


# Discounting Rates and Investment Appraisals for Emerging Low-Carbon Technologies: **Carbon Capture, Utilisation and Storage & Offshore Wind**

## Part II

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# Executive Summary

As China expects its economic growth to continue growing rapidly for the foreseeable future, its electricity demand is predicted to simultaneously witness an abrupt increase (by 150% in 2030 relative 2010 levels), with coal-fired power generation remaining an integral part of the energy mix in the coming decades. The Chinese Government forecasts its national greenhouse gas emissions to peak by 2030 and has internationally committed to reducing its emissions by significant proportions. In this respect, it has considered the promotion of Carbon Capture and Storage (CCS) as s serious climate mitigation strategy, one that would also allow its economy to sustainably prosper. The further utilisation of captured carbon for alternative industrial purposes (CCUS) also promises to considerably reduce the high investment costs incurred at this early stage of technology development. In a similar vein, China's high-potential offshore wind power was also identified as a prime candidate to complement the electricity demand of the most energy-consuming coastal cities.

Part I of this report delineates the financial metrics utilised in appraising the financial viability of low-carbon technology projects. Most significantly, we investigate the implications of adopting social discount rates instead of commercial discount rates to evaluate low-carbon technologies, the profitability of investments in such technologies, the risks perceived in the process and alternative methodologies of determining social discount rates. The attention devoted to the controversial choice of an SDR is largely justified by the practical realities of decision-making in public investments. Although not explicitly portrayed as such in the media, the debate about the scale of government financial support for carbon-reducing investments is in large a reflection of the debate regarding the optimal value of the SDR. Guided by the Ramsey Formula, the choice of the SDR reflects society's weighing of utility of consumption today as opposed to that of future utility, i.e. of future generations' welfare, and is therefore a debate fraught with ethical predicaments. While the Stern Review adopts very low values for an SDR (i.e. 1.4%), critics acknowledge that future generations will be richer and thus better equipped to mitigate, and adapt to, the effects of climate change, subsequently suggesting the endorsement of higher SDRs in cost-benefit analyses. Alternative

SDR computational methods are suggested, such as applying declining discount rates for projects running further away into the future. Social discount rates are much lower than the commercial ones computed using conventional finance packages, and so the stock market undervalues long-term emissions-reducing projects in favour of short-term higher-earning investments. The adoption of SDRs in cost-benefit analyses of green projects would eventually decrease the support received from the government, and would also require some de-risking strategies for investments in low-carbon technologies.

The study's Part II undertakes a holistic approach to present the financial, political, and social cases for CCUS and offshore wind (OSW) within China. This entails a detailed investigation of the current status quo for both markets, policy reforms and their effectiveness, and economic and social developmental barriers. This is supplemented by two theoretical case studies to appraise the financial viability of typical CCUS and OSW projects in China (in Guangdong and Jiangsu, respectively). Sensitivity analyses and Monte Carlo simulations are further applied using varying discount rates to better inform investors of the potential riskiness and likelihood of investment profitability under different mid-to-longer term scenarios. Our findings suggest that CCUS could become economically feasible if a suite of supporting schemes were exploited, namely the financial benefits generated by sale of carbon credits under the CDM, the sale of liquid carbon to $CO_2$-EOR gas and oil companies, and through raising public money in the form of governmental grants or CCUS-dedicated funds. It is imperative that, in the absence of these mechanisms, an on-grid tariff of US$87.5/MWh is required to generate desirable returns on investment. This figure could be lowered to US$67 if a 30% grant towards capital was attainable, with a Guangdong ETS carbon price held at US$8/t$CO_2$.

Assuming carbon prices in the range of US$20-25/t$CO_2$, or liquid $CO_2$ sold at US$16-20/t$CO_2$ to EOR-$CO_2$ utilising industries, with preferential tax status and/or tax exemption policies, the required on-grid tariff for CCUS investments could reach levels as low as US$55-58/MWh, rendering CCUS projects more economically attractive than alternative power sources (e.g. nuclear, onshore wind, and gas-fired plants). By virtue of its lower total investment and low labour cost advantages as compared to international projects, China has the opportunity to enforce strong carbon pricing policies through its anticipated national ETS in 2017. However, a clear and long-term climate mitigation policy should be executed as early as possible to avoid carbon lock-in investments. It is also crucial to note that, with a persisting lack of CCUS knowledge amongst the Chinese lay people, governmental authorities in conjunction with project developers could smoothen out the integration of CCUS into industrial practices by acquiring a social license prior to, and during, project development phases. This could be attained via the promotion of communication exchange programmes, engagements in public education classes, and the enhancement of information exchange and project disclosure strategies.

For offshore wind power, despite its immense power generation potential and the priority status it receives from the Chinese Government, technologies remain highly costly at this nascent stage of development. Those OSW projects already consented had received bidding feed-in-tariff (FiT) levels of 0.62-0.73CNY/kWh, proving too low to produce sensible returns, attract investors, and drive a long-term deployment plan for offshore wind in China. Policy support for offshore wind is normally expected to undergo trial-and-error phases, as was the case for onshore wind. Nevertheless, the present work deems a minimum FiT level of 0.85-1CNY/kWh indispensable to capture the globally renowned potential that the Chinese offshore wind sector boasts. Supply chain companies and relevant stakeholders in offshore projects seem ready to deliver but are awaiting the appropriate market signal before they lock-in investments within the industry. The government can potentially reduce perceived risks by implementing appropriate taxations cuts, announcing preferential loan policies, improving the quality and technical level of wind-power enterprises, assisting small and medium enterprises (SMEs) to penetrate the market, alleviating approval barriers for wind projects under the CDM, and meticulously revising the feed-in-tariff levels necessary to ensure an orderly and accelerated development of the Chinese offshore wind sector.

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*Unless stated otherwise, all figures and tables included within this paper are the product of the author's own work.



## Tables

# Introduction

At the 2009 Copenhagen Climate Summit, China pledged to reduce its $CO_2$ emissions by 40-45% by 2020 (relative to 2005 levels), and it has since been debated whether this commitment is ambitious or merely representative of business as usual[1]. A joint study by Tsinghua University and Massachusetts Institute of Technology (MIT) suggests that, in order for China to honor its Copenhagen targets, it must maintain a continuous effort to reduce emissions at a 3% per year from 2016 through 2050, in which case China's carbon emissions would not peak until 2040 (Zhang et al., 2014). This comes at a time when the country has been experiencing swift economic growth, with its GDP increasing at a 10% per annum rate over the past thirty years (World Bank, 2015). Accompanying this growth was an enormous step-up in coal demand – 9% on average between 2000 and 2010, in contrast to a 1% global growth if the Chinese demand contribution were excluded (US Energy Information Agency, 2013). The exploitation of coal as its main energy resource has also been widely recognised as the salient driver of China's economic growth (Best & Levina, 2012).

While its tremendous coal reserves made it the largest global coal producer, in 2010, Chinese coal consumption accounted for more than half of the global cumulative use (IEA, 2011b), doubling the consumption of the world's second largest coal consumer, the United States. Locally, more than two thirds of the country's energy supply relies on coal usage, equivalent to a staggering third of all consumption worldwide. The electricity power sector retains the tiger's share with over half of overall consumption, while 80% of all Chinese electricity generation comes from coal. In light of China's concerns for energy security and sustained economic prosperity, it is expected the nation will continue to utilise coal as its primary energy source for decades to come[2]. On China's sustainable development, the International Energy Agency (IEA) acknowledges that considering "the pace of China's economic growth and the resulting increase in emissions over the next ten years, together with China's commitment to addressing the problem of global climate change, it is likely to

[1] See Zhang (2011a,b) for a discussion on the credibility and stringency issues regarding China's carbon reduction commitments and their associated implications.

[2] Coal-fired power plants construction is skyrocketing in China at a rate equivalent to 2x500MW plants deployed per week, each producing around 3 million $CO_2$ tonnes ($tCO_2$) per annum (MIT, 2007).

bring CCS[3] technologies into focus with crucial actions for deployment necessary between 2020 and 2030" (Best & Levina, 2012).

Along with carbon transportation and storage, China's development strategy would additionally involve the efficient utilisation of separated carbon for alternative uses, a process dubbed as carbon capture, utilisation and storage (CCUS). The Ministry of Science and Technology (MOST) defines CCUS in terms of isolating carbon dioxide from industrial and other emission sources, transporting the captured $CO_2$ for storage or utilisation, in turn achieving long-term $CO_2$ isolation from the atmosphere. Carbon utilisation in soft drink production or for enhancing the efficiency of oil recovery in oil and gas industries (Section 1.1.3) is gaining international popularity as a promising method to promote the commercial feasibility of CCUS (The Climate Group, 2011). Currently, there exist 12 large-scale integrated projects (LSIPs) at different phases[4] of CCUS project development cycles in China (Figure 1). It is worthy of note, however, that although these developments reflect serious efforts and ever-growing interests in CCUS as a long-term emission reduction solution, a CCUS-dedicated national framework (or amendments to existing policies) to accommodate technology demonstration and development is yet to be established in China (Li et al., 2012a; Liang et al., 2014; Viebahn et al., 2015).

Also, because the Chinese electricity demand is projected to abruptly increase in the near future (by 150% by 2030 relative to 2010 levels) (Liu et al., 2013), the Chinese Government has been for some time pursuing the diversification of its energy mix with more effective, cleaner and strategically suitable sources of energy. More significantly, demand for electricity is primarily clustered around populous coastal regions[5] and also remains heavily coal-based, with coal fueling 61% of power generation in Guangxi, for instance, rising to

[3] Carbon capture and storage (CCS) is hereby defined as a suite of techniques designed to capture $CO_2$ contained in flue gases from large point sources (e.g. fossil fuel power plants, cemeteries, steel production, etc.) before exiting to the atmosphere. Carbon is then transported via pipelines and eventually injected into suitable underground geological storage facilities (e.g. deep saline aquifers or depleted gas and oil fields) (Berstein et al., 2006).

[4] Six projects are in the identification stage, three in the evaluation stage, and four in the definition phase. The Shenhua Project in Inner Mongolia has been in pilot demonstration since 2011. It is noteworthy that none of the Chinese CCUS projects has yet entered an investment phase (Li et al., 2015a).

[5] Nine coastal provinces and two municipalities were responsible for 53% of overall Chinese electricity demand in 2011.

figures as high as 99% in Shandong in 2011 (Ma et al., 2012). With the drastic environmental impacts of coal usage put aside, the increase in energy consumptions further calls for increased need for imported coal (e.g. from Australia) or its transfer from inland provinces in the north and west. Additionally, although China's rich onshore wind resource has been identified as a fundamental source to replace some of that demand, the strongest wind potential remains predominantly concentrated in its northern and western regions, and so harvesting it would require considerable (and costly) expansions to the current national transmission grid system (Lu et al., 2013).

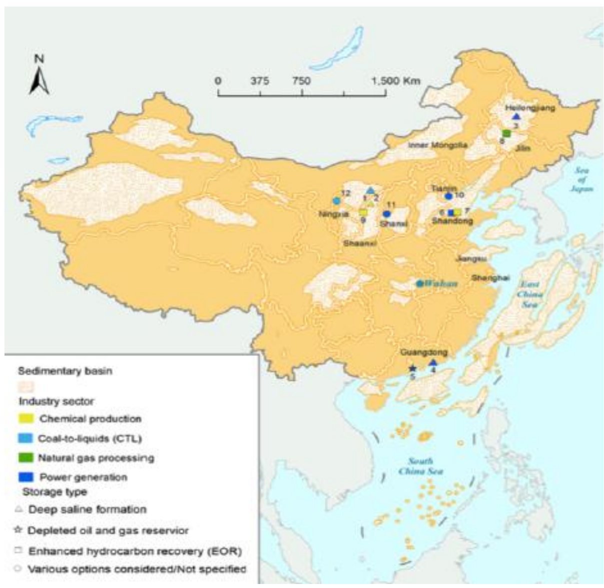


**Figure 1.** Overview of LSIPs CCUS projects in China, by storage type and industry sector. Adopted from Li et al. (2015).

As an alternative solution for convenient and long-term energy supply of coastal regions, offshore wind has emerged as a resource that could simultaneously achieve significant emissions reductions. In 2012, the Wind Energy Outlook estimated China's offshore wind resource as equivalent to 200GW in waters between 5-25m, and up to 500GW at water depths of 5-50m (Li et al., 2012b). In another assessment, the Chinese Wind Energy Association (CWEA), jointly with Sun Yat-Sen University, acknowledged that the technical potential for wind energy within 100km off China's coastline is about 11.6PWh, more than double the nation's electricity demand combined (Lu et al., 2014). In their forecasts of offshore wind contribution to the Chinese energy supply, Hong and Møller (2011) suggested that the rich resource could economically contribute to 56%, 46%, and 42% of the coastal region's overall electricity demands by 2010, 2020, and 2030, respectively.

In this realisation, the Chinese Government has committed itself to become a global leader in offshore wind development, however, because only a few benchmark projects have been deployed to date, a unanimous opinion on the extent of needed government financial support is yet to be reached. While the feed-in-tariff mechanism has been the main financial driver of offshore wind projects, already-consented projects have received tariffs in the range of 0.62 and 0.73/kWh, deemed not substantial enough to generate desirable economic returns (Carbon Trust, 2014a).

One of the factors driving (and in turn reflecting) the uncertain risk of profitability of investments in low-carbon projects is the choice of the discount rate in their pre-developmental evaluation phase. Higher discount rates are generally applied to technologies with higher risk perception. A detailed investigation of the choice of specific discount rates and the implications of adopting social discount rates instead of commercial discount rates to evaluate low-carbon technology investments were discussed previously in Part I of this report. In Part II, Chapters 1 and 2 respectively provide overviews of the status quo of CCUS and offshore wind industries in China. These cover the corresponding political climates, local and international market potentials, main market drivers, and factors influencing project technical feasibility and financial profitability. These are further integrated into two hypothetical case studies to appraise CCUS and offshore wind projects. Chapter 3 discusses implications and concludes.

# Carbon, Capture, Utilisation and Storage

With China's heavy dependence on coal for meeting the bulk of its energy demands over the next few decades, the widespread deployment and marketisation of carbon capture, utilisation and storage technologies remains a crucial route to reduce both China's and global overall emissions. Having not reached commercialisation status anywhere in the world thus far, the current growth trends in CCUS technologies suggest they are not likely to find large-scale applications before 2030. In the Deep Decarburization Pathways Project and in MIT's joint study with Tsinghua University, market experts do not project any CCUS facilities on power plants before 2030, however, with the assumption that CCUS could become readily available beyond this timeline, 80% of gas-fired power plants and 90% of coal-fired ones are expected to be CCS-retrofitted by 2050 (Zhang et al., 2014).

The Global Carbon Capture and Storage Institute (GCCSI) (2011) identifies the most worldwide common challenges for CCUS in terms of the uncertainty of $CO_2$ capture technologies, high energy penalty, perceived risk for $CO_2$ storage, and most notably the lack of legal and regulatory frameworks. According to Viebahn et al. (2015), the most important requirement to deriving a successful long-term CCUS strategy in China is developing "a reliable *storage capacity assessment* for the country". Thus far, existing storage capacity evaluations take for granted the presence of sufficient long-term geological storage capacities while other studies show considerably contradicting results, confirming the high uncertainty and associated lack of knowledge, as also admitted by Zhou et al. (2010) and Liu & Gallagher (2010). The following sections focus on CCUS policy and research development in China, underlining key technological and financial challenges and the steps undertaken to overcome them.

## 1.1. Market Overview

### 1.1.1. Policy Making

In its 2006 "State Long-term Science and Technology Development Plan (2006-2020)", the State Council emphasised the adoption of "efficient, clean, and near-zero carbon emissions fossil energy utilisation technology" in advancing Chinese energy technologies. Subsequently, the National Development and Reform Commission (NDRC) commissioned China's National Climate Change Programme in 2007, recommending the "development of carbon capture and storage technology" (NDRC, 2007). Over the same year, MOST, along with the NDRC and other ministries, released China's Scientific and Technological Actions on Climate Change – a clean energy development plan highlighting the role of CCUS in meeting its objectives (MOST, 2007). The 2010 white paper on China's Policies and Actions for Addressing Climate Change, issued by the Information Office of the State Council, acknowledged CCUS as "one of the greenhouse gas emissions reduction technologies that China will focus on investigating" (Information Office of the State Council, 2010). It was only a matter of time before CCUS was listed as one of the central technologies to be developed during the Twelfth Five-Year Plan period (2011-2015) in both its "combating climate change" and "energy saving environmental protection industry" sections (MOST, 2011).

Despite the commitments, the Chinese government is yet to create a concrete nationwide legal framework or introduce amendments to existing laws to accommodate the regulation of large-scale CCUS deployment. Nonetheless, a multitude of Chinese authoritative agencies have engaged in various scope studies, developed technology roadmaps, and recommended guiding policies to overcome persisting gaps and barriers. Table 2 provides an overview of the main regulatory standards and notices since 2006, though it is important to note that their effectiveness remains limited as they are not legally enforceable (Chen et al., 2013) and are not particularly driving a long-term development plan (Mo et al., 2013).

In a 2012 workshop held in Beijing between the Carbon Sequestration Leadership Forum (CSLF), Administrative Centre for China's Agenda (ACCA 21), and MOST, the effective designation of a CCUS-specific legal and regulatory framework was addressed and the need for international cooperation in developing one was deemed indispensable. As a result, in 2013, the NDRC issued its notice on promoting CCUS demonstration, underpinning the need to assess health, safety and environment impacts and the development of an evaluation standard for the technology's environmental regulation (Table 1).

**Table 1.** Regulatory Guidelines and Policies for CCUS development in China.

| Year | Standards, Plans, Recommended Practices and Guidelines |
|---|---|
| **2006** | National Medium- and Long-Term Science and Technology Development Plan (2006-2020). |
| **2007** | China's National Program on Climate Change (2007-2010). |
| **2007** | National Scientific and Technological Actions on Climate Change (2007-2020). |
| **2011** | 12th Five-Year Plan for Scientific and Technological Development |
| **2011** | National 12th Five-Year Plan Working Program on GHG Emission Control (No. 4 Document). |
| **2011** | China's Policies and Actions for Addressing Climate Change. |
| **2012** | 12th Five-Yeat Plan GHG Control Working Program Task Assignment (No. 68 Document). |
| **2013** | 12th Five-Year National Carbon Capture, Utilisation and Storage Science and Technology Development Special Plan. |
| **2013** | Notice of NDRC on Promoting Carbon Capture, Utilisation and Storage Pilot and Demonstration (NDRC Climate [2013] Document No. 849) |
| **2013** | Proposal on Accelerate the Development of Energy Efficiency and Environment Protection Industries. |

### 1.1.2. R&D and International Efforts

Jointly with research institutes and Chinese universities, CCUS research, development and demonstration (RD&D) has been driven by governmental authorities and large state-owned petroleum companies, with main funding channeled through MOST and the Natural Science Foundation of China (Li et al., 2013b). Specialised investigations on CCUS viability included demonstrations on its potential for emission reductions, $CO_2$ capture, geological storage, various capture technology options, and utilisation in enhanced oil recovery ($CO_2$-EOR), to name a few. Tabulated below is a list of the principal CCUS R&D projects undertaken by various research institutes, enterprises and universities, mostly funded by the Chinese Government[6] (Table 3).

