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Electricity portfolio innovation for energy security: The case of carbon constrained China

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ABSTRACT

China's energy sector is under pressure to achieve secure and affordable supply and a clear decarbonisation path. We examine the longitudinal trajectory of the Chinese electricity supply security and model the near future supply security based on the 12th 5 Year Plan. Our approach combines the Shannon–Wiener, Herfindahl–Hirschman and electricity import dependence indices for supply security appraisal. We find that electricity portfolio innovation allows China to provide secure energy supply despite increasing import dependence. It is argued that long-term aggressive deployment of renewable energy will unblock China's coal-biased technological lock-in and increase supply security in all fronts. However, reduced supply diversity in China during the 1990s will not recover until after 2020s due to the long-term coal lock-in that can threaten to hold China back from realising its full potential.

1. Introduction

1.1. Background on energy and electricity supply security

Access to energy is one of the most important aspects of modern and developed economies. Its importance extends wider than that of other commodities because without it they cannot be produced, delivered to the market, or used. Energy is used in all primary and secondary forms but during the last two decades the role of electricity has been rising (Armaroli and Balzani, 2011). This is not only a result of a proportional increase in energy consumption but also of a substitution of fuels with electricity. For example this is taking place in buildings as electricity increasingly substitutes oil and gas for temperature control and cooking. It is also evident in rail and road transport with urban and intercity trains as well as private vehicles becoming electrically powered. Finally in industrial processes electricity substitutes steam driven processes (Khatib, 1993; Balat, 2006; Kalkuhl et al., 2012; Turton and Moura, 2008; Shi and Lai, 2013).

Electricity is a flexible form of energy not only for consumers but also for producers. As a secondary energy carrier electricity can be generated with the use of primary fuels or renewable energy resources. Therefore producers do not have to rely solely on a certain fuel. When electricity is produced by renewable energy sources then it is the only form of energy with minimal environmental impact (Armaroli and Balzani, 2011; Blesl et al., 2010; Knapp, 1999).

Given the necessary role for energy and electricity in national security and economic development, it is not a surprise that securing their supplies is implicitly or explicitly amongst the top priorities of every country. Following the definition for energy supply security by Grubb et al. (2006) energy supply can be considered secure when its price does not disrupt the economy. This definition goes a step further than a simplified approach that is based on resource availability i.e. the resource supply is secure when it is available. The introduction of price puts forward the dimension of affordability which is paramount for energy supply security. Moreover, this price is not introduced at an absolute level but one that is relative to the capacity of a given economy to absorb it. At a national level, governments use a number of strategies to ensure supplies such as utilising indigenous resources, improving foreign relations with energy producing countries and facilitating efficient operation of energy markets (Flavin and Dunn, 1999; Energy Security in a Multipolar World (ESMW) Research Cluster, 2011; Nuttall and Manz, 2008). In this paper we examine the role of electricity portfolio innovation in combining seemingly conflicting targets i.e. electricity supply security and climate change mitigation. The approach adopted is focused on technology policy innovation in a way that differentiates it from a technology research approach.

Diversity of production methods is a major strength for electricity supply security (Stirling, 1994). However, most of the energy security literature refers to primary energy resources and electricity tends to be under-represented in energy security research. A main reason for

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this is that electricity does not rely on a single resource for its production since it is produced in numerous ways; thus it requires a broader understanding of the energy context in order to encompass existing and alternative generation scenarios as they impact stability of supply and price dynamics. Furthermore, in contrast to most other commodities, electricity is not easily stored in a financially viable way. Therefore storage is a missing link in electricity's supply chain, although this excludes solutions that would suggest buffering (Makansi and Abboud, 2002; Zafirakis et al., 2013a; Poudineh and Jamasb, 2014). Whilst there is significant capacity for energy storage in China, this is an evolving issue both in means of policy (Zhanga et al., 2015) and development of technological solutions (Yang et al., 2015).

On top of the difficulties that concern securing electricity supply, the electricity sector is a leading source of greenhouse gases (GHGs) in many developed and emerging economies. It also is the most concentrated sector in terms of emissions per source, and accounts for more emissions than any other sector (Metz et al., 2007; Verbong and Geels, 2010; Kaldellis et al., 2004). At the same time potential reductions in the carbon intensity of the electricity sector can benefit other sectors, which can be partially electrified. For these reasons policies to reduce GHGs in most countries target primarily the electricity sector (Australian Government Productivity Commission, 2011; van den Bergh, 2013). Reducing the carbon intensity of the electricity sector may include policies such as increased use of renewable energy sources and nuclear energy, substitution of coal with natural gas where possible, introduction of carbon capture and storage (CCS) technologies as well as efficiency improvements in existing power stations. Arguably, several of these substitutions, change the electricity sector's fuel mix and as a result contribute to changes in the electricity supply security (Chalvatzis, 2012; Zha and Ding, 2014). By focusing on electricity portfolio innovation we model the impacts of these substitutions and offer a technology mix forecasting tool and analyse multiple levels of impacts including environmental, social and technological.

1.2. China as a case study

China is currently managing the largest programme of low carbon technologies in the world (World Bank, 2012). This includes unprecedented investment in nuclear energy and renewables, particularly hydro and wind energy. This is not always incentivised by policies that could have wider social benefits (Zafirakis et al., 2013b) but rather is driven by a "dash for electricity generation". At the same time, the Chinese government's 2012 Energy Policy (Chinese Government, 2013) lists increased coal production amongst its top five key targets. This is not a surprise because the Chinese electricity sector relies heavily on coal. Until 2009 coal used for electricity came almost exclusively from indigenous resources in China. However, gradual ore depletion, increasing direct coal consumption and rapidly growing electricity demand led China to become the world's largest coal importer soon after it started importing (International Energy Agency (IEA), 2012). In parallel, the supply of nuclear fuel to China relies heavily on imports; it is forecast that by 2020, 2/3 of uranium sources will be imported, roughly half of all non-indigenous sources coming from foreign imports and half from Chinese overseas possessions (Xie et al., 2011; Guidolin and Guseo, 2012). The forecast increased energy demand (particularly fossil fuels) is one of the main reasons for which China has not subscribed to international agreements to control emissions of greenhouse gases.

