Comparative Life-cycle Assessment of Non-fossil Electricity Generation Technologies: China 2030 Scenario Analysis

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Abstract

Replacement of fossil fuels with alternative sources of electricity requires additional inputs for energy conversion, transmission, and distribution equipment. The low density and intermittency of renewable energy sources necessitates a high ratio of capacity additions to substitute for a given amount of fossil fuel generation. Lifecycle assessment of the energy, water, and emissions implications of renewable electricity generation technologies quantifies the input requirements, tradeoffs, and feasibility of large-scale electricity transition.

China has the world's fastest growing electricity system in terms of total scale and renewable electricity generation. The Chinese government has published a renewable energy target of 20% of primary energy use by 2020. Electricity generation is expected to grow at more than 4% per year through 2030, from 3,000 TWh in 2008 to almost 10,000 TWh in 2030. This study performs a hybrid LCA of selected electricity generation technologies to quantitatively assess the energy, water, and carbon dioxide emissions implications of achieving a renewable energy mix in China by 2030 that would be consistent with a long-term global atmospheric carbon concentration of 450 ppm. The electricity generation technologies covered here include wind, nuclear, solar PV, concentrated solar power, coal combustion, and hydro-power. This study's results indicate that moving from a reference to 450 ppm electricity generation trajectory in China would yield significant energy, water, and emissions savings over the lifecycle of the generation equipment.

Contents

1. Introduction

In 2007, China surpassed the United States to become the largest emitter of energy-related carbon dioxide (Levine 2008). Total Chinese energy use grew at an average annual growth rate of 9% between 2000 and 2009, and more than 90% of 2009 energy use was from fossil fuels (NBS, 2010). In order to address energy security, local environment, and global climate change concerns, the Chinese government has set ambitious targets for increased renewable energy use. The current government renewable energy target is to derive 20% of primary energy from renewable (non-fossil) sources by 2020.

Replacement of fossil fuels with renewable sources of electricity requires additional inputs for energy conversion, transmission, and distribution equipment. The low density and intermittency of renewable energy sources necessitates a high ratio of capacity additions to substitute for a given amount of fossil fuel generation. This project uses lifecycle assessment of renewable electricity generation technologies to quantify the input requirements, tradeoffs, and feasibility of large-scale electricity transition. Hybrid LCA of hydro-power, coal-fired, solar PV, concentrated solar power (CSP), wind, and nuclear generation technologies are used to assess the energy, material, water, and emissions implications of achieving a renewable energy mix in China consistent with global atmospheric carbon concentrations of 450 ppm.

The first portion of this study is comprised of a comparative LCA of solar PV, CSP, wind, nuclear, coal-fired, and hydro-power electricity generation. The outputs of the LCA are total energy use and production, water use, and related carbon dioxide-equivalent emissions for each of these technologies. The second portion of the study examines the implications of moving from the IEA's *World Energy Outlook 2010* Reference Case Scenario for China's electricity generation in 2030 to their 450 ppm Scenario, which includes more aggressive renewable electricity generation growth.

2. Existing Research

2.1. Renewable Electricity Generation Technologies

2.1.1 Hydropower

Assuming sustainable dam operations, hydropower is a renewable energy source, that has been commonly included in previous global comparative LCA for electricity generation systems (Gagnon 2006, Dones 2003, Svensson 2002), generally yielding high environmental performances in terms of energy requirements and green house gas emissions, with impacts sometimes orders of magnitude beneath other energy sources (Dones 2003).

However, the wide variety of types, size, purposes and implementation sites for hydropower infrastructures (Table 1) complicates the generalization of these previous studies that are mainly based on data from Switzerland, Sweden, Finland or Canada, where environmental monitoring is intensive. The life cycle phases entailing the largest environmental impact are typically the manufacture and construction of the dam and equipment (Dones 2003), which are largely dependent on the dam material and design, as well as on the site geology. Moreover, the global warming potential linked to greenhouse gases emitted by the flooded reservoir and to the inability of the flooded vegetation to sequestrate carbon is mainly linked to the site topography, vegetation and climate, and should not be underestimated (Gagnon 1996).

Table 1. Main governing parameters of hydropower plants

Type	Main Purpose	Size	Site
Run of River	Hydropower	Hydro	Hydrology
Rock filled dam	Flood control	Small hydro (<100MW)	Geology
Earth filled dam	Irrigation	Mini hydro (<10MW)	Topography
Gravity dam	Drinking water supply	Micro hydro (< 1MW)	Vegetation
Arch dam	Leisure	Pico hydro (<100kW)	Climate

Nonetheless, relevant for this assessment on China are two particular papers. Zhang (2007) has completed a life cycle inventory of two representative Chinese dams through an economic input output life cycle analysis (EIO-LCA). The study considers a medium (44MW) rock filled embankment dam and a large (3.6GW) concrete arch dam; it is based on primary economic data collected on site in China and disaggregated in life phases. However, Zhang (2007) uses the US economic input output matrix as a proxy. Based on the economic data collected by Zhang (2007), a new EIO-LCA based on the recently available environmental impact matrix for China (CMU 2009) is proposed in this paper to model the environmental impact of conventional hydropower production. Yet neither small and run-of-river plants, nor very large hydropower projects are well modeled by these two categories because of scale effects. Gagnon (2006) observed life cycle emission factors decreasing with the capacity of the hydropower project.

Unfortunately most of the existing data on small hydro is from alpine projects (Bauer 2007) and not particularly representative of Chinese conditions, per se. No relevant data is thus available to model the numerous small and run of river plants in China. Them being represented by the impact calculated for the 44MW dam is thus certainly a source of modeling uncertainty, which nonetheless does not significantly affect the results of the study, as small hydro power (< 10 MW) represented only 3.5% of the 638GW of China installed hydro in 1999 (Fuggle 2000). At the other extreme of the capacity range, Ribeiro (2010) has established a very detailed process LCA for Itaipu dam (Brazil), which is the only hydropower complex even close to matching projects like the Three Gorges dam in terms of size, power and dam type, and will thus serve as a proxy to model China's largest dams.

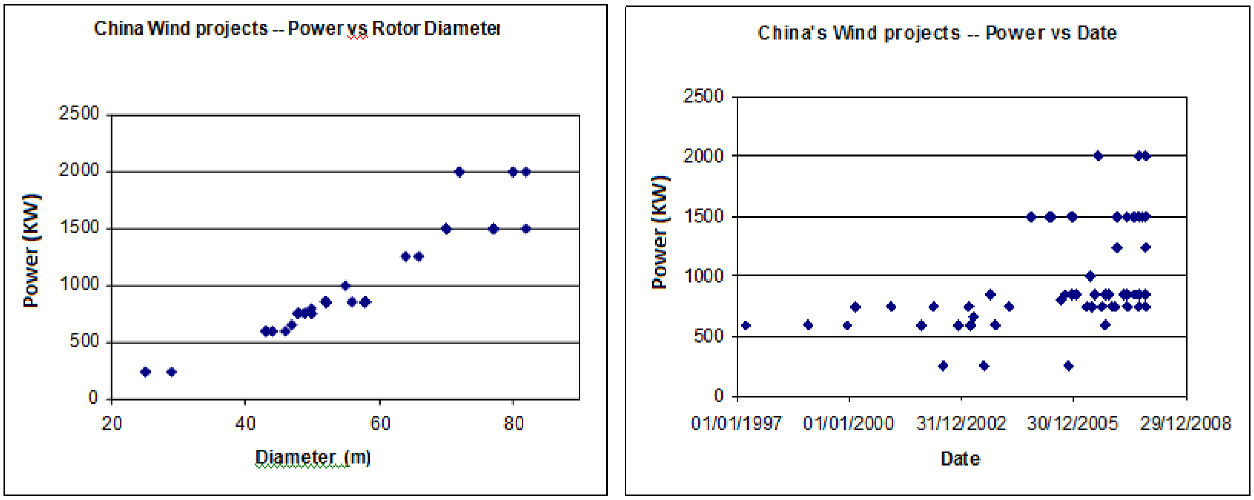
2.1.2 Wind Power

Wind power has undergone a tremendous development in the last two decades and is expected to be one of the most cost-effective and convenient renewable energy technologies to tackle climate change. Wind turbines can be operated onshore and offshore. The latter offers better capacity factor and don't challenge other land potential use.

Several LCA studies have been done on energy return ratio and on greenhouse gas emissions (Martinez 2007, Vestas 2006). Lanzen (2001) and Kubizewski (2009) review different LCA done on wind turbine; the average energy return on investment (EROI) based on these reviews of 132 studies is 25.2, thus positioning wind power today as the least energy intensive electricity (Kubizewski 2009). Both of the studies suggest that increasing tower heights and turbine diameters increase the EROI while decreasing the CO2 emission factors. Therefore, the current trend leads to larger turbines: 2MW is the current standard and 5MW turbines are expected to dominate the market in the near future. With heights reaching 200 meters, this ever growing trend is expected to be limited for logistical and practical installation reasons.

In published Chinese wind studies, the capacity of individual turbines increases linearly with their diameter (Figure 1), while higher towers enables catching more powerful and more regular wind leading to better capacity factors. Figure 1 also displays the evolution of the capacity of Chinese wind project over time. While most projects before 2000 were based on 500 to 1000 kW wind turbines, a threshold has been reached in 2005 with the commissioning of 1.5 MW and 2.0 MW turbines. The current practice in China involves the commissioning of projects with 2 to 3 MW turbines (CWPC, 2010). China became in end 2009 the second largest producer of wind power (Global Wind Energy Council) and is now the largest developer in the world. The country is expected to be the leader in the wind energy sector as soon as 2011.

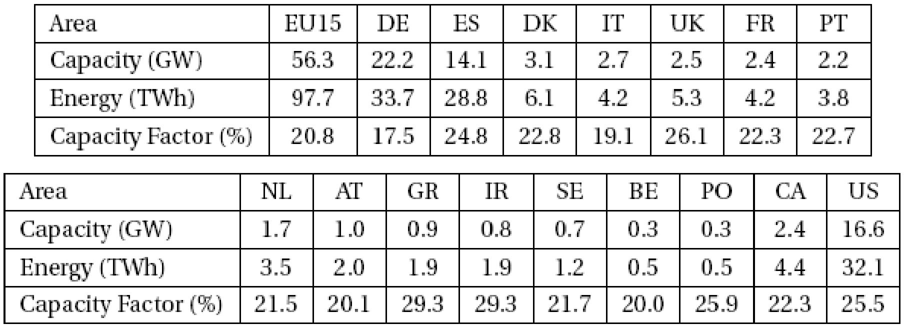
Figure 1: China wind projects power versus rotor diameter and scale over time (kW)



Source: (China Wind Power Center, data available until 2008, accessed October 2010)

The claimed capacity factor is among the most sensitive parameters in wind life cycle assessments. Wind doesn't always blow with the expected intensity on the turbines, yielding to a significant uncertainty on the capacity factor. Yet recent turbines are much taller than the previous generations and catch a stronger and more regular wind. Hence the capacity factor becomes better with time. On Figure 2, capacity factors for different European countries and for the US are shown. China's officially stated average capacity factor was 20% in 2008 (CWPC 2008 report), which is very close the European one. In this study, the capacity factors forecasted by the European agency for wind power (EWEA) will be applied: 29.8% for onshore wind turbines and 45% for offshore wind turbines.

Figure 2: Average 2003-2007 wind power capacity factor in EU and USA



Area	EU15	DE	ES	DK	IT	UK	FR	PT
Capacity (GW)	56.3	22.2	14.1	3.1	2.7	2.5	2.4	2.2
Energy (TWh)	97.7	33.7	28.8	6.1	4.2	5.3	4.2	3.8
Capacity Factor (%)	20.8	17.5	24.8	22.8	19.1	26.1	22.3	22.7

Area	NL	AT	GR	IR	SE	BE	PO	CA	US
Capacity (GW)	1.7	1.0	0.9	0.8	0.7	0.3	0.3	2.4	16.6
Energy (TWh)	3.5	2.0	1.9	1.9	1.2	0.5	0.5	4.4	32.1
Capacity Factor (%)	21.5	20.1	29.3	29.3	21.7	20.0	25.9	22.3	25.5

Source: (Boccard, 2008).

2.1.3. Solar Photovoltaic (PV) and Concentrated Solar Power (CSP)

Interest in renewable electricity generation has spurred research in a range of solar technologies from conventional PV to concentrating solar thermal technologies (Table 2). For example, recent research has found that unconventional PV generation with alternative semiconducting materials such as FeS2, CuO, and Zn3P2 can deliver the same lifetime energy output as high-grade silicon when material reduction is achieved (Wadia 2009). Rather than speculating on solar power technology evolution, this report focuses on existing, proven PV and CSP technology.

The two most common metrics for evaluating PV technology are the energy payback time (EPBT) and the carbon intensiveness of electricity production (g CO2/kWh). The energy and carbon intensity of solar PV module production depends on the type of solar cell, panel orientation and angle, local solar irradiation resource, type of installation, efficiency of the balance of system (BOS) components, system capacity, lifetime, conversion efficiency degradation rate, and status quo local electricity mix.