In efforts to narrow the technological gap between Chinese CCUS progress level and more advanced international levels, China has engaged in a wide range of technology exchange

[6] Funding sources include the "National Basic Research 973 Program", the "National High Technology Development 863 Program", and the "National Major Science and Technology Program".

projects and communication initiatives with institutions in the United States[7], United Kingdom, Japan[8], Italy, and Australia. These include, but are not limited to, China-UK Cooperation on Near-Zero Emissions Coal (NZEC), Support to Regulatory Activities for Carbon Capture and Storage (STRACO2), China-Australia Geographic Storage (CAGS), Cooperation Action within CCS China-EU (COACH), CSLF, and Sino-Italy Cooperation on Clean Coal Technologies (SICCS). However, despite the common vision of CCUS roadmaps developed by governments and agencies in these countries, each nation retains its unique features and adopts distinct technology approaches and focus to CCUS deployment[9]. Appendix I provides an overview of the international CCUS policy actions to date, as presented by the IEA (2014) and the Asian Development Bank (ADB) (2015). Also provided is a summary of international cooperation projects in China (Appendix II).

### 1.1.3. Prospects of the "U" for Chinese CCUS

Utilisation of $CO_2$ refers to the act of industrially or agriculturally utilising $CO_2$ for its physical, chemical, or biological features for the purpose of producing products of commercial values, while also reducing emissions compared to business-as-usual (BAU) processes (Li et al., 2013b; Xie et al., 2013). Commercial returns brought by $CO_2$ utilisation can play an important role in offsetting the high costs of CCS and so facilitates the commercialisation of CCUS technologies (GCCSI, 2011). In China, carbon capture and utilisation (CCU) technologies are proven but are not yet commercial, however, studies indicate a potential of hundred million tons per year in emission reductions and an industrial production equivalent to 300 billion CNY/year within 20-30 years, if major CCU technologies are properly exploited (Xie et al., 2013). Table 2 summarises types of $CO_2$ utilisation technologies currently available in the market.

[7] US-Chinese collaboration includes the deployment of two (demonstration) oilfield-based projects by US-company Alston and China Datang Corporation.

[8] This includes Sino-Japanese CCS/EOR projects installed to capture $CO_2$ exhausted by 2x600MW coal-fired power plants in northeast China.

[9] It is imperative to note that most of these roadmaps are contracted to research organisations with the aim to provide a clear country-specific, and thus are not legally binding.

**Table 2.** Types of $CO_2$ utilisation technologies.

| Type | Application Field | Technology |
|---|---|---|
| **Geological Utilisation** | Energy Production | $CO_2$-EOR, $CO_2$-ECBM, $CO_2$-EGR, $CO_2$-ESGR, $CO_2$-EGS |
| | Mineral Resources | $CO_2$-EUL, $CO_2$-EWR |
| **Chemical Utilisation** | Materials | $CO_2$-CTP, $CO_2$-CTU, $CO_2$-CTPC, $CO_2$-CTPEC, $CO_2$-CTPES |
| | Energy | $CO_2$-CDR, $CO_2$-CTL |
| | Organic Chemicals | $CO_2$-CTM, $CO_2$-CTD, $CO_2$-CTF |
| | Inorganic Chemicals | $CO_2$-SCU, $CO_2$-ISCU, $CO_2$-PCU, $CO_2$-PCM |
| **Biological Utilisation** | Energy and Feed additives | $CO_2$-AB |
| | Fertiliser | $CO_2$-AF, $CO_2$-AS, $CO_2$-GF |
| **Source:** Li et al., (2013b); ACCA 21 (2014) | | |

However promising, exponents of CCUS hold that although the purpose of $CO_2$ utilisation is achieving overall emission reductions, utilising $CO_2$ (e.g. in carbonated drinks, fire suppression, etc.)[10] would only isolate it from the atmosphere for a short period of time, thereby not permanently reducing emissions. Gale (2013) also argues that whether geological utilisation technologies, say $CO_2$-EOR [11] , permanently enhance emissions reduction depends on where the boundary about the oil field is drawn. It is debated that when taking into consideration that EOR only leads to further usage of oil as a primary fossil fuel, the process would be merely be transferring emissions from one sector to the other (e.g. energy production to transportation in this case). However, even critics would widely agree that pursuing $CO_2$-EOR for sole economic purposes at the early stages of CCUS development offers the potential to significantly close the persisting financial gap in the sector[12].

Considering China's current economic structure and its high dependence on carbon-intensive energy sources with heavy chemical industries, $CO_2$-EOR can still assist in mitigating the effects of climate change, even if not on a permanent basis. Given the social

10 China Shenhua Energy Company and China Huaneng Group have each developed integrated CCUS projects that are considered some of the largest coal-fired CCUS projects globally (Duncan Coneybeare, 2013).

11 EOR is applied in projects as China SINOPEC's $CO_2$ Capture and EOR pilot project, operational on the Shengli oilfied, and also applicable in the Tianjin Dagang 330MW CCS Project.

12 The gap between CCUS-retrofitted plant investment and what coal-fired power plants would cost otherwise.

and technical barriers of $CO_2$ storage methodologies, such as health and safety issues and the securisation of public acceptance for CCUS (see below), $CO_2$ utilisation presents an ideal way of handling $CO_2$ after it has been captured in the meantime, until geological storage activities become mainstream practices.

**Table 3.** A list of major CCUS R&D projects in China.

| Timeline | Project | Host & Participating Agencies |
|---|---|---|
| 2003 - 2005 | Study on multi-component gas adsorption/desorption mode mechanism of $CO_2$-ECBM | China University of Mining & Technology, Beijing |
| 2006 - 2010 | Utilisation of greenhouse gases as resource in EOR and geological storage | China Petroleum Group Science and Technology Research Institute, Huazhong University of Science and Technology, Institute of Geology and Geophysics, CAS, China University of Petroleum, Beijing |
| 2007 - 2008 | Improved model of $CO_2$ injection and $CH_4$ recovery | China University of Mining & Technology |
| 2007 - 2009 | Effects of matrix property on coal swelling and $CO_2/CH_4$ permeability change in the process of $CO_2$-ECBM | Institute of Coal Chemistry, CAS |
| 2008 - 2010 | The Capture and Storage Technology of $CO_2$ | Tsinghua University, East China University of Technology and Institute of Geology and Geophysics, CAS, etc. |
| 2008 - 2010 | $CO_2$ Capture and Purification Technology with High-Gravity and Application | Sinopec Shengli Oilfield Branch, Beijing University of Chemical Technology, Beijing University of Technology and China University of Petroleum (East China), etc. |
| 2008 - 2010 | Experimental study on different swelling effects of coal matrix in the process of $CO_2$-ECBM | China University of Mining & Technology, Beijing |
| 2008 - 2010 | Safe Development of Natural Gas Reservoirs with $CO_2$ and $CO_2$ Utilization Technology | China Petroleum Group Science and Technology Research Institute, PetroChina and PetroChina Jilin Oilfield Branch, etc. |
| 2008 - 2010 | Development of Songliao Basin Volcanic Gas Reservoirs and $CO_2$ utilization demonstration Project | PetroChina Jilin Oilfield Branch and China Petroleum Group Science and Technology Research Institute, etc. |
| 2009 - 2011 | Key technology research of $CO_2$-EOR and sequestration | China Petroleum Group Science and Technology Research Institute, China Petroleum and Chemical Group Institute of Exploration and Development, etc. |
| 2009 - 2011 | $CO_2$-algae-Biodiesel Critical Technology Research | ENN Group, Jinan University, etc. |
| 2009 - 2011 | Influencing factors and mechanism of $CO_2$ diffusion in porous media | China University of Petroleum, Beijing |

| Timeline | Project | Host & Participating Agencies |
|---|---|---|
| 2009 - 2011 | Applied basic research of $CO_2$-ECBM in deep unmineable low permeability coalbeds under solid-flow-thermal coupling conditions | Liaoning Technical University |
| 2009 - 2011 | New $O_2/CO_2$ Cycle Combustion Equipment R&D and System Optimization | Huazhong University of Science and Technology, etc. |
| 2010 - 2014 | Nationwide $CO_2$ Geologic Storage Potential Assessment and Demonstration Project | China Geologic Survey Bureau, Institute of Rock and Soil Mechanics, CAS and Peking University, etc. |
| 2011 - 2013 | Study on the migration law and permeability enhance mechanism in the process of supercritical $CO_2$ inject into low permeability coal seams | Liaoning Technical University |
| 2011 - 2013 | Study on the binary gas-solid coupling and dual porosity effect in the process of $CO_2$–ECBM in deep coalbeds | China University of Mining & Technology |
| 2011 - 2014 | Technology Development and Demonstration of 300,000 Tonnes $CO_2$ Capture and Geologic Storage of High Concentrations $CO_2$ from Coal-to-liquid Project | China Shenhua Group, Beijing Institute of Low-Carbon Clean Energy and Institute of Rock and Soil Mechanics, CAS, etc. |
| 2011 - 2014 | Critical Technology, Equipment Research and Development and Engineering Demonstration of 35MWth Oxy-Combustion Carbon Capture | Huazhong University of Science and Technology, Dongfang Electric Group and Sichuan Air Separation Equipment Group, etc. |
| 2011 - 2014 | Critical Technology Development and Demonstration of $CO_2$ Emission Reduction by Blast Furnace Iron making | Chinese Society of Metals and Iron and Steel Research Institute, etc. |
| 2011 - 2015 | Basic Research of $CO_2$ Emission Reduction, Storage and Utilization | China Petroleum Group Science and Technology Research Institute, PetroChina, etc. |
| 2011 - 2015 | $CO_2$-EOR and storage technology demonstration Project of Songliao Basin | PetroChina Jilin Oilfield Branch and China Petroleum Group Science and Technology Research Institute, etc. |
| 2011 - 2015 | Critical technology of $CO_2$-EOR and storage | Institute of S&T Research, PetroChina and PetroChina Jilin Oilfield Branch, etc. |

| Timeline | Project | Host & Participating Agencies |
|---|---|---|
| **2011 - 2015** | Technology on deep coal-bed methane development and its application | China United Coal-bed Methane Company, etc. |
| **2012 - 2014** | QSAR study on thermodynamic properties and transfer properties of $CO_2$-EOR system | Tianjin University |
| **2012 - 2014** | Study on the thermal-flow-solid interaction mechanism of $CO_2$-ECBM | China University of Mining & Technology |
| **2012 - 2014** | Study on the mechanisms of $N_2/CO_2$ mixed gases enhanced coalbed methane and the best gas component ratio | Institute of Rock and Soil Mechanics, CAS |
| **2012 - 2014** | Nationwide $CO_2$ Geologic Storage Potential Assessment and Demonstration Project | China Geologic Survey Bureau, Institute of Rock and Soil Mechanics, CAS and Peking University, etc. |
| **2012 - 2014** | Study on large-scale $CO_2$ utilization and storage technology in the novel EGS | Tsinghua University, the Administrative Center for China's Agenda 21, Institute of Rock and Soil Mechanics, CAS, Chinese |
| **2012 - 2015** | Study on the damage mechanism of $CO_2$-EOR process | China University of Geosciences, Beijing |
| **2012 - 2015** | Interaction between supercritical $CO_2$ and coal and its effect on $CO_2$ storage in the process of $CO_2$-ECBM | Shandong University of Science and Technology |
| **2012 - 2015** | Study on synthetic utilization and development of "Hot Dry Rock | Jilin University, Tsinghua University, Tianjin University, Guangzhou Institute of Energy Conversion, CAS, PetroChina, Institute of Rock and Soil Mechanics, CAS, etc. |
| **2012 - 2016** | Technology development and demonstration of $CO_2$ capture, EOR and storage from large-scale coal-fired power | Sinopec Shengli Oilfield Branch Company, Institute of Rock and Soil Mechanics, CAS, Peking University |
| **2012 - 2016** | Interfacial properties research of $CO_2$ capture by alcohol amine and supercritical $CO_2$-EOR process | North China Electric Power University, etc. |
| **2013 - 2015** | Study on the interaction between $CO_2/CH_4$ and rock mass in the process of ESG | Chongqing University |

**Sources:** ACCA (2012, 2014), Li et al. (2015a), and Xie et al. (2013).

## 1.2. CCUS Investment Case Study

### 1.2.1. Plant Assumptions

In appraising the cases for prospective large-scale deployment of new coal-fired power plants with carbon capture technologies – or the retrofitting of capture facilities to existing power plants, it is important to assess the influence of technical and economic factors and other project inputs on the profitability of their investments. Capital costs of both base and carbon capture plants, fuel (coal) prices, annul operational and maintenance costs, in addition to the base load factor and net supply efficiency, to name a few, are amongst the most crucial input parameters to consider for building a case for CCUS. In the present study, we aim to investigate the financial viability of a CCUS project in China (Guangdong province) using plant performance calculations and cost data as disclosed in the energy literature within the Chinese realm, and others compiled from available market information (see for instance, Wu et al., 2013; Liang et al., 2014, and Viebahn et al., 2015). Judging by the majority of the currently existing coal-fired power plants in China, this simulative case assumes a 1GW ultra-supercritical post-combustion power plant (USCPC), boasting 41% net supply efficiency (LVH) before CCUS retrofitting (Viebahn et al., 2015). As an average of efficiency penalties between 2020 and 2050, we assume an efficiency loss of 7 percentage points for CCUS-retrofitted plants (~34% LVH).

Factoring in Chinese country-specific conditions, the power plant's cost figures and its O&M are representative of mean values collected from various existing cost assessments (Zhao et al., 2008; NZEC, 2009; Zhu & Fan, 2011; IEA, 2011a; and Wu et al., 2013). An average of US$1350/kW is chosen for capital expenditures for the USCPC+CC plants, maintaining that the capture facility accounts for an additional cost of 25% of the original base plant (Liang et al., 2014). The plant is assumed to run at an 85% load factor as of the second operational year onwards (60% in the first), with non-fuel O&M amounting to 5% of CAPEX (IEA, 2011a). As per the European Commission's (2009) standards, variable O&M are taken as a flat US$6/kW rate, while the costs of $CO_2$ transport, storage and monitoring constitute some US$20/t$CO_2$ for offshore storage projects[13,14].

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[13] As opposed to US$15/t$CO_2$ for transport and onshore storage (6$ for transport and 9$ for storage).

**Table 4.** Technical and financial assumptions adopted in the CCS model case study in China.

| Parameter | Data | Unit/Note |
|---|---|---|
| **Project Timeline** | | |
| Construction Phase | 3 | Years |
| Operational Phase | 20 | Years, post-closure phase duration uncertain |
| **Technical Assumptions** | | |
| Plant Type | USCPC | Ultra Super Critical Post-Combustion Coal |
| Capacity before Retrofit | 1GW | |
| Net Capacity | 800MW | With 90% capture |
| Net Supply Efficiency (LVH) | 34.1% | With CCS; 41% without CCS |
| Load Factor | 85% | 60% during the first year |
| Emissions Factor | 758.7 | Gram $CO_2$/kWh; Base Plant |
| | 97.7 | Gram $CO_2$/kWh; Plant with CCS |
| $CO_2$ Captured | 852.2 | Gram $CO_2$/kWh |
| $CO_2$ Avoided | 661 | Gram $CO_2$/kWh |
| Fuel Feedrate | 2350 | Output/LVH |
| Lifetime Degrading Factor | 1% | |
| **Cost Evaluation** | | |
| ***CAPEX*** | | |
| Coal & CCS Capital | 1350 | $/kW |
| Capture-to-Base Plants ratio | 25% | |
| Decommissioning Cost | 5% | of TPC; equal to salvage value |
| ***OPEX*** | | |
| Fixed O&M | 5% | Annually of CAPEX |
| Variable O&M | $6/kW | |
| $CO_2$ Transport & Storage | $20/t$CO_2$ | |
| Insurance | 2% | Annually of CAPEX |
| **Financial Inputs** | | |
| Corporate Tax | 25% | |
| Discount rate | 12% | 10% for base plant |
| Depreciation | 20 | Years (linear) |
| On-grid Tariff | Varies | For case study simulation purposes |
| Debt-to-Equity Ratio | 50:50 | Variable for different simulations |
| Coal Price | 3.5 – 5 | $/GJ; varies for sensitivity analysis |
| $CO_2$ Emissions Price | 0 | **$**/t$CO_2$; varies for sensitivity analysis |

**Sources:** MIT (2009); Reiner & Liang (2009); Wu et al. (2013); Bloomberg (2014); Liang et al. (2014).

[14] The CCUS literature and real-life case studies suggest lower values for $CO_2$ transport in the Chinese context than the international figures adopted here (IFP, 2010), due to lower costs of labour and, in particular, equipment in China. However, it is worthy of note that although this study implicitly aims at incentivising investments in large-scale CCUS applications, a conservative approach is endorsed in evaluating costs and simulating scenario analyses, hence the choice of the internationally-applicable US$20/t$CO_2$ figure.

As far as fuel prices are concerned, the IEA (2009) projected coal prices to follow an analogous growth trend to international oil prices [15], translating to a minimum of US$3.44/kWh (for 2010) and a maximum of US$4.63/kWh in 2050, for coal exhausted in non-retrofitted plants. A coal price in the range of US$4.55/kWh to US$5.36/kWh is estimated for CCUS-incorporating ones. As such, a price range of US$3.5 to US$5/kWh is adopted for coal prices as one variable parameter in this study's sensitivity analysis, to assess the impacts of their fluctuations on the required on-grid tariff for USCPC+CC. A corporate tax of 25% is applicable to the model's earnings, and a 50% debt financing leverage ratio at 6% interest rate is endorsed in the baseline scenario. The latter's implications on the selected real required rate of return, i.e. the discount rate, are critical as private stakeholders – already requiring higher return than public lenders – would require an even higher return on their investments with increasing financial leverage, i.e. with higher debt-to-equity ratio. Guided by project investment models of already-existing coal-fired plants, and using the return on investment as discount rate for CCUS retrofitted projects (Wang & Du, 2016), a 10% discount rate is maintained for base plants, rising to 12% for the UPCSC+CC investment at the baseline scenario (i.e. with 50% financial leverage). This figure is taken as 15% with a 75% loan-financing scheme. Table 4 above summarises the technical and financial inputs assumed in the following case study simulations.

