Sustainability of China's electricity system; proposal for a structured analysis

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Abstract

A methodological framework has been designed to analyze the sustainability of China's electricity sector in the wake of the 13th Development Plan for the Electricity Sector (2016-2020). The proposal is based on ISO 14040 but also incorporates some features from the "new LCA" approach described in the CALCAS project. Discussion is provided about its practical implementation, including definition of objectives through sustainability questions and sub-questions, definition of scope, definition of scenarios, functional unit, selection of sustainability issues and indicators, suitability of analysis tools, availability of inventory data and aggregation methods to facilitate decision making.

Keywords: Sustainability, renewables, China, electricity, LCA, LCSA

1. Introduction

The prevailing energy model based on the massive consumption of fossil fuels is utterly unsustainable. For this reason, most industrialized countries are undergoing reforms to stimulate energy efficiency, endorse the use of local and renewable energy resources, and promote the deployment of cleaner technologies both for energy use and transformation (EIA, 2016, IEA, 2016). As the world's second largest economy and first greenhouse gas emitter, China plays a key role in the international energy market and in the fight against global warming. Despite recent reforms, China's economy remains highly dependent on fossil fuels, with coal accounting for 64 % of its total primary energy consumption, followed by crude oil (18.1 %) and natural gas (5.9 %) (NBSC, 2016). Likewise, China's electricity mix is also strongly dominated by coal, which supplied 65.2 % of the 5,911 TWh generated in 2016. Other resources contributing to electricity generation include hydropower (19.2 %), oil (5.0 %), wind (4.0 %), nuclear (3.5 %), natural gas (3.1 %) and solar (1.1 %) (China Energy Portal, 2017). With the aim of improving energy security, economic stability and comply with international environmental agreements, China has set a series of highly ambitious energy and climate targets under its 13th Five Year Plan (FYP) for Economic and Social Development (2016-2020) (NPC, 2016). These take the form of the Development Plan for the Electricity Sector (2016-2020) (NDRC, 2016b), the Development Plan for Renewable Energy (2016-2020) (NDRC, 2016a) and a series of specific plans focusing on geothermal, solar, wind and biomass energy. These actions will mobilize a 2500 billion CNY investment (345 billion €), will generate 13 million direct jobs and should reach a 27 % contribution of non-fossil fuels to the electricity mix in 2020 (NDRC, 2016b). Owing to its international significance, the evolution of the electricity sector in China has been the subject of various publications, which describe future scenarios (between 2020 and 2050) based on technical, economic, policy and energy performance indicators (He *et al.*, 2016, IRENA, 2014, Yang *et al.*, 2016, Zhao and Luo, 2017, Zhou *et al.*, 2013, Zou *et al.*, 2017). Some of these publications also provide projections on greenhouse gas (GHG) emissions based on envisaged electricity demands and technology mixes. However, the transformation of China's energy system will not only affect its carbon footprint, but will have profound effects on all the different elements that conform the three dimensions of its sustainability including environment, economy and social welfare. Furthermore, the interactions between the Chinese economy and the international markets will ensure that these effects will inevitably expand to other territories. Identifying and quantifying such potential consequences is essential in order to optimize the design of programs and policies, and also to adopt measures to mitigate, prevent and compensate any adverse effects. Life Cycle Sustainability Analysis (LCSA) refers to a comprehensive methodology designed to evaluate the effects generated by a product on its surrounding environment, the economy and society as a whole. The life cycle approach ensures that the analysis takes into consideration the entire value chain of the product, which typically includes raw material extraction, manufacturing and construction, transmission and distribution to final user, utilization and end-of-life. At present, the most widely adopted methodology to LCSA is the one proposed by UNEP/ SETAC (UNEP and SETAC, 2011). Based on the standardized framework of ISO 14040 (ISO, 2006), this relies on performing independent evaluations of the environmental, economic and social performance of the product under consideration using Environmental LCA (E-LCA), Life Cycle Costing (LCC) and Social Life Cycle Analysis (SLCA), respectively. This mechanistic approach, captured in the conceptual formula "LCSA = LCA + LCC + SLCA", is often criticized for its lack of flexibility and for obviating the interdependences that exist between the elements that compose real systems. The CALCAS project (Heijungs *et al*., 2009) (*Coordination Action for innovation in Life Cycle Analysis for Sustainability*) proposed an evolution to this framework that may be particularly applicable to the evaluation of energy systems. This "new LCA" relies on expanding the scope of conventional LCA to incorporate the three sustainability dimensions, which are evaluated in an integrated manner. The "new LCA" allows more flexibility in the selection of objectives and in the use of the analytic tools, which should take into consideration not only physical relationships between the system and its surroundings (as in conventional LCA) but also behavioural relations, economic valuation, time effects, rebound effects, market and demand changes, etc (Schepelmann *et al*., 2009). Despite its potential, few examples of the use of this novel approach have been published in the literature (Hu *et al*., 2013). The sustainability of electricity systems has been the subject of numerous publications aimed at investigating specific technologies (Corona and San Miguel, 2015, Corona *et al*., 2016a, Corona *et al*., 2016b, Corona *et al*., 2017, Evans *et al*., 2009, Genoud and Lesourd, 2009, Hui *et al*., 2017, Yu *et al*., 2011) or the performance of certain regions/countries characterized by a given electricity demand and technology mix. Examples of these include Germany (Roth *et al*., 2009), Australia (May and Brennan, 2006), UK (Stamford and Azapagic, 2014), Mexico (Santoyo-Castelazo *et al*., 2014), Turkey (Atilgan and Azapagic, 2016) and Mauritius (Brizmohun *et al*., 2015) (no such investigation has been produced for China). All these analyses follow the mechanistic approach proposed by UNEP/ SETAC (UNEP and SETAC, 2011), in some cases including a final aggregation step. The aim of this paper is to describe a structured framework to carry out the LCSA of China's electricity system. This is seen as a first step in a collaborative effort aimed at incorporating sustainability information to the process of decision making in the design of energy plans. The purpose also extends to define objectives, identify inventory data requirements, indicators and analysis tools suitable for this purpose, and also evaluate potential risks and limitations in the analysis of China's electricity system.