Table 2: Summary of PV and CSP LCA Literature

Reference	**Summary**
Azzopardi and Mutale (2010)	Compares hybrid quantum dot with conventional PV technologies; results show that lifetime must be more than 1 year and efficiency greater than 1% for net-energy ratio (NER) to be greater than 1 (minimum threshold for sustainability)
Fthenakis and Alsema (2006)	Quantitative review of EPBT and GHG emissions for multi- and mono-crystalline wafers and ribbon technologies and cadmium telluride (CdTe) PV ground installations using 2004 data; BOS lifecycle energy requirement estimated at 542 MJ/m^2 and 29 kg CO2e/m^2; EPBT for complete installed PV system range from 1-2.7 years, GHG emissions range from 21-59 gCO_2e/kWh, depending on irradiation and other factors
Li, et al. (2007)	Forecasts China cumulative installed PV capacity between 10 and 100 GW in 2030
Nawaz and Tiwari (2006)	EPBT is in the range of 7-26 years, depending on solar radiation, PV efficiency, and BOS
Pacca, et al. (2007)	Comparative assessment finds that thin-film has better performance than multi-crystalline in terms of Net Energy Ratio (NER; 5 versus 3); EPBT (3 years versus 7); and carbon-intensiveness (g CO_2/kWh; 30 versus 70)
Sherwani, et al. (2010)	Comparative assessment finds that best PV technology is amorphous followed by poly-crystalline, followed by mono-crystalline PV; thin-film (amorphous) modules have lower primary energy embodiment, but also lower efficiency (6-10% versus 10-16% for poly-crystalline PV)
Ito, et al. (2009)	Comprehensive LCA of six types of PV (multi-crystalline silicon, single-crystalline silicon, amorphous silicon, thin film silicon, CIS, and CdTe) for hypothetical installation in the Gobi Desert (in China and Mongolia); EPBT ranges from 2.1-2.8 years
Lechon, et al. (2006)	LCA of two concentrated solar power plants in Spain; EPBT calculated as 12.2 months for central tower system and 12.5 months for parabolic trough system; 203 g CO2e/kWh for central tower and 185 g CO2e/kWh for parabolic trough system

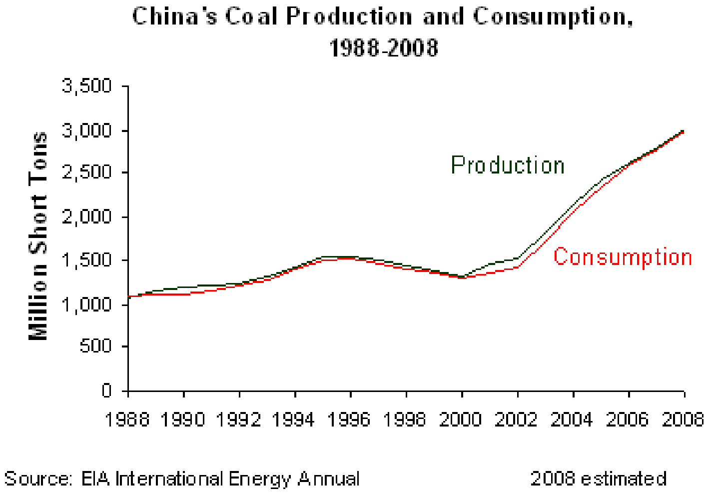
Although CSP is less costly than PV, it has not been deployed or written about as widely. The Lechon, et al. (2006) data on CSP in Spain serve as proxy data for examining CSP deployment in China.

2.1.4. Coal

Coal is responsible for 70 percent of China's total primary energy consumption, and China is both the largest consumer and producer of coal in the world (IEA website). According to the

International Energy Agency, China holds an estimated 114.5 billion short tons of recoverable coal reserves, the third-largest in the world behind the United States and Russia and about 13 percent of the world’s total reserves. There are 27 provinces in China that produce coal. Northern China, especially Shanxi Province, contains most of China's easily accessible coal and virtually all of the large state-owned mines. Coal from southern mines tends to be higher in sulfur and ash, and therefore unsuitable for many applications. In 2008, China consumed an estimated 3 billion short tons of coal (Figure 3), representing nearly 40 percent of the world total and a 129 percent increase since 2000. Coal consumption has been on the rise in China over the last eight years, reversing the decline seen from 1996 to 2000. More than 50 percent of China’s coal use in 2006 was in the non-electricity sectors, primarily in the industrial sector. The other 50 percent is used in the power sector.

Figure 3: China Coal Production and Consumption, 1988-2008

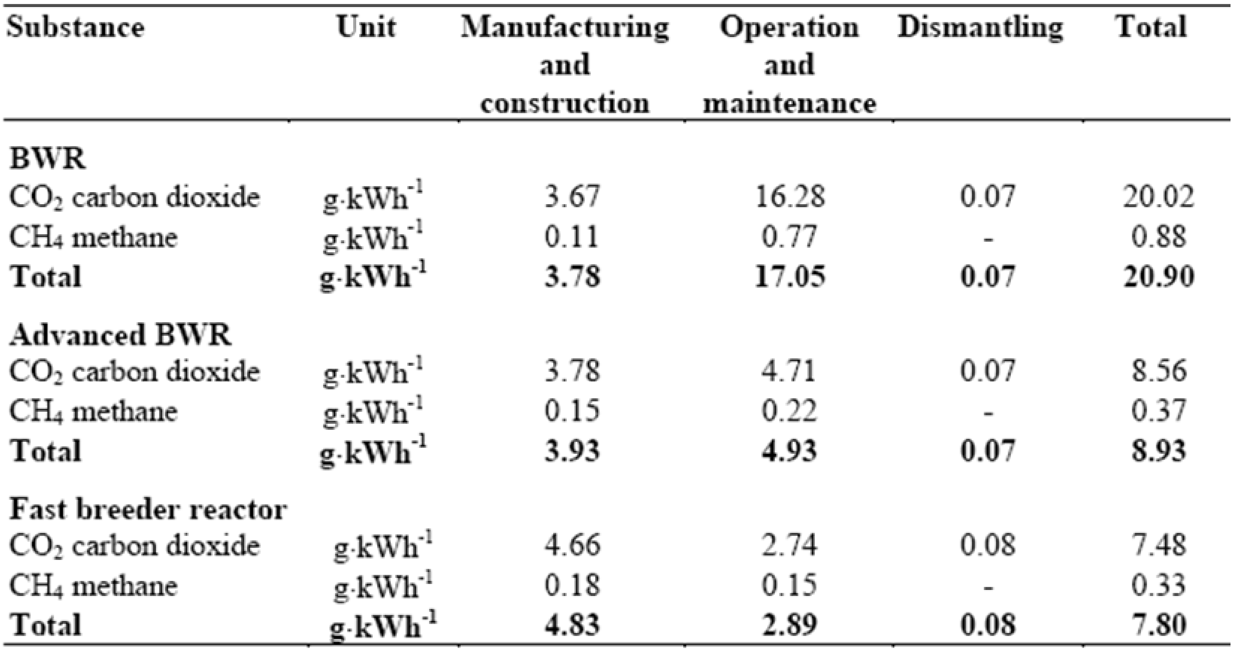


Life cycle assessments from Xi (2007) and Dones (2007) reveal that more than 90% of CO2 emissions are due to the combustion of coal fuel itself, while construction of the infrastructure is considered negligible. Finally, although the impact is not considered in this paper, coal fired generation is also mentioned to be responsible for emissions of other toxic gazes, especially SO2, which is largely responsible for acidification.

2.1.5. Nuclear

The amount of literature on the internet about LCA of nuclear power generation is limited compared to conventional energies generation or even compared with lower cost types of energy supply such as wind power or solar. First, the decommissioning stage of the power plant is still very difficult to model. Too few nuclear power plants have been already decommissioned to provide a statistical relevant view of the stage. Secondly in the nuclear field, the risk of accident should be accounted, especially in term of environmental impact. But two factors are still difficult to assess: the probability of accident and the consequences of an accident. Those two factors depend on where the plant is located. A general LCA for nuclear generation is thus very difficult to perform. In our Chinese case, we focus on the material requirement, on the energy requirement and on the CO2 emitted by the life cycle of various sources of energies. In case of no accident and easy decommissioning, environmental impacts are mainly occurring during the plant construction and during the supply chain of the uranium fuel, say transport, mining and enrichment (Svensson 2002). Even though uranium is present worldwide, only a few soils have a concentration high enough to allow a profitable mining. Thus the uranium production occurs mainly in Canada, USA, Australia, South Africa and Nigeria (IEA website).

Figure 4: Lifecycle greenhouse gas emissions from Japanese nuclear power plants



Substance	Unit	Manufacturing and construction	Operation and maintenance	Dismantling	Total
BWR					
CO_2 carbon dioxide	$g \cdot kWh^{-1}$	3.67	16.28	0.07	20.02
CH_4 methane	$g \cdot kWh^{-1}$	0.11	0.77	-	0.88
Total	$g \cdot kWh^{-1}$	**3.78**	**17.05**	**0.07**	**20.90**
Advanced BWR					
CO_2 carbon dioxide	$g \cdot kWh^{-1}$	3.78	4.71	0.07	8.56
CH_4 methane	$g \cdot kWh^{-1}$	0.15	0.22	-	0.37
Total	$g \cdot kWh^{-1}$	**3.93**	**4.93**	**0.07**	**8.93**
Fast breeder reactor					
CO_2 carbon dioxide	$g \cdot kWh^{-1}$	4.66	2.74	0.08	7.48
CH_4 methane	$g \cdot kWh^{-1}$	0.18	0.15	-	0.33
Total	$g \cdot kWh^{-1}$	**4.83**	**2.89**	**0.08**	**7.80**

Source: Svensson, 2005.

Enrichment processes worldwide are done through gas diffusion method or gas centrifuge method. The gas centrifuge method is less energy intensive than the diffusion one (Van Engelenburg & Nieuwlaar, 1992) but diffusion is still largely used. The various enrichment techniques, type of nuclear reactors, and uranium supply chain of nuclear power plants entail big differences in LCA of CO2 and energy impact. Figure 4 presents CO2 impacts or the life cycle of three Japanese power plants mentioned in Svensson's paper (2005). The CO2 impact vary from 7.5 gCO2e/kWh for the most recent technologies to 20 gCO2e/kWh for the old one.

The Ecoinvent 2.0 database includes a LCA of nuclear energy chain specific to China. This LCA is an extrapolation of the European model performed for the China Energy technology Program and carried out from 1999 to 2003 (Dones et al, 2007). This comparative LCA uses the Ecoinvent data, which have the advantage to be relatively modern and focused on China.

2.2. Life-cycle Assessment Modeling Approaches

Lifecycle assessment models can be categorized among three types: economic input-output LCA (I-O LCA), process-based LCA, and hybrid LCA, which combines I/O and process analysis.

Economic I-O LCA uses a top-down approach that generates average sector energy use and emissions values not always appropriate for case study research (Chang 2010). A well-known example of economic input-output LCA in the United States is the Carnegie Mellon EIO LCA. The U.S. EIO LCA is based on the Department of Commerce, Bureau of Economic Analysis input-output table, which describes 491 sectors of the economy in 1997. A China EIO LCA model is also available with 2002 data. The model combines aggregate process information with input-output data to calculate an amount of emissions, energy use, and employment per dollar of production in a given sector. EIO-LCA analysis is limited to goods and services as defined by the Department of Commerce--i.e., the user must make additions and assumptions to assess a larger and more complex unit such as a building or electricity generation.

This study uses GaBi LCA software to perform and aggregate its analysis. This study is a hybrid LCA in the sense that it combines GaBi process LCA with EIO LCA approaches.

2.3 Water need and impact

Water is a key component for electricity generation, both as a medium for converting thermal energy to electricity and as a cooling and cleaning agent. As part of the comparative assessment, this study quantifies the water requirements of coal and non-fossil electricity generation technologies.

2.3.1 Definition of water use

Water resources, for long ignored and not subject to worries are becoming precious as population increases and industrialization and intensive agriculture are developed worldwide. The water use can be studied based on a need point of view: how much water is required to per functional unit of the studied system. Industries and agriculture companies will look attentively at the water potential supply of a potential location and compare it to their water need, define as their future water withdrawal.

Environmentalists will look at the water use not from a withdrawal point of view but as a consumptive point of view. The consumption of water is defined as the water which is removed from the water environment and that will not be potentially useable (or at least not immediately, as the water always eventually come back to the environment).

The US Geological Survey provides definitions of the different water use (Hutson, 2004):

- **consumptive use**—the part of water withdrawn that is evaporated, transpired, incorporated into products or crops, consumed by humans or livestock, or otherwise removed from the immediate water environment
- **water withdrawal**—water removed from the ground or diverted from a surface-water source for use.
- **instream use**—water that is used, but not withdrawn, from a surface-water source for such purposes as hydroelectric-power generation, navigation, water-quality improvement, fish propagation, and recreation. Instream water-use estimates for

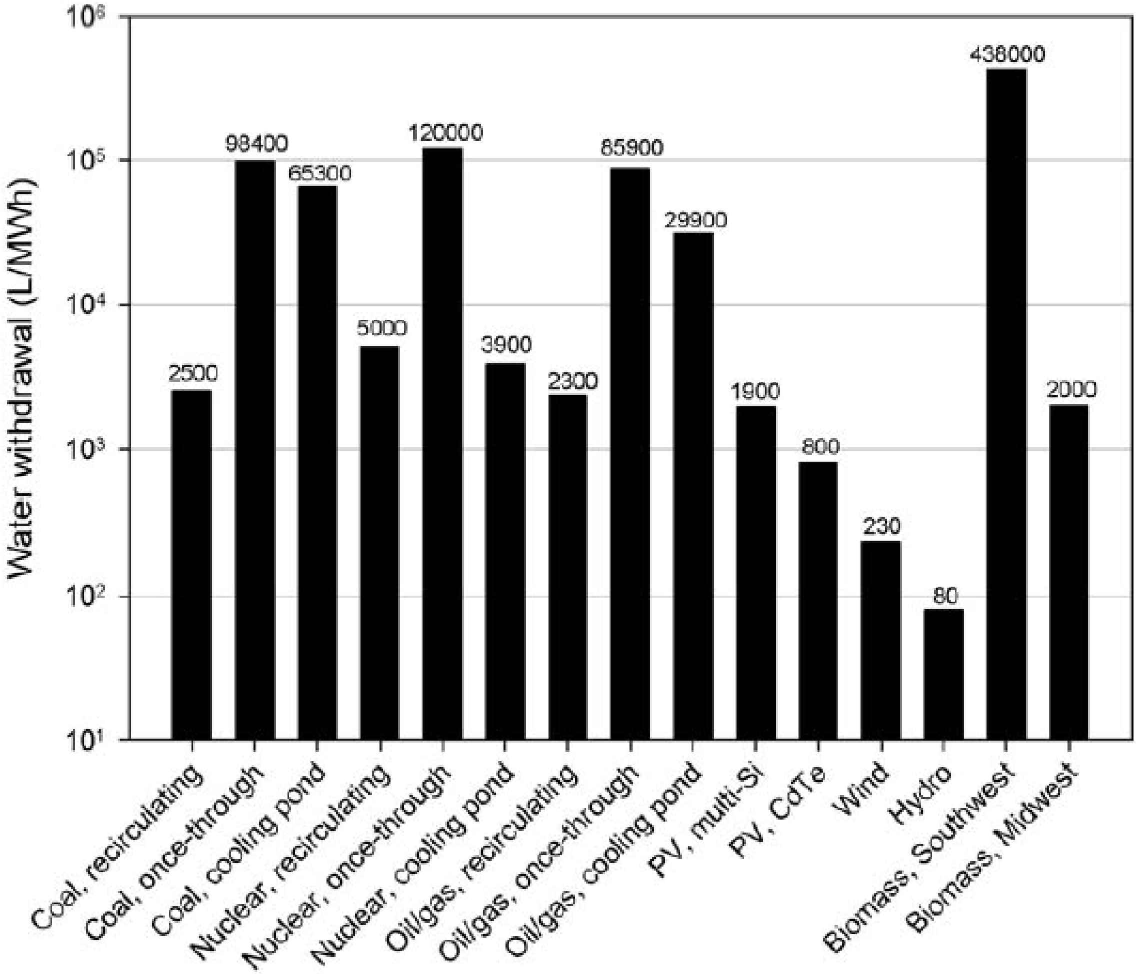
hydroelectric power were included in previous water-use Circulars but were omitted for 2000.