### 1.2.2. Sensitivity Analyses of the Required On-Grid Tariff

#### *Fuel Prices*

As attested by Zhao et al. (2009) and Wu et al. (2013), because Chinese power plants bear lower capital costs than most other countries (e.g. United States), the coal price – already accounting for a significant portion of operational costs (~25% according to Liang et al., 2014) – would account for a relatively larger portion of the total project expenditure. This directly impacts the profitability of the project by elevating the volatility of the required on-grid tariff –or the carbon price needed to justify CCUS investment – to coal price

[15] IEA (2009) assumed the price of an oil barrel to be 87$ in 2010, rising to US$115/barrel in 2030, and up to US$132/barrel in 2050.

variations. Therefore, with the uncertainty of future fuel prices, it is here assumed that coal prices can range from US$3.5/kWh to US$5/kWh, with 4$ and 5$ figures taken as chief values for the purpose of scenario analyses (Fig. 2). A comprehensive assessment of the impact of different coal price assumptions on the expected cost of energy, project net present values, and the cost of carbon avoidance at different required rates of return (5-20%) is presented in Appendix IV. It is noteworthy that while a 10% required rate of return is assumed for the base plants in all scenarios, an additional 2% is added to the required rate of return to compensate investors for the extra risk perceived in CCUS investments.

An on-grid tariff of US$87.5/MWh is required to generate a 12% IRR when assuming a US$4/GJ fuel price for a CCS plant (Figure 2). Increasing the price to US$5/GJ significantly raises the required tariff to US$97.8/MWh (+11.8%), if the same rate of return is to be maintained. These values are significantly lower for the base plant, requiring a moderate US$51.2/MWh for a US$4/GJ coal price (70.8% higher for USCPC+CC from the base plant's required tariff), and US$60.7/MWh on-grid tariff at a $5/GJ price (a 61% corresponding tariff increase). Needless to say that around US$10/MWh would normally make or break financial cases for the feasibility of clean technologies (e.g. nuclear), an equivalent reduction in CCS required on-grid tariffs would not suffice to justify large-scale investments at present. If (somehow) an IRR of 10% were deemed worthwhile for investors in CCS, the required on-grid tariff would be reduced slightly by US$0.8/MWh and US$1.2/MWh at $4/GJ and $5/GJ coal prices respectively.

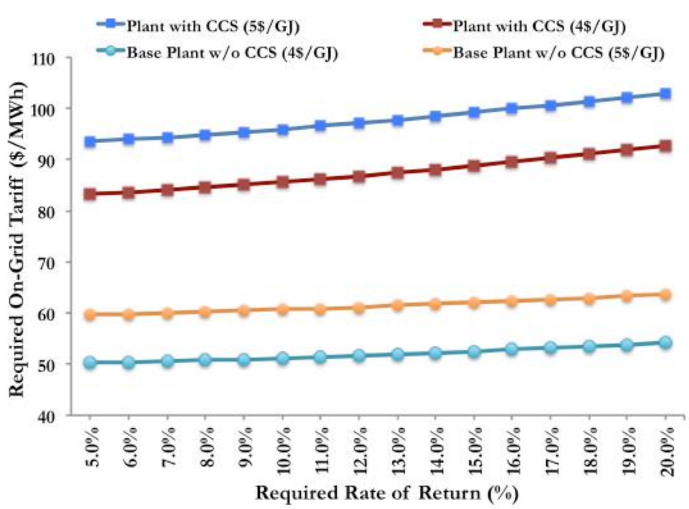


**Figure 2.** Required on-grid tariffs ($/MWh) to finance a CCS project in China at different required rate of returns and coal prices ($4/GJ and $5/GJ).

Note that the above observations are held under the assumption of 50% financial leverage i.e. debt-to-equity ratio is 50:50. Variability in this ratio has the effect that, as project financing through loans outweighs that from private money, the required on-grid tariff would be subject to reductions due to the lower rate of return on debt (fix interest of 6%). Counter intuitively, as the debt:equity ratio increases, private investors would require a higher return on their investment. Still, it remains not substantial enough to offset the influence of higher debt ratios, and the result is a net decrease in the required rate of return. In other words, the more debt capital replacing equity, the less pressure there is to meet the desired rate of return on the difference between rate of return on equity (ROE) and debt financing[16]. In the case of 75% debt financing (i.e. debt:equity ratio is 3:1), ROE is maintained as an average of 15%. The impact of changing financial leverage ratios in the investment model is portrayed in Fig 3.

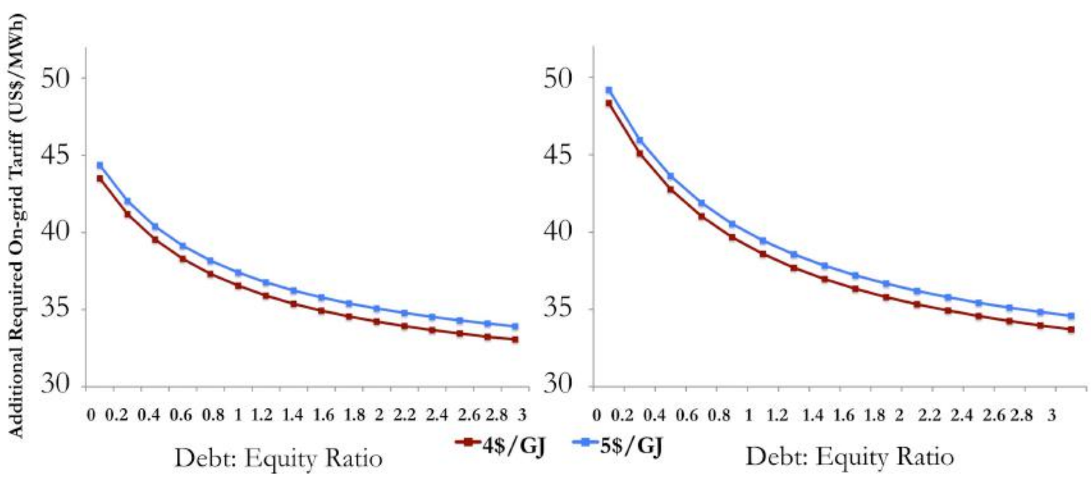


**Figure 3.** Additional required on-grid tariff for a USCPC plant compared to a base plant at varying leverage ratios, assuming a 10% required rate of return for the base plant and 12% (left) and 15% (right) for capture-ready plants.

It is imperative to note that, with a fuel price of US$4/GJ, no financial leverage (100% equity financing), and a required rate of return of 12%, an on-grid tariff of US$43/MWh is necessary to finance the project (i.e. an additional US$7/MWh from a 50:50 investment portfolio's). This value would fall to US$33/MWh if a 75% debt-financed model were adopted (3:1 debt:equity ratio). If a 15% discount rate were applied in the 75% debt model

[16] This difference is equivalent to 6% at a 12% IRR (ROE – debt fix interest), and 4% at a 10% IRR.

scheme, only a slight increase of US$0.7/MWh would be required to the on-grid tariff (i.e. US$33.7/MWh). However, this value surges to US$48.4/MWh at the other side of the financial-leverage spectrum (with 100% equity).

Assuming a higher fuel price of US$5/GJ and a 12% required rate of return has the effect that, with no financial leverage, the additional required on-grid tariff would be US$44.3/MWh. This figure would drastically decrease to US$37.4/MWh and US$33.9/MWh with 50% and 75% debt financing respectively. It is hereby worthy to mention that there is a considerable difference of US$16/MWh (49-33) in the additional required on-grid tariff between the most conservative estimates ($5/GJ coal price with 15% rate of return) and the more optimistic ones ($4/GJ with 12% rate of return).

Figure 4 shows that, not only does varying fuel prices from US$3.5/GJ to US$5/GJ aggravate the need to increase the required on-grid tariff in order to maintain the same project net present value, but it also significantly alters the cost of carbon avoidance ($/t$CO_2$). With a 12% rate on return and a US$3.5/GJ fuel price, carbon costs amount to only US$32.7/t$CO_2$, rising to $41, $48, and $56/t$CO_2$ for $4, $4.5, and $5/GJ fuel prices respectively.

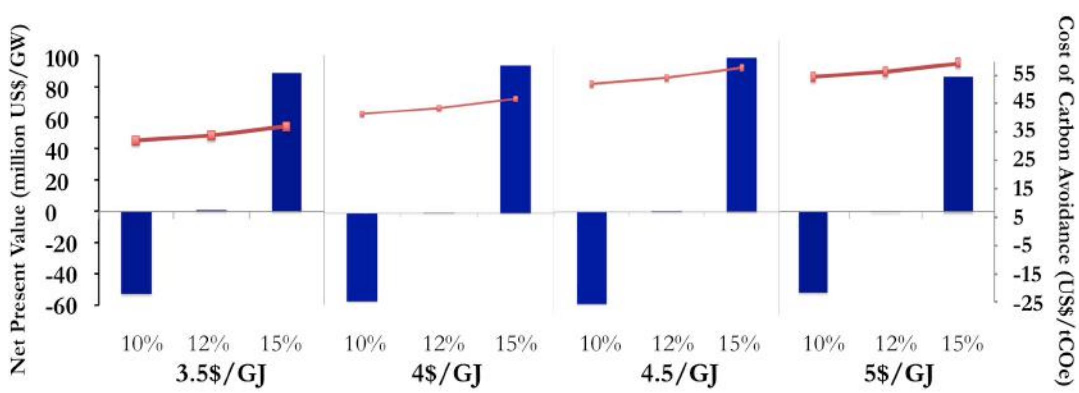


**Figure 4.** Sensitivity analysis of project NPV ($/GW) and cost of carbon avoidance ($/tCOe) to fuel prices and required rate of return.

Focusing on the cost of carbon avoidance, Figure 5 further illustrates its variability according to various discount rates (5-20%) and fuel prices ($4 or $5/GJ), assuming a 50% debt financing scheme. Under baseline assumptions of 12% rate of return and 4$/GJ fuel price, the carbon cost is US$41/$tCO_2$ and rises to $59.3/$tCO_2$ under the more pessimistic scenario of $5/GJ and 15% rate of return.

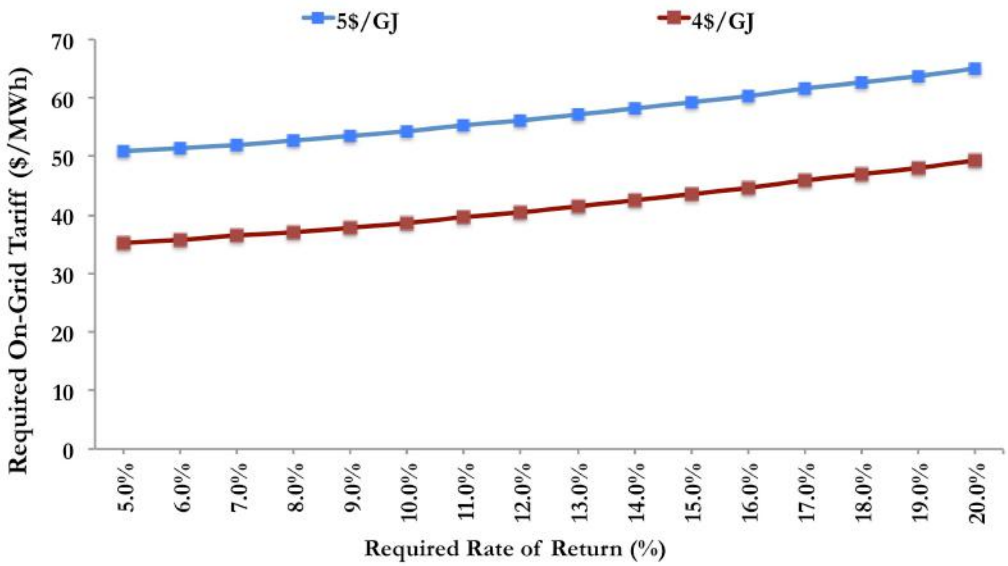


**Figure 5.** Required cost of carbon to finance a CCS project in China under different fuel cost assumptions ($4/GJ and $5/GJ).

### *Carbon Prices & Governmental Support*

It has been reasonably argued that carbon-pricing mechanisms can act as a potential driver to economically promote CCUS investments, as higher carbon prices help enterprises more effectively offset the costs of their emissions. This study analyses the critical values of carbon prices needed to justify investments in CCUS retrofitting at scale, in parallel with given levels of local and foreign governmental support. In this respect, scenarios of differing carbon prices combined with various proportions of public support grants (of CAPEX) are considered. This is performed using an NPV approach and through an examination of the required on-grid electricity tariffs under those scenarios. Here, the clean development mechanism (CDM) is considered to be operating effectively. The CDM is a volatile carbon pricing mechanism that offers a global platform for emissions trading between developed and developing countries in the form of certified emissions reduction credits[17] (CERs).

[17] According to UNEP, China ranks first worldwide in CDM projects, accounting for around 43% of total projects in the world (Zhang et al. 2014a).

In the Chinese context, the fact that power plants do not have the same absolute emission caps as developed countries qualifies emission reductions achieved through CCUS as certified emission reductions. However, because China's domestic carbon market is yet to be fully established, and since the CERs generated from CCUS investments are traded at the European Climate Exchange market, estimates from historical European carbon trading prices will be used in our simulations[18]. An overview of the trends in carbon prices as traded on the EU emissions trading scheme (EU-ETS) is depicted in Fig 6.

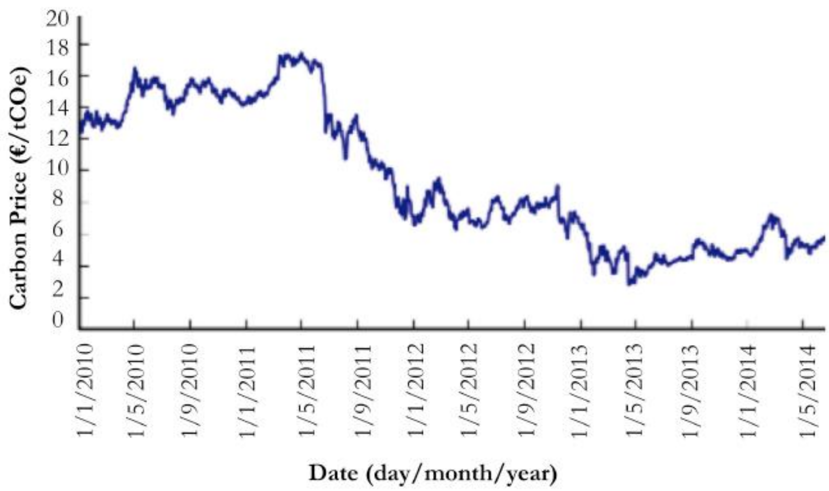


**Figure 6.** Trend of carbon prices (€ /tCOe) between 2010 and mid-2014.

It is crucial to mention that as carbon prices have been steadily plummeting since 2011 (with a slight price recovery during 2014), price discovery of future traded carbon credits remains considerably difficult. For the purposes of this report, if revenue generated from CER sales were accounted for in the cash flow model, the cash inflow equation would be modified as follows:

$$\textbf{Net benefits} = CER.P_c + P'_e.Q_e - I_{CCS} - TC_{CO2} - SC_{CO2} - C_{O\&M} - P_e.Q_r \qquad (1)$$

*Where* CER denotes the number of certified emission reductions (per $tCO_2$), $P_c$ is the price of carbon ($\$/tCO_2$), $P'_e$ is the electricity tariff ($/kWh), $Q_e$ is the project's electricity output (kWh), $I_{CCS}$ is the capital cost (per $), $TC_{CO2}$ represents the cost of transportation for $CO_2$ captured and $SC_{CO2}$ its storage (per $), $C_{O\&M}$ is the cost of operation and maintenance ($),

[18] Since the carbon market is a relatively new market, there is insufficient data to make price projections.

$\boldsymbol{P_e}$ is electricity at grid price ($/kWh), and $\boldsymbol{Q_r}$ is the power lost due to efficiency penalties (kWh). CER revenues are calculated as follows:

$$CER_t = \Phi \times IC \times RTt \times EF \times CR \qquad (2)$$

*Where* $\Phi$ is unit efficiency (%), *IC* is the installed capacity (MW), *RT* is the running time at time period *t* (hr), *EF* stands for the emission factor ($gCO_2$/kWh), and *CR* is $CO_2$ capture efficiency. A sensitivity analysis simulating the required on-grid electricity tariff is undertaken as a function of carbon price levels ranging from 0 to $25/$tCO_2$ and governmental grant support from 10% to 30% (replacing debt in the investment model). The analysis further simulates the parameters under two distinct discount rates (12 and 15%)[19]. Results are tabulated in Table 5. To put these figures into perspective, a benchmark price corresponding to the countrywide on-grid tariff for nuclear power generation will be used for financial comparability with CCUS projects. This tariff is taken as 450 CNY/MWh (~$68 at the time of publishing) – a level far below gas-fired power generation on-grid tariffs (530 CNY/MWh eq. to $80/MWh).

Under a 12% required rate of return and at current carbon prices, a 30% level or higher governmental support renders CCUS investments more economically desirable than for nuclear power plant projects. Similarly, if a carbon price of $15/$tCO_2$ or higher was applicable, only minimal public support (10% or lower) is required in order generate profitable returns. The general prevailing trend is a reduction of $2.5/MWh for the required on-grid tariff with every additional 10% in grants of overall CAPEX, and a decrease of $3/MWh for every $5 added to the price of carbon. For a higher rate of return of 15%, the impact of every additional 10% of grants translates to a $3/MWh reduction, equivalent to the effect of adding 5$ to the carbon price on the on-grid tariff.

[19] A 50% financial leverage ratio is assumed, whereby governmental support grants would replace some of the debt portions.

**Table 5.** Required on-grid tariff for USCPC + CCS plants at different carbon prices and policy support levels with **a)** 12% required rate of return, and **b)** 15% required rate of return. (50:50 debt-to-equity ratio). Green dotted values indicate a lower tariff required than nuclear on-grid tariffs, and red ones are higher.

**a)**

| Carbon Price ($/tCOe) | Public Support (Grants) | | |
|---|---|---|---|
| | 10% | 20% | 30% |
| 0 | 78.7 | 76.1 | 73.6 |
| 5 | 75.7 | 73.2 | 70.7 |
| 10 | 72.7 | 70.2 | 67.7 |
| 15 | 69.8 | 67.2 | 64.7 |
| 20 | 66.8 | 64.3 | 61.7 |
| 25 | 63.8 | 61.3 | 58.8 |

**b)**

| Carbon Price ($/tCOe) | Public Support (Grants) | | |
|---|---|---|---|
| | 10% | 20% | 30% |
| 0 | 80.1 | 77.1 | 74.2 |
| 5 | 77.1 | 74.1 | 71.2 |
| 10 | 74.1 | 71.2 | 68.2 |
| 15 | 71.2 | 68.2 | 65.2 |
| 20 | 68.2 | 65.2 | 62.3 |
| 25 | 65.2 | 62.3 | 59.3 |

In addition to a diverse combination of governmental policy support and the provision of national and international grants to promote CCUS demonstration, the Chinese Government can support CCUS through tax exemption (Liang et al., 2014). The influence of tax exemption on the required on-grid tariff is presented Table 6. In the specific case for a CCUS project in Guangdong province, it is worthwhile to note that tax exemption combined with low public support (10% or lower), and with a carbon price of US$8/t$CO_2$ in the Guangdong ETS, the required on-grid tariff for CCUS can be reduced to levels in the range of US$66-68/MWh. If the carbon price were to increase to US$20/t$CO_2$, the resultant required on-grid tariff would be in the range of US$56-58/MWh.