2. Methodological proposal

Error! Reference source not found. describes the methodological framework proposed for the LCSA, which is based on ISO 14040 (ISO, 2006) but incorporates some elements from the "new LCA" described in CALCAS (Heijungs *et al*., 2009). This involves four steps: 1) Definition of goal and scope, leading to description of the system, definition of boundaries, functional unit, identification of sustainability issues, indicators and analysis tools; 2) Definition of scenarios of China's electricity system, including current and foreseen states; 3) Modelling, which refers to the use of analysis tools to transform inventory data into impact indicators; 4) Aggregation step, aimed at integrating results into a single sustainability indicator; and 5) Interpretation, intended to set conclusions, limitations and recommendations based on the objectives set in step 1. The practical implementation of these steps to evaluate the sustainability of China's electricity sector is discussed below.

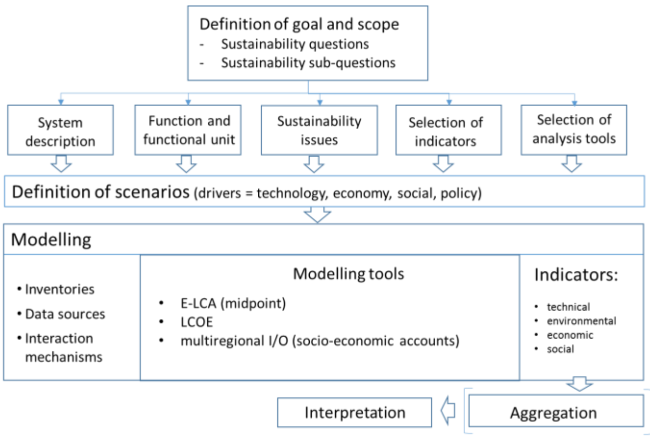

Figure 1. *Proposed methodological framework for the LCSA of China's power system*

2.1 Definition of goal and scope

Five elements have been considered in step, as follows:

2.1.1 Main objective of the LCSA

The objective of the LCSA has been framed in the main sustainability question (MSQ): "How does the *Development Plan for Renewable Energy* affect the sustainability of China's electricity system?" This objective is achieved in two stages: first, describing the sustainability of the existing electricity system; and second, describing how sustainability evolves with time as a result of implementing the Plan for Renewable Energy, which is used to define future scenarios.