2.3.2. Importance of water assessment

In order to meet China's energy requirement, a water use life cycle assessment is important to study the feasibility of the various development scenarios. As water is becoming a scarce and thus a precious resource, a scenario where China goes for only water consumptive technologies could eventually meet water supply barriers, in case of competitive use with agriculture or other sectors. If global warming entails an increase in violent climatic events, such as droughts and floods, this claim would be even more relevant. Consequently, in order not to enter in competition with other water needs and in order to go for a better feasibility of different energies generation scenarios, this study focuses on water withdrawal need of the different generating power plants.

The next step to develop a broader and more intelligent vision of water use would be to study the water consumption of energy generating system. This would give an impact oriented view of water use in electricity generating systems and would lead to a better understanding of water real use (amount of water that is not immediately available for other purposes because of the system studied).

Figure 5: Comparison of water withdrawal across fuel cycle



Source: Fthhenakis et al, 2010.

Most of the literature available focused on the water withdrawal need of conventional energies systems (Coal, Natural Gas, Hydro and Nuclear) but few are focusing on renewable energies. Water consumptive use literature is even more difficult to find. However a recent paper reviewed the existing literature on the subject and modeled the withdrawal consumption of most of the electricity generation power plant in the US (Fthenakis, 2010). This papers claims that water consumption data for the material acquisition and construction stages of renewable technologies are undetermined, due to lack of information on the extent of water recycling in these facilities. Yet they gathered data and provide a water withdrawal life cycle study for almost all kind of US electricity generation (Figure 5).

2.3.3. Method developed in this study for water withdrawal use of Chinese power plants

Fuel and material mining for projects construction: The water use impact is modeled through a hybrid process-EIO LCA approach. The materials requested in the different power plants construction and maintenance are defined with processed method whereas the impact of each material is defined through the EIO-LCA Carnegie Mellon database, which include data focused on China.

For the construction step, the water need to prepare the concrete (most of the time prepared on construction site with cement, sand and local water), the water ratio of 0.6 kg of water used for every kg of cement is used. During maintenance if spares are changes, the material water content of the spares is taken into account through the material required to replace them.

For the operation phase, the water evaporation of the extra surface created by dams is considered with an ratio of 750mm of water evaporated per year. The data is Chinese specific and come from experiences in Shangdong provinces (Fu G. et al. 2004). The cooling towers water use vary from 2.68 kg/kWh to 8.43 kg/kWh depending on the power plant studied (Dones, 2009). For instance the BWR nuclear power plant has a bigger water use than the PWR one. Data regarding solar PV water withdrawal come from the review of various technologies water consumption [Fthenakis, 2010, Figure 5] and from a special study of the NREL focused on concentrated solar power [Macknick, 2010]

2.3.4. Other water LCA method focused on environmental externalities

The method for water use LCA developed in the available literature are mainly focused on water need (withdrawal use) of the electricity generating systems. Our LCA also provide a withdrawal approach, with the advantage of disaggregating the data for different subcategories of power plants (small, medium and big hydro, offshore and onshore wind turbine).
An environmental approach would focus on water consumption, global warming and pollution. The global warming is a consequence of water evaporation in the atmosphere mainly due to cooling systems and reservoir lakes for hydropower. Polluted waters are also to be included in an environmental LCA as they are not immediately available for the local water environment.

3. Life Cycle Assessment

3.1 Goal

Aimed at assessing the environmental impact in terms of global warming potential, water use and energy requirements of power supply strategy options for China in 2030, the goals of the LCA are two-fold:

- The first objective is to establish comparative life cycle assessments of 12 power generation technologies and identify technologies with the highest potential for reducing the energy- and carbon-intensiveness of China electricity production in 2030.
- LCA results of all 12 technologies are then aggregated to estimate the absolute environmental life cycle impacts of the two 2030 China demand scenarios compare them to the current situation. The environmental cost of change, embedded in the transition from China's current situation to each of the projected scenarios, is then estimated through energy, water, and CO2 payback calculations

3.2. Scope

3.2.1. Comparative LCA of power generation technologies

3.2.1.a. Systems and functional unit

A comparative life cycle assessment of 12 existing and emerging power generation technology types is here suggested, through the analysis of one representative plant per technology, which technical characteristics are given in Table 3. The function of each of the 12 systems is to produce electricity during the life-time of the power generation plants, while the functional unit of analysis is one kWh of produced electricity at the plant. The environmental impacts of the technologies are then compared in terms of global warming potential (g CO2 eq/kWh), energy requirement (MJ/kWh), water use (kg/kWh) and land use (m2*yr/kWh).

Table 3. Technical parameters of the 12 modeled representative plants

	Hydro			**Solar**			**Wind**		**Coal**		**Nuclear**	
Technology and characterisics	Rock filled embankement dam 88.8 m crest 0.44km2 lake	Concrete arch dam 305 m crest 9.44 km2 lake	Concrete gravity dam 190m crest 1045 km2 lake	Photo Volataic mix	Concentrated solar (Tower)	Concentrated solar (parabolic trough)	On Shore	Off Shore	Ultra Super Critical	Subcritical pulverized	Boiling water reactor 4% Centrifuge enriched MOX and reprocessing	Pressured water reactor 3.8% Centrifuge enriched No reprocessing
Capacity (GW)	0.044	3.6	14	1	0.017	0.05	0.3	0.3	0.3	0.3	1.5	1
Life time (Years)	100	100	100	30	25	25	20	20	40	40	55	40
Capacity factor	0.26	0.5	0.38	0.17-0.19	0.17	0.16	0.298	0.45	0.43	0.34	0.93	0.93
Total energy (TWh)	10	1577	4660	47-52	2.6	4.7	16	24	46	46	672	326
Location and source	China Zhang 2007	China Zhang 2007	Brazil Ribeiro 2010	China Ito 2009	Spain Lechon 2008	Spain Lechon 2008	Danemark Vestas 2006	Danemark Vestas 2006	China Dones 2007	Japan Dones 2007	European Union Dones 2009	European Union Dones 2009

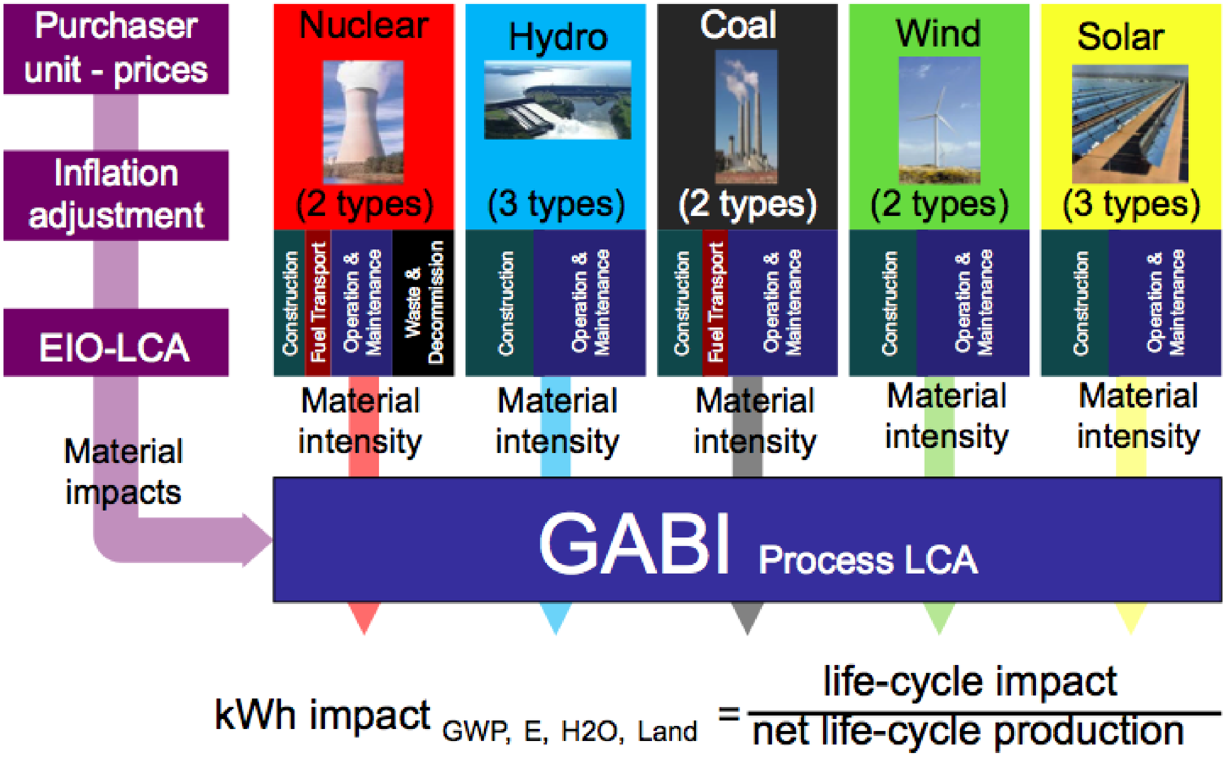
3.2.1.b. Model Type

The environmental impact of each representative plant is modeled through a hybrid life cycle assessment, whereby an economic input-output life cycle assessment (EIO-LCA) is embedded into a process LCA to model the manufacture of the individual components. Because it considers the entire history of economic transaction embedded in a product, the EIO-LCA enables a complete modeling of the environmental impacts of the product's manufacture chain. However, the definition of the products that can be modeled is limited by the disaggregation level of the input-output economic matrix, which makes EIO-LCA an ill adapted technique to model products that are either not well defined, or whose value chain is not clearly constrained (e.g., power supply). On the other side, process-based LCA allows an accurate taking into account of specific process sequences forming complex products, but complicates the modeling of a manufacture chain that really takes all the inherent processes into account. The type of hybrid LCA that is suggested here takes advantage of the EIO-LCA's inclusiveness in modeling the manufacture of well-defined individual product (like steel or cement), while a process based LCA modeled on the GaBi 4 software (PE international) enables their combination to form complex products (like electricity from a coal power plant).

3.2.1.c. Model Structure

The hybrid LCA configuration that was used for each plant is depicted on Figure 6. The material intensities required for each particular plant over their lifetime are identified in the literature and used to build a process LCA model in Gabi. Meanwhile, quotes on unit prices for the required materials (e.g. the price of 1Mt of steel, copper, cement, etc) in China are gathered and entered in the web-based Carnegie Mellon EIO LCA-tool, which returns the corresponding environmental impacts based on the Chinese 2002 economic input-output matrix. Inflation is taken into account using the US consumer price indexes of 2002 and 2009 as proxies. Once material intensities and material unit-impacts gathered, the process LCA model is compiled and run.

Figure 6. Comparative hybrid LCA of 12 representative technologies



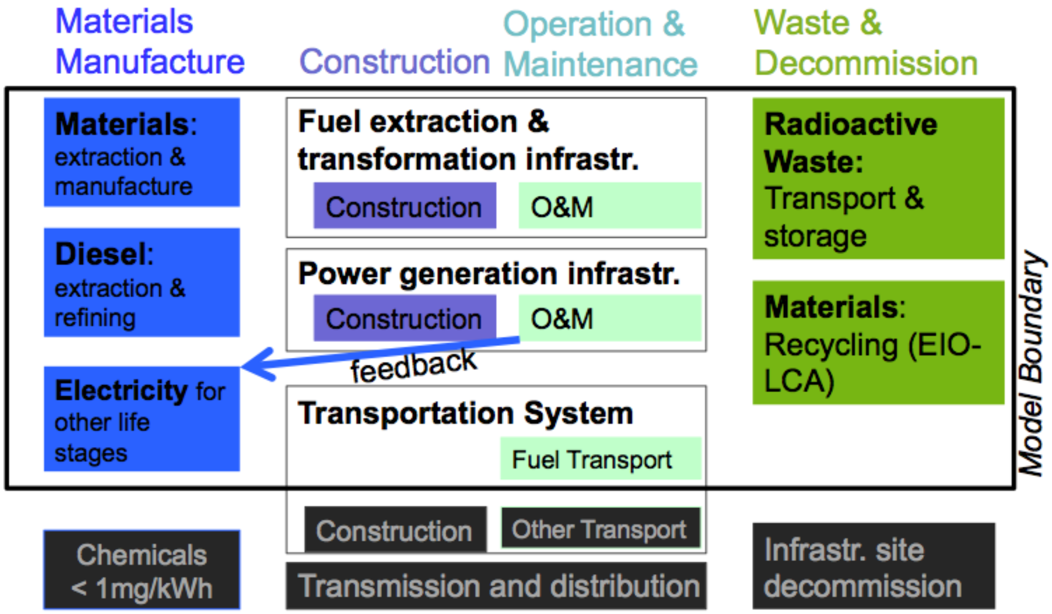
3.2.1.d. Boundaries

The whole life cycle of each plant was taken into account with four stages: the manufacture of all required material excluding the energy content of the fuels themselves, the construction of the infrastructure, their operation and maintenance, and the handling of waste and decommissioning. For technologies requiring a fuel processing chain (i.e. coal and nuclear), this life cycle approach was applied to all infrastructures directly involved in the extraction and processing of the fuel.