**Table 6.** Required on-grid tariff for USCPC + CCS plants at different carbon prices and policy support levels with **a)** 12% required rate of return, and **b)** 15% required rate of return. (with tax exemption).

**a)**

| Carbon Price ($/tCOe) | Public Support (Grants) | | |
|---|---|---|---|
| | 10% | 20% | 30% |
| 0 | 71.1 | 68.8 | 66.6 |
| 5 | 68.5 | 66.2 | 64.0 |
| 10 | 65.8 | 63.6 | 61.3 |
| 15 | 63.2 | 60.9 | 58.7 |
| 20 | 60.5 | 58.3 | 56.0 |
| 25 | 57.9 | 55.6 | 53.4 |

**b)**

| Carbon Price ($/tCOe) | Public Support (Grants) | | |
|---|---|---|---|
| | 10% | 20% | 30% |
| 0 | 72.3 | 69.7 | 67.0 |
| 5 | 69.7 | 67.0 | 64.4 |
| 10 | 67.0 | 64.4 | 61.7 |
| 15 | 64.4 | 61.7 | 59.1 |
| 20 | 61.7 | 59.1 | 56.5 |
| 25 | 59.1 | 56.4 | 53.8 |

# Offshore Wind

China started to focus on the development of a local wind energy industry in 2005, however, its efforts did not materialise until 2007 when the first demonstration project was put into operation. Due to high construction costs and the nascent nature of the technologies, offshore wind installations witnessed a halt between 2006 and 2007. It was not until 2010 that the technology's installed capacity started growing rapidly, reaching 389.6MW locally and ranking third in deployed offshore wind capacities in the world (after the UK with 2861MW and Denmark with 832MW) (Zhao & Ren, 2015). China's first round of concession bidding commenced in September 2010, the winning bidders of which were developers of projects totaling 1GW of power capacity, all located in subsidiary counties of Yancheng city, Jiangsu province. Two of these farms were offshore and two intertidal. Table 7 summarises details of the first concession round projects.

**Table 7.** First concession round project details.

| Project | Developer | Capacity | Feed-in Tariff (CNY/kWh) |
|---|---|---|---|
| **Jiangsu Binhai Offshore Wind Farm** | China Datang Corporation Renewable Power Compnay | **300MW** | 0.7370 |
| **Jiangsu Sheyang Offshore Wind Farm** | China Power Investment Corporation | **300MW** | 0.7047 |
| **Jiangsu Dongtai Intertidal Wind Farm** | Shandong Luneng Group | **200MW** | 0.6235 |
| **Jiangsu Dafeng Intertidal Wind Farm** | China Longyuan Power Group | **200MW** | 0.6396 |

While project developers originally planned to complete the projects within 4 years, construction procedures only commenced 3 years later, in September 2013. This, in part, came as a result of the lack of coordination – and strategic conflicts – between major governmental bodies. In particular, the National Energy Administration's (NEA) chief objective was to reduce costs and overcome those technical challenges associated with installing farms further offshore i.e. by relocating construction sites to near-shore areas. On the contrary, the State Oceanic Administration (SOA) argued that, in order to save space for fishing activities, transportation, and other marine uses, wind farms are to be preferably located further from shore[20]. In the meantime, project developers bore additional capital costs, as they were forced to relocate projects from their initially planned sites[21]. Such discouragements to offshore wind project undertakers, and the investment bodies supporting them, were considerably alleviated as the NEA and SOA released a set of clear frameworks and regulations. These delegated responsibility for developers to secure site approval from the SOA[22], and in turn selection bids and agreement on feed-in-tariff rates would be taken up with the NEA (Table 11 below, section on Policies for Construction Management).

## 2.1. Chinese Market Overview

### 2.1.1. Main Industry Players

Meanwhile on a global scale, investments in wind energy were booming as it was recognised as a primary clean alternative to fossil fuels. Despite having only deployed a modest capacity of 39MW throughout 2013, Chinese wind turbine manufacturers perceived an opportunity to penetrate the renewables market, by pushing agendas that prioritise the securitisation of strategic first-mover advantages in a country that is at the forefront of global wind energy development. In effect, Chinese manufacturers Sinovel, Goldwind and Dongfang Electric managed to swiftly enter the elite top 10 list of global wind manufacturers (GWEC, 2012). As of 2012, Sinovel and Goldwind had secured around 2/3 of the market shares of offshore wind turbine manufacturers in China (Table 8) (Zhao & Ren, 2015).

As far as project developers go, offshore wind development in China has been widely monopolised by a handful of state-owned utilities (SOE) – those with the most

[20] The fact that the NEA had a commitment to develop offshore wind projects in China when the SOA had no such mandate (Quartz & Co., 2013) did not help resolve said argument in an effective and timely fashion.

[21] For example, the Dongtai project had to be relocated 10km further offshore to allow for the conservation of a wildlife protected area, the Sheyang project was stuck in the design phase due to conflicts of military use in the area, and Binhai and Dafeng projects had only applied for construction approval from the NEA in 2013.

[22] In their "Interim Measure Implementing Rules for the Management of the Development and Construction of Offshore Wind Power", the NEA and the SOA formulated the area layout principles of offshore wind farms, specifying that future projects should be located at least 10km from shore and in at least 10m water depth (if the tidal flat is wider than 10km). This would further input into the site selection criteria as stipulated under this report's project appraisal case study (see below).

accumulated experience from onshore and gas & oil industries (Carbon Trust, 2014a). Supported by the Chinese Development Bank (CDB), it comes as no surprise that only around 8 cash-rich SOEs dominate the offshore wind market, given the inability of small and medium enterprises (SME) to afford the high investments required at this stage. Those utilities, owning a massive 98% of cumulative current installed capacity, are investment-driven by the long-term financial returns that a highly prioritised offshore wind industry promises. They are also bound by legislation under the Renewable Energy Law (REL) to source *at least* 3% of their energy from non-hydro renewable alternatives, a figure that rises to 8% by 2020.

**Table 8.** The cumulative market shares of offshore wind turbine manufacturers in China, as of 2012.

| Manufacturers | Wind Turbines Quantity | Installed Capacity (MW) | Market Shares |
|---|---|---|---|
| Sinovel | 56 | 170 | 39.7% |
| Goldwind | 44 | 109.5 | 25.5% |
| Siemens | 21 | 49.98 | 11.7% |
| United Power | 22 | 39 | 9.1% |
| Chongqing Sea Outfit | 4 | 14 | 3.3% |
| Shanghai Electric | 6 | 13.6 | 3.2% |
| Dongfang Electric | 2 | 8 | 1.9% |
| XEMC Windpower | 2 | 7.5 | 1.7% |
| Envision | 3 | 7 | 1.6% |
| Ming Yang | 3 | 6 | 1.4% |
| Sany Electric | 2 | 4 | 0.9% |
| **Total** | 165 | **428.58MW** | **100%** |

**Source:** Zhao & Ren (2015)

Of these utilities, China Longyuan Power Group, subsidiary of China Guodian Corporation and the largest onshore wind power producer in China, owns the tiger's cut of market shares, in terms of current and planned future capacity (Fig. 7). Towards achieving the 100GW target of deployed wind energy by 2015 (5GW of which is offshore[23]), 200GW by 2020, 400GW by 2030 (30GW offshore), and 1000GW by 2050 (Yuanyuan, 2012), these utilities combined had 5GW of planned capacity already consented and a further 12.3GW in the pipeline. A summary of the top Chinese offshore wind developers and their company turnovers is provided in Table 9, with Figure 7 demonstrating their

[23] It is now widely acknowledged that the sector had missed its 5GW deployment target set for 2015 (Wind Power Monthly, 2013), despite witnessing an installation boom during 2014.

corresponding installed and consented capacities. Assuming typical capital costs of the UK's Round 1 and 2 projects of £1.2–1.5m/MW, and based on the fact that China Longyuan spent some EUR1.6 billion to develop 1GW (Quartz & Co., 2013), a cost of around 13m CNY/MW is assumed for future capacity (as also assumed in the financial simulations below)[24]. This projects a total investment of around 233 billion CNY for the 8 aforementioned SOEs towards developing their forecasted projects.

**Table 9.** Summary of China's top 8 offshore wind developers.

| Developers | Total Planned Capacity (GW) | Turnover (EUR millions) | Notes |
|---|---|---|---|
| **China Longyuan Power Group** | 7.7 | 2075 | Raised 291m EUR in equity money. |
| **China Three Gorges** | 1.1 | N/A | |
| **China Datang Corporation** | 1.5 | 526 | Plans to invest 7.4bn EUR in offshore wind projects |
| **China Guangdong Nuclear** | 2.0 | N/A | |
| **China National Offshore Oil Corporation (CNOOC)** | 1.2 | 21,568 | Received 1.7bn EUR from the Chinese Government to develop 1 GW of offshore wind in Bohai Bay. |
| **China Huadian Group** | 2.0 | 262 | Plans to invest 738m EUR in Jiangsu province. |
| **Shenhua Group** | 1.9 | 14,724 | |
| **China Huaneng Group** | 1.3 | N/A | |
| **TOTAL** | **17.9GW** | | |

**Sources:** 4coffshore (2013); Quartz & Co. (2013); Carbon Trust (2014b)

[24] Based on an exchange rate of 1/10.14 for CNY:GBP and 1/8.18 for CNY:EUR in 2014.

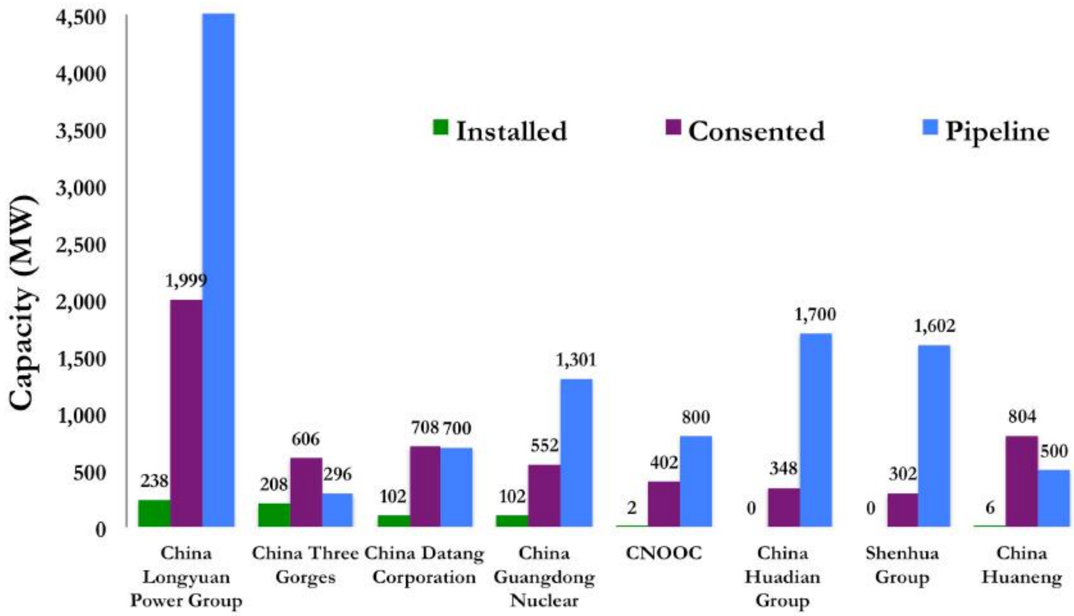


**Figure 7.** Capacity installed and consented for Chinese offshore wind developers.
Based on: 4coffshore (2013).

### 2.1.2. Resource Potential

The exploitation of China's significant wind energy potential represents a major step in overcoming its challenges to transit towards cleaner energy resources, energy independence, and the adoption of effective $CO_2$ emissions reduction strategies. By the end of 2013, the global cumulative wind capacity reached 318GW – with 35.5GW added only throughout that year – while the Chinese economy retained its position as the leading player in wind energy development globally, ahead of the USA. China accumulated 91.4GW in 2013 (28.7% of global total capacity) of which 16.1GW were added in the same year (GWEC, 2013; EWEA, 2014). Although relatively dwarfed by the 2680GW of estimated onshore wind potential that Chinese territories enjoy, the offshore wind resource in China still accounts for a whopping exploitable 180GW along its Northern and Southeastern coastal areas[25] (Caralis et al., 2014). Further offshore, at 5-50m water depths and 70m height, wind power can contribute up to 500GW, reflecting broad prospects for various developments and applications (Li Junfeng, 2012).

[25] Coastal areas are hereafter defined as the areas at 5-25m water depths and 50m height.

The focus of the upcoming development and construction of offshore bases will be concentrated in Jiangsu[26] and Shandong provinces (Carbon Trust, 2014b; Yang et al., 2015), while developments would be propelled in other provinces including Shanghai, Zhejiang, Guangdong, Guangxi, Hebei, Fujian, and Hainan (Zhao & Ren, 2015). In response to the (rather predicted) slow growth of offshore wind installed capacities throughout 2013[27], the Chinese Government, in its 'twelfth five-year plan of renewable energy, promoted the planning and development of offshore wind power. The NEA sped up the process of project approval in its "Development and Construction Scheme of Nationwide Offshore Wind Power (2014-2016)", and 44 projects totaling 10GW were approved in the aforementioned provinces (Sun et al., 2015). Fig. 8 shows the specific distribution of the approved installed capacity of offshore wind projects in China (2014-2016), and Table 10 demonstrates the development plan of China's southeast coastal provinces for offshore wind power by 2020.

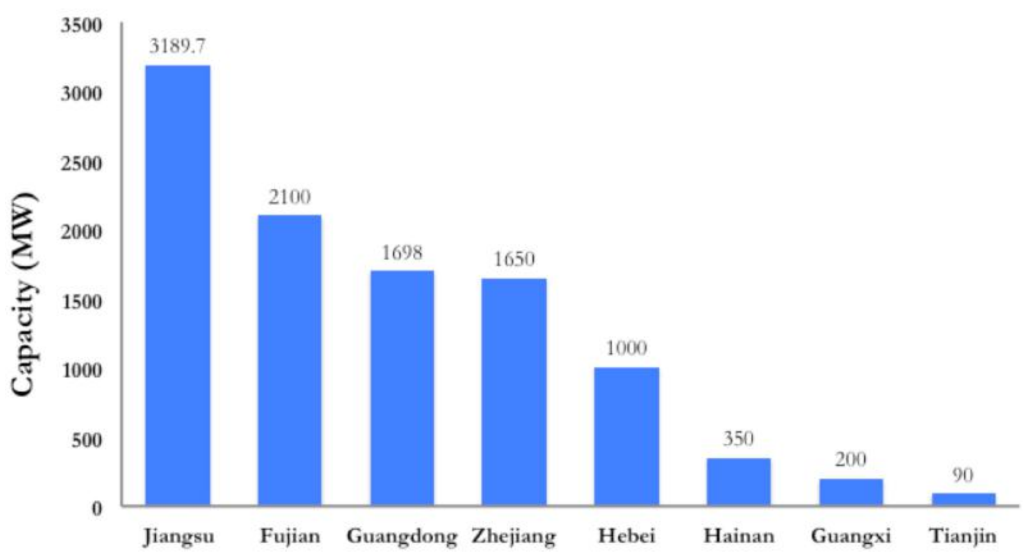


**Figure 8.** Installed capacity as approved in the Construction Scheme (2014-2016). Based on Fenglifadian (2014).

[26] Jiangsu enjoys an approximate 1000km of coastline with a coastal shoal land area that accounts for one quarter of China's total (Wu et al., 2014).
[27] Only 428.6MW deployed, i.e. less than 10% of the 2015 5GW objective.

**Table 10.** Development plan of Southeastern Chinese provinces for offshore wind.

| Region | Planned Installed Capacity (MW) | | |
|---|---|---|---|
| | Intertidal | Offshore | **Total** |
| **Jiangsu** | 2900 | 6550 | 9450 |
| **Zhejiang** | 500 | 3200 | 3700 |
| **Shandong** | 1200 | 5800 | 7000 |
| **Shanghai** | 200 | 1350 | 1550 |
| **Fujian** | 300 | 800 | 1100 |
| **Total** | **5100** | **17700** | **22800** |

**Source:** Carbon Trust (2014a), Wu et al. (2015)

### 2.1.3. Policy Support and Performance

The Chinese Government had enacted a series of policies to support its wind power development since 2005. These chiefly included supports for R&D (2005-2013), project planning (2009-2014), construction management (2010-2011), and the most recent prices – franchise bidding price (2010) and benchmark price (2014). Table 11 summarises the policies promulgated by the Ministry of Industry and Information Technology (MIIT) and the NDRC in support of the R&D of offshore wind in China from 2005 to 2013. On the financial frontier, however, these policies did not involve the R&D investment plan or subsidies desired by sector actors (Zhao & Ren, 2015).

During the first concession bidding rounds for offshore projects (2010), a price-based bidding prompted the prevailing of extremely low bids, ones made intentionally by developers keen to enter the young market. This race-to-the-bottom bidding resulted in low and unprofitable FiTs[28]. It is believed that power companies might have been initially satisfied with such low rates, as they sought to impress central and local governments (Innovate Norway, 2013) on top of the perks of gaining first-mover advantages and unprecedented access to offshore industries (Quartz & Co., 2013). It comes as no surprise, then, that construction stalled in the past few years, fostered by the inability of companies

[28] Tariffs were only around 30% higher than those established for onshore wind projects (Carbon Trust, 2014b), although offshore projects costs were at least double those of onshore ones (Zhao & Ren, 2015).

to generate commercial returns against such FiTs[29] (Table 8) (Hong & Möller, 2012). Proponents of Chinese offshore wind policies suggest the adoption of a geographically adjusted subsidy mechanism based on project sites, as now is the case for onshore wind projects. Appendix IV elaborates on the four regions/categories as allocated for the division of onshore benchmark FiTs.

In the same vein, in 2012, NEA had commissioned the China Renewable Energy Engineering Institute (CREEI) that aims at researching appropriate levels for offshore wind FiTs. However, no timeline was set for the announcement of the tariffs, and as evidenced by Carbon Trust interviews with the National Renewable Energy Research Centre, NDRC viewed the promotion of onshore wind as a more imminent priority (Carbon Trust, 2014a). CREEI sought the establishment of a stable benchmark FiT model that sets different tariff levels for different areas, depending on their wind resources and costing portfolios. The latter two, along with the depth of water, bank clearance, and weather conditions, to mention a few, are all factors affecting the investment costs of offshore wind (and hence the financial incentive/subsidy required) –factors that can differ even within waters of the same area (Li et al., 2014a). Taking Jiangsu and Zhejiang provinces as examples, it can be noted that the investment cost, cost pricing, and even the benchmark prices for Zhejiang are greater than their Jiangsu counterparts (Caralis et al., 2014), suggesting the current financial policies of offshore wind power are not conducive for the healthy establishment of a balanced offshore wind industry in China.