2.1.2 Broad system definition

Definition of China's electricity system should cover three analysis levels: technology, sector and global. Inventory data required to describe each one of these levels are described below:

- Technology: energy resources including fossil and renewables (location, characteristics, extraction, processing); power generation (technologies, infrastructures, efficiencies), transmission and distribution (including transmission capacity and grid

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Table 1: Proposed sustainability questions, sustainability issues, analysis tools and indicators for the analysis of China's electricity system

SUSTAINABILITY QUESTION	Analysis level*	Sustainability issues	Inventory/data requirements	Analysis tools (also additional tools)	Indicators (also additional indicators)	Units
SQ1-ENV: SQ1-ENV: What is the environmental performance of China's electricity system? SQ2-ENV: What is the efficiency of China's power generation system?	T	• Climate change • Emissions to air • Emissions to water • Emissions to soil • Resource depletion • Water stress • Energy efficiency	• China's electricity mix • China's electricity demand • LC emission factors of power technologies adapted to China • LC efficiency factors of power technologies adapted to China • Transmission infrastructures • Energy policy analysis	**Attributional E-LCA (Midpoint)** (Also: Consequential E-LCA; Dynamic E-LCA)	Abiotic resour. deple. (elements) **Abiotic resour. deple. (fossil fuels)** **Global warming** **Acidification** Eutrophication **Human toxicity** and ecotoxicity Ozone layer depletion Photochemical oxidants creation Particulate matter formation **Water stress** Agricultural/urban land occupation Natural land transformation **Cumulative Energy Demand**	kg Sb eq./kWh MJ/kWh kg CO_2 eq./kWh kg SO_2 eq./kWh kg PO_4 eq./kWh kg DCB eq./kWh kg CFC-11 eq./kWh kg C_2H_4 eq./kWh kg PM_{10} eq./kWh m^3/kWh m^2/yr/kWh m^2/kWh MJ/KWh
SQ3-ECO: What is the economic cost of electricity in China?	T	• Economic costs	• China's electricity mix • LC cost of power technologies adapted to China • Energy policy analysis	**LCOE** (Also: Extern-E)	Levelized cost of electricity	US$/kWh
SQ4-ECO: What is the contribution of China's electricity sector to wealth generation? SQ5-SOC: What is the contribution of China's electricity sector to employment generation?	S	• Wealth generation • Employment	• Disaggregated economic data • Multiregional I/O tables • Socio-economic accounts	**Multiregional I/O** (Also SHDB)	**Value added** **Direct/indirect labour generation** Labour compensation Labour quality	US$/kWh Hours/TWh US$ US$ (high, med, low)

* T = Technology; S = Sector; G = Global   **Bold**: selected analysis tools and indicators (also additional tools and indicators to be considered)

- stability); operation (emissions factors); end of life (recycling and waste management scenarios).
- Sector: power demand; technology mix targets; environmental standards; electricity pricing rules; regulatory framework (objectives, incentives, taxes) and international commitments.
- Global: economic, material and energy flows between China's electricity sector and the international markets.

2.1.3 Description of scenarios

As discussed, the main scenario of the analysis refers to China's existing electricity system. Additional scenarios include those generated as a result of implementing the Development Plan for Renewable Energy (2016-2020) (NDRC, 2016a). A more ambitious approach may involve developing and evaluating additional scenarios resulting from the application of certain energy policies, as a means to evaluate their consequences. Energy Transition Modelling (ETM) may be used to ascertain the evolution of the energy and electricity sectors in China under different technical, economic and policy circumstances.

2.1.4 Function and functional unit

The function of the system is defined as follows: "to meet the demand for electricity of the Chinese economy ensuring sufficient supply, affordability, grid stability and power quality". The functional unit would be one unit (1 MWh) of electricity generated in such conditions.