The boundaries of the model are displayed on Figure 7, which calls for the following remarks:

- The power transmission and distribution infrastructure is not taken into account because it is very site specific and depends highly on the topology of the network, which is unknown at this point
- Chemicals and materials used in the construction and operation and maintenance stages of the infrastructure with an intensity smaller than 1 mg/kWh generated are neglected.
- The transportation of people and materials (excluding the fuels) to the sites, and the transportation infrastructure itself is left out of the model, because both are highly site specific and no aggregated Chinese data were available.
- Yet the transportation of the fuel, which turns out to be significant in China, is taken into account using Chinese data on average transportation distances and modes for each fuel. The extraction and refining of the required transportation fuel is taken into account.
- An average recycling rate for China is embedded in the EIO-LCA for all considered materials. Yet radioactive contaminated materials (i.e. nuclear fuel waste and contaminated material from the decommissioned plants) required special care. Transportation and process of this contaminated waste to their final storage facilities are thus taken into account.
- Finally, there is a feedback effect embedded in the fact that electrical power is required to build and operate the infrastructure that generates it. This feedback effect can be accounted for in the model by taking life cycle environmental impact data of electricity production from another source (e.g. EIO-LCA) as a model input. Yet doing so makes the wrong assumption of a homogenous power mix in the whole country and requires price data on electricity, which is rather volatile. Therefore this model assumes self-use and calculates the net power production by subtracting to the total power production the power required to build and operate the fuel chain infrastructure. Doing so makes sense if the reasonable assumption is made that technologies are geographically clustered – i.e. the power mix of a hydropower or wind-prone region is dominated by the corresponding power type.

Figure 7. Model boundaries



3.2.1.e. Technology assumptions

Hydropower

The three plants representing Chinese hydropower in this model are all dams with capacities higher than 44MW, two of which come from an EIO-LCA established by a Chinese scholar on two specific Chinese dams (Zhang 2007), while a LCA of Itaipu (Brazil) is taken as a proxy for the very large dams. Small and run of river hydropower plants are therefore not specifically modeled, yet small hydropower only represented 3% of Chinese installed hydropower capacity in 1999 (Fuggle 2000).

The energy and materials necessary to build the dam and appurtenant structures are expected to be a significant part of the total impacts. The impact linked to the manufacture of the materials and fuel necessary to construct the infrastructure is accounted, as well as the emission linked to diesel combustion of construction machines and blasting (ANFO explosives). In opposition, the impacts linked to the manufacture of the construction machines, the explosives, and the impact of transporting people and materials to the site have been excluded. The electromechanical parts are replaced once in the 100 years period that is considered in the dam assessment. This replacement accounts for the totality of materials costs during the use life phase of the project. The electricity necessary to the operation and maintenance of the dam is directly deducted from the power production.

Finally, green house gas emission from the reservoir is also accounted. The methane emission linked to the initial biomass decay in the reservoir is accounted in the construction stage, assuming a boreal forest carbon content (C) of 9kgC/m2, 20% of which are subject to anaerobic digestion (Horvath 2005). Additionally, the displacement of the terrestrial ecosystems the leads to the disruption of its carbon sequestration potential is accounted for in the operation and maintenance stage. The net ecosystem production (NEP) is calculated based on the following equation (Horvath 2005):

$$NEP = NPP - \frac{C}{t}[\frac{kg}{m^2 yr}]$$

Where a net primary productivity (NPP) of 0.429kgC/m2Yr (Gower 2001) is considered for the case of a boreal forest, which is the vegetation type assumed by Zhang (2007) in is LCA of two Chinese dams. Finally, a turnover time (t) of 33 years is also considered (Horvath 2005).

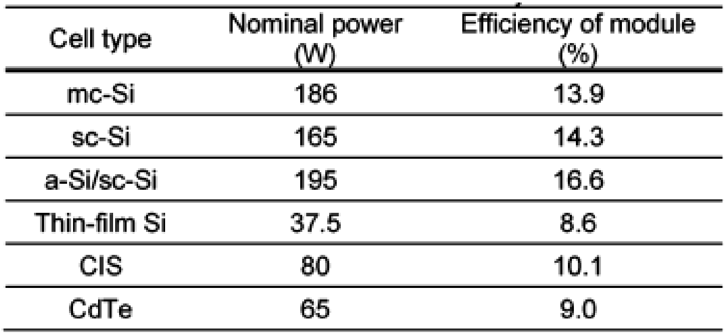
ii. Solar

The three solar technologies that are considered in the model include a mix of PV technologies and two concentrated solar technologies: central tower and parabolic trough.

The concentrated solar plants are a 17 MW central tower plant and a 50 MW parabolic trough plant, two currently operational Spanish plants whose life cycle has been assessed by Lechon (2009) in a process LCA. Lechon's global warming potential and energy use results have been aggregated into construction and operation and maintenance phases and included in the model as such. The backup natural gas combustion however, which accounts for 15% of the total generated power has been left out; and the Spanish power mix that is assumed by Lechon to meet the power needs of the plants are replaced by the net power generation concept introduced above.

For photovoltaic, Ito (2009) calculates the LCA of a planed 1GW PV plant in the Gobi desert. Material production in China and Japan, and Gobi desert transportation distances and solar irradiation are assumed. Ito (2009) also assumes the mix of cell types and range of efficiencies described on Table 4. Again, Ito's global warming potential and energy use results was taken as such in our model, and aggregated in construction and operation and maintenance stages. Nevertheless, the fact that 100km of transmission lines are included in Ito's (2009) results has to be kept in mind, which will induce a slight overestimation of the environmental impact for PV in our model that considers power generation at the plant.

Table 4. Photovoltaic technology mix used in large-scale PV in the Gobi desert



Cell type	Nominal power (W)	Efficiency of module (%)
mc-Si	186	13.9
sc-Si	165	14.3
a-Si/sc-Si	195	16.6
Thin-film Si	37.5	8.6
CIS	80	10.1
CdTe	65	9.0

Source: Ito. et al. (2009)

iii. Wind

The two plants representing China's wind power are both 300MW wind farm composed of 100 turbine of 3MW exploited either onshore or off-shore. Chinese turbines manufacturers, such as Sinovel, dominate the current market in China, which complicates the access to China specific data on wind energy. Therefore, data from Vestas (Vestas 2010), the Danish World leader in turbine manufacturing that also dominated the Chinese market in the 1990's and 2000's, will be used as a proxy. Specifically, Vestas conducted and internal, third party peer-reviewed LCA on their turbines, from which data for the current study is drawn (Vestas 2006).

The energy and materials necessary to manufacture the turbines and to build the wind power plant are expected to be a significant part of the total impacts. The impact linked to the manufacture of the materials and fuel necessary to construct the infrastructure is accounted, as well as the emission linked to diesel combustion of construction machines. Although significant, the impacts linked to the manufacture of the construction machines and the impact of transporting people and materials to the site have been excluded, in order to be consistent with the assessment of the other technologies.

Half the generators and gear-boxes are expected to be replaced in the 20 years life time of the plants that is here considered. This replacement accounts for the totality of materials costs during the use life phase of the project. The electricity necessary to the operation and maintenance of the plant is directly deducted from the power production.

iv. Coal

The representative plant for current coal combustion in China is a standard subcritical pulverized hard coal combustion plant of 300MW, which has been modeled in the frame of the ecoinvent project (Dones 2007), which is mainly based on primary Chinese data collected in Shandong province, and proxy data from Slovak plants are introduced to complete the data set. Additionally, in order to take into account technology evolution a 300MW ultra-supercritical plant is also considered and assumed to be an emerging technology possibly representative of a significant ratio of coal combustion in 2030 China. Material intensity and efficiency data are drawn from Japanese (Uchiyama 1995) and US (Beer 2007) cases respectively. The full coal chain is considered, including the underground mining of hard coal, its transportation and its combustion in the representative 300MW plants. Again, the impact linked to the manufacture of the materials and fuel necessary to construct the infrastructure is included, as well as the emission linked to diesel combustion of construction machines and blasting (ANFO explosives). On the other hand, impacts linked to the manufacture of the construction machines, the explosives, and the impact of transporting people and materials to the sites have been excluded.

Coal transportation modes and distances, which turn out in China to be quite significant, are taken from Ou (2010), who reports the transported coal ratio and the transportation modes, distances and fuel consumption displayed on Table 5. An additional 100km of light truck tranportation (1200kJDiesel/tkm) is assumed for all transported coal.

Table 5. Transportation mix for coal in China

Transportation mode	Ratio of total coal	Distance (km)	Total fuel consumption (kJ/tkm)
Train (55% Diesel, 45% electric)	50%	1000	240
Water ways	17%	650	148
Long distance truck	8%	310	1362
No long distance transportation	25%	NA	NA

Source: Ou, 2010.

Finally, coal is pulverized and combusted in the representative coal power plants and disposed of on-site as ash tailings. The emissions linked to coal combustion and the land-use linked to the tailing are accounted, while the electricity necessary to the operation and maintenance of the plants is directly deducted from the power production.

v. Nuclear

The representative plant for current nuclear power in China is a 1GW pressurized water reactor, which has been modeled in the frame of the ecoinvent project (Dones 2007), which has also been modeled in the frame of the ecoinvent project (Dones 2008) with Chinese conditions. The ecoinvent model from which the data used in this project have been taken, is mainly based on an extrapolation of European data, which was originally performed for the LCA work for the

China Energy Technology Program (CETP), carried out in 1999-2003 by Dones. Additionally, in order to take into account technology evolution a 1.5GW boiled water reactor is also considered, with a nuclear fuel chain that includes the reprocessing of waste by feeding remaining uranium and plutonium (a.k.a. MOX) in the pre-generation fuel chain. Nuclear waste reprocessing is here assumed to be an emerging technology possibly representative of a significant ratio of nuclear power in future China. Material intensity and efficiency data are drawn from existing European nuclear fuel chains that were assessed by Dones (2009) in the frame of the ecoinvent project.

The uranium chain involves the oversea mining an milling of uranium ore, the conversion to UF6, the centrifuge technology for the enrichment of the UF6 to 3.8% U235, the manufacture of nuclear fuel, the generation of power by the nuclear reactor, the processing and possible reuse of the nuclear waste, and the transportation and appropriate storage of radioactive waste. Transportation processes along the fuel chain, including the shipping of foreign uranium ore (yellow cake) and the transportation of radioactive waste are accounted in the model. The transportation processes, mode and distance that were assumed for China are summarized in Table 6.

Table 6. Transportation mix for the nuclear fuel chain in China (Dones 2009)

Transported cargo	Mode	Distance (km)	Fuel Consumption (kJ/tkm)
Yellow cake import	Sea tanker	5000	23
Converted UF6	Rail (55% diesel, 45% electric)	1000	240
Enriched UF6	Rail (55% diesel, 45% electric)	2500	240
Reprocessing fuel to enrichment plant	Rail (55% diesel, 45% electric)	2500	240
High radioactive waste	Rail (55% diesel, 45% electric)	500	240
Low radioactive waste	Rail (55% diesel, 45% electric)	1000	240

Impacts linked to the manufacture of the materials and fuel necessary to construct the infrastructure are accounted, as well as the emission linked to diesel combustion of construction machines and blasting (ANFO explosives). The impacts linked to the manufacture of the construction machines, the explosives, and the impact of transporting people and materials to the sites have been excluded. In the operation and maintenance phase, the electricity necessary to supply all the processes of the chain is accounted for by applying the net energy production concept described above. Finally, the transportation, processing and storage of radioactive waste from both nuclear fuel waste and contaminated materials from decommissioned plants are included.

3.2.3. Scenario Analysis

In order to estimate the environmental cost embedded in meeting China’s power demand in 2030 given the 2008 situation, results from the comparative LCA of the 12 considered technologies are integrated in the scenarios described hereunder. The integration is done according to the following formula:

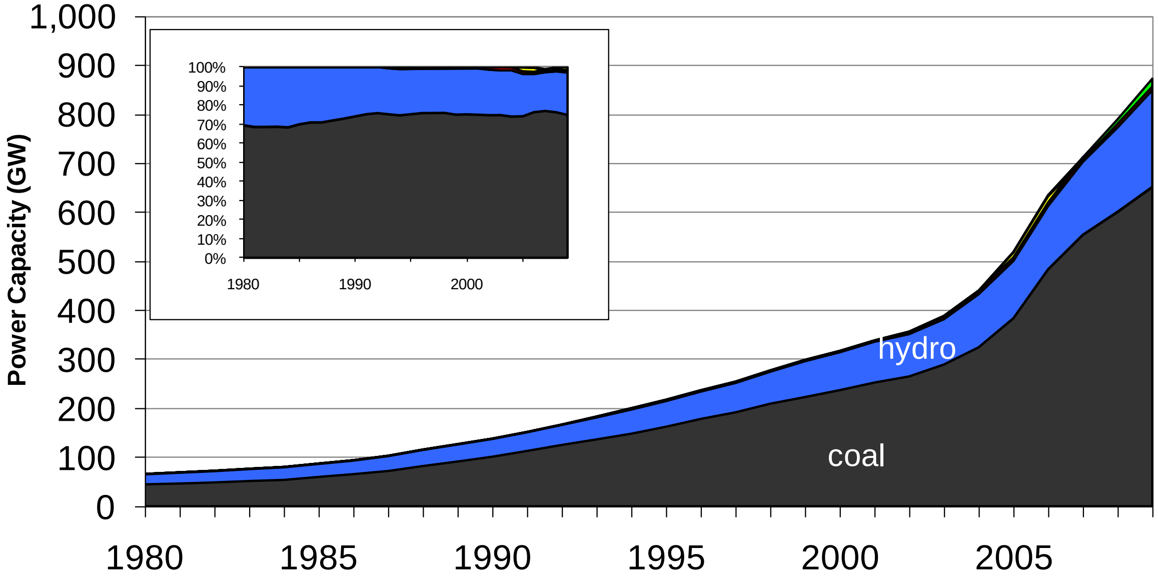
$$LCA_j = \sum_{i}^{12\_technologies} LCA_i * E_{i,j}$$

where LCA_i is the per kWh impacts of the technology i, $E_{i,j}$ the power generated by technology i in scenario j, and LCA_j the total impact of scenario j.