[29] It is worth noting that, as the FiTs originally assigned to the first concession round proved low to support commercial viability, the NEA had granted permission to the four projects to reapply for new FiT levels (Wind Power Monthly, 2013), seeing projects as China Datang re-applying for an FiT increase from its 0.737 to 0.860 CNY/kWh.

**Table 11.** An overview of the main support policies for offshore wind power in China since 2005 (continued below).

| Date | Policy | Relevance to Offshore Wind Power |
|---|---|---|
| **Support Policies for R&D** | | |
| **Nov. 2005** | "The development guidance catalogue of renewable energy industry" | The guide catalog delineated the technology R&D for offshore wind turbines. |
| **Mar. 2008** | "The 'eleventh five-year plan' of renewable energy development" | Facilitate the provision of the R&D, testing, equipment manufacturing and demonstration of pilot offshore wind projects. |
| **Mar. 2010** | "The wind power equipment manufacturing industry admittance standard (draft)" | Prioritising the development of an offshore wind power manufacturing industry. |
| **Feb. 2013** | "The decisions on the modification of 'industrial structure adjustment catalog (2011 Edition)' relative clauses". | "The R&D and manufacture of offshore wind turbines" and "offshore wind farms construction and equipment manufacture" were added to the new energy clause of encouraged industries. |
| **Support Policies for the Planning of Projects** | | |
| **Jan. 2009** | "Preparation rules of offshore wind power projects planning report (trial)" | Formulate the principles, procedures, contents, depth and technical requirements that should be followed in offshore wind projects planning report. |
| **Jan. 2009** | "Preparation rules of offshore wind power projects pre-feasibility study report" | Regulate the basis, task, content, depth and technical requirements of offshore wind farm projects pre-feasibility study report preparation. |
| **Apr. 2009** | "Outline of offshore wind farm projects planning" | Set the work scope, principle, content, methods, responsibilities and organization management for offshore wind power planning . |
| **Aug. 2012** | "The 'twelfth five-year plan' of the renewable energy development" | Proceed with the development and construction of offshore wind power actively, the installations reach 5 GW by 2015 and 30 GW by 2020. |
| **Aug. 2014** | "Development and construction scheme of offshore wind power (2014-2016)" | Involve 44 offshore wind projects, total installed capacity is more than 10 GW. |

| Date | Policy | | Relevance to Offshore Wind Power |
|---|---|---|---|
| **Support Policies for the Construction Management of Offshore Wind Projects** | | | |
| **Jan.2010** | "Interim measure for the management of the development and construction of offshore wind power" | | Improve the system and mechanism of offshore wind power farms construction and management, and strengthen the management of all phases. |
| **Jul. 2011** | "Interim measure implementing rules for the management of the development and construction of offshore wind power" | | Further clarify the specific procedures and management requirements of offshore wind power planning and projects construction. |
| **Sep. 11** | "Ration of cost estimate for offshore wind power projects" | | Establish rules for offshore wind power projects construction and management, in order to regulate the planning and design of offshore wind farms. |
| **On-grid Prices for Offshore Wind Projects** | | | |
| **Date** | **Policy** | **Price Standard** | **Price** |
| **Feb. 2010** | The first franchise bidding | - | Bidding power price: intertidal wind power price of US$102.3/MWh and US$104.9/MWh: near-shore wind power price of US$115.6/MWh and US$120.9/MWh. |
| **Jun. 2014** | "The notice on offshore wind power feed-in tariff" | The non-bidding projects, which have been put into operation prior to December 31, 2016. | Benchmark price (tax-inclusive): Near-shore wind power price of US$139.4/MWh; Intertidal wind power price of US$123.0/MWh |
| | | The bidding projects, which have been put into operation prior to December 31, 2016. | Bidding power price: The on-grid price of the projects subject to tender cannot be higher than the benchmark price of similar projects. |

**Sources:** Carbon Trust (2014); NDRC (2011); NDRC (2008).

## 2.2. OSW Investment Case Study

### 2.2.1. Model Assumptions

In the particular case of wind energy, project profitability is a function of a number of uncertain input factors: wind speed, farm capacity, operability and cost breakdown, and, expectedly, a set of macroeconomic aspects influencing the applied interest and discount rates. Information regarding uncertainty matters is especially important in the decision-making process for potential private investors in the project pre-decision stage, as well as to policy makers seeking to adapt, or amend, public support schemes to accommodate the industry's investment state and other regional particularities. Under these circumstances, profitability of wind farms becomes merely a random outcome driven by the combined impact of variability in each of those uncertain parameters. In order to simultaneously account for this joint effect – and the risk of its eventuality – a Monte Carlo simulation is conducted to appraise the project, instead of the traditional approaches of scenario simulations or sensitivity analyses. A Monte Carlo simulation approach, integrated into our cash flow model, takes into account randomly generated samples of the uncertain inputs, in order to produce confidence estimates about the stipulated output variable (e.g. NPV, IRR, etc.). A literature review of current lifetime cost estimates was conducted in order to inspect CAPEX and OPEX metrics for offshore wind energy farms in China, and the averages of determined results were used as inputs in this case study's simulations.

Jiangsu, representing an area of constant energy shortages (and consequently high demand for energy) and considerable resource potential for offshore wind development (Yang et al., 2015), is chosen as location for the proposed offshore wind farm in this study; a 300MW farm consisting of 100x3MW Sinovel turbines. As advised by the specifics of Shanghai Dong Hai project, a net load factor of 29% is assumed at the baseline scenario, as an average between 25% (most pessimistic) and 32% (most optimistic) to account for the variability in wind conditions (World Bank, 2010). Capital costs are taken as an average of CNY 14-19m/MW (i.e. 16.5m CNY/MW) with fixed operational and maintenance costs accounting for 2% of CAPEX, while variable O&M equal 150 CNY/MWh (EWEA, 2013). Although FiT levels would vary according to site particularities, a proposed 850

CNY/MWh is assumed here, as a conservative lower bound level as currently applicable to some wind projects. The study simulates profitability under varying FiT levels from 700 CNY/MWh to the market desirable level of around 1000 CNY/MWh (Carbon Trust, 2014b).

Assuming a discount rate of 10% and corporate taxation of 15%, a 70:30 debt-to-equity ratio is endorsed in the investment model, with China Development Bank's interest rate of 6.56% taken as an average return on loans, along with 11.58% for ROE (Smirnova et al., 2012). CDB remains the largest expected contributor to channeling public funding, while asset financing[30], public market financing and venture capital and private equity financing are identified as key sources of financing the remaining required investments (Smirnova et al., 2012). Public market financing also enables key developing and manufacturing companies to substantially raise capital growth for reinvestments. Furthermore, venture capital and private equity risk appetite portfolios render them important financing sources to promote project development and technology innovations. Table 13 provides an overview of the engineering and financial assumptions made in this study.

### 2.2.2. Uncertainty Analysis in OSW Farm Profitability

According to the nature of factor uncertainties, the randomness in each parameter is approximated using specific statistical distributions that are applied according to available experimental and market data. Parameters with known minimum and maximum values, i.e. fixed range boundaries, obey a uniform distribution, while triangular distributions, characterising a symmetrical deviation about a mean value, are selected if there is a high likelihood for an average outcome of the uncertain variable. In our case, a uniform distribution is assumed for the range of capital costs as specified earlier, with feed-in-tariffs and load factors obeying a triangular distribution. Table 12 summarises these inputs under differing scenarios.

[30] Asset financing is considered the main global source of clean technology investments, with China receiving more than half of these finances in 2012 that played a central role in the promotion of wind projects in China (Pew Charitable Trusts, 2012). This source of financing is largely used during equipment installation and capacity generation phases.

**Table 12.** Monte Carlo simulation input data.

| Parameter | Pessimistic | Medium | Optimistic |
|---|---|---|---|
| **Load Factor** | 25% | 29% | 32% |
| **CAPEX (million CNY)** | 14 | 16.5 | 19 |
| **FiT (CNY/kWh)** | 0.70 | 0.85 | 1.00 |

**Table 13.** Parameter inputs for case study financial simulation of offshore wind project case study in China.

| Parameter | Data | Unit/Note |
|---|---|---|
| **Project timeline** | | |
| Pre-development | 6 | Years |
| Licensing & construction | 2 | Years |
| Operational lifetime | 20 | Years |
| **Technical data** | | |
| Average load factor | 29% | |
| Turbine Brand | Sinovel | |
| Number of Turbines | 100 | |
| Capacity per Turbine | 3 | MW |
| Total Project Capacity | 300 | MW |
| Water Depth | 10-20 | Meters (m) |
| Distance from Shore | 20 | Meters; Near-offshore project |
| **Cost Evaluation** | | |
| ***CAPEX*** | | |
| Pre-operating Costs | | |
| Licensing and Permissions | | |
| Construction Costs (per MW) | 16,000 | CNY/kW |
| ***OPEX*** | | |
| Fixed O&M | 0.15 | CNY/kWh (Carbon Trust, 2014b) or taken as a yearly 2% of capital costs (i.e. 320 CNY/kW) |
| Insurance Costs | 1-2% | % of total capital cost |
| **Financial Metrics** | | |
| Corporate Tax | 15% | Since 2009, Value Added Tax (VAT) for wind power has been reduced from 17% to 8.5%, and the income tax from 33% to 15% (Xiliang et al., 2012). |
| Debt-to-Equity Ratio | 80:20 | |
| Cost of Debt | 6.56% | |
| Cost of Equity | 11.58% | |
| Discount Rate | 10% | Sensitivity analysis included with 8%, 5%, and 3% discount rates |
| Depreciation | 20 | Years |
| Decommissioning Cost | 5% | % of total capital cost |
| Electricity Price | 0.85 | CNY/kWh |

Under the defined conditions and running 1000 iterations at each analytical step, the distribution of the levelised cost of energy is characterized by a mean value of 1080 CNY/MWh and a confidence interval of 925-1027 CNY/MWh ($p$<0.05) (Fig 9a). This assumes that feed-in-tariffs are taken as an uncertain variable of range 700-1000 CNY/MWh. However, if FiT is fixated at 850 CNY/MWh, the resulting NPV (in CNY/MW) would obey a triangular distribution with the highest likelihood for an NPV around 2.2m CNY/MW, with 87% probability of generating NPV>0 (Fig 9b).

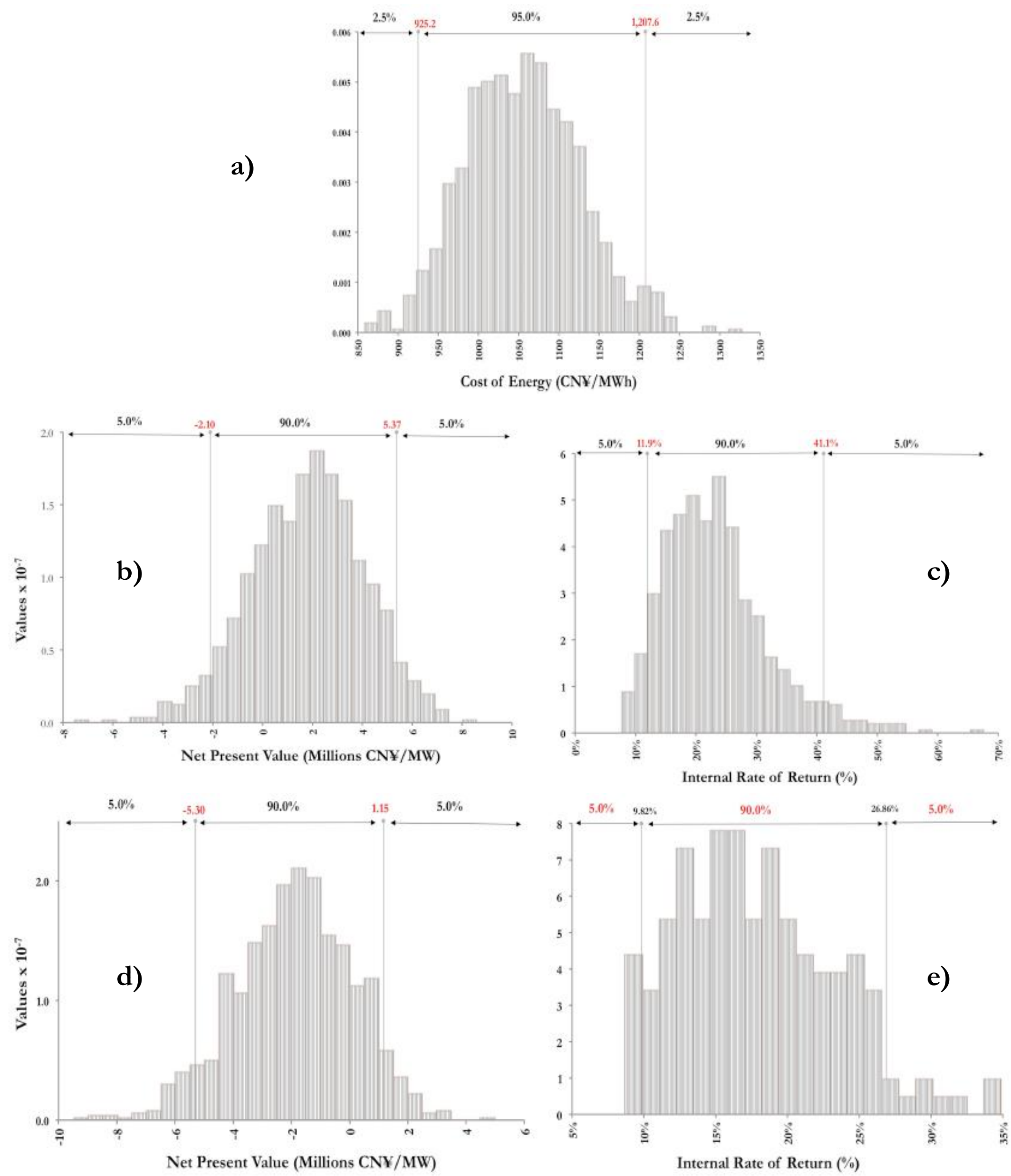


**Figure 9.** Simulation results for net present value (CNY/MW), internal rate of return, and cost of energy under different assumptions.

This high profitability likelihood is also reflected in the corresponding internal rate of return generated, with p (IRR>12%)= 94% and p (IRR>20%)= 68% ($p$<0.01) (Fig 9c). If the model is further modified to account for current (lower) market FiT levels (e.g. 700 CNY/MWh), there is only a modest 33% probability of generating a positive net present value, with the chance of achieving an IRR>20% plummeting to 24% (where profitable returns would only result due to low capital costs and high wind potential throughout the project's lifetime) (Fig 9d,e). Table 14 delineates the results of a sensitivity analysis of the cost of energy with varying load factors (25-32%) and capital costs (14-19m CNY/MW) (discount rate=10%). Dotted cells represent conditions under which a positive NPV with an IRR>12% are generated with different FiT assumptions: **1)** white is for FiT = 1000 CNY/MWh, **2)** grey for 850 CNY/MWh, and **3)** black for 700 CNY/MWh. With 700 CNY/MWh, only projects with very *simultaneously* attractive technical and financial conditions generate NPV>0 and IRR>12% with ~10 year payback period (PBP) (i.e. load factor is greater than 27% and capital costs fall in the range of 14-15m CNY/MW).

For FiT=850CNY/MWh, the maximum LCOE with which profitable returns on investments are generated (regardless of the variation in uncertain parameters) is 1050 CNY/MWh. It is also noteworthy that, if costs of capital investment could be reduced to around 14m CNY/MW, a desirable returns profile can be guaranteed regardless of the uncertainty in the wind potential range at a certain location. For FiT = 1000 CNY/MWh, a project is most certain to achieve an IRR of +12% with PBP<10 unless most pessimistic conditions are simultaneously assumed (load capacity < 26% and CAPEX > 18m CNY/MW).

**Table 14.** Sensitivity analysis of LCOE, NPV, and IRR to variations in assumed load factors and capital costs.

| | CAPEX (Million CNY/MW) | | | | | |
|---|---|---|---|---|---|---|
| **Load Factor** | **14** | **15** | **16** | **17** | **18** | **19** |
| 25% | ○◐ 1029 | ○ 1092 | ○ 1154 | 1217 | 1280 | 1343 |
| 26% | ○◐ 995 | ○ 1055 | ○ 1116 | ○ 1176 | 1236 | 1297 |
| 27% | ○◐● 964 | ○◐ 1022 | ○ 1080 | ○ 1138 | ○ 1196 | 1254 |
| 28% | ○◐● 935 | ○◐ 991 | ○◐ 1047 | ○ 1103 | ○ 1159 | 1215 |
| 29% | ○◐● 908 | ○◐● 962 | ○◐ 1016 | ○ 1070 | ○ 1124 | ○ 1178 |
| 30% | ○◐● 882 | ○◐● 935 | ○◐ 987 | ○◐ 1039 | ○ 1092 | ○ 1144 |
| 31% | ○◐● 859 | ○◐● 909 | ○◐● 960 | ○◐ 1011 | ○ 1061 | ○ 1112 |
| 32% | ○◐● 837 | ○◐● 886 | ○◐● 935 | ○◐ 984 | ○◐ 1033 | ○ 1082 |

# Research Analysis

## 3.1. The Global Status of Chinese CCUS

The CCS cash flow model simulation makes it clear that Chinese CCUS projects could incur costs of energy cheaper than alternative gas-fired power systems as well as those of nuclear power. This supports the IEA's view that CCUS technologies, although having not been demonstrated at large scale, "can still be competitive on a levelised cost of electricity basis with solar, wind…"(IEA, 2012). From a China perspective in particular, CCUS costs remain strikingly lower than those observed in developed regions (e.g. US and Europe), let alone the fact that the EU is now witnessing a slowdown in CCUS development in contrast to the priority status that the field is presently receiving in China (Renner, 2014). Costing differences in CCUS between emerging countries in East Asia, particularly China, and more mature western markets, can be attributed to at least four factors: **1)** the effect of economies of scale that is a corollary to China's tendency to build many power systems with standardised designs, **2)** the lack of need to import raw materials and the abundance of nationally-produced commodities, culminating in lower prices than those traded in the free market, **3)** substantially lower costs of labour in China, and **4)** the presence of fewer regulatory constraints in the country, to name a few.

However, because Chinese CCUS projects are still in their preliminary stages of development and data compilation remains hampered by confidentiality concerns, we compare results of the contemporary research to those of the (limited) case studies focusing on the Chinese CCS realm (e.g. Zhao et al., 2008; NZEC, 2009; Finkenrath, 2011; Wu et al., 2013; and Liang et al., 2014). Results are further critiqued using more publicly available data from international projects. Most notably, the American experience with EOR, Canada's Weyburn CCS project[31], Norway's Snohvit and Sleipner projects, and CCS undertakings in the Algerian In Salah project all feed in to the assessment of the Chinese market positioning on the global map.

[31] Weyburn-Midale CCS project, located in Saskatchewan, Canada, is the largest of its kind in the world (as of 2008).