With regard to nuclear power China is leading the world in the second phase of what is often called the "nuclear renaissance" (Grimes and Nuttall, 2010), referring to the post-Chernobyl and Three Mile Island rapid development of nuclear energy that takes place mainly in Asia. The IAEA suggests that 72% of the reactors currently under construction are found in five countries China (29 including 2 at Taiwan); India (6); South Korea (5); Pakistan (2); and Russia (10) (International Atomic Energy Agency (IAEA), 2014). However, recent studies cast doubt on the uranium supply over the forthcoming decades (Guidolin and Guseo, 2012; Dalla Valle and Furlan, 2014).

The aim of this paper is to introduce electricity portfolio innovation as an approach the can successfully deliver on conflicting targets. China provides for an excellent case study to demonstrate dominant paradigms of energy supply security in the past, present and future as they are reflected in energy policy transitions. Even though China has a rapidly developing economy, the legacy of its energy sector creates strong pathway dependencies that need to overcome. Methodologically, we contribute a multi-perspective technology planning tool that bridges strategic views of the past with those of the present and the future.

This manuscript continues with a brief description of the case study i.e. the Chinese electricity sector and its specific challenges. Following that, in the third section we describe the methodological approaches used for assessing electricity supply security. In this section there is explicit reference to the data that was used for this study. The fourth section presents and discusses our results and finally the paper concludes with the implications beyond China's borders of electricity security in China.

2. Electricity sector of China

2.1. Current situation

China's electricity sector is the largest in the world, and electricity consumption in the country reached 5322 TWh in 2013 (National Energy Administration, 2014), with generation expected to rise to 9845 TWh by 2020 (State Grid Energy Research Institute China, 2013) (Fig. 1). China is the world's largest consumer of coal and its electricity sector is the largest single source of coal demand, consuming approximately half of the country's coal.

Prior to economic liberalization in 1978, China's electricity sector was operated by the Vertically Integrated State Owned Utility (VISOU), which has undergone significant transformations and is now privatized and dismantled (Ma and He, 2008). The resulting competition increased the generation capacity that was needed to satisfy China's growing demand, which comes primarily from the industrial sector; from 1980 to 2012, electricity generation grew 16-fold and is projected to continue (Kahrl et al., 2011a; Wei et al., 2006). Energy security concerns dictate that China meet its electricity needs with domestic resources, resulting in a system heavily reliant on coal. Recent developments and national policy demonstrate China's will to diversify its primary fuel mix in electricity generation. However, exploitation of coal resources is the top national energy priority (China National Renewable Energy Centre, 2013).

Approximately 75% of China's electricity demand comes from continuous production industrial facilities, causing a relatively flat demand profile. This flat profile is conducive to China's predominately inflexible base-load generation, however leads to integration problems for

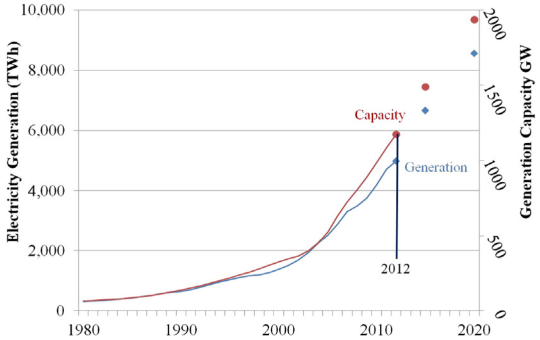

Fig. 1. Past and projected electricity generation and electricity generation capacity in China.

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intermittent resources. China's inflexible system may be increasingly inappropriate as the electricity demand profile becomes more volatile with anticipated increases in residential and commercial demand.

Geographical diversity of resource location and demand centres is a major problem for China's power sector, as coal is predominately found in the North and demand centres are located largely in the East. Some non-coal power sources face the same problem. For example, hydropower is located predominately in the South, whilst wind resources are mostly located in the North and Northeast. In the case of wind power, this causes frequent curtailment and also non-connected installed capacity rates of up to 25% in areas such as East Inner Mongolia that have received the bulk of China's wind capacity buildup (Ming et al., 2013).

Whilst renewable energy plays only a small role in China's electricity generation, it is worth noting that various legislations have been passed to encourage it. Notably, The Renewable Energy Law (REL) in 2005 requires non-hydro renewable power generation to account for 3% of the electricity generation by 2020. This has succeeded in stimulating certain technologies; wind capacity grew from 0.3 GW in 2000 to 25.8 GW in 2010 (Wang et al., 2009). Also, China's 12th 5 Year Plan, discussed further below, suggests aggressive clean energy targets, including an increase in the share of non-fossil fuel consumption of primary energy to 11.4% by 2015 (Xinhua Net News, 2011).

China's electricity consumption continues to grow rapidly, reaching a growth rate of 7.2% in the first three quarters of 2013, whilst electricity production for the same period grew at 6.8% (China Electricity Council (CEC), 2013). Given the dominate position of coal in the electricity production fuel mix (76% in 2012) it is natural that coal will remain the dominant fuel source for China to meet growth in electricity demand for the foreseeable future.

Increased concern about climate change has put major greenhouse gas (GHG) emitters under scrutiny by the international community. China's rapid development since its partial economic liberalization in 1978 has come at great environmental expense (Economy, 2004) and resulted in annual GHG emissions of 7222 $GtCO_2e$ in 2010 making it the world's leading emitter. China's electricity sector specifically has become a focal point, both because of its strain on global natural resource supplies and emission-intense nature. Internationally the electricity sector accounts for 42% of annual GHG emissions from fossil fuels; nationally, China's electricity sector accounts for over half of its total emissions (International Energy Agency (IEA), 2013).

