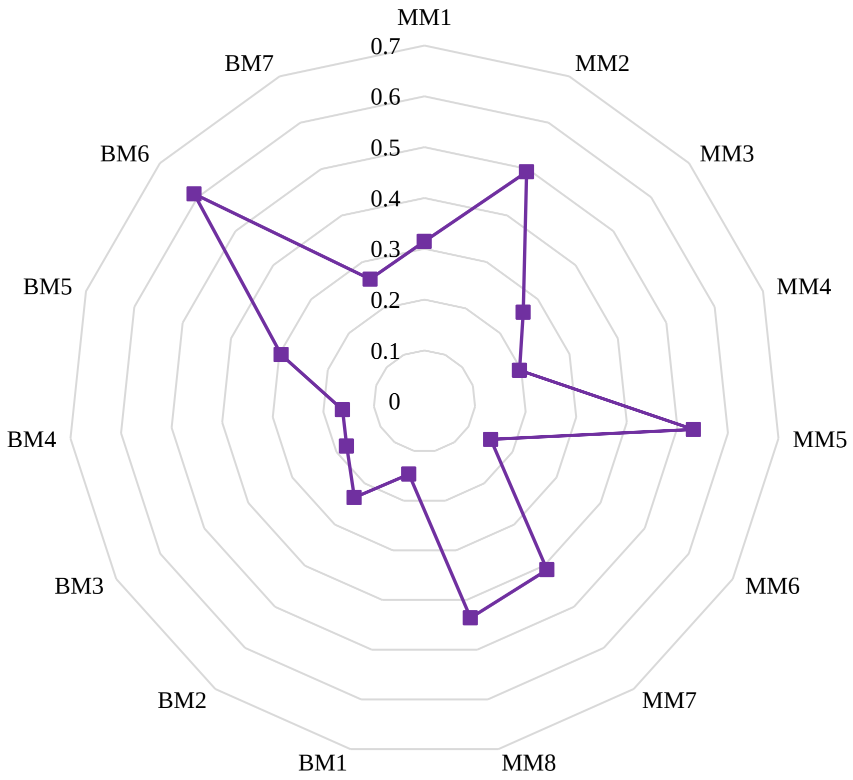


Figure 5: Average efficiency of 15 energy conservation measures in China

The geographical representation of the average energy efficiencies of the six regions is illustrated on the map of China (Figure 7). Measures adopted in EC showed low efficiency while measures in NWC and NEC showed high efficiency. In relatively developed regions, provinces usually have more modern industries, more advanced technologies, higher management levels, and better quality human resources, which will, undoubtedly, enable them to use resources more efficiently (Zhang, Bi, Fan, Yuan, & Ge, 2008).