2.1.5 Sustainability sub-questions

The number, scope and technical complexity of these sub-questions need to be adapted to the time and resource constrains of each project. In this case, the MSQ has been broken down into five sub-questions (SQ), each one focusing on a specific aspect of sustainability. The same approach may be utilized to analyze present and future scenarios. Table 1 provides a summary of these SQ including information about analysis level, sustainability issues covered, proposed analysis tools, indicators, and inventory/data requirements and availability. *SQ1-ENV: What is the environmental performance of China's electricity system?* This question may be approached using an impact oriented or a damage oriented methodology, as in midpoint and endpoint attributional E-LCA, respectively. The former option has been selected as it incorporates fewer uncertainties to the analysis. Based on international and national significance (as discussed by the authors), the following six indicators may be considered: Global warming (kg CO_2 eq./kWh), Abiotic resource depletion (MJ/kWh), Particulate matter formation (kg PM10 eq./kWh), Acidification (kg SO_2 eq./kWh), Human toxicity (kg DCB eq./kWh) and Water stress (m^3/kWh). The first two describe global impacts while the others refer to local impact categories. Indicators would be calculated multiplying activity factors (as determined considering electricity demand and technology mix inventories) by the emissions factors that correspond to specific technologies. Background data could be obtained from conventional life cycle inventory databases (i.e. Ecoinvent, ELCD), which would need to be adapted to the peculiarities of China's energy system with regard to fuel properties, extraction and processing technologies, location and transport, power generation technology characteristics (efficiency, emission standards, water use, capacity factors, etc.), grid (transmission capacities and losses) and end-of-life scenarios (reuse, recycling, landfilling of materials). ReCiPe Midpoint (H) World is selected as the most appropriate impact assessment method. The analysis of future scenarios, as defined in the Development Plan for Renewable Energy or determined by other means, may benefit from the use of time-dependent characterization factors as in dynamic E-LCA methodology. Consequential E-LCA may be adopted to evaluate the penetration of specific technologies or the substitution of certain energy vectors (as with electric vehicles). *SQ2-ENV: What is the efficiency of China's power generation system?* The Cumulative Energy Demand (CED) method may be used to quantify the efficiency of China's electricity system. Analysis tools and inventory data requirements would as in SQ1-ENV. *SQ3-ECO: What is the economic cost of electricity in China?* The Levelized Cost Of Electricity (LCOE) has been selected as the most suitable method to quantify (US$/kWh) the economic cost of power generation using a life cycle approach. An option considered to be of interest involves disaggregation between private and public costs, the latter derived from the application of public incentives and taxes. Up-to-date economic inventories for energy resources and technologies may be source from US-EIA (US-EIA, 2016), IEA (IEA, 2015, IEA, 2017) and the European Commission (JRC, 2014). These values would need to be adapted to the Chinese market taking into consideration technology characteristics, incentives, taxes, labor, financial and raw material costs (Yi *et al*., 2016). An extension to this analysis may involve calculation of externalities using methodology like the one provided by ExternE (EXTERNE, 2017). *SQ4-ECO: What is the contribution of China's electricity sector to wealth generation?* Multiregional I/O may be used to quantify the effects of China's electricity sector on a series of macro-economic performance indicators for China and the global economy. Life cycle monetary flows of the electricity sector would be used as inventory data. Value added (VA) has been identified as the most suitable indicator. Multiregional I/O databases covering China and the Asian region suitable for this investigation may include those published by World Input Output Database (WIOD) (Timmer *et al*., 2015), OECD/WTO (OECD/WTO, 2017), Asian Development Bank (ADB-MRIO) (ADB, 2017) and Eora (EORA, 2017). *SQ5-SOC: What is the contribution of China's electricity sector to employment generation?* Employment has been selected as the key indicator of socio-economic performance for the electricity sector. Direct employment factors specific economic activities in the energy sector have been published by international institutions (Rutovitz *et al*., 2015). However, Multiregional I/O methodology would be required to determine these values using a life cycle perspective. Data requirements would the same as in SQ4. The key indicator for total employment (hour/TWh) may be disaggregated (direct, indirect and induced) and may also incorporate information about capital compensation, employment quality (high, med, low skilled), etc. Life Cycle Social Analysis (LCSA) methodology would be required to estimate other social performance indicators like injuries, fatality rates, fair salary, collective bargaining, absenteeism, training, gender equality, discrimination, etc. This approach could be used to evaluate specific elements/actions within China's electricity system. Social risks associated with China's electricity system may also be evaluated at a macro level by integrating I/O methodology with background inventory data as provided by the Social Hotspot Database (SHDB) (Rodríguez-Serrano *et al*., 2016, Rodríguez-Serrano *et al*., 2017, SHDB, 2017). A drawback of this methodology is that it is not suitable to evaluate future scenarios.

3. Modelling

As discussed above, a range of analysis tools (including attribution and consequential E-LCA, dynamic E-LCA, multiregional I/O, LCOE, I/O-SHDB) have been proposed to transform inventory data into sustainability performance indicators. This list may be expanded to cover additional objectives, depending on the availability of time and resources.

4. Multi-criteria analysis

Multi-criteria decision analysis (MCDA) methods may be used to integrate individual indicators into a single sustainability score to facilitate decision making. This may be useful particularly when comparing alternative scenarios, as would be the case in this investigation. However, it is often argued that this aggregation step incorporates subjectivity, uncertainty and does not necessarily provide added value to the analysis. Analytical hierarchy process (AHP) has been identified as the most appropriate method in this analysis.