In addition to reducing carbon emissions, China urgently needs to combat air pollution. So far, this issue has been approached mostly on a regional and urban basis but as the European and North American experience suggests the most dangerous pollutants are easily transferred across borders (Kaldellis et al., 2007). Synergies between air pollution and carbon reduction are straight-forward in all the decarbonisation options, particularly those suggesting focusing on renewable energy sources and nuclear.

2.2. China's historic electricity fuel mix development

Since its early stages (Fig. 2) the Chinese electricity sector relied heavily on China's large coal endowment (Energy Information Agency (EIA), 2011). This abundant and cheap fuel supply facilitated China's heavy industry development, which required continuous electricity supply and therefore coupled well with the base-load features of coal-fired power systems. Coal thus became deeply embedded in China's 20th century energy system. During that early phase electricity generation in China relied also on hydropower (21.44%) and oil (16.92%).

Although natural gas resources were being developed in China since the early 1970s, natural gas fuelled electricity generation began slowly in 1980 and remained almost insignificant until after 2000 (Figs. 3, 4 and 5). In fact during the 1980s the fuel mix of the Chinese electricity sector remained almost unchanged with fluctuations only between the shares of coal and hydropower. These were owned to the variability of precipitation patterns that dictated the availability of hydropower (Fig. 3). The role of oil, despite substantial in the 1970s and 1980s, declined rapidly since then as the fuel was designated for the transportation sector.

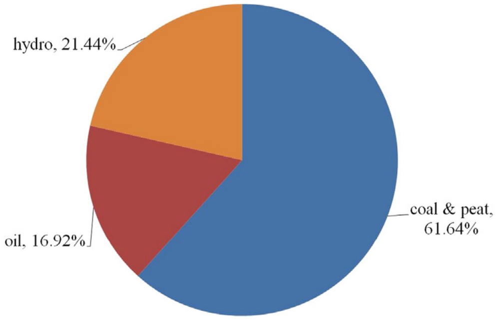

Fig. 2. Chinese electricity sector's fuel mix in 1972.

In fact, it was not until the 1990s that coal's role in the Chinese electricity sector exceeded 70% (Fig. 4) and remained at that (or higher) level ever since (International Energy Agency (IEA), 2015). In that period and leading to 2000s (Fig. 5) the Chinese electricity fuel mix began including more options including non-hydro renewable energy generation.

It is important to mention, that at least in the beginning (Fig. 5) the introduction of renewable energy sources such as wind and bio-fuels did not reduce the role of coal which remained very high. In fact both renewable energy sources and coal increased their contribution during that period mainly by reducing the share of oil. However, despite the explosive growth (74% average annual growth between 2005 and 2012) of the non-hydro renewable energy its role remained insignificant even in 2012 (Fig. 6). Hydropower on the other hand, has had a constantly significant role in China's power generation portfolio accounting for between 24% (1974) and 15% (2003) throughout the period 1972 to 2012. Government targets to increase the installed capacity of China's hydropower to 300 GW by 2020 (from 219 GW in 2010) (Fig. 7) in order to ensure that hydro will continue to make an important contribution to China electricity portfolio mix into the mid-term future.

Even during the 2010s (Fig. 6) and later towards 2020 (Fig. 7) the role of coal has remained constantly higher than 75%. In fact it was close to that period, in 2007, that coal reached its peak with 80% contribution (China Energy Statistical Yearbook, 2001–2010). The near future plans (Fig. 7) for the Chinese electricity sector include an increased role for nuclear energy which is expected to reach 6%, up from 1.95% in 2012 (International Atomic Energy Authority (IAEA)).

China is increasing the role that gas will play in its energy mix by increasing production and by building the infrastructure needed to boost imports via pipeline and liquefied natural gas. However, the growth in the use of natural gas in power generation is not expected to maintain pace with the growth of electricity demand, and by 2020 official

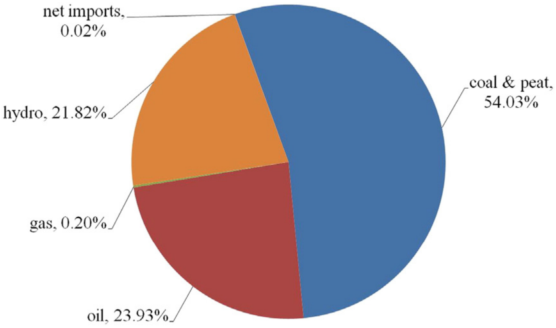

Fig. 3. Chinese electricity sector's fuel mix in 1982.

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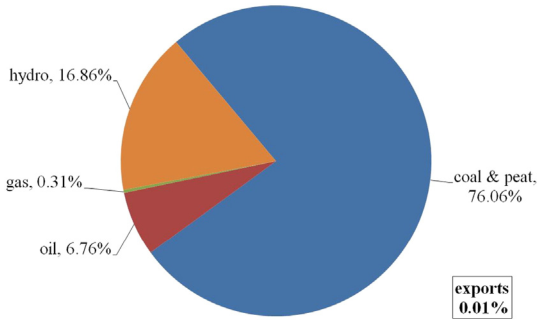

Fig. 4. Chinese electricity sector's fuel mix in 1992.

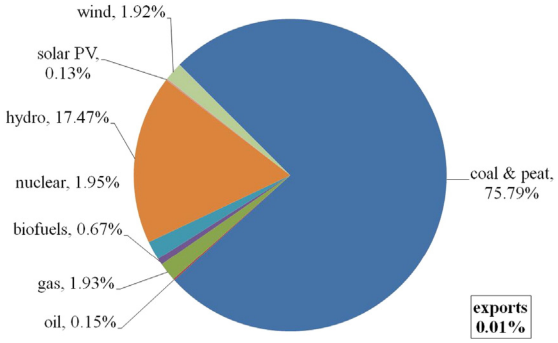

Fig. 6. Chinese electricity sector's fuel mix in 2012.

estimates predict that natural gas' use in electricity generation will dip to 1.85% of total supply (United States Energy Information Administration and Country Information: China).

