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Editorial

Energy and its sustainable development for China: Editorial introduction and commentary for the special issue of Energy – The international journal

1. Introduction

Energy resourcing, use, and its economic, environmental and social impacts have a critical influence on development in general and on sustainable development in particular. Noting that among the nations China tops the world in population, energy consumption (from 2010) and greenhouse gas emissions (from about 2008), and has one of the highest growth rates among the world's nations in its energy consumption and economy, it is obvious that its sustainable development is of vital need both to China and to the rest of the world. The Guest Editors of this Special Issue (SI) of Energy – The International Journal have therefore invited leading experts, mostly from China, to share their knowledge by reviewing most[1] of the key aspects of sustainable energy development in China, including their views of possible sustainable paths to the future. It gives us great pleasure to present this SI "Energy and sustainable development for China" of ENERGY – The International Journal.

This Editorial Introduction provides a very brief summary of the most recently available energy and emissions data[2] in an international context, outlines the structure of the SI, summarizes the main points in the SI papers (in some cases with some commentary and updating), points to relations between different papers, fills some information gaps, and offers the Guest Editors' brief summary and additional comments for some sustainable paths to the future.

For the readers' convenience, the articles in the SI are classified into the following four categories:

- Energy strategy and technical road map
- Non-renewable energy technologies and use
- Renewable energy
- Environmental aspects and technology,

but many papers fall into more than a single category.

2. Sustainable energy development requires harmonious progress of economy, environment, and society

Availability of adequate and affordable amounts of energy is an absolute need for satisfactory social development, a fact that is especially significant for people and entire nations that lack it. The inequity in energy use worldwide, shows that six out of seven people (including the average citizen of China) consume less than ¼ of the remaining seventh person, and that one-third of humanity lacks access to modern energy forms and services (interpolated from [1–3]), including nearly a quarter who have no access to electricity. This is of course very worrisome for the present and perhaps even more so for the future when energy-poor people [4] will advance to acceptable energy use levels and consequently raise the worldwide energy use with all its impacts.

Since the 1990's China is engaged in rapid economic and social development and at present has one of the largest energy consumptions in the world and one of the highest energy and GDP annual growth rates (9.1% for both in 2009). These magnitudes and growth unfortunately cause severe environmental impact on air, water and land, and it now is also one of the larger emitters of CO_2. It also still lags in all sustainability metrics, environmental, economical and social; employing the commonly used Human Development Index formulated and monitored by the United Nations, China is in the 92d place among the 182 countries considered [5]. These negative consequences are unsustainable for both China and the world and it is obvious therefore that it should progress significantly.

Considering the size of China's population, the quantity of its energy resources is relatively low. For example, the estimated per-capita energy resources of coal and hydropower is only about 50% of the world average, and of oil and gas resources it is only 1/15 of the world average [1,2]. In China's advance towards a higher standard of living for its 1.33 billion people, it is thus faced with the conflict between rapid economic development, the associated energy use and environment pollution, and energy and resource shortages and depletion. It must not choose the model, taken historically by many of the currently developed countries, of energy use development first and treatment of the negative environmental and social impacts afterwards.

The profound question that these problems create is: what is the optimal path to China's sustainable development that ensures a reasonable socio-economic standard to its people, which harmoniously integrates use of resources, energy conversion, and environmental protection for China and the world? To start

[1] Practicalities of assembling and peer-reviewing such a large number of papers have regrettably not permitted adequate inclusion of all important topics.

[2] The data is mostly for the years 2007–2009. Some differences exist between the data in the Editorial Commentary and those in the SI papers, as well as between those among some of the individual papers, mostly because the data used were not always for the same year as sources. Furthermore, a sad fact is that there is a large uncertainty in the accuracy and completeness of the energy data from and about China.

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answering this question, domestic and international energy experts have been invited to contribute to this SI to deeply explore and thoroughly review the Chinese energy situation and its development tendency, aiming to provide the readers with a picture that is as realistic as possible. Some of the authors are professors from universities or research institutes; some are from the governmental energy development offices such as the National Energy Administration of China, and some are highly experienced engineers from the industrial sector.

The accomplishment of this SI was partially based on several projects in which some the Guest Editors and authors have been involved. For example, the Engineering Academy and Scientific Academy of the China and the USA are conducting a cooperative project with energy and environmental issue, and some of papers were based on the reports written by the top scientists in China in this project. Some other papers are based on some reports from other projects, which concern to China's plans and needs of key technologies in the energy area in the next 5–15 years.