3.2.3.a. Current situation and 2030 scenarios

China’s electricity system is growing rapidly to meet rising demand from heavy industry, new urban areas, and export-oriented manufacturing. Since the start of its reform and opening program China’s electricity generation has grown at an average rate of more than 9% per year, from 301 TWh in 1980 to 3,280 TWh in 2007 (NBS, 2010). Figure 8 illustrates the growth of China's generation capacity, particularly coal-fired electricity, between 1980 and 2009. The explosive growth of energy use and related carbon dioxide emissions, particularly after 2001, exceeded the highest forecasts of Chinese and international experts (Levine and Aden, 2008). China’s electricity system doubled its capacity between 2000 and 2007 (from 320 to 710 GW) and high growth is expected to continue. In its reference scenario, the International Energy Agency (IEA) forecasts China’s total generation capacity will expand at an average annual growth rate of 4.7% over the next twenty years to reach 2,100 GW in 2030 (IEA, 2010). This is equivalent to building the capacity equivalent of the entire U.S. electricity grid over less than 20 years.

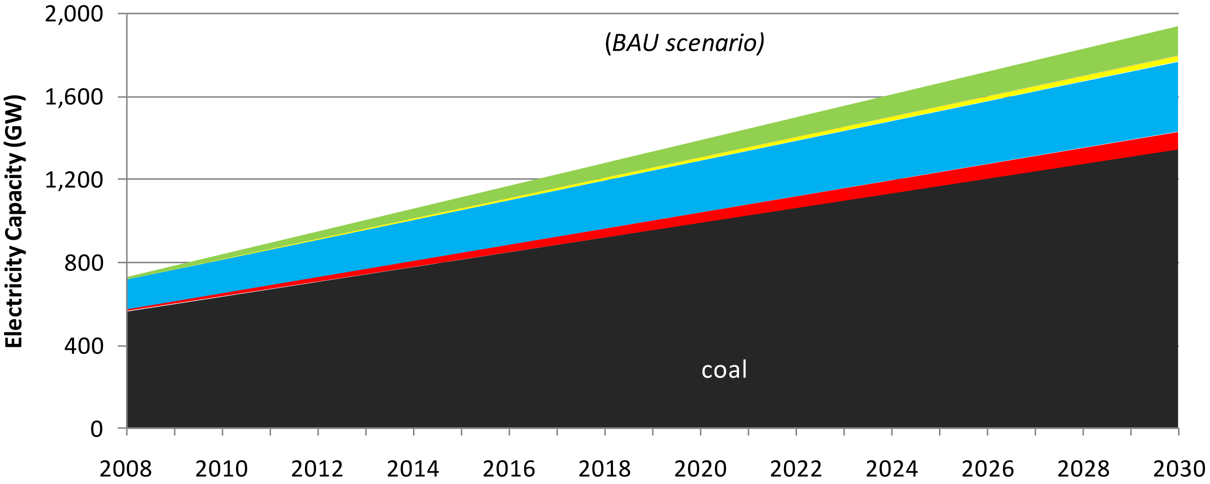
Figure 8: China Electricity Generation Capacity by Fuel, 1980-2009



Source: NBS, 2010.

This project uses two scenarios to assess the impact of non-fossil electricity generation growth in China. Both scenarios are based on the IEA's China 2030 electricity capacity and generation values published in the *World Energy Outlook 2010*. Figure 9 illustrates the growth of electricity capacity by fuel from 2008 to 2030. In the reference scenario coal remains the dominant fuel, while total capacity continues to grow at an average annual growth rate of more than 4%.

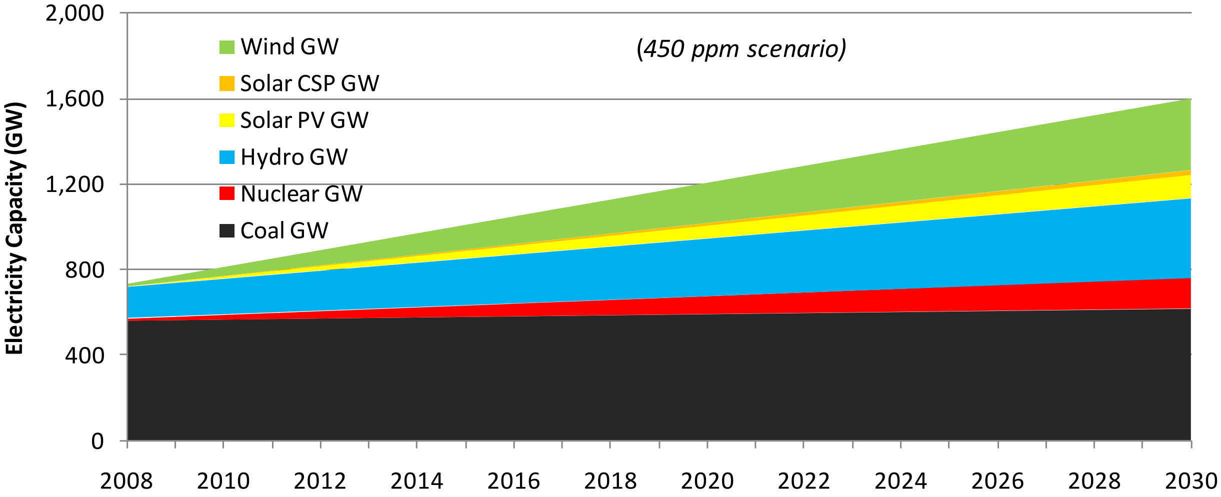
Figure 9: China Reference Scenario Electricity Generation Capacity by Fuel (2008-2010)



Source: IEA, 2010.

There are two key differences between the reference and 450 ppm scenarios: fuel mix and efficiency. Whereas the reference scenario includes 29% non-fossil capacity by 2030, the 450 ppm scenario non-fossil share of capacity reaches 57% in 2030. In so far as both scenarios assume that demand is met, the 450 ppm scenario also includes end-use efficiency improvements that reduce total electricity demand by 18% in 2030. As such, the 450 ppm scenario requires less 2030 generation capacity than the reference scenario. Figure 10 shows the growth of non-fossil capacity under the 450 ppm scenario.

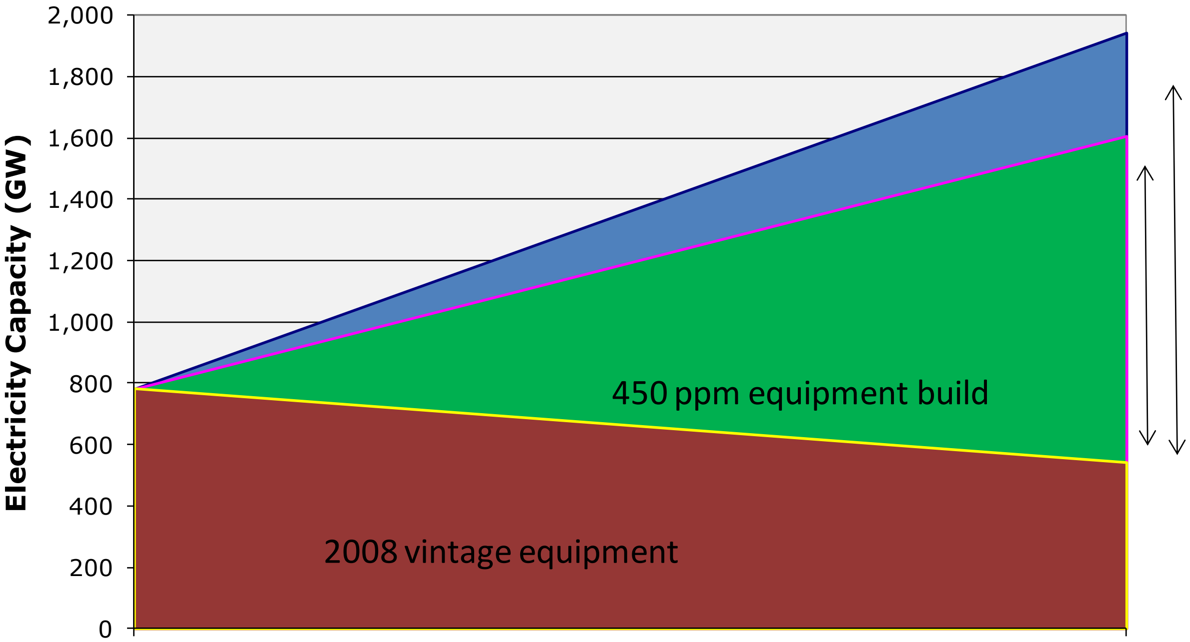
Figure 10: China 450 ppm Scenario Electricity Generation Capacity by Fuel (2008-2010)



Source: IEA, 2010.

The three points of interest in this study are existing capacity in 2008, BAU scenario capacity in 2030, and 450 ppm scenario electricity capacity in 2030. Over the 22 years between 2008 and 2030, some electricity generation capacity is retired or decommissioned. Among the six electricity generation technologies modeled in this project, coal and wind power capacity include expected retirement. Figure 11 shows the effect of retirement on total capacity build requirements. Coal-fired generators were retired under a 30-year lifetime assumption--i.e., the amount of capacity retired in 2011 is equivalent to the amount of new capacity added in 1981. All of the current 12 GW of 2008-vintage wind power capacity are retired by 2030; therefore, all 142 GW of 2030 reference scenario wind capacity are new build.

Figure 11: China Electricity Generation by Equipment Vintage (2008-2030)



The results shown in Section 3.4 below incorporate the additional build required to replace retired capacity. The three transitions modeled in this project are expansion from 2008 to 450 ppm scenario 2030 capacity (the shorter line on the right side of Figure 11), expansion from 2008 to reference scenario 2030 capacity (the longer line on the right side of Figure 11), and the marginal difference between reference and 450 ppm scenario 2030 development (as illustrated by the blue area of Figure 11).

3.2.3.b. Modeling assumptions

Model scope

The first assumption to keep in mind is the scope of the model, which is limited to 12 technologies representing hydropower, wind, nuclear power, solar PV and concentrated solar power and coal-fired electricity generation. Other power sources such as oil, gas, biomass, geothermal or wave energy are not taken into account. These unaccounted technologies represent 2%, 7% and 14% of China's total power generation in 2008 and 2030 business as usual and 2030 450ppm scenarios respectively. Furthermore, the external costs related to the efficiency measures that reduce the total energy demand in the 2030 450ppm scenario are not taken into account.

Technology shares and aggregation

Each of the 5 considered power sources is modeled by one to three representative plants, whose weight is attributed according to the assumptions summarized in Table 7.

Table 7. Technology aggregation assumptions

Technology	Assumption
Hydropower	
44MW Rockfill	Category shares according to 2008 Chinese dam park reported by the international comity of large dams (Fuggle 2008)
1.6GW Arch	Future scenarios takes into account the plannified construction of large dams in the same report
14GW gravity	Xiluodu (13.8GW) dam project is added to Three Gorges dam in the 14GW category for 2030
Wind	
Onshore	All curent wind mills are assumed onshore. Given the 20 year lifetime, all existing mills are decommissioned in 2030
Offshore	50% of future windmills are assumed to be offshore
Solar	
PV	PV is described as its own category in the WEO scenarios
Concentrated Tower	A generation share of 1/3 central tower and
Concentrated Trough	2/3 parabolic trough is assumed for concentrated solar
Coal	
Subcritical	All curent plants are assumed subcritical a decommissioning rate of 10.4GW/yr is assumed for 2030 scenarios
Ultrasuper critical	All future plants are assumed ultrasupercritical
Nuclear	
No Reprocessing	All curent nuclear fuel chains are assumed without reprocessing
Reprocessing and MOX	All future nuclear fuel chains fill include reprocessing and MOX

There is an inherent modeling assumption in the fact that the wide variety of sizes, sites and efficiency of plants for each power sources are modeled by a restricted amount of representative plants. For instance, the electricity produced by all the large (1-10 GW) dams in China is assumed to have the same normalized impact as the electricity produced by the specific 3.6GW concrete arch dam that is considered in the model. This uncertainty is linked to the very function of modeling: simplifying reality. Unfortunately, increasing the amount of categories would decrease the related uncertainty at the cost of complicating the model; and this option is anyway limited by the availability of data.

Time

Our inability to accurately and certainly predict the future forces the following blunt assumptions to be made. In addition to assumptions made in the World Energy Outlook (2010) on China’s future power capacity, an important assumption concerns technology evolution. The inclusion in 2030 scenarios of emerging technologies that are not currently implemented in China (i.e. offshore wind, concentrated solar power, and reprocessed/MOX nuclear power) aims at mitigating this source of uncertainty. However, research on new technologies is booming at the moment, and it is possible that new, game changing power technologies will be discovered in the next 20 years.

Furthermore, the influence of climate change on the availability of renewable energy resources is uncertain, as Himalayan water as well as cloud and wind patterns are affected. The climate models that are required to take this effect into account however are both global and complex and go beyond the scope of this research. Another source of uncertainty is the geographical adjustment of the economy as growth expands beyond coastal areas. This shift can help to reduce the transport and transmission requirements of fuels and electricity and demand centers move closer to primary energy sources located in northern and western China.

3.3 Life Cycle Inventory

3.3.1. Inputs from the technosphere

The main inputs from the technosphere, here defined as the physical environment affected by humans, for 8 selected technologies are given in Table 8 in terms of material intensity and unit costs per kWh of life-time produced electricity, disaggregated into construction and operation and maintenance inputs. The multiplication of the material intensities and the corresponding unit costs gives a good estimate of the cost related to each material for each technology and life stage, which can be entered on the web-based EIO-LCA tool (eiolca.net) to compute the related environmental impact. Price estimates in 2002 USD are inflation-adjusted using the US consumer price index.