Photovoltaic power has also experienced rapid growth, but is predicted to play a much less significant role in China's overall generation mix. Biomass, geothermal, tidal and other forms of renewable energy have not historically been significant sources of electricity, nor are they predicted to account for any substantial generation in China's short and mid-term energy future. By 2012, photovoltaic electricity has produced 6350 GWh and is expected to exceed 35,500 GWh by 2020.

2.3. China's coal consumption & production

Growth in China's coal consumption is closely linked to growth in electricity generation. 76% of its electricity was generated from coal in 2012 (International Energy Agency (IEA), 2015), and electricity production accounted for 49% of total coal consumption (China Energy Statistical Yearbook, 2001–2010). Growth in demand remains one of China's largest obstacles in curbing its consumption of coal; average growth of electricity generation between 2002 and 2012 was 11.5% (International Energy Agency (IEA), 2015). China's State Grid Economic Research Institute (SGERI) projects high and low demand scenarios for the electricity sector in 2020 of 8510 TWh and 6947 TWh respectively (State Grid Energy Research Institute China, 2013). Non-coal energy targets are already aggressive. Growth in installed capacity of non-coal electricity generation is expected to rise from the 224 GW in 2009 to 586 GW in 2020, with the resulting 2200 TWh of estimated output signifying an upper limit of what would be technically feasible in that timeframe (Kahrl et al., 2011b). Therefore, the differences in SERGI's demand scenarios would include between 6310 TWh and 4747 TWh of predominantly coal-based sources from a 2009 baseline of 3557 TWh coal generated electricity. This implies a large growth potential of coal consumption from China's electricity sector, the extent of which is largely dependent on China's ability to manage growth in its electricity demand.

Given its large domestic coal endowments, China's coal production has historically far exceeded its consumption. Looking specifically at coal used in electricity production, net bituminous coal exports peaked in 2001 at 68.6 million tons. China's production of bituminous coal has grown rapidly in recent years, rising from 1.21 billion tons in 2000 to 2.88 billion tons in 2012, with an average growth rate of 7.45% (International Energy Agency (IEA), 2015). However, during that same period, China's demand for coal grew even faster, and surpassed local supply; consumption of bituminous coal rose from 1.26 billion tons in 2000 to 3.10 billion tons in 2012 — an average growth rate of 7.80% for the same period. Whilst bituminous coal imports only accounted for 0.61% of total steam coal consumption in 2000, by 2012 imports accounted for 6.86%; an 11-fold increase in reliance on bituminous coal imports for electricity generation (International Energy Agency (IEA), 2015). This supply and demand imbalance has been mirrored in other coal consumption sectors, and shifted China's position as a significant coal exporter to the world's number one importer in 2009; in that year China imported 126 Mt of coal, which accounted for 15% of global coal trade. By 2012, China imported 303 million tons of coal, accounting for just over 25% of global coal trade (International Energy Agency (IEA), 2015).

China's dependence on coal imports is projected to continue, in part due to a national guidance to limit coal production capacity to 4.1 billion tons during the Chinese 12th 5 Year Plan period of 2011–2015 (Fig. 8), according to government news sources (Xinhua Net News, 2011). Problems resulting from production and use of coal resources are well documented and the central government policies help to mitigate issues such as preserving indigenous supplies, limiting the strain on existing coal transportation infrastructure, and reigning-in environmental damage caused by coal mining (Tu and Johnson-Reiser, 2012; Xinhua Net, 2012).

Compounding China's increasing reliance on coal imports is the trend towards electrification. The IEA estimates that electricity accounted for 6% of China's final energy consumption in 1990, and by 2007 had grown to 19%. IEA forecasts this figure to rise to 27% by

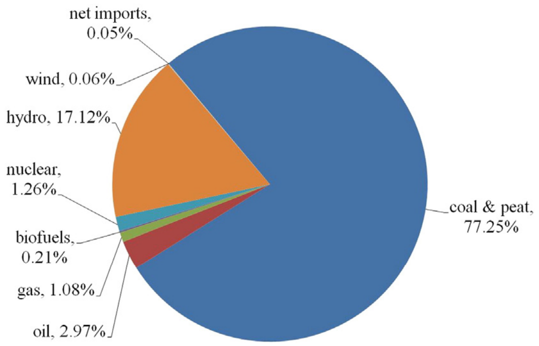

Fig. 5. Chinese electricity sector's fuel mix in 2002.

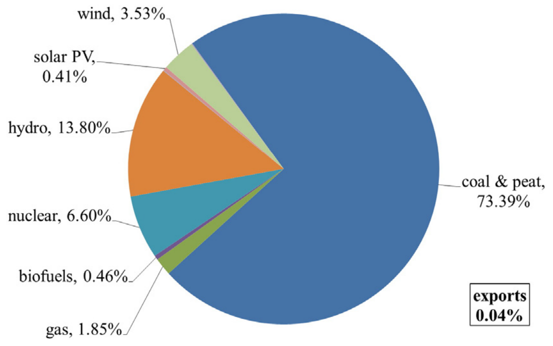

Fig. 7. Projected Chinese electricity sector's fuel mix in 2020.