5. Interpretation

The interpretation stage aims to provide responses to the sustainability questions (MSQ and SQ) framed above. These should be used to identify the elements with the highest contribution (both positive and negative) to the sustainability of China's electricity system and identify the best scenarios, thus conditioning the design and implementation of future energy plans.

6. Conclusions

This paper describes a methodological framework to be used in the sustainability analysis of China's electricity system. The proposal is based on ISO 14040 but also incorporates additional features from the "new LCA" (as described in the CALCAS project) aimed primarily at improving flexibility in the selection of objectives and the use of analysis tools. Discussion regarding the practical implementation of this methodology and the availability of inventory data has been regarded as a first step in this endeavor. An additional challenge not covered in this paper involves analyzing the connections between the electricity sector and the overall energy system in China, which unfailingly compete for some areas of the market and should be evaluated as a whole.

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References:

ADB, 2017. Asian Development Bank, multi-regional input-output tables (ADB-MRIO)

Atilgan, B., Azapagic, A., 2016. An integrated life cycle sustainability assessment of electricity generation in Turkey. Energy Policy, 168-186

Brizmohun, R., Ramjeawon, T., Azapagic, A., 2015. Life cycle assessment of electricity generation in Mauritius. J. Clean. Prod., 565-575

China Energy Portal, 2017.

Corona, B., Cerrajero, E., López, D., San Miguel, G., 2016a. Full environmental life cycle cost analysis of concentrating solar power technology: Contribution of externalities to overall energy costs. Solar Energy, 758-768

Corona, B., San Miguel, G., 2015. Environmental analysis of a Concentrated Solar Power (CSP) plant hybridised with different fossil and renewable fuels. Fuel. 0, 63-69

Corona, B., Bozhilova-Kisheva, K.P., Olsen, S.I., San Miguel, G., 2017. Social Life Cycle Assessment of a Concentrated Solar Power Plant in Spain: A Methodological Proposal. J. Ind. Ecol., n/a-n/a

Corona, B., Rúa, C.d.l., San Miguel, G., 2016b. Socio-economic and environmental effects of concentrated solar power in Spain: A multiregional input output analysis. Solar Energy Mater. Solar Cells, 112-121

EIA, 2016. International Energy Outlook 2016, U.S. Energy Information Administration (EIA); http://www.eia.gov/outlooks/ieo

EORA, 2017. Eora multi-region IO database

Evans, A., Strezov, V., Evans, T.J., 2009. Assessment of sustainability indicators for renewable energy technologies. Renewable and Sustainable Energy Reviews. 5, 1082-1088

EXTERNE, 2017. External Cost of Energy - EXTERNE

Genoud, S., Lesourd, J., 2009. Characterization of Sustainable Development Indicators for Various Power Generation Technologies. International Journal of Green Energy. 3, 257-267

He, Y., Xu, Y., Pang, Y., Tian, H., Wu, R., 2016. A regulatory policy to promote renewable energy consumption in China: Review and future evolutionary path. Renewable Energy, 695-705

Heijungs, R., Huppes, G., Guinée, J., 2009. A scientific framework for LCA—deliverable (d15) of work package 2 (wp2) CALCAS project. Institute of Environmental Sciences, Leiden University (CML)

Hu, M., Kleijn, R., Bozhilova-Kisheva, K.P., Di Maio, F., 2013. An approach to LCSA: the case of concrete recycling. International Journal of Life Cycle Assessment. 9, 1793-1803

Hui, J., Cai, W., Wang, C., Ye, M., 2017. Analyzing the penetration barriers of clean generation technologies in China's power sector using a multi-region optimization model. Appl. Energy, 1809-1820

IEA, 2017. Investment costs for power generation. International energy agency.