Table 8. System interactions with the technosphere

Process input from the technosphere		Unit Price 2002$/t	14GW gravity Hydro	Onshore Wind	Offshore Wind	Subcritical Coal	Ultrasuper critical Coal	No Reprocessing Nuclear	Reprocessing and MOX Nuclear
Steel (g/kWh)	Constr.	563	1.7E-01	2.0E+00	1.2E+00	3.8E-01	3.7E-01	1.2E+00	1.5E+00
	O&M		1.0E-01	8.0E-02	4.8E-02	3.8E-01	3.8E-01	5.0E-02	3.7E-02
Cement (g/kWh)	Constr.	58	5.3E-01	1.2E+00		1.0E+00	9.8E-01	1.9E+00	2.1E+00
	O&M							1.6E+00	1.6E+00
Copper (g/kWh)	Constr.	6974		2.0E+00	1.2E+00	1.8E-03	1.7E-03	4.8E-03	2.6E-03
	O&M			2.9E-02	1.7E-02				
Epoxy (g/kWh)	Constr.	2939		2.4E-01	1.4E-01				
	O&M								
Glass fibers (g/kWh)	Constr.	2728		5.9E-02	3.6E-02				
	O&M			0.0E+00					
Aluminum (g/kWh)	Constr.	1975		7.7E-01	4.6E-01	2.2E-03	2.2E-03	1.2E-03	7.2E-04

	O&M							3.0E-04	1.3E-04
Polyester (g/kWh)	Constr.			1.0E-01	6.3E-02				
	O&M								
Electrical power (kWh/kWh)	Constr.							2.1E+02	1.8E+02
	O&M		1.0E-01			8.9E-03	8.9E-03	3.0E-03	2.9E-03
Diesel (MJ/kWh)	Constr.	4100 RMB	2.3E+00					3.9E-03	3.5E-03
	O&M					8.5E-03	8.5E-03	4.1E-03	5.0E-03

The assessment of the two remaining hydropower technologies (namely the 44MW rockfilled and 1.6GW arch dams) is based on the economic input output life cycle assessment established by Zhang on two Chinese dam projects in 2007. However, the cost estimates gathered by Zhang (2007) are here computed in the EIO-LCA web tool using (when possible) the Chinese 2002 input-output matrix that was not yet available in 2007, and an alternate calculation of the greenhouse gases emitted by the reservoir is here assumed (cf. section 3.2.1.e). Cost estimates and the considered industry sectors are summarized in Table 9 for both hydropower plants.

Table 9. EIO-LCA data for medium (44MW) and large (1.6GW) hydropower (Zhang 2007)

Designation	**Industry sector**	**Value (1e6 RMB (2002))**	
Construction		**Rockfilled 44MW**	**Arch 1.6GW**
Cement (0.5 construction materials)	Cement and cement asbetos product (CN)	7	795
Steel (0.5 construction materials)	Steel processing (CN)	7	795
Machineray and equipment (turbines, etc)	(US) Turbine and turbine generator set units manufacturing	20	2140
Structural metals (valves, pipes, gates, etc)	(US) Fabricated pipe and pipe fitting manufacturing	4	210
Diesel	Petroleum refining (CN)	6	284
Operation and Maintenance			
Machinery and equipment	(US) Turbine and turbine generator set units manufacturing	95	18,350
Structural metals	(US) Fabricated pipe and pipe fitting manufacturing	95	18,350

Finally, the results from Ito (2009) and Lechon (2008), for solar photovoltaic and thermal respectively, are here directly included in the model in terms of per kWh impact on the environment. Inputs from the technosphere are therefore not considered for these technologies, and their life cycle inventory will be treated in the following section where inputs/outputs with the environment are considered.

3.3.2. Interactions with the environment

The life cycle inventory for all 12 technologies in terms of inputs and outputs with the environment are given in Table 10. To ease the comparison across technologies, all impact values normalized by the total lifetime power production. The environmental impacts that have been computed in this study are the resource requirements in terms of coal and uranium ore, the water use, the total energy requirement, and the global warming potential.

Table 10. System interaction with the environment

		44MW Rockfilled Hydro	1.6GW Arch Hydro	14GW gravity Hydro	Onshore Wind	Offshore Wind	Subcritical Coal	Ultrasuper critical Coal	No Reprocessing Nuclear	Reprocessing and MOX Nuclear	Solar PV	Solar concentrated central tower	Solar concentrated parabolic trough
Input													
Coal or uranium ore (g/kWh)							350.31	276.85	0.00	0.00			
Water (kg/kWh)	Constr	3.33	0.46	17.19	0.02	0.01	24.26	24.01	29.44	32.78			
	O&M	3.38	0.49	17.20	0.40	0.24	24.29	24.04	29.46	32.80			
Land Use (m2*yr/kWh)		0.44	0.0006	0.02	0.01	0	0.0005	0.0004	0.0002	0.0002	0.02	0.02	0.00
Total energy (MJ/kWh)	Constr	0.02	0.02	0.01	0.17	0.11	1.31	1.04	0.09	0.08	0.90	0.22	0.24
	O&M	0.005	0.003	0.003	0.01	0.01	0.03	0.02	0.04	0.05	0.00	0.00	0.00
Output													
Radioactive waste (m3/kWh)													
	High								0.02	0.01			
	Low								5.55	5.38			
GWP	Constr	5.38	2.10	14.90	15.46	10.52	312.87	247.36	10.78	4.03	68.44	22.76	31.17
(gCO2eq/kWh)	O&M	3.22	0.70	13.61	0.37	0.22	884.59	827.73	1.65	1.25			

3.3.3. Data evaluation and uncertainties

Adapted from Junnila (2003), a pedigree matrix is used for data quality assessment (Table 11). The assessment is based on evaluation scores ranging from 1 (best) to 4, for three relevant criteria: the data acquisition method, and their temporal and geographical correlation with the assessed system.

Table 11. Pedigree matrix for data quality evaluation

Points	Acquisition method	Temporal correlation	Geographical correlation
1	Measured data	Data less than three years old	Exclusively Chinese data
2	Peer reviewed publication	Data less than 5 years old	Chinese geographical data (e.g. distances, exposition, evaporation). International material intensity data having been used as proxy for China in peer reviewed publications.
3	Calculated data based on peer reviewed assumption	Data less than 10 years old	Chinese geographical data (e.g. distances, exposition, evaporation). International material intensity proxy
4	Calculated data partly based on non qualified assumption	Data more than 10 years old	Exclusively international proxy data

The data quality evaluation giving each technology's score for each evaluation criteria is displayed on Table 12.

Table 12. Data evaluation table

Technology	Acquisition method	Temporal correlation	Geographical correlation	Principal source
Hydropower				
44MW Rockfill	3	1	1	Zhang (2007), China
1.6GW Arch	3	1	1	Zhang (2007), China
14GW gravity	2	1	3	Ribeiro (2008), Brasil
Wind				
Onshore	3	2	4	Vestas (2006), Danemark
Offshore	3	2	4	Vestas (2006), Danemark
Solar				
PV	2	1	2	Ito (2009), China
Concentrated Tower	2	1	4	Lechon (2008), Spain
Concentrated Trough	2	1	4	Lechon (2008), Spain
Coal				
Subcritical	3	1	2	Dones 2007, EU
Ultrasuper critical	3	1	2	Dones 2007, EU
Nuclear				
No Reprocessing	3	1	2	Dones 2009, EU
Reprocessing and MOX	3	1	2	Dones 2009, EU
Unit prices	4	1	3	Chinese wholesaler website quotations, 2010

Data acquisition for material intensities is either directly a direct transcription of peer-reviewed publications (score 2), or results from calculations involving data from several peer reviewed publication (score 3). On the temporal side, while all data are fairly recent and therefore well correlated to the studied system in its 2008 state, uncertainties linked to technology and price evolutions between 2008 and 2030 have already been mentioned. Because of the lack of English written China specific publications on domestic power generation technologies, the geographic provenance of technology data, and therefore the related uncertainty, is rather wide. Indeed, while data for medium (44MW) and large (1.6GW) hydropower come from a published LCA of Chinese dams in Chinese conditions, wind power and thermal solar power data come from assessments of Danish and Spanish technologies that were not necessarily installed in sites offering the same wind potential and sun exposition as China's Gobi desert. In between, coal and nuclear data consider European technologies implemented in China's setting of fuel transportation distances, while the LCA of very large hydropower and solar photovoltaic is based on foreign material intensities and Chinese climatic conditions.

However, the model's main source of uncertainty is its high reliance on Chinese unit prices, which are uncertain and volatile. A sensitivity analysis considering the effect of price variation on the model's outputs would therefore be a logical next step from the current work.

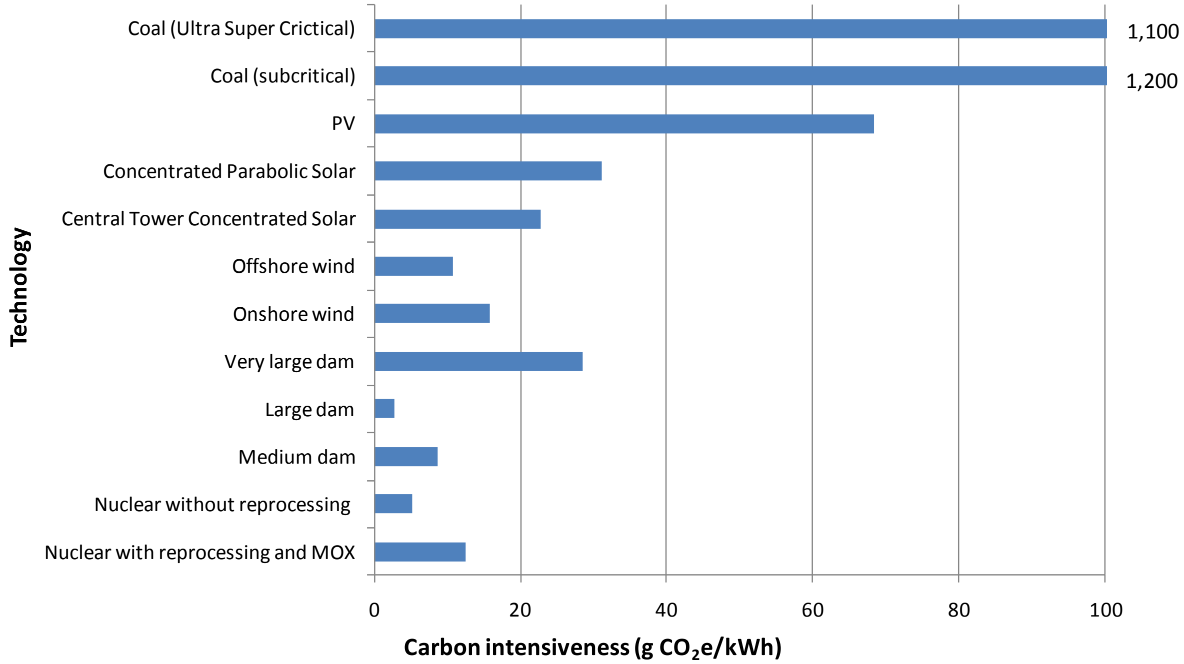
3.4. LCA results

3.4.1. Technology comparison.

3.4.1.a. Greenhouse gases analysis.

The clean technologies carbon intensiveness ranges from 5 gCO2e/kWh (large dam, the lowest carbon intensive technology) to 68 gCO2e/kWh (solar photovoltaic, the most carbon intensive clean technologies, as can be seen on Figure 12). However all non-fossil technologies are very low carbon emitters compared to coal, which emits more than a kilogram of lifeycle CO2e for each kWh generated. The offshore wind is a lower emitter than onshore due to its higher generation (regular and strong wind offshore). Modern nuclear power plants emit more carbon than old generation, because of all the industrial chain of recycling. One the other hand, modern nuclear produces far less wastes thank to the integration of mix-oxide plutonium in the fuel production chain and thanks to the high rate of uranium recycling.

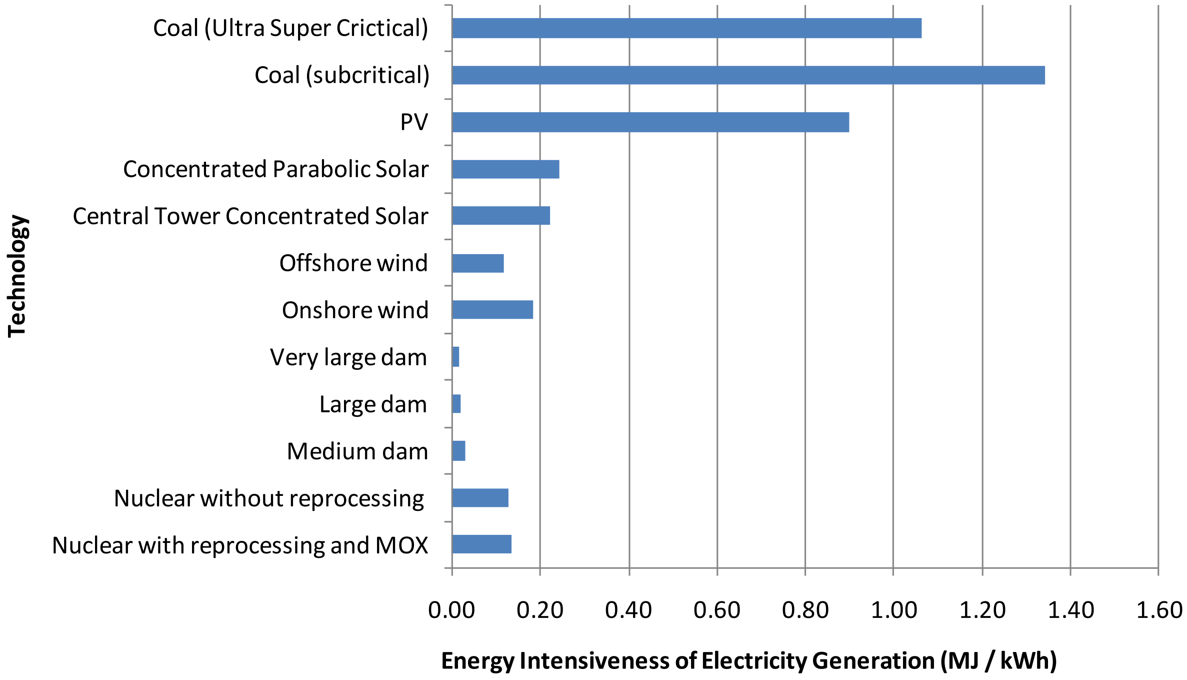
Figure 12: Carbon intensiveness comparison of the studied technologies



3.4.1.b Energy input

The energy intensity reveals similar patterns than carbon intensiveness, at the exception of solar PV, which is almost as energy intensive than coal power (0.9 MJ/kWh for PV against 1.2 MJ/kWh for coal, Figure 13). Again, hydropower is the least energy intensive source, followed by nuclear and wind. The thermal solar generation shows also as a low energy intensive technology, just above 0.20 MJ/kWh. For nuclear and coal, the energy content of the fuel (coal or uranium) is not included in the energy input, otherwise their intensiveness would be over 3.6 MJ/kWh, which represent the limit for an energy ratio of one.