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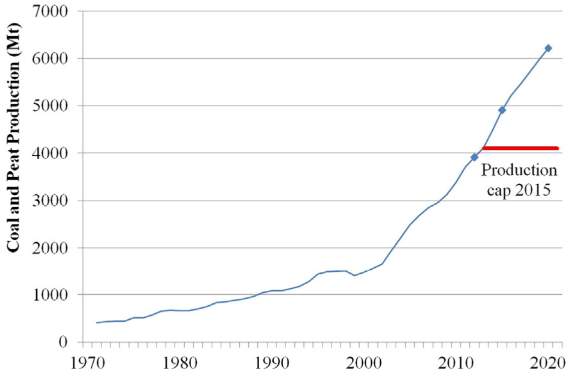

Fig. 8. Past and projected coal and peat production in China with production cap.

2020 as an increasing share of the energy it consumes comes in the form of electricity (International Energy Agency (IEA), 2009a).

China's recent reliance on coal imports marks a turning point in China's energy security, and more specifically its electricity security. Most research on China's energy security focuses on the substantial gap between oil production and consumption. Indeed, China's national energy strategy historically has been to rely on domestic resources, which until recently it has successfully done for all major energy sources other than oil (Leung, 2011; Cao and Bluth, 2013; Zhongxiang, 2011). However, a predominant focus on oil overlooks the recent, and growing, production/consumption imbalance of coal, which plays a much larger role in China's overall energy portfolio. The implications for China's electricity security and of its existing and future fuel mix scenarios have not been sufficiently explored by existing literature.

3. Methodology

Until recently researchers focused on defining energy security (Winzer, 2011) and establishing theoretical or qualitative frameworks to conduct energy security analyses (Hughes, 2012; Sovacool and Mukheree, 2011). Energy policy studies are increasingly incorporating quantitative indicators serving as proxies for measurements of energy security (Martchamadol and Kumar, 2012; Sovacool, 2013a,b; Chuang and Ma, 2013). The two most distinct quantitative approaches for energy supply security use measures of diversity or measures of energy dependence, both of which will be reviewed here. Other energy security indicators comprise of a combination of dependence, diversity, other macroeconomic indicators and stochastic approaches (International Energy Agency (IEA), 2007a,b).

Import dependence and diversity of supply reflect on two different paradigms in energy security. Firstly, the import dependence framework has been the dominant approach to understanding energy security since the industrial revolution until the 1990s. It highlights national control on energy resources as the most important goal in security energy supply. Historically, this has been a paradigm fit for countries that had adequate indigenous energy supply or had the military prowess to acquire resources internationally. However, high quality energy resources (e.g. high quality coal and relatively easy to access oil and gas) in industrialised countries have been used to power development, and these countries were left with lower quality fuels at their disposal. Developed countries were increasingly required to import higher quality fuels and develop alternative indigenous energy sources, which led to the emergence of the diversity paradigm in energy supply security.

The adopted approach is straight-forward and novel. It is straight-forward because we use the most established concepts to assess supply security; dependence and diversity. Both are estimated with straight-forward indices that were used before in the energy security literature. The novelty of our approach is that never before was the combination of these indices used to analyse the long-term past and mid-term future electricity supply security status of China. In the following sections the details of the quantified measures of dependence (Section 3.1) and diversity (Section 3.2) are provided. The data used is mainly available through the International Energy Agency (IEA).

3.1. Electricity supply dependence

The concept of energy dependence may seem obvious with regard to reliance on primary fuels. However, further analysis by Frondel and Schmidt (2008) resulted in an indicator assessing the specific risks associated with each primary fuel, taking into account information about the worldwide supply of that fuel and its importance for the country in question. Chalvatzis and Hooper (2009) and Chalvatzis (2012) provided a clear focus on electricity supply security. The authors suggested a new index that takes into account the direct electricity imports and imports of primary energy resources that are used to generate electricity. Hence:

$$\text{Dependence}\quad D = D_e + D_f \tag{1}$$

where:

D	(%) electricity supply dependence
D_e	(%) dependence on direct electricity imports
D_f	(%) dependence on primary fuel imports for electricity generation.

3.2. Electricity supply diversity

There are several quantitative approaches on energy diversity. Cohen et al. (2011) proposed global and country-specific diversification indices for oil and gas supplies. Le Coq and Paltseva (2009) used energy import diversification, combined with measures of political risk, risks in energy transit and economic costs of supply disruption to define indices evaluating the risks of disrupting oil, gas and coal supplies in Europe. These quantitative measures of energy diversity generally focus on the use of Shannon–Wiener (Grubb et al., 2006; Stirling, 1994; Hickey et al., 2010; Jansne and Seebregts, 2010) and Herfindahl–Hirschman indices (Grubb et al., 2006; Cohen et al., 2011; Jun et al., 2009; Ferreira et al., 2011).

3.2.1. Shannon–Wiener Index

The Shannon–Wiener Index was originally used in the disciplines of ecology and genetics in order to describe diversity in species populations and specific genomes. Stirling (1994) introduced it first to energy supply diversity. According to Grubb et al. (2006), when the Shannon–Wiener Index is below 1 it indicates a significant lack of diversity, whilst an index higher than 2 indicates a diverse fuel mix which means that there is no overreliance on certain options. However, Hickey et al. (2010) acknowledge that one difficulty of using the Shannon–Wiener Index in energy diversity appraisal is that there is no “explicit range of values that would indicate excessive or insufficient fuel diversity”. For n number of fuels (options) available in the electricity fuel mix the Shannon–Wiener Index (SWI) is:

$$\mathrm{SWI} = -\sum_{i=1}^{n} S_i \cdot \ln S_i \tag{2}$$

where:

S_i	the share of fuel (option) i in total available electricity.

For the calculation of the SWI each fuel available in the electricity fuel mix represents one option. Each option's share is expressed as a segment lower than one i.e. a share of 20% would be used in the calculations as 0.2. The SWI is minimised to zero when only one option is available and can be maximised with infinite options.