IEA, 2016. World Energy Outlook 2016, International Energy Agency (IEA), DOE/EIA-0484(2016)

IEA, 2015. Projected Cost of Generating Electricity, International Energy Agency (IEA), Organization for Economic Cooperation and Development - Nuclear Energy Agency (OECD-NEA), 2015 edition

IRENA, 2014. Renewable Energy Prospects: China, REmap 2030 analysis

ISO, 2006. ISO 14040:2006 Environmental management - Life cycle assessment - Principles and framework

JRC, 2014. ETRI 2014. Energy Technology Reference Indicator projections for 2010-2050. JRC Science and Policy Reports, European Commission

May, J.R., Brennan, D.J., 2006. Sustainability Assessment of Australian Electricity Generation. Process Safety and Environmental Protection. 2, 131-142

NBSC, 2016. China Statistical Yearbook 2015, National Bureau of Statistics of China (NSBC), http://www.stats.gov.cn/tjsj/ndsj/2016/indexeh.htm

NDRC, 2016a. 13th FYP development plan for renewable energy, National Development and Reform Commission (NDRC) of China

NDRC, 2016b. 13th FYP development plan for the electricity sector, National Development and Reform Commission (NDRC) of China

NPC, 2016. 13th Five Year Plan (FYP) for Economic and Social Development (2016-2020), National People Congress (NPC)

OECD/WTO, 2017.
OECD/WTO Trade in Value Added database

Rodríguez-Serrano, I., Caldés, N., De la Rúa, C., Lechón, Y., Garrido, A., 2016. Using the Framework for Integrated Sustainability Assessment (FISA) to expand the Multiregional Input–Output analysis to account for the three pillars of sustainability. Environment, Development and Sustainability

Rodríguez-Serrano, I., Caldés, N., de la Rúa, C., Lechón, Y., 2017. Assessing the three sustainability pillars through the Framework for Integrated Sustainability Assessment (FISA): Case study of a Solar Thermal Electricity project in Mexico. J. Clean. Prod., 1127-1143

Roth, S., Hirschberg, S., Bauer, C., Burgherr, P., Dones, R., Heck, T., Schenler, W., 2009. Sustainability of electricity supply technology portfolio. Ann. Nucl. Energy. 3, 409-416

Rutovitz, J., Dominish, E., Downes, J., 2015. Calculating global energy sector jobs: 2015 methodology. Institute for Sustainable Futures, University of Technology Sydney

Santoyo-Castelazo, E., Stamford, L., Azapagic, A., 2014. Environmental implications of decarbonising electricity supply in large economies: The case of Mexico. Energy Conversion and Management, 272-291

Schepelmann, P., Ritthoff, M., Santman P., Jeswani H., Azapagic A., 2009. D10 SWOT analysis of concepts, methods and models potentially supporting life cycle analysis; Deliverable (D10) of work package 3 (WP3) CALCAS project

SHDB, 2017. Social Hotspot Database

Stamford, L., Azapagic, A., 2014. Life cycle sustainability assessment of UK electricity scenarios to 2070. Energy for Sustainable Development, 194-211

Timmer, M.P., Dietzenbacher, E., Los, B., Stehrer, R., de Vries, G.J., 2015. An illustrated user guide to the world input–output database: the case of global automotive production. Review of International Economics, 575-605

UNEP, SETAC, 2011. Towards a Life Cycle Sustainability Assessment: Making informed choices on products, http://www.unep.org/pdf/UNEP_LifecycleInit_Dec_FINAL.pdf, ISBN: 978-92-807-3175-0 ed, Paris

US-EIA, 2016. Capital Cost Estimates for Utility Scale Electricity Generating Plants, United States Energy Information Administration (US-EIA), U.S. Department of Energy, November 2016

Yang, X.J., Hu, H., Tan, T., Li, J., 2016. China's renewable energy goals by 2050. Environmental Development, 83-90

Yi, B., Xu, J., Fan, Y., 2016. Inter-regional power grid planning up to 2030 in China considering renewable energy development and regional pollutant control: A multi-region bottom-up optimization model. Appl. Energy, 641-658

Yu, F., Chen, J., Sun, F., Zeng, S., Wang, C., 2011. Trend of technology innovation in China's coal-fired electricity industry under resource and environmental constraints. Energy Policy. 3, 1586-1599

Zhao, X., Luo, D., 2017. Driving force of rising renewable energy in China: Environment, regulation and employment. Renewable and Sustainable Energy Reviews, 48-56

Zhou, N., Fridley, D., Khanna, N.Z., Ke, J., McNeil, M., Levine, M., 2013. China's energy and emissions outlook to 2050: Perspectives from bottom-up energy end-use model. Energy Policy, 51-62

Zou, P., Chen, Q., Yu, Y., Xia, Q., Kang, C., 2017. Electricity markets evolution with the changing generation mix: An empirical analysis based on China 2050 High Renewable Energy Penetration Roadmap. Appl. Energy, 56-67.