From a review of the literature, it is conceivable that there exist sizeable discrepancies in CCS-cost evaluation methodologies among different public studies – a direct repercussion of the absence of a clear and commonly agreed upon set of data on boundary conditions, namely the applied discount rates and the fuel prices incurred (Rubin et al., 2007). Nevertheless, China-specific reports almost unanimously agree on the extent of CCUS costs' cutback when compared to projects in foreign countries. For instance, Renner (2014) explains part of the costing difference between Chinese and European CCUS in terms of cheaper O&M costs (80% higher in Europe), and lower net efficiency penalties (7 percentage points in China and 9 in EU). The implications of the latter transpire in the need for higher fuel consumption (i.e. higher costs) with decreasing net efficiency.

To neutralise the dissimilarities of multiple cost calculation methodologies, the GCCSI (2011) suggested adopting a calibration method to standardise the levelised costs of energy and cost of $CO_2$ avoided, returning less heterogeneous results. GCCSI (2011) acknowledges that "the different cost estimates observed in the various studies arise due to differences in assumptions regarding technology performance, cost of inputs or the methodology used to convert the inputs into levelised costs. Many of these differences disappear when the assumptions are normalised and a common methodology is applied". Renner (2014) attributes the residual differences in LCOE after normalisation to the already-mentioned discrepancies in O&M cost assumptions, ones that can potentially differ by a factor of three.

## 3.2. Financial Viability of CCUS

### 3.2.1. Required On-Grid Tariffs

As far as the costs of energy produced are concerned, on average LCOE of coal-fired power plant with CCUS in China is 60% higher for onshore storage (US$86.5/MWh) than the cost of energy generated by a corresponding non-retrofitted reference plant, and 75% higher for offshore storage (US$93/MWh). In the EU, these figures are 80% higher than their reference plant counterparts, reflecting European LCOE values that are 35-45% higher than those in China. Liang et al. (2014) admits that although the costs of developing CCS for Guangdong-based coal-fired plants can be higher than the national Chinese average, its LCOE might still be well below US$100/MWh. Confirming this are our findings (Appendix IV) that suggest an LCOE of US$92-94/MWh, when an optimistic US$3.5/GJ fuel price is assumed, rising to US$97-99/MWh if a more conservative assumption of US$4.5/GJ coal price is advocated.

Under the assumption of US$4/GJ for future prices of coal, combined with a moderate baseline scenario (12% discount rate, 50% financial leverage), the observed additional on-grid tariff to finance CCS is US$36/MWh. Under a more conservative fuel price of US$5/GJ, the figure rises to US$44/MWh. The joint alteration of techno-economic assumptions for the required rate of return (12% to 15%) and increasing debt:equity ratio to 3:1 lowers the required on-grid tariffs to US$33/MWh. Liang et al. (2014), suggesting an additional tariff of US$31.8/MWh under the same 75% financing leverage scenario, recognises the potential to close the financial gap for CCS by endorsing a variety of financing mechanisms, notably the CDM, governmental grant support, special funds dedicated to CCUS development, and potential venture capital resourcing[32].

The introduction of government grants into the investment mix has the potential to reduce the required tariff by US$3/MWh for every 10% debt-replacing proportion made towards capital. To put this into context, a 30% grant scheme would bring the CCS financial gap down to around US$25/MWh and US$22/MWh, for 15% and 12% required rate of return respectively. This makes it evident that, in order to leverage the additional required investment, a national carbon tax – or its monetary equivalent in carbon credits under the CDM – can potentially bridge the remaining gap. More specifically, a carbon price of US$10/t$CO_2$ could reduce the required on-grid to US$63.9/MWh under the same granting scheme (and to US$60.9/MWh if tax exemption is assumed).

It is also imperative to mention that, although not extensively discussed in this report, an additional route to financing $CO_2$ capture is the sale of carbon to oil companies, as one of

[32] VC investment portfolios do not allow them to be prime candidates for investing in CCS, considering they generally invest US$$1m to US$$20m in a project. Nonetheless, Liang et al., (2014) suggests channeling CCS investment as an independent endeavor than the reference plant's investment, rendering VC's resources relatively more substantial.

the most sought-after carbon *utilisation* routes. It is estimated that $CO_2$ dissolution into oil induces a reduction in oil volume expansion and the viscosity of oil by 30% to as much as 80% (Zhang et al., 2014a). This would reduce the interfacial tension between oil and water, thereby enhancing the recovery of oil. The recovery improvement efficiency of $CO_2$ flooding ranges between 7-15%, with the production service life of the oil well extended to as long as 20 years. This becomes even more cost-effective the closer the plant geographically is to oilfields.

However, if this route were exploited, CERs would most likely not be generated, as under the CDM mechanism projects are required to demonstrate 'additionality'. This implies that the economic feasibility of the project *must* predominantly rely on the revenue it generates from the sale of CERs, and it would not have been feasible, i.e. undertaken, otherwise. This renders CDM project validation in parallel with $CO_2$-EOR exploitation unattainable, and subsequently, project developers would need to make a one-off choice between the revenue from $CO_2$-EOR or CDM credits as proposed earlier. It follows that, if substituting carbon credits revenues in the present investment model, the sale of liquid $CO_2$ to neighbouring oil companies for a price ranging from 15 to US$20/t$CO_2$ would have an equal weight in offsetting the need for additional investments (Tables 6 & 7). With this price range, the required on-grid tariff to finance CCUS would be brought down to a range of US$55-58/MWh.

### 3.2.2. Carbon Pricing

The costs of carbon avoidance fall in the ranges of US$35-50/t$CO_2$ and US$50-65/t$CO_2$ under US$4/GJ and US$5/GJ assumptions for coal prices, respectively (Appendix IV). The results are in harmony with those reported in earlier studies on the impact of carbon prices on CCS investments in China, particularly Sekar et al.'s (2007) projection of 0.19-0.25CNY/kWh, or US$38-50/t$CO_2$. These, however, remain substantially higher than MIT's (2007) early prediction of a $CO_2$ price of US$30/t$CO_2$[33]. With the assumption of a coal price of US$4/GJ, Wu et al. (2013) recently estimated carbon to cost US$55/t$CO_2$, rising to US$61/t$CO_2$ with US$5/GJ, in order to justify large-scale investment in CCS.

[33] Estimated as US$25/t$CO_2$ for $CO_2$ capture and pressurization and 5$/t$CO_2$ for transportation and storage.

Additionally, in her investigation of the $CO_2$ switching price[34] between CCUS and non-CCUS coal-fired power plants, Renner (2014) establishes that, for onshore transport and storage, CCS coal plants become more cost-effective (in terms of lower LCOE) than non-CCS plants beyond a price of 35€/t$CO_2$ (i.e. US$47/t$CO_2$)[35]. For offshore transport and storage, this figure increases to 45€/t$CO_2$ (US$60/t$CO_2$). To put these values into context, we note that that the corresponding required $CO_2$ price in the EU should currently be in excess of 115€/t$CO_2$ (US$153/t$CO_2$) in order for CCUS plants to become more profitable than reference ones.

While it has been widely conceded that carbon regulations play a key role in CCUS profitability and deployment (Giovanni and Richards, 2010), current carbon prices (e.g. 40 CNY/t$CO_2$ or US$6.4/t$CO_2$) are not substantial enough to incentivise the practical adoption of CCS technologies. Although a national ETS is yet to be established, and the fact that the lack of a free market has triggered much debate on ETS viability in China, seven local pilots have been operating as macro-laboratories since 2011 (Zhang et al., 2014b). Although these pilots differ in their market designs, implementation strategies and local regulations, they collectively secured China's ETS market position as the one of the largest in the world, second only to the EU-ETS[36].

In this respect, Li et al. (2015b) realises that in China "$CO_2$ pricing and CCS technology are mutually reinforcing in reducing $CO_2$ emissions yet keeping the economic effectiveness". The present study reveals that a high carbon price is conducive to achieving the level of cost competitiveness desired by investors with low- and high-risk appetite alike. Li et al. (2015b) further views that the opportunity to cost-effectively decarbonise the Chinese power sector cannot be captured if CCUS was not commercially available. The study also admits that a case for CCUS cannot be made unless carbon prices reach a level of US$50-60/t$CO_2$, assuming other in-parallel financing mechanisms were not simultaneously available at the disposal of CCUS technology developers (Liang et al., 2014). This reflects

[34] The $CO_2$ switching price is the price of carbon beyond which CCS plants become more economical than the same plants without CCS; it is the $CO_2$ price for which the NPV of the differential project (NPV of CCS – NPV of ref) is null.

[35] Using yearly Euro:USD conversion rate of 1.33 at the date of publishing (2014).

[36] The total emission allocations of pilots (excluding Chongqing ETS) amounted to 1115 million tons in 2014 (World Bank, 2014).

the sensitive knock-on effects that variations in carbon prices can have on CCS development prospects and on its eventual contribution to emissions reductions in the Chinese power and industrial sectors.

### 3.2.3. Societal Perception of CCUS

In the CCS literature today it can be markedly discerned that planning CCUS projects in close proximity to residential areas – and even the explorations of potential storage sites – has evoked considerable opposition from local communities (see for example, Terwel et al., 2011; Wallquist et al., 2010). In the Chinese context, Yang et al. (2016) define the factors affecting public perception of people towards CCUS in terms of four drivers: public cognition, perceived risks, perceived benefits, and environmentalism. Although the study concede that most of the surveyed Chinese lay people were either not aware of CCUS technologies or even the scientific implications of rising atmospheric $CO_2$ levels [37], perceived risks of CCUS were recognised as having the most negative effects on the willingness to accept CCUS deployments in China. Perceived risks of the public generally involve concerns of accidental incidents, potential $CO_2$ leakage, and even earthquakes resulting from underground gas storage (Seigo et al., 2014). The other three drivers all have positive influence on the public perception of CCUS and so play an opposing role to perceived risks in the public's decision to support or oppose CCUS development.

Further survey-based studies on the public acceptance of CCS in China, however limited, advocate the conclusions of Upham and Roberts (2010), van Alphen et al. (2007), and Wallquist et al. (2012) that the sense of security of the lay people is the prime requirement for enhancing the public acceptance towards CCUS. Chen et al. (2015) admit that despite the anxieties regarding CCUS safety measures and the general misconceptions, the general attitude towards the technologies is not strictly opposing, but is rather more suspicious than is supportive.

Another key factor influencing the public perception of the Chinese lay people towards CCUS, Yang et al. (2016) believe, is the public trust in CCUS stakeholders. With only very

[37] Other studies also report very low rate of respondents (<35%) who have knowledge of CCUS technologies (e.g. Chen et al., 2015), and a high number of surveyees who are not aware of the pros and cons of CCUS or which environmental issues it can solve (Li et al., 2014b).

limited knowledge of the perceived risks and benefits expected from CCUS, the general public finds it difficult to evaluate the merits and drawbacks of a nascent technology, and so eventually rely on relative, more informed, stakeholders to abate their fears of such new endeavours. A study on gene technology by Siegrist (2000) confirms that, with increasing public trust in an organisation, perceived risks of new technologies are minimised in comparison to those who distrust the organisation. This implication, at the margin, proposes further actions to strengthen the public's perception of CCUS considering that **1)** in the absence of public trust, stakeholders would in turn be reluctant to implement new projects as people view them as highly risky and potentially unprofitable undertakings, **2)** the general public tends to question the profit-making motives of project developers and, in turn, their concern for public welfare, and **3)** in the Chinese case, especially, market available data can be exceptionally unreliable and knowledge of the technical merits of CCUS substantially unrecognised.

Urgent measures are needed to create and maintain the public's trust in stakeholders and in the prospects (and necessity) of the technology. It is essential for relevant market stakeholders and the local government to facilitate communication and transparency in the decision-making process. It follows that improving lay people's cognition of CCUS could not only accelerate proving and long-term deployment of the technologies, but also ameliorate the Chinese people's cultural and scientific literacy, while also increasing their awareness to environmental issues. Successful CCUS projects must acquire a "social license", as Li et al. (2014) coins it, whereby the administration of public education, establishment of information disclosure systems for CCUS projects, and the promotion of public data exchange are pivotal steps if China is to unlock its local and international potential in the CCUS market.

## 3.3. Factors Driving OSW Profitability

### 3.3.1. Site Selection & Load Factors

Caralis et al. (2014) found that in the case of onshore wind, sites with higher wind potential in China generally incurred higher investment costs. This in turn offsets the additional profits that would have been otherwise generated under a high FiT levels. In other words, a tradeoff effect plays out between selecting high-energy farm sites associated with higher capital costs and others with moderate capacity factor and lower upfront costs, however the profitability rates were found to be similar. This is in part due to the fact that the influence of increased capacity factors on profitability diminishes when accounting for grid-related risks (Li et al., 2013a). It is also more prominently a direct impact of the variability in FiT levels between different geographical categories which cancel out the effect of differing capacity factors and investment costs on the profitability rates. This proves the fairness of the established FiT system for the onshore wind industry in China. For offshore wind power, taking the IRR as a profitability index makes it evident that a change of 0.1 CNY/kWh in FiT under fixed assumptions (Fig. 9) drives a 8-10% change in IRR, a quite large range that reflects the respective volatility in variable inputs. For instance, Feng et al. (2014) report a variability of 11 percentage points of wind power load factors in different locations along the coasts of Jiangsu.

This intrinsic variability in wind potential on the Chinese coastline, as well as globally, often manifests in a poor correlation between demand of electricity and its intermittent supply (Kempton et al., 2010; Yu et al., 2011). Despite this, Lu et al. (2013, 2014) envisage an imminent opportunity for offshore wind development to offset the need of building coal-fired systems to meet future demand in Jiangsu[38]. A distribution of offshore wind facilities over three coastal economic zones: Yangtze-River Delta, Bohai Bay, and Pearl-River Delta, has the potential to significantly minimise the temporal variability of overall offshore wind power output. Lu et al. (2013) acknowledge that as much as 28% of total wind capacity can be deployed as base load power to replace the requirements on capacity for coal-fired plants.

[38] Demand of electricity in Jiangsu is projected to increase from 331TWh (2009 levels) to 800TWh in 2030 (Lu et al., 2014).

In a separate study, Lu et al. (2014) propose interlinking offshore wind facilities from five Jiangsu-centered provinces and realise a potential of achieving $CO_2$ emissions reduction of 115 to 200 million $tCO_2$ relative to BAU scenarios (i.e. using coal-fired power generation). This is equivalent to a range of 29-51% in emissions abatements from potential power generation addition scenarios, equivalent to abatement costs as low as US$17/$tCO_2$ and up to US$29/$tCO_2$ under high coal-price scenario. The integration of those and this report's findings elucidates the significant opportunity that the Chinese government can exploit in cost-effectively meeting its international emission reduction commitments, when compared to more expensive technologies as CCS. If FiT levels could be enhanced to levels equal or higher than 0.85CNY/kWh, this opportunity, also shared by private investors, could be captured whilst also engaging in and promoting an industry that has a high returns portfolio at its best, and a satisfactory one (with a +85% chance of generating IRR>12%) at worst.

### 3.3.2. Feed-in-Tariffs & CDM Revenue

Many studies have recently investigated the investment signal that certified emissions reductions could send in promoting tendering offshore wind energy projects. According to reports from the World Wide Fund (WWF), revenue from the sale of CERs in the carbon market could contribute as much as 10% of the overall project investment (ECOFYS, 2008). One evident advantage from the inclusion of wind projects under the CDM, besides the obvious economic incentive, is market transparency. With no CDM, it would be virtually impossible to explore technical and economic performance data for wind projects. However, under the CDM, project developers are obliged to disclose such data in their project design documents (PDD) and the publicly-available validation and verification documents. The presence of such supporting mechanisms has the effect that, as projects have access to higher revenue, they would be able to afford higher-efficiency, higher capacity, and more costly turbines exported from international manufacturers, thus releasing the demand pressure on local turbine manufacturers.

ECOFYS (2008) foresaw an expected increase of 1.1 to 1.4 percentage points in the IRR, if investors were to undergo the CDM route. It also recognised that, due to risk factors involved with CER issuance, wind energy projects have an approximate 80% CER delivery rate. In a risk assessment model simulation by Li et al. (2013a), it was shown that the revenue from CER sales could generate a positive NPV, even if the wind power generated electricity were not fully connected to the grid. Using a real-life example, the United Nations Framework Convention on Climate Change (UNFCCC) anticipated the IRR of Shanghai Donghaidaqiao project – an offshore wind energy project with a winning bid of 0.978 CNY/kWh – to be marginally 10% even with CERs. Nonetheless, it is worthy of note that capital costs of Donghaidaqiao in 2008 were estimated at 26,000 CNY/kWh, a staggering 36-85% higher than the range of investment costs today (i.e. 14,000-19,000 CNY/kWh).

With the latest announcement that Jiangsu offshore projects are eligible for tariffs between 0.62 CNY/kWh and 0.737 CNY/kWh, a report by the Energy Storage Chinese Net (2014) as well as this study's simulations show that even an FiT level of 0.85 CNY/kWh can still be considered low for investors. The relative ambiguity in the subsidy policy support in the near future will certainly have a negative influence on the initiatives of wind power investors today (He et al., 2016). Here the role of national and local governments becomes prominent in incentivising the development of offshore wind project through preferential measures. These could include, but are not limited to, the implementation of appropriate taxations cuts, the announcement of preferential loan policies, the improvement of the quality and technical level of wind-power enterprises, the assistance of SMEs to penetrate the market, the alleviation of approval barriers for wind projects under the CDM, and the appropriate revision of the feed-in-tariffs necessary to ensure an orderly and accelerated development of the Chinese offshore wind industry.

## 3.4. Conclusion

China, the largest emerging economy, is experiencing an unprecedented demand for energy and will keep heavily relying on coal over the next few decades. The economic value and abundant supply of coal mean that China's pattern of development will not change in the foreseeable future. However, China has considered the introduction of CCUS to reduce the carbon footprint of its current and future coal-fired power plants, in order to meet its long-term legally-binding emissions abatement targets and play an important role on the international political frontier. This comes at a time when China is witnessing some booming renewable energy developments and achieving ever-changing advancements in the policy support and financial aspects of low-carbon technologies. This report undertook a holistic investment appraisal approach to demonstrate the financial status, political developments, and social and economic appeals for CCUS and offshore wind industries in China.

It is evident that CCUS technologies remain a fundamental, feasible, and strategic choice to reap multiple national benefits, from a sound and cost effective route to (alternative and permanent) emissions reductions and environmental welfare (e.g. treating industrial waste) to economic merits (e.g. through offsetting the extra cost of carbon incurred in the $CO_2$ capture stage). The $CO_2$ utilisation process is perceived as a key technology option for the sustainable social and economic development of China over the next decades (Li et al., 2015), and should be treated at the same footing with the other stages (capture, transportation, and storage). However, the lack of a Chinese national CCS-specific policy framework remains the most salient non-financial barrier to accelerating CCUS readiness.