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3.2.2. Herfindahl–Hirschman Index

The Herfindahl-Hirschman Index (HHI) is used widely in competition economics to measure market concentration, which is the opposite of diversity. It is also known as the Simpson Index in ecology. Unlike SWI, HHI is a measure of concentration rather than a measure of diversity. Therefore the higher the HHI, the higher the concentration; thus the lower the diversity. The HHI index is calculated as the aggregate of the squared share of each option.

$$\mathrm{HHI} = \sum_{i=1}^{n} S_i^2 \qquad (3)$$

where:

S_i the proportion of option *i* expressed as a percentage.

Similar to the calculation of SWI, each fuel represents an option for HHI. The options' shares are expressed as percentages, i.e. a share of 20% would be used in the calculations as 20. The US Department of Justice (2013) suggests that HHI lower than 1500 indicates a competitive marketplace and higher than 2500 indicates a highly concentrated marketplace. Following this guidance Grubb et al. (2006) suggest that these values can be used to assess energy supply diversity.

3.3. Conflicting paradigms and the justification for combining indices

The purpose of this paper is to evaluate the role for electricity policy innovation in combining conflicting targets such as electricity supply security and climate change mitigation. Given the disparity of the two energy security paradigms (dependence and diversity), a comprehensive evaluation of energy supply security has to include both approaches. No single approach has been ruled out in the literature for providing the complete picture; on the contrary it has been shown (Chalvatzis, 2012) that different countries can achieve energy security goals with varying degrees of diversity and dependence based on their specific circumstances. The progress made in electricity portfolio innovation depends on a large number of parameters including regional politics, access to resources and socio-technical trajectories.

Our approach proceeds one step further than just including the two energy security paradigms by providing a deeper view into the evaluation of diversity. This is achieved by using the two different metrics of Shannon–Wiener and Herfindahl–Hirschman. Both indices have a certain weakness with regard to the level of their sensitivity to fuel mix changes (Grubb et al., 2006; Chalvatzis, 2012; Hickey et al., 2010) and their combined use offers a straight-forward way to discount diversity overestimations. Furthermore, their combined use with quantitative dependence offers a complete review of supply security.

4. Results and discussion

4.1. Electricity supply dependence

Following the process described in Section 3, we calculate the long-term import dependence of the Chinese electricity sector (Fig. 9). China has been a net importer of oil and gas since the 1990s. However, these fuels played only a small role in electricity generation between 1990 and 2012. In contrast, solid fuels were produced in China and their production consistently followed domestic demand; therefore it can be said that until 2008, China produced nearly all the fuels it required to generate power. The electricity sector's total dependence was consistently below 1% until 2008 and reached 7.8% in 2012. This sudden electricity dependence growth can be attributed by nearly 69% to coal imports exceeding 7% in 2012. In comparison approximately 6.6% is attributed to natural gas, 23% to nuclear and less than 1% to oil imports. In the near future, by 2020 the import dependence of the Chinese electricity sector is predicted to reach an unprecedented 32%.

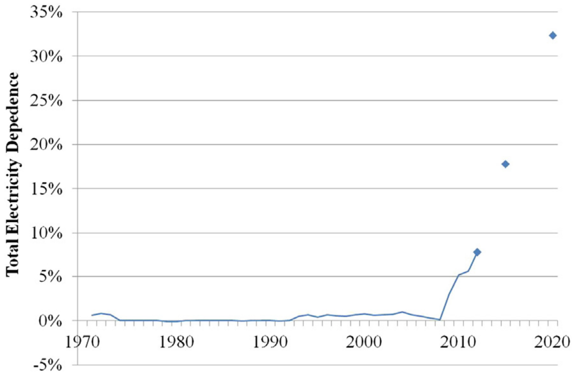

Fig. 9. Past and projected electricity supply dependence in China.

For several countries nuclear energy is considered to be a predominantly indigenous source. However, for China nuclear energy is heavily relying on uranium imports. China imported 16,126 tons of uranium in 2011, not much less than the 17,135 tons it had imported in 2010, according to the General Administration of Customs (China Daily, 2012a). The National Energy Administration predicts that imports will remain the same or be increased during 2012 and the World Nuclear Association predicts that they will reach 20,000 tons by 2020 (China Daily, 2012b). Approximately 95% of uranium imports to China are coming from Kazakhstan, Uzbekistan, Namibia and Australia whilst China produced about 1000 tons in 2012. However, it is reported that China consumes less than 7500 tons of natural uranium annually leading to conclusions that large amounts of imported uranium are used for stockpiling (Bloomberg, 2010). In addition to securing increased uranium imports, China needs to accelerate the development of uranium processing plants that will allow it to produce nuclear fuel rods (Reuters, 2013).

As it has been demonstrated, all thermal power generation increases the import dependence of the Chinese electricity sector since it relies to some extent on imported fuels. Only renewable energy sources can potentially reduce electricity import dependence. By 2020 the official planning of the Chinese Government predicts a fuel mix that will have an increased role for wind energy, solar PV and bio-fuels by 1.61%, 0.28% and 0.39% (since 2012) respectively (Fig. 7). However, this increased role for renewable energy sources will be shadowed by a reduction of 3.68% in hydropower which will result in 1.4 percentage units of decrease for renewable energy sources. Clearly this is not adequate to overcome the impact of growth in nuclear and coal energy imports on overall electricity dependence.

Specifically, as it has been discussed in Section 2, China is bound by its own policies to increase coal imports rapidly since it will restrict indigenous coal production; therefore even though reliance on coal is reduced by 3.2% as a percentage of the total generation fuel portfolio between 2012–2020, coal import dependence will increase from 7.16% in 2012 to 37% during the same period as the total consumed amount increases. At the same time the contribution of nuclear energy will increase significantly from 1.95% to 6.6%.