The intention of this SI is to: (a) describe the current situations and trends and describe China's plans and needs in the energy area in the next 10–20 years, (b) focus on addressing the question as to how China may be satisfying these needs, and the related energy resource, technologies, the economic, environmental and social consequences, and (c) answer the question whether this can be done in a sustainable way, and how. The invited papers describe resources, technologies, environmental measures and consequences, social consequences (including existing and needed political action), and economics. The authors were encouraged to use quantitative descriptions and comparisons with other countries and the world as whole and these were indeed included.

We hope that the SI would be an important and timely contribution to the scientific literature.

3. Energy strategy and technical road map

The fractions of the energy resources supplying the primary energy demand are shown in Fig. 1. More than 70% is met by coal.

"Neither stopping the development to deal with climate change nor developing the economy without considering the climate change is acceptable" is a very pertinent quote from the opening SI paper by Jiang et al. [6] [3]. Considering its economic and social situation, China is obliged to improve the condition of its people, but not by simultaneously creating environmental damage for itself and the rest of the world, of magnitude that future generations may not be able to tolerate. Having at present to use coal for 70% of its energy needs at a relatively low efficiency at that, the environmental effects and hazards to miners are most severe. The policies that Jiang et al. recommend for the future start with energy savings including significant modernization of the energy conversion industry to improve efficiency, and simultaneously recommend energy resource switching to renewable and nuclear energy, with much improved energy regulations and management systems by government. Examples of areas where such regulatory improvements are needed include for electric generation and transmission sectors to allow sale of energy to large utilities by small producers, to structure the electric industry so that it allows commercial development and sale of renewable energy, especially the intermittent types like wind and solar, appropriate enforcement power and effective action over the energy industry and users, fair market practices, and proper resolution between China's national and local conflicts related to such problems. As to the latter, it is impossible to

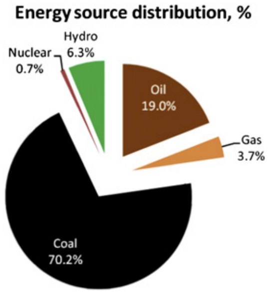

Fig. 1. Total energy consumption in China, by type (2009) [2]. The only renewable energy included is hydropower.

have a policy for national benefit when different local governments chose not to participate. Equally important but difficult to implement is the recommendation that the government should promote energy price reform to gradually form an equitable pricing mechanism that reflects all externalities, such as resource scarcity, market demand and supply, and the cost for pollution control, which would thus also be the basis for a more equitable comparison between different energy resources and conversion system, especially useful for promoting the development of renewable energy. To demonstrate the magnitude of externalities, they cite an estimate that the cost of only the externalities for coal is 117% higher than the 600 Yuan RMB per ton price of coal in 2009.

As amply demonstrated in the analyses reported by He et al. in SI paper [7], aggressive energy policies formulated to promote energy efficiency and energy conservation, in part by decreasing the energy intensity of activities and products, will also result in substantial environmental benefits that include, by the year 2030, a CO_2.emissions reduction of 22% relative to those in 2009, and more than 100 billion US$ of health benefit. The SI paper by Li et al. [8] focuses on the concept of "circular economy" founded on efficient resource use and waste stream feedback, where recycling of energy and materials is an essential part of any energy saving and pollution reduction process. Noting that the efficiency of energy use in China is only about 33%, at least 10% (and in some cases up to 50%) lower than that in the developed countries, they give a number of quantitative examples from the Chinese process industry (that consumes about 70% of China's energy) with recommendations that include process integration, for possibly large improvements in both energy efficiency and pollution reduction.

Transportation is rapidly growing in China and has major effects on energy and emissions, as described in detail in the SI paper by Hu et al. [9]. China had about 10 million motor vehicles (all following numbers exclude motorcycles) in 1990 [10], a number that has increased to about 57 million in 2007 and 85 million in 2009 [11], amounting to a recent growth rate of about 22%/year. If the current trend continues, China's is expected to have 400 million motor vehicles (about 62% of the current number of motor vehicles in the entire world!), with commensurate increase in fluid fuel demand, by the year of 2030. Apart from the negative environmental and social effects related to emissions, congestion, accidents and other consequences, this would be a major burden on fuel supply since China is already a net importer of fluid fuels. Through improving fuel economy, encouragement of use of hybrid-electric, electric, and clean diesel vehicles, improvement of alternative fuel supply such as biomass-based or from coal (as long as they are affordable and do not cause unacceptable environmental problems), and development of public transport, the potential energy saving capacity is estimated to be 60% by 2030, which, at least technically, could keep the oil demand by on-road vehicle at the current level. Several very significant uncertainties in attaining these goals