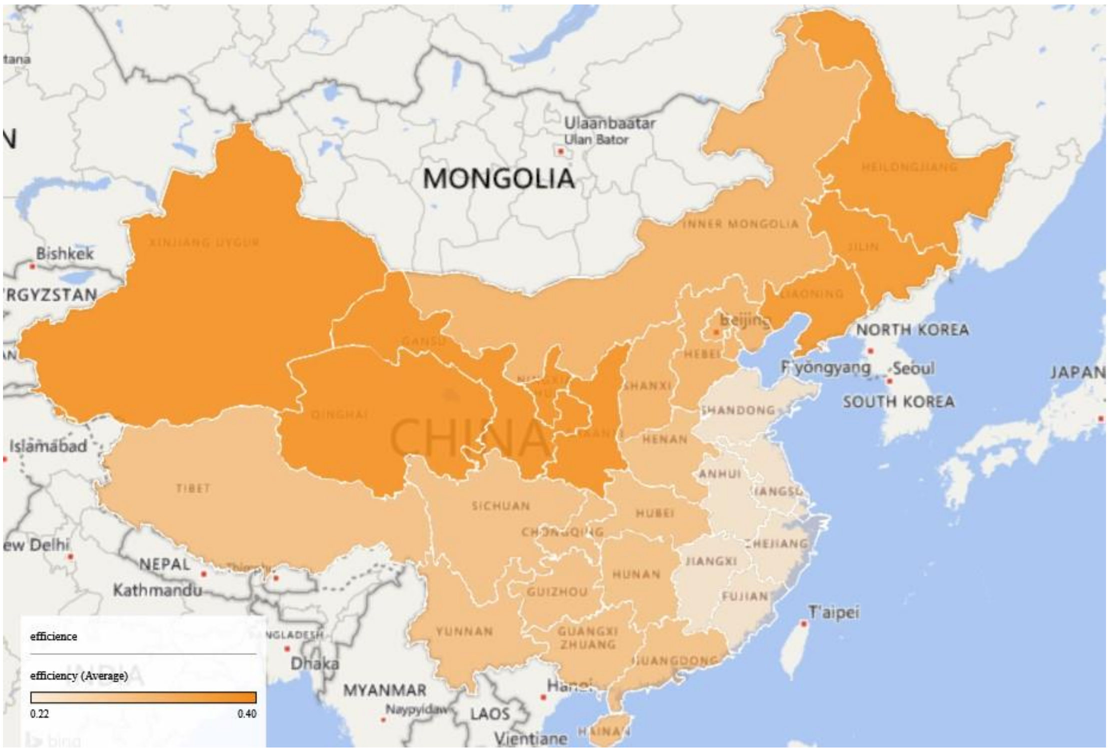


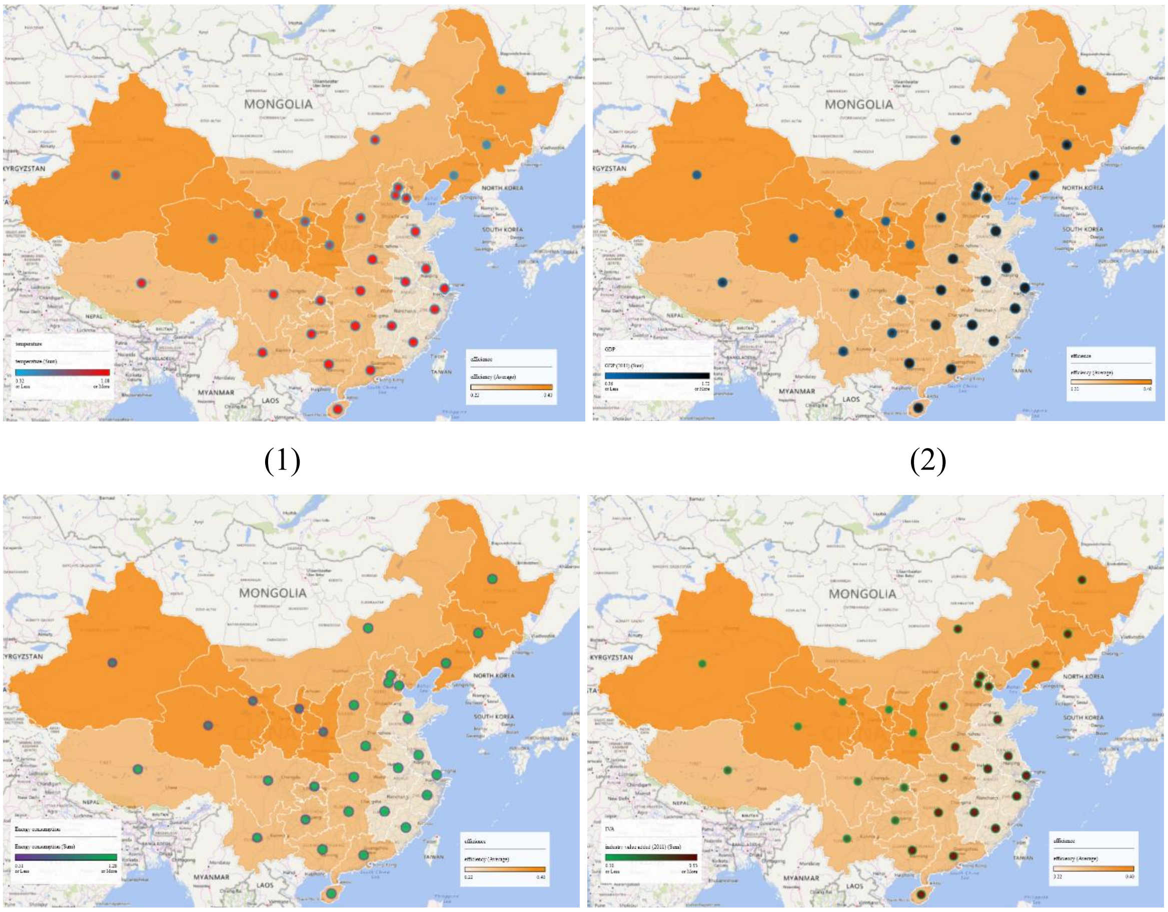
Figure 6: Average efficiency of energy conservation measures in six regions in China

Advanced technologies could change the energy structure and improve energy efficiency. For instance, Jiangsu and Guangdong are the top two provinces, with the highest investment in R&D experiments. EC is highly developed, with advanced technologies, and has adopted energy conservation measures widely. Shanxi, a province in NWC China, has been widely known as a resource-based and less-developed province that relies dominantly on the coal mining industry. The energy consumption in Shanxi is significantly high. In 2015, investment in coal mining reached 104.7 trillion CNY, accounting for 26.13% of the domestic coal mining investment (“National Data,” 2015).

5.2 Energy efficiency vs. regional characteristics

Figure 8 reveals the relationship between energy conservation measures’ efficiency and regional characteristics. Temperature, gross domestic product (GDP), energy consumption and industry value added (IVA) have been recognized as the factors affecting energy efficiency (A. Greening, Greene, & Difiglio, 2000; Ang, 2006; Honma & Hu, 2008; Shi, Bi, & Wang, 2010;

Shi et al., 2010; K. Wang, Yu, & Zhang, 2013b). The results show that high efficiency of energy conservation measures tends to occur in areas with low GDP, low energy consumption, low temperature, and low IVA. This discovery matches the real conditions of regional development in China.