4.2. Electricity supply diversity

Import dependence is only one aspect of energy supply security. For a country like China that has enormous energy needs, diversity of energy resources is at least equally important. Due to the lack of appropriate data we are not examining import origin diversity, i.e. the diversity of countries, regions and sources that China imports its energy resources from. In fact it is often commented that China has adopted a long-term strategic approach on this issue including foreign acquisitions and stockpiling of energy resources (Bloomberg, 2013; China Daily, 2011; Xinhua, 2012). Diversity is examined here in the context of the different resources used for electricity generation. Our approach is

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based on the actual contribution of each resource to the available electricity rather than on the installed capacity of different technologies. As mentioned in Section 3 we have used two complimentary indices, HHI (Fig. 10) and SWI (Fig. 11).

Both indices are highly sensitive to the total number of options used in the fuel mix; therefore they tend to show a disproportionately large diversity increase even when an option with negligible contribution is introduced to the fuel mix (Chalvatzis, 2012). To enhance the robustness of our approach against this over-sensitivity, we estimate the respective indices 3 times; one that includes all options (even those with negligible contribution); one that includes all options with a contribution higher than 1% and one that only includes options with a contribution higher than 3%. It is clear that SWI is more sensitive than HHI to options with negligible contribution as it occurs from the significant difference between the 3 curves (Fig. 11). It is noteworthy that the number of fuel mix options that are taken into account in these calculations varies throughout the examined period (1972–2020) between 3 and 8 when accounting for all options, 3 and 5 when only accounting for options with a contribution higher than 1% and 2 and 3 when only accounting for options with a contribution higher than 3%. The number of options follows an increasing trend when all options are considered (from 3 to 8) and a similar increasing trend when only options with a larger than 1% contribution are considered (from 3 to 5). Conversely, the number of options follows a decreasing trend (from 3 to 2) when only options with a larger than 3% contribution are considered.

Despite the aforementioned sensitivity differences both indices show similar trends. It is reminded that HHI is a measure of concentration which is opposite to diversity and for this reason the two indices appear to mirror each other. The diversity of the Chinese electricity sector was increased between 1970 and 1980 as a result of the large role of oil and natural gas in the fuel mix (Figs. 2 and 3). Following the 1980s diversity followed a downwards trend for 3 decades reflecting the dominance of solid fuels in the electricity sector's fuel mix. As the contribution of non-coal energy resources in the fuel mix is predicted to increase the diversity is expected to improve significantly. Specifically, resources like nuclear, bio-fuels, wind and solar PV are projected to increase their share between 2012 and 2020 and make a positive contribution to diversity. However, it is important to notice that despite the projections for diversity improvement, diversity will not reach its 1970's level until after 2020 even if all fuel mix options are taken into consideration in its estimation.

4.3. Electricity sector decarbonisation

Electricity sector decarbonisation is often perceived as a threat to energy supply security. That is based on a more traditional paradigm of energy security that puts emphasis on import independence and has been prominent in most countries until recently (Valentine, 2011). As it has been shown, China relied entirely on indigenous energy resources for electricity generation until very recently. It has done so at the expense of supply diversity and at the expense of the environment. Weak climate change policies and pathway dependence in the energy technologies used are the main reasons why China remains in a carbon lock-in trajectory (Bertram et al., 2013). It does so even though coal has to be imported and therefore does not support the energy security “dogma” of using indigenous resources. International trade and China's role as the world's main producing country explain partly the constantly increasing emissions (Minx et al., 2011).

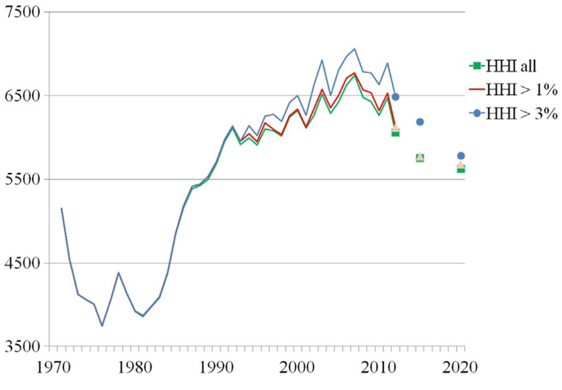

Fig. 10. Past and projected HHI.

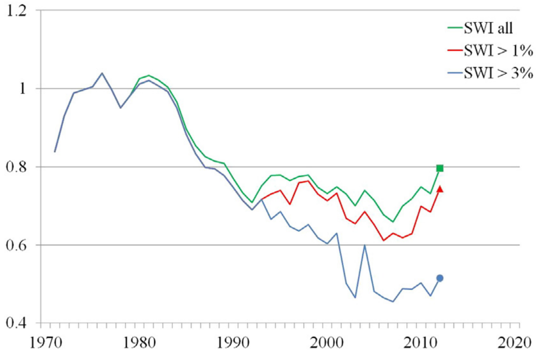

Fig. 11. Past and projected SWI.

In theory, decarbonisation of the Chinese electricity sector could be assisted by a greater contribution of natural gas that would substitute coal. Since the emission ratio between natural gas and coal is approximately 2 (subject to technologies used and fuel quality) it is fair to suggest that the potential of this substitution would be highly beneficial (Zha and Ding, 2014; Aguilera and Aguilera, 2012). However, demand for natural gas exceeds supply and therefore imports are required. At present China imports natural gas with pipelines from Myanmar (Financial Times, 2013), Turkmenistan, Uzbekistan and Kazakhstan (Platts, 2013). There is also a proposed pipeline from the Russian Siberia and there are regular LNG shipments from Qatar, Australia and Malaysia (Wall Street Journal, 2013). According to the IEA, China has huge unexploited reserves of coalbed methane but less so of conventional natural gas (International Energy Agency (IEA), 2009b).