On a project basis, an on-grid tariff of US$87/MWh, or a carbon price of US$41/t$CO_2$, is required to retrofit CCS on a USCPC coal-fired power plant. If 75% of investment costs were financed through debt, jointly with either a tag price of US$15-20/t$CO_2$ for carbon sold for $CO_2$-EOR purposes or a carbon market price not lower than US$20-25/t$CO_2$, on-grid tariffs could be reduced to levels below US$65/t$CO_2$. Furthermore, CCS projects can benefit from economic assistance provided by CCS-dedicated funds, national and local governments, and multilateral banks through grant support schemes. If a project secures a 30% grant proportion of the total project cost, it can lower the required on-grid tariff to levels as low as US$55.5/MWh, rendering clean energy generation from CCS plants more economically viable than alternative clean options (e.g. nuclear, onshore wind and gas-fired combined cycle plants).

On a global scale, the costs of developing CCUS in China remain much lower than in other more developed countries. This is attributed to the abundance of locally-sourced raw materials/commodities and the absence of constraining regulations, coupled with exceptionally low Chinese labour costs. China is also expected to soon boast one of the largest national emissions trading scheme in the world, with a high potential to bring CCUS to the market if the carbon price was substantial enough. Nonetheless, a clear and long-term climate mitigation policy should be executed as early as possible to avoid carbon lock-in investment. It is also imperative to note that, as a lack of national (and international) knowledge of CCUS's social, environmental and economic benefits persists amongst lay people, it is essential for CCUS projects to acquire a "social license" by educating the public, promoting communications policies, and enhancing information exchange and disclosure programmes.

As is expected in the nascent stages of a new technology, policy support would undergo a "trial and error" phase before reaching a clear consensus on the level of support needed, the most technology-lagging components in terms of need for further R&D activities, and on identifying the main market barriers hampering an orderly technology development. In this respect, offshore wind projects, as did onshore wind farm before them, are projected to undergo a few bidding rounds before a desirable level to both lenders and developers can be formulated. Earlier studies along with the present work advise that FIT levels be determined on a project by project basis, as projects from different areas and even along the same coastline can considerably vary in their particularities. In Jiangsu, load factors ranging from 25-32% have been reported, with an average total cost of 16.5m CNY/MW. Under these assumptions, Jiangsu-based offshore farms would required an FIT between 0.85 and 1 CNY/kWh to generate desirable IRRs (>12%) with a significantly positive NPV. Cost reductions that are corollaries of an enhanced cooperation with experienced foreign companies, and within China itself, can play a salient role in reducing the perceived risks of offshore wind investments. The Chinese Government, by setting a sustainable long-term incentive mechanism can increase demand for electricity generation from offshore wind farms, thus paving the way for the ready-to-deliver supply chain to commit funds within the industry.

# References

4coffshore (2013). Available at: http://www.4coffshore.com/ [Accessed December 5, 2015]

Administrative Centre for China's Agenda 21 (2012). *Carbon capture, transport, utilization and storage: progress and prospects*. Science Press, Beijing.

Administrative Centre for China's Agenda 21 (2014). *An Assessment Report on $CO_2$ Utilization Technologies in China*. Science Press, Beijing.

Al-Juaied, M. (2010). *Analysis of financial incentives for early CCS deployment*. Harvard Kennedy School, Belfer Center for Science and International Affairs.

Asian Development Bank (2015). *Roadmap for carbon capture and storage demonstration and deployment in the People's Republic of China*. Available at: http://hub.globalccsinstitute.com/sites/default/files/publications/197678/roadmap-carbon-capture-storage-demonstration-deployment-peoples-republic-china.pdf [Accessed January 11, 2016]

Bernstein, L., Lee, A., & Crookshank, S. (2006). Carbon dioxide capture and storage: a status report. *Climate Policy, 6*(2), pp. 241-246.

Best, D., & Levina, E. (2012). *Facing China's Coal Future: Prospects and Challenges for Carbon Capture and Storage* (No. 2012/5). Available at: http://173.254.52.9/~undersx4/wp-content/uploads/2014/03/Facing-Chinas-Coal-Future-IEA.pdf [Accessed November 21, 2015]

Bloomberg New Energy Finance & UNEP (2014). *Global trends in Renewable Energy Investment*. Available at: http://www.unep.org/pdf/Green_energy_2013-Key_findings.pdf [Accessed December 26, 2015]

Caralis, G., Diakoulaki, D., Yang, P., Gao, Z., Zervos, A., & Rados, K. (2014). Profitability of wind energy investments in China using a Monte Carlo approach for the treatment of uncertainties. *Renewable and Sustainable Energy Reviews*, *40*, pp. 224-236.

Carbon Trust (2014a). *Detailed appraisal of the offshore wind industry in China*. Available at: https://www.carbontrust.com/media/510530/detailed-appraisal-of-the-offshore-wind-industry-in-china.pdf [Accessed December 7, 2015]

Carbon Trust (2014b). *Offshore wind in China: Sharing the UK's policy experience*. Available at: https://www.carbontrust.com/media/510538/carbon-trust-offfshore-wind-policy-report.pdf [Accessed December 9, 2015]

Chen, Z. A., Li, Q., & Zhang, X. (2013). The implementation of European Energy Programme for recovery CCS demonstration projects and inspirations to China. *China Population, Resources and Environment*, *23*(10), pp. 81-86.

Chen, Z. A., Li, Q., Liu, L. C., Zhang, X., Kuang, L., Jia, L., & Liu, G. (2015). A large national survey of public perceptions of CCS technology in China. *Applied Energy*, *158*, pp. 366-377.

Duncan Coneybeare (2013). *China could lead in CCS, Utilities Unbundled Issue 14, June 2013*. Available at: http://www.ey.com/Publication/vwLUAssets/China_could_lead_in_CCS/$FILE/China_could_lead_in_CCS_UU_14.pdf [Accessed November 22, 2015]

ECOFYS (2008). *The value of carbon in China – Carbon finance and China's sustainable energy transition*. Available at: http://acs.allianz.com/files/9114/0378/5313/wwfcarbon_markets_china.pdf [Accessed December 22, 2015]

Energy Storage Chinese Net (2014). *The lagging development of offshore wind power in China*. Available at: http://www.escn.com.cn/news/show-124583.html [Accessed December 24, 2015]

Ernst & Young (2009). *Cost of and financial support for offshore wind, report for the Department of Energy and Climate Change*. Available at: http://webarchive.nationalarchives.gov.uk/+/http:/www.berr.gov.uk/files/file51142.pdf [Accessed November 26, 2015]

European Wind Energy Association (2013). *Financing offshore wind farms*. Available at: http://www.ewea.org/fileadmin/files/library/publications/reports/Financing_Offshore_Wind_Farms.pdf [Accessed December 23, 2015]

European Wind Energy Association (2014). *Wind in power – 2013 European statistics*. Available at: http://www.ewea.org/fileadmin/files/library/publications/statistics/EWEA_Annual_Statistics_2013.pdf [Accessed December 3, 2015]

He, Z., Xu, S., Shen, W., Long, R., & Yang, H. (2016). Overview of the development of the Chinese Jiangsu coastal wind-power industry cluster. *Renewable and Sustainable Energy Reviews*, *57*, 59-71.

Hong, L., & Möller, B. (2011). Offshore wind energy potential in China: under technical, spatial and economic constraints. *Energy*, *36*(7), pp. 4482-4491.

Feng, Y. H., Jiang, Y., Qiu, Y. N., Su, D. W., Li, H. F., Huang, Z., & Cui, Y. (2014). Performance Analysis of Coastal Wind Farms in Jiangsu, China. In *Applied Mechanics and Materials*, *448*, pp. 1858-1864.

Fenglifadian (2014). *The development and construction scheme of offshore wind power (2014-2016).* Available at: http://www.fenglifadian.com/news/201408/17872.html [Accessed December 12, 2015]

Finkenrath (2011). *Cost and performance of carbon capture from power generation*. Available at: https://www.iea.org/publications/freepublications/publication/costperf_ccs_powergen.pdf [Accessed January 3, 2016]

Giovanni, E., & Richards, K. R. (2010). Determinants of the costs of carbon capture and sequestration for expanding electricity generation capacity. *Energy Policy*, *38*(10), pp. 6026-6035.

Global Carbon Capture and Storage Institute (2011). *Accelerating the uptake of CCS: Industrial use of captured carbon dioxide*. Available at: http://www.globalccsinstitute.com/sites/www.globalccsinstitute.com/files/publications/14026/accelerating-uptake-ccs-industrial-use-captured-carbon-dioxide.pdf [Accessed January 10, 2016]

Global Wind Energy Council (2012). *Global wind report – annual market update 2012*. Available at: http://www.gwec.net/wp-content/uploads/2012/06/Annual_report_2012_LowRes.pdf [Accessed December 4, 2015]

Global Wind Energy Council (2013). *Global wind statistics, 2012, 11/2/2013*. Available at: http://www.gwec.net/wp-content/uploads/2013/02/GWEC-PRstats-2012_english.pdf [Accessed December 3, 2015]

Hong, L., & Möller, B. (2012). Feasibility study of China's offshore wind target by 2020. *Energy*, *48*(1), pp. 268-277.

Innovate Norway (2013). *The transition to green energy in China, Japan, and Korea – A window of opportunity for Norwegian business*. Available at: http://www.innovasjonnorge.no/Documents/old/PageFiles/4014/Energy%20report%20NEA%20v3.pdf [Accessed December 14, 2015]

International Energy Agency (2009). *World Energy Outlook 2009*. Available at: http://www.worldenergyoutlook.org/media/weowebsite/2009/WEO2009.pdf [Accessed December 28, 2015]

International Energy Agency (2011a). *Cost and performance of carbon dioxide capture from power generation*. Available at: https://www.iea.org/publications/freepublications/publication/costperf_ccs_powergen.pdf [Accessed December 28, 2015

International Energy Agency (2011b). *World Energy Outlook*. Available at: http://www.iea.org/publications/freepublications/publication/WEO2011_WEB.pdf [Accessed November 21, 2015]

International Energy Agency (2014). *Carbon capture and storage: legal and regulatory review, Edition 4*. Available at: https://www.iea.org/publications/insights/insightpublications/CCSReview_4thEd_FINAL.pdf [Accessed January 10, 2016]

Information Office of the State Council (2010). *China's Policies and Actions for Addressing Climate Change*.

Kempton, W., Pimenta, F. M., Veron, D. E., & Colle, B. A. (2010). Electric power from offshore wind via synoptic-scale interconnection. *Proceedings of the National Academy of Sciences*, *107*(16), pp. 7240-7245.

Li Junfeng (2012). *China wind power outlook*. China Environmental Science Press. Available at: http://www.gwec.net/wp-content/uploads/2012/11/China-Outlook-2012-EN.pdf [Accessed December 11, 2015]

Li, J., Liang, X., Cockerill, T., Gibbins, J., & Reiner, D. (2012a). Opportunities and barriers for implementing $CO_2$ capture ready designs: a case study of stakeholder perceptions in Guangdong, China. *Energy Policy*, *45*, pp. 243-251.

Li, J., Cai, F., Qiao, L., Xie, H., Gao, H., Yang, X., Li, X. (2012b). *China Wind Energy Outlook 2012*. Available at: http://www.gwec.net/wp-content/uploads/2012/11/China-Outlook-2012-EN.pdf [Accessed November 22, 2015]

Li, C. B., Lu, G. S., & Wu, S. (2013a). The investment risk analysis of wind power project in China. *Renewable Energy*, *50*, pp. 481-487.

Li, Q., Liu, G., Liu, X., & Li, X. (2013b). Application of a health, safety, and environmental screening and ranking framework to the Shenhua CCS project. *International Journal of Greenhouse Gas Control*, *17*, pp. 504-514.

Li, C.B., Li, P., & Feng, X. (2014a). Analysis of wind power generation operation management risk in China. *Renewable Energy*, *64*, pp. 266-275.

Li, Q., Liu, L. C., Chen, Z. A., Zhang, X., Jia, L., & Liu, G. (2014b). A Survey of Public Perception of CCUS in China. *Energy Procedia*, *63*, pp. 7019-7023.

Li, Q., Chen, Z. A., Zhang, J. T., Liu, L. C., Li, X. C., & Jia, L. (2015a). Positioning and revision of CCUS technology development in China. *International Journal of Greenhouse Gas Control*. Available at: https://www.researchgate.net/publication/273134811_Positioning_and_Revision_of_CCUS_Technology_Development_in_China [Accessed January 3, 2016]

Li, Y., Lukszo, Z., & Weijnen, M. (2015b). The implications of $CO_2$ prices for China's power sector decarbonization. *Applied Energy*, *146*, pp. 53-64.

Liang, X., Liu, H., & Reiner, D. (2014). *Strategies for Financing Large-scale Carbon Capture and Storage Power Plants in China* (No. 1430). Faculty of Economics, University of Cambridge. Available at: http://www.econ.cam.ac.uk/research/repec/cam/pdf/cwpe1430.pdf [Accessed December 27, 2015]

Liu, H., & Gallagher, K. S. (2010). Catalyzing strategic transformation to a low-carbon economy: A CCS roadmap for China. *Energy Policy*, *38*(1), pp. 59-74.

Liu, Z., Guan, D., Crawford-Brown, D., Zhang, Q., He, K., & Liu, J. (2013). Energy policy: A low-carbon road map for China. *Nature*, *500*(7461), pp. 143-145.

Lu, X., McElroy, M. B., Nielsen, C. P., Chen, X., & Huang, J. (2013). Optimal integration of offshore wind power for a steadier, environmentally friendlier, supply of electricity in China. *Energy Policy*, *62*, pp. 131-138.

Lu, X., McElroy, M. B., Chen, X., & Kang, C. (2014). Opportunity for offshore wind to reduce future demand for coal-fired power plants in China with consequent savings in emissions of $CO_2$. *Environmental science & technology*, *48*(24), pp. 14764-14771.

Ma, J., Zhang, W., Luo, L., Xu, Y., Xie, H., Xu, X., Li, Q., Zheng, J., Sheng, L. (2012). *China Energy Statistical Yearbook 2012*; China Statistics Press: Beijing. pp. 1057.

Massachusetts Institute of Technology (2007). *The future of coal*. Available at: http://web.mit.edu/coal/ [Accessed December 23, 2015]

Massachusetts Institute of Technology (2009). *Retrofitting of coal-fired power plants for $CO_2$ emissions reduction*. Available at: https://mitei.mit.edu/system/files/meeting-report.pdf [Accessed December 27, 2015]

Ministry of Science and Technology (2007). *China's Scientific and Technological Actions and Climate Change*.

Ministry of Science and Technology (2011). *Twelfth Five-Year Science and Technology Development Plan*.

Mo, J. L., Zhu, L., & Fan, Y. (2013). Carbon price stabilization mechanism and its implication for China. *Adv. Clim. Chang. Res*, *9*(5), pp. 368-375.

National Development and Reform Commission (2007). *China's National Climate Change Programme*.

National Development and Reform Commission (2008). *The 'eleventh five-year plan' of renewable energy development*. Available at: http://www.docin.com/p-5124218.html [Accessed December 26, 2015]

National Development and Reform Commission (2011). *The development guidance catalogue of renewable energy industry*. Available at: http://www.nea.gov.cn/2015-12/13/c_131051692.htm [Accessed December 12, 2015]

Near Zero Emissions Coal (NZEC) Initiative (2009). *Carbon dioxide capture from coal-fired power plants in China – Summary report for NZEC work package 3 September 2009*. Available at:

http://www.canadiancleanpowercoalition.com/files/7313/0179/5690/GS35%20-%20Techno-economic-Comparison-WP3-Final-English.pdf [Accessed December 28, 2015]

Pew Charitable Trusts (2012). *Who's winning the clean energy race?*. Available at: https://www.bnef.com/insightdownload/7504/pdf/. [Accessed December 22, 2015]

Quartz & Co. (2013). *Offshore wind China*. Available at: http://qvartz.com/wp-content/uploads/Offshore-wind-China.pdf [Accessed December 7, 2015]

Reiner, D., & Liang, X. (2009). *Stakeholder perceptions of demonstrating CCS in China.* Available at: http://www.ccs.cam.ac.uk/files/stakeholder-perceptions-of-demonstrating-ccs-in-china [Accessed December 26, 2015]

Renner, M. (2014). Carbon prices and CCS investment: A comparative study between the European Union and China. *Energy Policy*, *75*, pp. 327-340.

Rubin, E. S., Chen, C., & Rao, A. B. (2007). Cost and performance of fossil fuel power plants with $CO_2$ capture and storage. *Energy policy*, *35*(9), pp. 4444-4454.

Seigo, S. L. O., Arvai, J., Dohle, S., & Siegrist, M. (2014). Predictors of risk and benefit perception of carbon capture and storage (CCS) in regions with different stages of deployment. *International Journal of Greenhouse Gas Control*, *25*, pp. 23-32.

Sekar, R. C., Parsons, J. E., Herzog, H. J., & Jacoby, H. D. (2007). Future carbon regulations and current investments in alternative coal-fired power plant technologies. *Energy Policy*, *35*(2), pp. 1064-1074.

Siegrist, M. (2000). The influence of trust and perceptions of risks and benefits on the acceptance of gene technology. *Risk analysis*, *20*(2), pp. 195-204.

Smirnova, I., Tumanova, I., Radchenko, S.,Toma, L., Viruzab, P., Baeva, A. (2012). *Investment Attractiveness of the Offshore Wind Power Sector in the People's Republic of China.* Available at: http://www.th-nuernberg.de/fileadmin/Fachbereiche/bw/studienschwerpunkte/international_business/Master/CAIFD/SeminarPapers/Wind_Power_Sector_in_China_SeminarPaper.pdf [Accessed December 22, 2015]

Sun, S., Liu, F., Xue, S., Zeng, M., & Zeng, F. (2015). Review on wind power development in China: Current situation and improvement strategies to realize future development. *Renewable and Sustainable Energy Reviews*, *45*, pp. 589-599.

Terwel, B. W., Harinck, F., Ellemers, N., & Daamen, D. D. (2011). Going beyond the properties of $CO_2$ capture and storage (CCS) technology: how trust in stakeholders affects public acceptance of CCS. *International Journal of Greenhouse Gas Control*, *5*(2), pp. 181-188.

The Climate Group (2011). *CCUS in China – 18 key issues*. Available at: http://www.theclimategroup.org/what-we-do/news-and-blogs/report---ccus-in-china-18-key-issues/ [Accessed November 20, 2015]

Upham, P., Roberts, T., Best-Waldhober, M. D., Brunsting, S., Desbarats, J., Duetschke, E., ... & Riesch, H. (2010). *Public Perceptions of CCS: the results of Near $CO_2$ European Focus Groups*. Available at: http://www.communicationnearco2.eu/fileadmin/communicationnearco2/user/docs/Near_CO2_WP4_report_final.pdf [Accessed January 3, 2016]

US Energy Information Agency (2013). *China consumes nearly as much coal as the rest of the world combined*. Available at: http://www.eia.gov/todayinenergy/detail.cfm?id=9751 [Accessed November 20, 2015]

Van Alphen, K., tot Voorst, Q. V. V., Hekkert, M. P., & Smits, R. E. (2007). Societal acceptance of carbon capture and storage technologies. *Energy Policy*, *35*(8), pp. 4368-4380.