[3] In this Editorial Introduction some of the citations are to the papers published in this SI, and some from other sources.

towards sustainable transportation include traffic efficiency, the central government's resolution to effectively work towards these goals and to price transport and its fuels with proper inclusion of their externalities, and consumers' choices. It is noteworthy that the worldwide trend to the use of electric vehicles, and China's strong demand for cars, offer Chinese industry an opportunity to compete in this new field where the competition is not yet fully established, by R&D of appropriate batteries and manufacturing of cars, and this has already started.

Nuclear power is part of power supply mix in China. As shown in Fig. 1, only about 0.7% of China's primary energy consumption is by nuclear power, but 6 new reactors are under construction to add to the 11 that are in operation [12]. As discussed in the SI paper by Zhou et al. [13], the obvious driving factors for nuclear power development include the brisk electricity demand, nearly zero CO_2 emissions, oil supply security, and increasingly positive public acceptance. It is, however, still unclear whether nuclear energy development for China, as in the rest of the World, is sustainable, firstly due to problems of reactor safety, nuclear waste treatment, and risk of proliferation of weapons material. In addition, nuclear technology diversity, shortage of uranium resources, and weak market competitiveness of nuclear power in the short term, as well as promising developments in clean coal combustion, are certain barriers that China's nuclear energy development also faces. Furthermore, we have learned from world experience with nuclear power that public acceptance is fickle, ranging from universal enthusiasm in the late 1950-s about the enormous potential of nuclear power to satisfy the world's energy demand economically, cleanly and safely, to the various later decisions (from the 1980s) on nuclear power moratoria in many countries that have been using it, and recently back to reserved acceptance due to global warming and oil and gas supply security concerns. These uncertainties pose serious difficulties for long range national and private sector planning. Zhou et al. [13] put forward some suggestions and recommendations for domestic nuclear technology development including the alleviation of some of the concerns and for upholding public acceptance.

Electric power generation poses a formidable challenge to China's sustainable development. Its electricity consumption has been experiencing world-record-defying growth rates, and for the year 2010 is expected to reach $(3.451)10^{12}$ kWh. Increased introduction of electric cars will add to the regular growth. Being coal-dominated and using relatively low efficiency power plants, it is the country's largest source of air pollution and GHG emissions. Furthermore, the transmission grid has difficulties in catching up with the growth rate. The inadequacy of transmission is not unique to China, and is common to most countries, including the more developed ones such as the US [14]. The SI paper by Zhou et al. [15] provides a detailed description of the transmission in China, noting that its power grid is one of the biggest interconnected power grids in the world but its structure is relatively weak as a whole, with many potential security issues, and low transmission capability of the single circuit.

Some estimates [16] show that the transmission and distribution energy losses were about 7%. The quality and extent of the electricity transmission grid is obviously of major importance in providing and distributing electricity to this rapidly developing country, but is also of critical importance for increasing the role of solar and wind power that are intermittent by nature and where the grid can thus provide an effective and economical substitute to electricity storage. In that context, it can connect the solar and wind energy rich western provinces, that have a relatively low power demand, to the southern and eastern regions of China where the demand is great. Such interconnection, mostly to make easier use of northwestern fossil fuel resources, is slowly under way anyway, via the "Power Transmission from the West to the East" plan that includes the development of new 1000 kV UHVAC and 800 kV UHVDC transmission systems.

To catch up with distribution, improve the reliability and stability of the delivered power, make good use of remote and renewable energy resources and to increase energy efficiency and reduce pollution, China's transmission grid development must be accelerated, interconnection of the regional power grids must be strengthened, and new technologies must be adopted to increase the transmission capacity.