However, the ongoing conflict with Ukraine (BBC, 2014) and the subsequent political discourse to end the European reliance on Russian gas led Russia to sign a long-term gas supply agreement with China in 2014 (Bloomberg, 2014). For China that was an important energy deal, given the role that natural gas can play in decarbonisation both by substituting coal and by enabling gas turbines to balance the intermittent renewable energy supply. The US$400 bn deal will supply 38 bn m^3/annum Russian gas to China for 30 years. Despite the fact that this is just 20% of the gas that Russia exports to Europe, it will allow China valuable time to develop its own gas resources; support further integration of intermittent renewables; substitute coal; and even consider investment in large scale compressed air energy storage systems (Zafirakis and Chalvatzis, 2014).

Whilst progress in the Chinese nuclear sector is underway, there are fuel supply limitations that need to be considered. However, the role of nuclear energy in improving energy supply security and contributing to a forward looking decarbonisation strategy is heavily contested. In addition to fuel supply uncertainty, the wisdom of decarbonising by investing in carbon-intensive infrastructure building is questioned (Sovacool and Cooper, 2008). In spite of this view, emerging economies (more so than other, “established” nuclear countries), appear to internalise in their climate change policies the aggressive development of nuclear energy (Sovacool and Valentine, 2010).

4.4. Pathway dependence and the risks for energy supply security

Pathway dependence and status quo bias are common in the energy sector and typical of centrally planned economies. China's main driver

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however, is not some higher level of political authority even though the global climate change regime often attempts to assume this role. Rapid economic development and endless thirst for energy resources have led China's fuel mix changes. There is little doubt that the established, vertically integrated (from mining to power generation), coal sector of China acts as a special interest group against any fuel mix changes ordered by the Government.

We find that the pursuit of secure energy supply in China appears to be leading its electricity sector away from the dominance of coal, towards a diversified fuel mix, which includes renewable energy sources, natural gas and nuclear energy. At this stage this is only a gradual, incremental change that will not deliver a radically different fuel mix in less than a decade. It does, however, produce noticeable results in diversifying the electricity sector. Unfortunately, this comes at a cost for the sector's import dependence but, as we have shown, this is partly because of China's self-imposed coal production limits.

Overall, the Government appears to have the strength to control the development of the fuel mix against the incumbent interests who would dictate a large-scale and long-term coal lock-in. Certainly, given that mining and electricity generation in China are mainly state controlled it is difficult to define a Government vs Coal interest groups dichotomy. In many ways the Chinese Government supports the coal sector with direct and indirect subsidies and the coal sector is used by the Chinese Government to implement its growth policies. However, certain decisions of the Chinese Government reflect a clear plan to control the coal sector and gradually reduce its strength.

Perhaps the most important indicators of this Governmental attitude are the cap in indigenous coal production (Fig. 8) and the restructuring of the coal sector. The latter includes shutting down approximately 2000 mainly small coal mines between 2014 and 2016. The move is designed to allow the Government to focus on improving production efficiency and safety record in the remaining 10,000 coal mines (Mining.com, 2014). In an additional step the four coal-fired power stations that have been supplying power to Beijing will be shut down by 2016 and will be replaced by natural gas power stations (Bloomberg Business, 2015).

In resisting to the dominant coal interests the Chinese Government is influenced by two more, often overlooked, issues. Firstly, is the water-energy nexus; the interrelation of water and energy as crucial components of each other's production. Chinese coal production is water intensive and this imposes productivity restrictions in a number of regions (Feng et al., 2014). Conflict around water management is not limited to China's coal production, but is a regular issue in exploiting high altitude water resources in the Western Provinces of the country (Sovacool et al., 2011). On the other side the regional disparities in energy efficiency and availability of natural and human resources produce a complex environment for energy policy discourse development. In other words, it is challenging to impose country wide regulations that are sensible and effective for all provinces. As a result, environmental policies often result in regional leakages of emissions and economic activity which exacerbate the aforementioned imbalances (Hubacek and Feng, 2014).

5. Conclusion

China's rapid growth rate presents a challenge as well as an opportunity for the country's energy future. The challenge is to secure increasing energy supplies whilst maintaining a decarbonisation trajectory. In contrast, the opportunity lies in transforming the historical coal lock-in into a diversified and secure energy supply system that will fuel the Chinese economy for the years to come.

We argue that China takes gradual steps to stir away from the monolithic coal-dominated fuel mix and increases the diversity of the electricity sector. In line with the long time leads required to update and modernise infrastructure, this process is slow but substantial. Fuel mix innovation is an effective way of increasing supply security, especially when indigenous coal production cannot cope with demand. It is recommended that the Government continues to work towards two main objectives. First, increase the share of renewable energy sources in the fuel mix and as a result maintain high energy independence. Secondly, improve diversity in the fuel mix; if imports are necessary, prioritise non-coal fuels, such as nuclear fuels and natural gas. These two objectives will improve further electricity supply security whilst allowing China to decarbonise its economy.

In optimising China's technological substitution, policy makers must design a path that will be influenced by the international energy prices and the role of technological damping caused by China or other countries. In this process climate policy, its effect on energy prices and their subsequent consequences onto the well-being of the global economy will also need to be considered (Mercure and Salas, 2013). Our results strengthen those of Wu et al. (2012) who suggest that controlling emissions and improving energy supply security are not conflicting targets for China. As the world anticipates the developments of COP 21 in Paris 2015 the strength of climate change policies is variable and could result in industry leakage for first movers (Otto et al., 2015). Equally, laggards, especially those with carbon intensive economies may suffer from stranded capacity if the most ambitious policies will be adopted (Johnson et al., 2015).

The success of China's decarbonisation trajectory is keenly observed by the international community. The capacity of the Chinese Government to commit to international emission targets is linked to its capacity to achieve these targets without compromising its energy supply security and development prospects. Further research on this issue should focus on the regions of China, their specific energy supply requirements and their capacity to contribute to the Chinese energy demand. The national dependence and diversity assessment provided in this manuscript have to be complemented with regional assessments in order to detail the most effective and secure decarbonisation policies.

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