Viebahn, P., Vallentin, D., & Höller, S. (2015). Prospects of carbon capture and storage (CCS) in China's power sector–An integrated assessment. *Applied Energy*, *157*, pp. 229-244.

Wallquist, L., Visschers, V. H., & Siegrist, M. (2010). Impact of knowledge and misconceptions on benefit and risk perception of CCS. *Environmental science & technology*, *44*(17), pp. 6557-6562.

Wallquist, L., Seigo, S. L. O., Visschers, V. H., & Siegrist, M. (2012). Public acceptance of CCS system elements: a conjoint measurement. *International Journal of Greenhouse Gas Control*, *6*, pp. 77-83.

Wind Power Monthly. (2013). *Analysis - China unable to achieve 5GW offshore wind goal by 2015*. Available at: http://www.windpowermonthly.com/article/1187293/analysis-china-unable-achieve-5gw-offshore-wind-goal-2015 [Accessed December 11, 2015]

World Bank (2010). *China: Meeting the challenges of offshore and large-scale wind power*. Available at: http://www-wds.worldbank.org/external/default/WDSContentServer/WDSP/IB/2015/09/30/090224b0828b4401/1_0/Rendered/PDF/China000Meetin0e0European0countries.pdf [Accessed December 23, 2015]

World Bank and ECOFYS (2014). *State and trends of carbon pricing 2014*. Available at: http://wwwwds.worldbank.org/external/default/WDSContentServer/WDSP/IB/2015/06/01/090224b0828bcd9e/1_0/Rendered/PDF/State0and0trends0of0carbon0pricing02014.pdf [Accessed January 3, 2016]

World Bank (2015). *China overview*. Available at: http://www.worldbank.org/en/country/china/overview [Accessed November 20, 2015]

Wu, N., Parsons, J. E., & Polenske, K. R. (2013). The impact of future carbon prices on CCS investment for power generation in China. *Energy Policy*, *54*, pp. 160-172.

Wu, J., Wang, Z. X., & Wang, G. Q. (2014). The key technologies and development of offshore wind farm in China. *Renewable and Sustainable Energy Reviews*, *34*, pp. 453-462.

Xie, H., Li, X., Fang, Z., Wang, Y., Li, Q., Shi, L., ... & Hou, Z. (2014). Carbon geological utilization and storage in China: current status and perspectives.*Acta Geotechnica*, *9*(1), pp. 7-27.

Xiliang, Z., Da, Z., & Stua, M. (2012). *Kickoff of Offshore Wind Power in China: Playoffs for China Wind Power Development*. Available at: http://sro.sussex.ac.uk/47233/1/Kickoff_of_Offshore_Wind_Power_in_China.pdf [Accessed December 10, 2015]

Yang, F., Chen, S., Zhang, X., & Wang, Z. (2015). *The Development and Operation of Offshore Wind Farms in China*. Available at: http://www.atlantis-press.com/php/download_paper.php?id=19590 [Accessed December 15, 2015]

Yang, L., Zhang, X., & McAlinden, K. J. (2016). The effect of trust on people's acceptance of CCS (carbon capture and storage) technologies: Evidence from a survey in the People's Republic of China. *Energy*, *96*, pp. 69-79.

Yu, D., Liang, J., Han, X., & Zhao, J. (2011). Profiling the regional wind power fluctuation in China. *Energy Policy*, *39*(1), pp. 299-306.

Yuanyuan, Liu (2012). *China increases target for wind power capacity to 1,000 GW by 2050*. Available at: http://www.renewableenergyworld.com/articles/2012/01/china-increases-target-for-wind-power-capacity-to-1000-gw-by-2050.html [Accessed December 6, 2015]

Zhang, Z.X. (2011a). In what format and under what timeframe would china take on climate commitments? A roadmap to 2050. *International Environmental Agreements: Politics, Law and Economics*, *11* (3), pp. 245-259.

Zhang, Z.X. (2011b). Assessing China's carbon intensity pledge for 2020: stringency and credibility issues and their implications. *Environmental Economics and Policy Studies*, *13* (3), pp. 219-235.

Zhang, D., Karplus, V. J., Cassisa, C., & Zhang, X. (2014a). Emissions trading in China: Progress and prospects. *Energy policy*, *75*, pp. 9-16.

Zhang, X., Wang, X., Chen, J., Xie, X., Wang, K., & Wei, Y. (2014b). A novel modeling based real option approach for CCS investment evaluation under multiple uncertainties. *Applied Energy*, *113*, pp. 1059-1067.

Zhao, L., Xiao, Y., Gallagher, K. S., Wang, B., & Xu, X. (2008). Technical, environmental, and economic assessment of deploying advanced coal power technologies in the Chinese context. *Energy Policy*, *36*(7), pp. 2709-2718.

Zhao, X. G., & Ren, L. Z. (2015). Focus on the development of offshore wind power in China: Has the golden period come?. *Renewable Energy*, *81*, pp. 644-657.

Zhou, W., Zhu, B., Fuss, S., Szolgayová, J., Obersteiner, M., & Fei, W. (2010). Uncertainty modeling of CCS investment strategy in China's power sector. *Applied Energy*, *87*(7), pp. 2392-2400.

Zhu, L., & Fan, Y. (2011). A real options–based CCS investment evaluation model: Case study of China's power generation sector. *Applied Energy*, *88*(12), pp. 4320-4333.

# Appendices

## Appendix I

**Table1A.** Summary of international CCS policy actions.

| Country | Regulatory Framework or Standard | Economic Incentives |
|---|---|---|
| **United States** | "Class VI" regulations for geological storage developed by US Environmental Protection Agency under Underground Injection Control Program and finalized in 2010; no projects permitted under the rule so far | • Federal funding for demonstrations (US$5 billion)<br>• Loan guarantee program (new US$8 billion program announced in 2014)<br>• Tax credits for $CO_2$ storage (US$10/ton for EOR and US$20/ton for storage)<br>• Proposed performance standards for new plants |
| **United Kingdom** | European Union Directive transposed Energy Act (2011) allows reuse of existing pipelines and infrastructure for CCS | Under electricity market reform of July 2011:<br>• Emission performance standards (new coal only with CCS)<br>• Carbon price floor<br>• Contract for difference<br>• Proposed emission reduction targets for electricity sector |
| **Australia** | • Offshore Petroleum and Greenhouse Gas Storage Regulations 2011<br>• Onshore regulated at state level | • A$23/ton carbon price<br>• A$1.68 billion in government funds for CCS Flagship Program |
| **Europea n Union** | Directive 2009/31/EC on geological storage of carbon dioxide transposed by the following countries into national law: Czech Republic, Finland, France, Germany, Ireland, Italy, Netherlands, Poland, Romania, Spain, an the United Kingdom | • European Union emissions trading scheme<br>• CCS funding planned under New Entrants Reserve and 79 projects applied; value estimated at €4-5 billion |
| **Canada** | • Canadian Standards Association published CCS standards under Z741-12<br>• State-level regulations adopted in Saskatchewan and Pipelines Act (1998), administered by Ministry of Energy and Resources | • Emission performance standard requiring new and old coal plants to be as efficient as natural gas plants; plants using 30% CCS can receive deferral<br>• Public funding for demonstrations totaling Can$3 billion |
| **Norway** | CCS-specific regulations still pending; draft regulations to be released simultaneously by Ministries of the Environment and Petroleum and Energy at some future date | • CCS requirement for natural gas developments (including future power plants)<br>• $CO_2$ tax applied to offshore developments. |

**Sources:** IEA (2014), ADB (2015)

**Table 2A.** CCUS international cooperation projects in China.

| Timeline | Project | Objectives | Chinese Host & Participants |
|---|---|---|---|
| **2006-2009** | Cooperation Action within CCS China–EU (COACH) | Application of carbon capture technology in coal-fired power plants, assessment of China's $CO_2$ geological storage potential, laws, regulations and financing mechanisms, etc. | ACCA21, Tsinghua University, Zhejiang University, Institute of Engineering Thermophysics, CAS, Xi'an Thermal Power Research Institute Co., Ltd, and GreenGen Corporation Limited. |
| **2007-2009** | China-EU Near Zero Emissions Coal (NZEC) cooperation, phase I and phase II (in 2013) | Enhance knowledge transfer and sharing; Modeling future energy requirements of China, taking CCS technology into account; Undertake case studies of potential $CO_2$ capture technologies; Build capacity in China for the evaluation of storage potential for $CO_2$; Perform initial screening of potential sites appropriate for geological storage of $CO_2$. | ACCA 21, Thermal power Research Institute, Tsinghua University, Thermal Physics Institute, CAS, etc. |
| **2008-2009** | Support of Regulatory Activities For Carbon Capture and Storage | Promote and strengthen S&T cooperation in the field of CCS within EU; Study and define major issues which must be considered in developing CCS regulatory framework; Promote international cooperation between EU and China in the field of CCS. | ACCA 21, Institute of Engineering Thermophysics, CAS, and Institute of Policy and Management, CAS. |
| **2009-2011** | China-Australia Geological Storage of $CO_2$ (CAGS) phase I, and phase [illegible] | Enhance the development and practice of science and technology in the field of $CO_2$ geological sequestration both in China and Australia. | ACCA 21, China Geological Survey, Institute of Rock and Soil Mechanics, CAS, Chinese Academy for Environmental Planning, Tsinghua University, etc. |
| **2010-2012** | Sino-Italy Cooperation on CCS Technology (SICCS) | Information exchange and basic research based on existing CCS activities of the two countries; Pre-feasibility study with a focus on capture, compression and transportation of $CO_2$ as well as systematic integration, safety, environmental impact, and economic evaluation; | ACCA 21, China Huaneng Group, Tsinghua University, etc. |

**Sources:** ACCA 21 (2012); Li et al., (2013b); Xie et al. (2013)

# Appendix III

**Table 3A.** Simulation results of sensitivity analysis of required on-grid tariffs, NPV, LCOE, and cost of carbon avoidance to changes in coal prices and required rates of return (with 50:50 financial leverage and 12% discount rate). Values in bold denote negative NPVs.

| Fuel Price ($/GJ) | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| 3.5 | | | | | 4 | | | | |
| Tariff ($/MWh) | Carbon Cost ($/tCOe) | NPV ($/GW) | IRR % | LCOE ($/MWh) | Tariff ($/MWh) | Carbon Cost ($/tCOe) | NPV ($/GW) | IRR % | LCOE ($/MWh) |
| 78.49 | 27.4 | **153,667,456** | 5.0% | 92.2 | 83.3 | 35.2 | **154,243,140** | 5.0% | 97.4 |
| 78.90 | 28.0 | **137,860,515** | 6.0% | 92.3 | 83.6 | 35.8 | **138,282,733** | 6.0% | 97.5 |
| 79.37 | 28.6 | **119,685,821** | 7.0% | 92.4 | 84.1 | 36.4 | **120,042,268** | 7.0% | 97.5 |
| 79.88 | 29.3 | **99,296,840** | 8.0% | 92.4 | 84.5 | 37.1 | **99,653,287** | 8.0% | 97.6 |
| 80.42 | 30.1 | **76,934,732** | 9.0% | 92.5 | 85.0 | 37.9 | **77,291,179** | 9.0% | 97.7 |
| 81.01 | 30.9 | **53,037,969** | 10.0% | 92.6 | 85.6 | 38.7 | **53,175,180** | 10.0% | 97.8 |
| 81.63 | 31.8 | **27,168,079** | 11.0% | 92.7 | 86.2 | 39.6 | **27,305,290** | 11.0% | 97.9 |
| 82.28 | 32.7 | 0 | 12.0% | 92.9 | 87.5 | 40.5 | 0 | 12.0% | 98.0 |
| 82.96 | 33.7 | 28,517,956 | 13.0% | 93.0 | 88.1 | 41.5 | 28,599,981 | 13.0% | 98.1 |
| 83.66 | 34.7 | 58,114,864 | 14.0% | 93.1 | 88.1 | 42.6 | 58,416,125 | 14.0% | 98.3 |
| 84.37 | 35.8 | 88,807,953 | 15.0% | 93.2 | 89.6 | 43.6 | 89,109,215 | 15.0% | 98.4 |
| 85.11 | 36.9 | 120,246,447 | 16.0% | 93.4 | 90.3 | 44.7 | 120,679,251 | 16.0% | 98.5 |
| 85.86 | 38.0 | 152,605,733 | 17.0% | 93.5 | 91.0 | 45.8 | 153,126,231 | 17.0% | 98.7 |
| 86.63 | 39.1 | 185,491,186 | 18.0% | 93.6 | 91.8 | 47.0 | 186,230,921 | 18.0% | 98.8 |
| 87.40 | 40.3 | 219,034,349 | 19.0% | 93.8 | 92.6 | 48.1 | 219,774,083 | 19.0% | 98.9 |
| 88.24 | 41.5 | 253,015,984 | 20.0% | 93.9 | 93.5 | 49.3 | 253,974,955 | 20.0% | 99.1 |

| Fuel Price ($/GJ) | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| 4.5$ | | | | | 5$ | | | | |
| Tariff ($/MWh) | Carbon Cost ($/tCOe) | NPV ($/GW) | IRR % | LCOE ($/MWh) | Tariff ($/MWh) | Carbon Cost ($/tCOe) | NPV ($/GW) | IRR % | LCOE ($/MWh) |
| 88.80 | 43.0 | **155,038,059** | 5.0% | 102.6 | 94.0 | 50.8 | **155,613,743** | 5.0% | 107.7 |
| 89.22 | 43.6 | **138,814,569** | 6.0% | 102.6 | 94.4 | 51.4 | **139,521,794** | 6.0% | 107.8 |
| 89.69 | 44.2 | **120,398,715** | 7.0% | 102.7 | 94.8 | 52.0 | **121,105,941** | 7.0% | 107.9 |
| 90.20 | 44.9 | **99,790,498** | 8.0% | 102.8 | 95.4 | 52.7 | **100,366,181** | 8.0% | 107.9 |
| 90.75 | 45.7 | **77,428,390** | 9.0% | 102.9 | 95.9 | 53.5 | **78,004,073** | 9.0% | 108.0 |
| 91.34 | 46.5 | **53,312,390** | 10.0% | 103.0 | 96.5 | 54.3 | **53,449,601** | 10.0% | 108.1 |
| 91.97 | 47.4 | **27,442,500** | 11.0% | 103.1 | 97.1 | 55.2 | **27,360,475** | 11.0% | 108.3 |
| 92.62 | 48.4 | 0 | 12.0% | 103.2 | 97.8 | 56.2 | 0 | 12.0% | 108.4 |
| 93.30 | 49.3 | 28,682,007 | 13.0% | 103.3 | 98.5 | 57.2 | 28,764,032 | 13.0% | 108.5 |
| 94.01 | 50.4 | 58,498,151 | 14.0% | 103.4 | 99.2 | 58.2 | 58,799,413 | 14.0% | 108.6 |
| 94.73 | 51.5 | 89,629,714 | 15.0% | 103.6 | 99.9 | 59.3 | 89,711,739 | 15.0% | 108.7 |
| 95.47 | 52.5 | 121,199,749 | 16.0% | 103.7 | 100.7 | 60.4 | 121,720,247 | 16.0% | 108.9 |
| 96.23 | 53.7 | 153,646,729 | 17.0% | 103.8 | 101.4 | 61.5 | 154,167,228 | 17.0% | 109.0 |
| 97.00 | 54.8 | 186,970,656 | 18.0% | 104.0 | 102.2 | 62.6 | 187,491,154 | 18.0% | 109.1 |
| 97.78 | 56.0 | 220,733,054 | 19.0% | 104.1 | 103.0 | 63.8 | 221,253,553 | 19.0% | 109.3 |
| 98.46 | 57.2 | 254,933,926 | 20.0% | 104.3 | 103.7 | 65.0 | 255,454,424 | 20.0% | 109.4 |

## Appendix IV

Benchmark feed-in tariffs for the four regions (categories) of onshore wind power projects in China are divided as follows:

- **Category I:** with benchmark FIT 0.51 CNY for sites located in Inner Mongolia autonomous region except: Chifeng, Tongliao, Xing'anmeng, Hulunbeier; Xinjiang Uygur autonomous region: Urumqi, Yili, Karamay,and Shihezi.
- **Category II:** with benchmark FIT 0.54 CNY for sites located in Hebei province: Zhangjiakou, Chengde; Inner Mongolia auton- omous region: Chifeng, Tongliao, Xing'anmeng, Hulunbeier; Gansu province: Zhangye, Jiayuguan,and Jiu.
- **Category III:** with benchmark FIT 0.58 CNY for sites located in Jilin province: Baicheng, Songyuan; Heilongjiang province: Jixi, Shuangyashan, Qitaihe, Suihua, Yichun, Daxinganling region, Gansu province except Zhangye, Jiayuguan, Jiuquan, Xinjiang autonomous region except Urumqi, Yili, Changji, Karamay, Shihezi,and Ningxia Hui autonomous region.
- **Category IV:** with benchmark FIT 0.61 CNY for sites located in all the other parts of China not mentioned above.

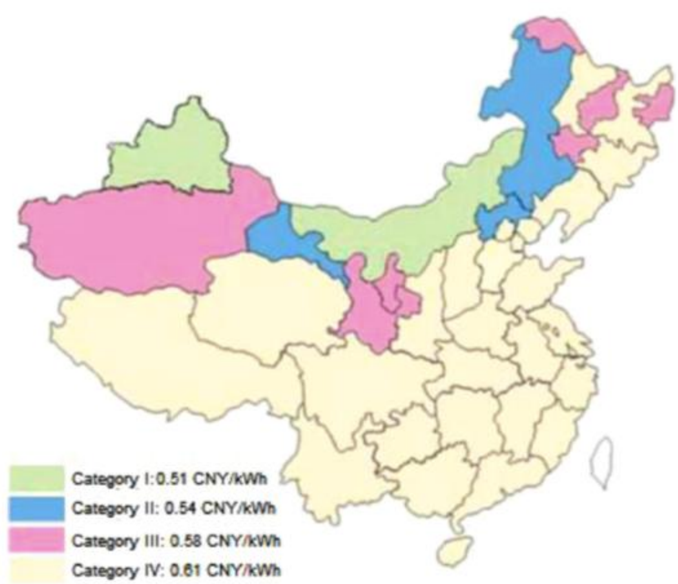


**Figure 1A.** Distribution of benchmark FiTs for onshore wind projects in China.

Having only begun to firmly develop in 2007, the Chinese offshore wind power sector was poised to reach 5GW by 2015 and 30GW by 2020, as delineated by the Chinese Government in its "twelfth five-year plan" of wind power (Zhao & Ren, 2015). Counter-intuitively, the growth of the sector was rather slower than expected (only 428.6MW [less than 10%] of the 2015 plan objectives were installed by 2013 (4coffshore, 2013). It wasn't until August 2014, when the NDRC imposed the "offshore wind power feed-in tariff policy" and backed the steady development of offshore wind power.

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