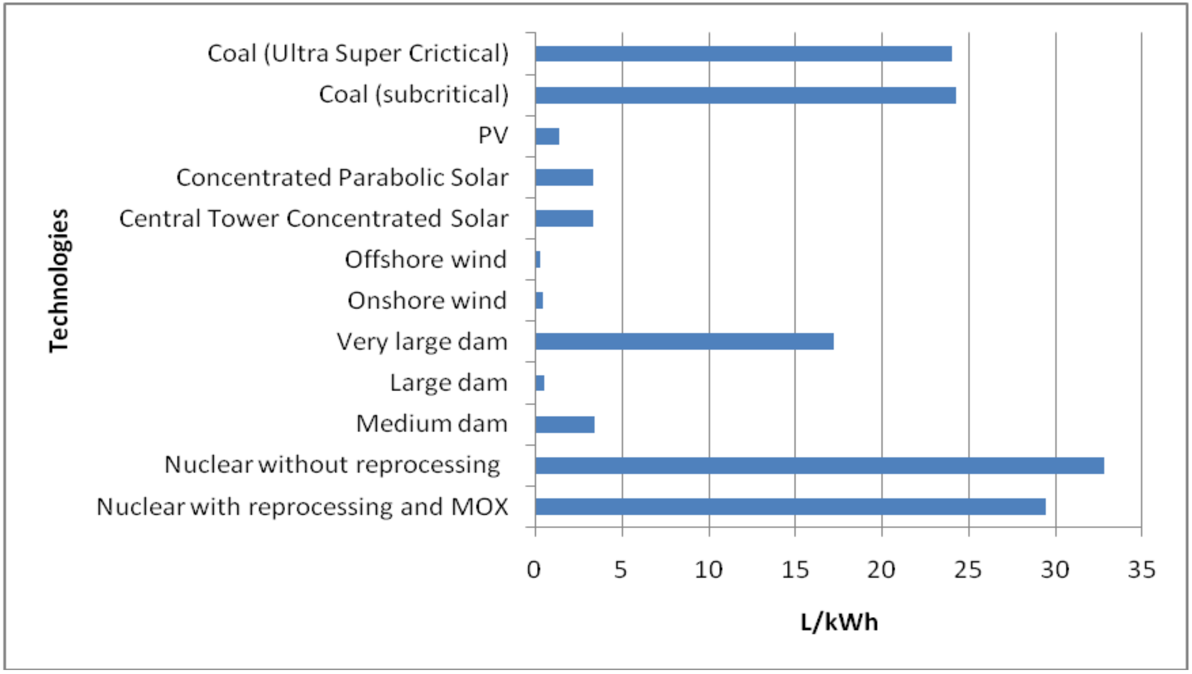
Figure 13. Energy intensiveness of Electricity Generation across technologies



3.4.1.c Water input

The water input required per kWh largely vary with the technology modeled. Fossil energy generation is the most water intensive with 25kg/kWh for coal and 30kg/kWh for nuclear(Figure 14). The reason is the massive water need of cooling systems. The difference between coal and nuclear may be explained by the water need of all the processing chain of nuclear fuel preparation. The large dam is also very water intensive, due to the massive reservoir lake created (The lake of the three gorges dam has the size of Switzerland). Among renewable energies, smaller dams, wind power, solar PV and CSP are the smallest water consumers with less than 3kg/kWh.

Figure 14: Water intensiveness of electricity generation across technologies.



3.4.1.d. Cost analysis

Electricity costs include fixed construction cost (infrastructure capital), fixed annual cost (such as annual insurance fees) and variable cost depending on the generation (as maintenance cost, fuel cost). The data used in this study come from two studies. The first one is from the US Energy Information Administration [EIA, 2010]; the second one is a study from the California Energy Commission [O'Donnel, 2009] The levelized cost is then calculated following the common way with our data of life span and capacity factor for each technology. The coal is the cheapest technology, with 6 dollar cents per kWh, slightly lower than nuclear, onshore wind and hydro (Table 13, 7 cent / kWh). Offshore wind is much more expensive than onshore wind (26 cents against 7 cents per kWh) and remains economically non attractive, compared to onshore generation. Solar PV is also expensive, but CSP is now just twice as expensive than the cheapest technologies.

Table 13: Normalized cost of various technologies

		Fixed cost at construction	Annual fixed cost	Variable cost cost	Lifetime	**Levelized cost**
Technology	CF	$2010/KW	$2010/KW	$2010/MWh	Years	**$/Kwh**
coal	57%	$ 3,006	$ 33	$ 4	40	**0.056**
nuclear	90%	$ 4,668	$ 118	$ 4	50	**0.061**
hydro	41%	$ 3,076	$ 13	$ -	100	**0.063**
Wind onshore	44%	$ 2,438	$ 28	$ -	20	**0.067**
solar CSP	43%	$ 4,190	$ 66	$ -	25	**0.114**
Wind average	32%	$ 4,207	$ 41	$ -	20	**0.164**
Wind offshore	27%	$ 5,975	$ 53	$ -	20	**0.261**
solar PV	19%	$ 5,300	$ 47	$ -	30	**0.285**

Source: EIA (2010); O'Donnel (2009)

Economically, onshore wind, hydro and nuclear are very competitive compared to coal. This study does not include any carbon capture and storage technologies that might be coming with the next generation of coal power plant. Introduction of carbon tax or pricing policies would also make coal-fired electricity generation less competitive due to its carbon intensiveness.

3.4.2. Scenario analysis

In this section we apply our findings on the two scenarios described in the above sections. What is the impact of higher non-fossil electricity generation? And what is the price to pay for it? This study's results provide quantitative answers to these questions.

Global warming potential

As shown on Table 13 the environmental cost of each scenario is similar regarding the CO2 construction cost, however it should be keep in mind that the 450ppm make the hypothesis that the society is more energy efficient and that efforts on research and development lead to reduced electricity usage. If the carbon intensiveness of equipment construction is regarded per KW, the 450ppm scenario infrastructures requires 284 kg of CO2e per kilowatt built whereas the infrastructures of the BAU scenario cost 220 kg of CO2e per KW built. That is, the construction and manufacturing of equipment for reference scenario development is less carbon intensive than 450 ppm scenario development due to the high energy embodiment of non-fossil electricity generation technologies.

Figure 15: Comparative CO2e impact of both generation scenarios

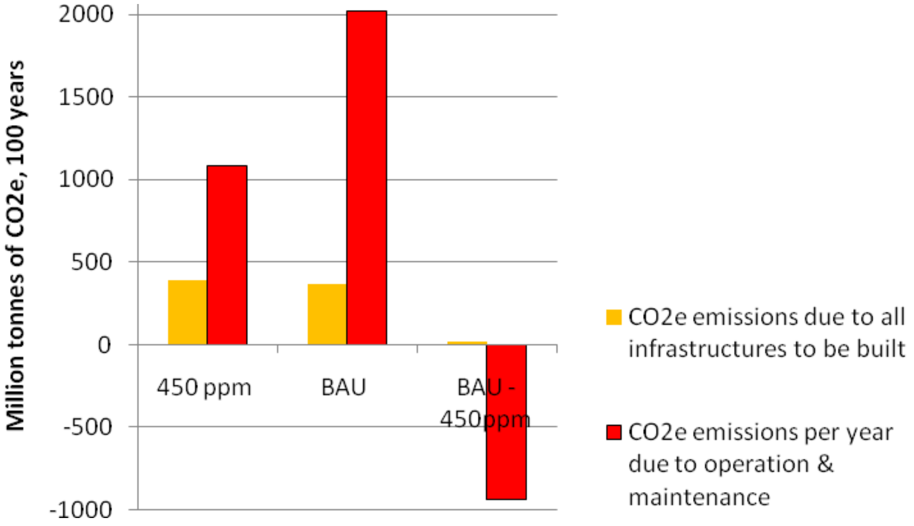
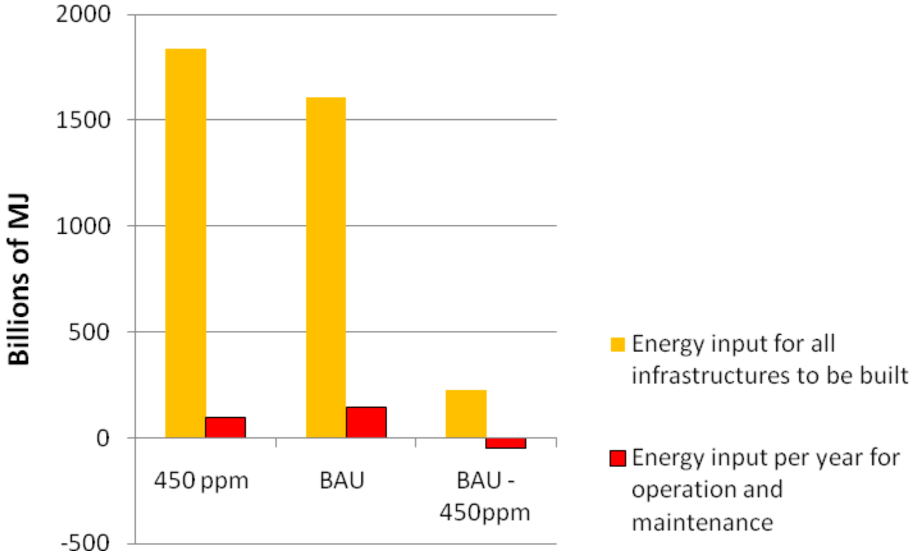


Figure 15 illustrates the lower CO2-equivalent emissions for 450 ppm scenario electricity generation operations and maintenance. The difference in the mix and in the overall generation leads to a large difference of CO2 emission for the two scenarios. Almost an extra billion ton of CO2 equivalent would be emitted per year if China decided to follow the hard path described by the business as usual scenario. A billion tons of CO2 represent an increase of 1ppm concentration of CO2 in the atmosphere every three years. The bars on the right side of Figure 15 illustrate the CO2-equivalent effects of moving from the reference to 450 ppm trajectory in 2030--the slight increase in embodied emissions would be completely overshadowed by the reduction of operational emissions.

b. Comparative energy requirement for the two scenarios

As shown in Figure 16, The energy required to build the infrastructures outweighs this time by ten the energy required to operate and maintain all the power plants. Coal and uranium embedded energy is not included in the study. Consequently the operation and maintenance energy is only represented by parts changes and transportation of fuel and humans responsible for the maintenance.

Figure 16: Comparative energy input for construction, O&M of the two scenarios



Building the set of infrastructure of the 450ppm scenario would cost 220 billion MJ of extra energy compared to the BAU. Then the generation of cleaner energy would save 50 billion MJ per year. Hence, the energy payback time of the 450ppm scenario is four and an half years. The remaining life time of generation (between 20 and 100 years depending on the technology) represents after four years a pure gain of energy.

c. Comparative cost of the two scenarios.

The 450ppm scenario set of power plants to build are slightly more expensive to build than the BAU scenario if you consider the per GW investment (by 10%, $ 3.11 billion per GW instead of $2.84 billion). But the overall capital investment is lower for the 450ppm scenario ($ 4.3 trillion against $ 4.7 trillion for BAU, as shown on Table 14), then the cost of operation and maintenance per year is by far at the advantage of the 450ppm scenario (58 billions of dollars compared to 285 billions of dollars).

Table 14. Overall comparative costs of the two scenarios

	Construction cost	Annual O&M cost	Average construction cost
Scenario	Billions of $	Billions of $	Billions of $ / GW
450 ppm	4,278	58	3.11
BAU	4,742	285	2.84

However, these figures represent the generation cost and total cost of the two scenarios is probably quite a bit larger. Renewable electricity generation implies tradeoff on the grid and thus, massive investment to integrate decentralized generation centers and to address frequency instability and generation intermittency. The cost estimates in Table 14 do not include investments required for electricity storage or grid upgrades to accommodate intermittent electricity sources. Much energy is currently spent into research on smart grid, but transmission and distribution networks still represent a big part of the investment necessary for a transition from a fossil-led generation system to a renewable one. Another factor that should be considered in a complete scenario analysis is the investment to improve energy efficiency and thus a lower final demand.

d. Comparative water withdrawal need of the two scenarios

Assumption

Data regarding water consumption come from the review of various technologies water consumption [Fthenakis, 2010, Table 15] and from a special study of the NREL focused on concentrated solar power [Macknick, 2010]. In the US, 50% of the thermal power plants (nuclear and coal) are equipped with cooling towers (EIA, 2010). For the two China-specific 2030 scenarios, most of the power plant will be replaced and as modern coal policies suggest to build cooling towers equipped plants (it reduces by 20 to 50 times the water need) we assume that two third of the Chinese power plant will be cooled with recirculating systems by 2030. The same assumption is made for nuclear. As concentrated solar power it is a totally new technology developed in arid area, CSP is supposed to be 100% equipped with cooling towers.

Results

The water need radically change across the scenario. The intensive use of coal in the BAU scenario and the lower energy efficiency implies a water withdrawal need that is twice as important as for the 450ppm scenario (149 billions of m3 / y versus 73 billions of m3 / y. (Table 15). To give a comparison, a billion cubic meters is the equivalent of one kilometer cube. The water need of the extra infrastructures to be built to meet the need of the BAU path, 149 km3 / year is equal to the volume of two months of the Yangtze flow, the third largest river in the world.