(1) (2)

(3) (4)

Figure 7: Energy conservation measures' efficiencies and regional characteristics. (1) relationship between energy conservation measures efficiency and temperature (red color shows high temperature, while blue color show low temperature); (2) relationship between energy conservation measures' efficiency and GDP (black color shows high GDP, while blue color show low GDP); (3) relationship between energy conservation measures' efficiency and energy consumption (green color shows high energy consumption' while purple color show low energy consumption); (4) relationship between energy conservation measures' efficiency and IVA (brown color shows high IVA, while green color show low IVA).

The relationship between temperature and efficiency of energy conservation measures can be demonstrated in the application of HVAC systems in the ESCO industry. The building area in northern areas accounts for 70% of the land area in China. The building energy consumption for heating is higher than in other areas (Cai et al., 2009). The average heating energy consumption in NC is up to three times that in developed countries (Zhao, Zhu, & Wu, 2009). Thus, there is enormous potential to improve the energy-efficiency. In the northern part of China, where the temperatures are low, the efficiency of energy conservation measures is higher than in other regions. The relationships between the efficiency of energy conservation measures and the other three variables (GDP, IVA, and energy consumption) all show negative patterns. Developed areas with high GDP usually show high energy consumption and high IVA. According to the cost performance cure (Christen, Adey, & Wallbaum, 2016; Richard Webb, 2011) and marginal utility theory, with the same amount of investment, less developed areas tend to have greater increases in the efficiency of energy conservation measures. Figure 8(1), Figure 8(2), and Figure 8(3) indicate that NWC is the exception among the six parts of China. NEC is recognized as a center of heavy industry in China that relies primarily on the oil industry and the coal industry (Wu & Li, 1995). It consumes abundant energy and emits a large amount of carbon dioxide. However, the state-dominated and inefficient production structure based on heavy industry has acted as one of the most important obstacles to economic growth (Démurger, 2001). One of the first launches of ESCOs in NEC was the Liaoning ESCO. Since then, the ESCO industry has developed rapidly in NEC. Consequently, the relationship between the efficiency of energy conservation measures and economic indicators shows positive relevance.

6 Conclusions and policy implications

Within a collection of outputs (energy-saving and energy-saving profit) and inputs (Investment and Contract periods), this study developed a data envelopment analysis (DEA) framework to evaluate the efficiency of energy conservation measures. The developed DEA framework was demonstrated in China, with 1,304 sets of data on Energy Service Company (ESCO) projects, including 15 energy conservation measures commonly adopted in building and manufacturing sectors in six parts of China. Results revealed that MM5 (reconstruction of Industrial Boiler Furnaces) was the most efficient measure in the manufacturing sector, while BM6 (Energy management system) was the most efficient measure in the building sector. The empirical results also showed that the energy conservation measures adopted in Northwest China (NWC) and Northeast China (NEC) were more efficient than were those in East China (EC). The efficiency differences between the six areas may arise from the imbalance of economic development between regions and the climatic conditions.

The findings of this research provided guidelines for the clients of ESCO projects to achieve the highest level of energy savings with the least investment. Firstly, guidelines for building sectors are proposed as follows. In North China (NC), clients can choose energy management systems when implementing energy retrofit projects. The most efficient way for clients in EC to use energy is to make changes in equipment frequency control according to their use time. In NEC, clients would be advised to improve their air conditioning. In South Central China (SCC), the heating system is regarded as the first choice when implementing energy conservation projects. In Southwest China (SWC) and NWC, although miscellaneous building system innovation is the most efficient measure, the efficiency is still low. Some high-efficiency energy conservation measures were not employed in all parts of China; it is advisable to promote such measures across China. For example, energy management systems could be promoted, as they have been shown to be efficient in NC and their performance does not depend on geographical location. Regarding the manufacturing sector, clients can adopt the following suggestions. In NC and EC, using residual industrial heat is the best choice for clients, while reconstruction industrial boiler furnaces are recommended for clients in NEC and Southeast China. In SCC China, the best solution would be to improve re-circulating cooling water systems. In NWC, clients can either choose to reconstruct their industrial boiler furnaces or make changes to their motors systems.

The improvement of energy-saving efficiency measures in ESCOs needs support from the government. Following the results in section 4, some suggestions are proposed. The government should implement different energy-saving policies according to both area and region. For instance, in NC, the government should either introduce a series of energy-saving policies or subsidize the use of residual industrial heat. In these regions, it is also necessary to improve the level of production technology and promote measures to achieve high levels of efficiency. In the northwest area, the efficiency of energy conservation measures is high, mainly because of the initial low level of technology. The government should keep promoting ESCOs to improve the regional energy efficiency. In NWC, the government mainly needs to strengthen the dissemination of information on energy conservation measures in industries and learn from other developed areas. With regard to EC, which is regarded as the most developed area in China, it is more important to focus more on energy-saving management and improving the techniques than it is to adopt current energy conservation measures.

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