Table 15. Comparative scenarios water withdrawal need

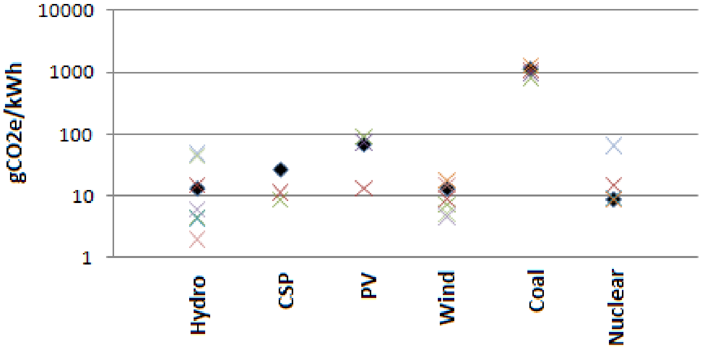
	Average water withdrawal input / kWh	Scenarios extra generation	Total water witdrawal
Scenario	Kg/kWh	TWh/year	Billions of m3 / year
450 ppm	16	4470	73
BAU	23	6594	149

3.4.3. Benchmark analysis

Greenhouse gases emissions benchmark

The benchmark comparison shows that our GHG emissions results for the various technologies studied are very consistent with the scientific literature reviewed. The solar power (PV and CSP) is in the upper part of the benchmark, nuclear is among low figures. Coal, wind and hydro are in the middle.

Figure 17: Benchmark comparison for greenhouse gases emissions

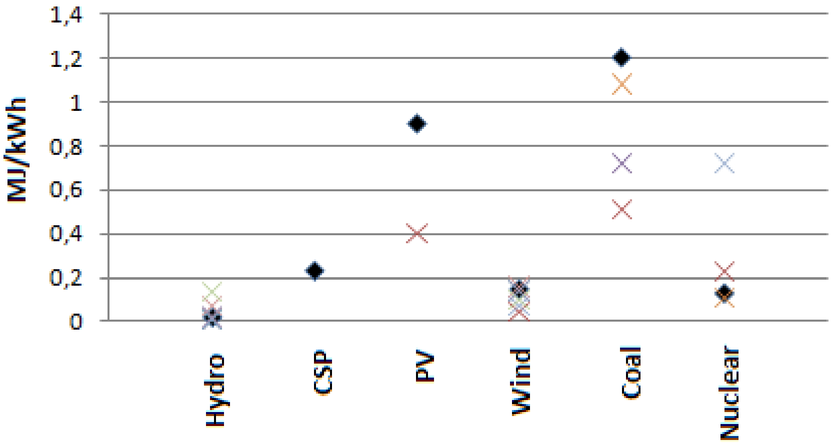


Sources: Jacobson MZ. 2009, Gagnon. 2001, Sherwani 2010, Ribero 2010, Ida 2010, Dones 2003, Ou 2010, Dones 2005, IEA 2001, Lenzen 2001, Zhang 2007, Vestas 2006,

Energy input benchmark

The benchmark comparison shows that our energy results for the various technologies studied are consistent with the scientific literature reviewed. PV seems high, but is compared with only one other source. Coal energy input is lightly above other figures, due to the China-specific transport distance data in our model and the big sensitivity of coal generation energy input to transportation.

Figure 18: Benchmark comparison for energy input



Sources: Sherwani 2010, Ribero 2010, Ida 2010, Jacobson MZ. 2009, Gagnon. 2001, Lenzen 2001, Zhang 2007, Vestas 2006, Dones 2003, Ou 2010, Dones 2005, IEA 2001

3.4.4. Sensitivity analysis

This project included two sensitivity analyses: double generation equipment lifetime and electrification of fuel transport. As expected doubling the lifetime of generation equipment reduces unit lifetime energy use and emissions by almost 50% and water usage to a lesser degree. Improvement of fuel transport efficiency, particularly transport of coal by electric rail as opposed to diesel rail and truck, yields immense energy and carbon savings that are comparable to switching from the reference to 450 ppm development trajectories. This finding is consistent with current analysis on the energy implications of China's coal transport bottlenecks (e.g., Aden, 2009).

4. Discussion and Conclusions

The results of this study indicate that increased use of non-fossil electricity generation technologies provides lifetime energy, emissions, and water savings compared to more fossil-intensive development. Among the generation technologies assessed in this study hydro, nuclear, and wind power have the lowest lifetime energy use and emissions per unit of electricity generated. Photovoltaic electricity generation is the most energy and carbon-intensive non-fossil technology reviewed here; nonetheless, these LCA results show that PV is still less energy and carbon intensive than coal. Water LCA results indicate that nuclear power is most water-intensive, and that all of the renewable electricity generation technologies are less water-intensive than coal per unit of electricity generated. On an aggregate level the reference scenario requires more than 40% more water per kilowatt-hour of electricity generated than the 450 ppm scenario.

Scenario results demonstrate that expanding China's electricity generation capacity will have a large lifecycle impact in terms of increased total energy use and emissions. Most of the energy required for new electricity generation is related to equipment and manufacturing, while most of the GHG are emitted in the operation and maintenance of the generation facilities. This is largely due to the GHG intensiveness of coal combustion and large hydropower reservoirs. Comparison of the 2030 reference case and 450 ppm scenarios shows that switching to a non-fossil electricity generation trajectory mitigates emissions growth over the lifecycle of the generation system and that the additional energy required to build the non-fossil electricity system is recouped in less than five years. Within the narrow bounds of electricity generation equipment (i.e., not including storage or grid improvements), the average construction cost of 450 ppm scenario generation mix would be 10% higher per gigawatt of capacity, whereas the aggregate annual operations and maintenance costs would be 80% lower due to independence from fossil fuel procurement costs. Beyond energy use, emissions, water use, and investment costs, the 450 ppm scenario also offers potential benefits in the areas of energy security, local environmental quality, human health, climate change mitigation, and sustainability.

4.1. Policy Implications

The relative savings and benefits inherent in the 450 ppm scenario perhaps explain China's unilateral actions in support of increased renewable energy use and improved energy efficiency. China's 2005 Renewable Energy Law set a target of deriving 15% of total primary energy use from renewable sources by 2020. In November 2009, the Chinese government announced a complimentary target of reducing the carbon intensity of GDP growth by 40-45% below 2005 levels by 2020. The comparative LCA results of this study indicate that hydro, nuclear, and wind power technologies would be most effective in reducing the emissions intensiveness of electricity generation. Given that fresh water resources are increasingly scarce in China, the water LCA results suggest that wind power may be the most appropriate technology for the most arid regions of the country.

4.2. Model Assessment and Further Work

This project combined process and economic input-output lifecycle analysis to produce a comparative assessment of coal and non-fossil electricity generation technologies in China. A variety of data sources and methods were needed to cover the range of currently existing technologies expected to generate electricity in 2030. While particular data points in the results are subject to uncertainty, the LCA approach used here provided a useful comprehensive assessment of some basic choices in how to develop China's electricity system. Further work could include additional data collection on emerging technologies, sensitivity analysis on the impacts of material price fluctuations on the input-output results, and inclusion of other, smaller-scale electricity generation technologies.

4.3. Conclusions

This comparative lifecycle assessment of electricity generation technologies indicates that increased non-fossil electricity generation will yield energy, water, and emissions savings compared to business-as-usual reliance on fossil fuels. Results show that the additional up-front energy use and emissions related to expanding non-fossil electricity generation capacity is recouped quickly in operational savings.

References

Aden N, at al. 2009. *China's Coal: Demand, Constraints, and Externalities.* Lawrence Berkeley National Laboratory Report LBNL-2334E.

Aden N, et al. 2009a. *How Can China Lighten Up? Urbanization, Industrialization, and Energy Demand Scenarios.* Lawrence Berkeley National Laboratory Report LBNL-3527E.

Azzopardi B and Mutale J. 2010. "Life cycle analysis for future photovoltaic systems using hybrid solar cells," *Renewable and Sustainable Energy Reviews* 14, no. 3 (April 2010): 1130-1134.

Bauer, C. & Bolliger, R. (2007) Teil VIII Wasserkraft Data v2.0. ecoinvent report, Swiss centre for Life Cycle Inventories , .

China Wind Power Center (CWPC). 2008. China wind power 2008 report, avalaible at http://www.cwpc.cn/cwpc/en/node/6666

CWPC. 2009. Distribution of China's wind projects <http://www.cwpc.cn/cwpc/en/information/reference/database/gmap>

Di, X., Nie, Z., Yuan, B., & Zuo, T. (2007) {Life cycle inventory for electricity generation in China}. The International Journal of Life Cycle Assessment 12, 217--224.

Dones, R. & Bauer, C. (2009) Teil VII Kernenergie Data v2.1 . ecoinvent report, Swiss centre for Life Cycle Inventories.

Dones, R., Bauer, C., & Roeder, A. (2007) Teil VI Kohle Data v2.0. ecoinvent report, Swiss centre for Life Cycle Inventories.

Dones, R., Heck, T., & Hirschberg, S. (2003) *Greenhouse gas emissions from energy systems: Comparison and overview*. PSI annual report.

Fthenakis V and Alsema E. 2006. "Photovoltaics Energy Payback Times, Greenhouse Gas Emissions and External Costs," *Progress in Photovoltaics* 14, no. 3 (May 2006), 275–280.

Fthenakis, V and H.C. Kim. 2010. "Life cycle use of water in US electricity generation" *Renewable and Sustainable Energy Review*. September 2010.

Fuggle, R. & Smith, W. T. (2000) Experience with Dams in Water and Energy Resources Development in the People's Republic of China. WCD Country Review Paper , .

Gagnon, L., Belanger, C., & Uchiyama, Y. (2002) "Life-cycle assessment of electricity generation options: The status of research in year 2001," *Energy Policy* 30, 1267--1278.

Gagnon, L. & van de Vate, J. F. (1997) "Greenhouse gas emissions from hydropower:: The state of research in 1996," *Energy Policy* 25, 7--13.

Horvath A. 2005. "Decision-making in Electricity Generation Based on Global Warming Potential and Life-cycle Assessment for Climate Change," University of California Energy Institute (UCEI) Energy Policy and Economics Working Paper Series #6. http://www.ucei.berkeley.edu/PDF/EDT_006.pdf

Hutson SS et al. "Estimated use of water in the United States in 2000". U.S. Geological Survey; 2004. http://pubs.usgs.gov/circ/2004/circ1268/.

International Energy Agency (IEA) 2009. *World Energy Outlook 2009*. Paris: IEA.

International Energy Agency (IEA) website (http://www.eia.doe.gov/cabs/China/Coal.html), consulted on 10/25/10.

Ito M, et al. 2009. "A Comparative LCA Study on Potential of Very-large Scale PV Systems in Gobi Desert," Institute of Electrical and Electronics Engineers*,* NY:IEEE.

Kubiszewski I et al, 2008, "Meta-analysis of net energy returns for wind power system", *Renewable Energy*, Vol 35, (Jan 2010) p218-225

Lenzen M, J. Munksgaard, 2002, "Energy and CO2 life-cycle analyses of wind turbines—review and applications", *Renewable Energy 26, July 02 p339-362*

Levine MD and Aden NT. 2008. "Global Carbon Emissions in the Coming Decades: The Case of China," *Annual Review of Environment and Resources*, Vol. 33: 19-38 (November 2008).

Martinez E et al, 2007, "Life cycle assessment of a multi mega-watt wind turbine" *Renewable Energy 34* (March 2009) 667–673

National Renewable Energy Laboratory, What Is the Energy Payback for PV? DOE/GO -102004-1847 (2004).

NBS. 2009. China Statistical Yearbook 2009. Beijing: National Bureau of Statistics

NBS. 2010. China Statistical Yearbook 2010. Beijing: National Bureau of Statistics

Nawaz I. and Tiwari GN. 2006. "Embodied energy analysis of photovoltaic (PV) system based on macro- and micro-level," *Energy Policy* 34, no. 17 (November 2006): 3144-3152.

Pacca S and Horvath A. 2002. "Greenhouse Gas Emissions from Building and Operating Electric Power Plants in the Upper Colorado River Basin," *Environmental Science & Technology*, ACS, 36(14): 3194-3200.

Pacca S, et al. 2007. "Parameters affecting the life cycle performance of PV technologies and systems," *Energy Policy* 35, no. 6 (June 2007): 3316-3326.

Pehnt, M. (2006) {Dynamic life cycle assessment (LCA) of renewable energy technologies}. *Renewable Energy* 31, 55--71.

Ribeiro, F. M. & Da Silva, G. A. (2010) {Life-cycle inventory for hydroelectric generation: a Brazilian case study}. Journal of Cleaner Production 18, 44--54.

Sherwani AF, et al. 2010. “Life cycle assessment of solar PV based electricity generation systems: A review,” *Renewable and Sustainable Energy Reviews* 14, no. 1 (January 2010): 540-544.

Svensson, B. & Husebye, S. (2002) Environmental and Health Impacts of Electricity Generation: A comparison of the Environmental Impacts of Hydropower with those of other gneration technologies. The International Energy Agency - Implementing Agreement for Hydropower Technologies and Programmes ,

Torcellini, P et al, 2004, “Consumptive water use for US power production” NREL database.

Vestas Wind Systems, Life Cycle Assessment of Offshore and Onshore Sited Wind Power Plants Based on Vestas V90-3.0 MW Turbines (Denmark, 2006)

Vestas Wind systems, wind turbines brochures of V90 turbine, 3,0MW offshore and onshore. http://www.vestas.com/en/media/brochures.aspx

Wadia C, et al. 2009. “Materials Availability Expands the Opportunity for Large-Scale Photovoltaics Deployment,” *Environmental Science & Technology* 43, no. 6 (March 15, 2009): 2072-2077.

Wen Liu et al. 2010. “Potential of renewable energy systems in China,” *Applied Energy,* In Press, Corrected Proof (n.d.).

Zhang, Q., Karney, B., MacLean, H. L., & Feng, J. (2007) {Life-Cycle Inventory of Energy Use and Greenhouse Gas Emissions for Two Hydropower Projects in China}. *Journal of Infrastructure Systems* 13, 271.