Due the rapid demand and generation growth, China's electric power industry has been going through reform, including *technological* to improve efficiency and lower emissions of power plants, and *regulatory* that increasingly follow the path of market-oriented reforms in the electricity sector worldwide, including a separation of generation from transmission and distribution and an emphasis on opening up the sector to competition. A recent study by Williams and Kahrl [17] finds, however, several fundamental shortcomings in its basic institutions and functions, including conflicts of interest between provincial and national interests, prices of electricity that do not include major externalities, inadequate transmission and distribution systems and lack of investment incentives for their improvement, ineffective regulation enforcement mechanisms that, for example, do not enforce the use of desulfurization equipment in coal power stations, abuse of feed-in tariff regulations that encourages installed capacity growth but not necessarily higher generation from renewable energy systems such as wind, and ineffective governmental backing of energy efficiency/demand-side management. They recommend that incentives on the one hand and penalties on the other, and a transparent unbiased policy supported primarily by China's central government, but also aided by OECD, will be of major importance in the development of independent regulatory capacity in China's electricity sector and thereby in advancing effective power generation growth.

4. Non-renewable energy technologies and use

About 70% of China's energy comes from coal and it is expected to remain dominant for at least the coming half a century, and the SI discusses this subject thoroughly. The SI paper by Yang et al. [18] describes the development of Chinese coal power generation since the 1980's. The recent rate of power generation increase is demonstrated by the fact that the year 2006 has seen the installation of additional 1000 MWe each 3.3 days, unprecedented in world power generation rate history. With the operation of large-capacity and high-efficient power units, the development of power plant IT and control technologies, and the improvement in operation and maintenance, have greatly improved the reliability and economy of coal-fired power generation units in China. The recommended path to the future is a focus on transition from small (<300 MW) units that are inherently less efficient, and constructing larger-capacity high-efficiency power units, retrofitting old 200–300 MW power units to achieve better performance, shutting down small-sized (<100 MW) power units, developing cogeneration, and on the environmental side applying high-efficiency dust separation technology, new flue gas desulfurization and de-NO_x techniques, employing advanced air-cooling technology for water conservation without significant efficiency loss, and increasingly introducing and developing large-capacity supercritical power units.

A large increase in power generation efficiency can be obtained by using combined cycles, but the current technology requires the conversion of the coal to gas or liquid fuels that would be used in gas turbines. The most prominent ongoing approach is the integrated gasification combined cycle (IGCC), the development of which should be accelerated worldwide. Other approaches, that convert coal to liquid fuels are worthy of further investigation and some are described in SI papers [19–21].

The SI paper by Xie et al. [22] addresses coal as being also an important raw material for chemical industry to produce useful gases, liquids and solids, which are then used to synthesize a variety of chemicals. The traditional coal chemical industry generally refers to gasification, liquefaction, coking, processing of coke and coal tar, the calcium carbide industry, and uses of coal as raw material to produce coal-based derivatives through oxidation- and solvent extraction processes. Established processes such as coking, in which China has a world leadership position, work well but need reduction of price and emissions, many others such as liquefaction to liquid fuels, gasification to synthetic gas fuels, and polygeneration to simultaneously produce methanol, dimethyl ether, dimethyl carbonate, and other organic chemicals, as well as power, are in various stages of commercialization and development.

As described in the SI paper by Guo and Fu [23], the iron and steel industry in China is one of the major energy consuming and polluting industries, accounting for consumption of about 15% of the total national energy and generating of 14% of the total wastewater and waste gas and 6% of the total solid waste materials. Its average energy intensity per weight unit of steel is about 20% higher than that in other advanced countries. Production of crude steel in China is expanding rapidly and it is the top steel producer in the world, with a share of about 38% in 2008. The energy efficiency is improving in the past few years, and significant energy savings are expected in the future by optimizing end-use energy utilization. The authors predict that China can reduce energy consumption by about 20% and total emission of main pollutants by more than 20%, per unit weight of steel, in the near future, if (a) large blast furnaces are introduced instead of small ones, (b) advanced technologies are introduced, such as coke dry quenching, top gas pressure recovery turbines, energy recovery from off-gas and molten slag, and pulverized coal injection in the blast furnace; (c) a recycling economy chain is created within the industry and (d) government takes measures to encourage steel works to apply energy saving technology and to limit the application of outdated technologies.

Large countries often have problems of uneven distribution and demand of resources, their mismatch, and uneven economic opportunity for parts of their population based on their location. A case in point are the western parts of China, which have notable resources of fossil fuels, very large resources of unused solar and wind energy, low population density (around 50 people/km^2, 1/16 of the most populated provinces), poorer economy (typically less than 1/3 of China's average GDP), and relatively much unused land. At the same time, China's eastern part has a much stronger economy and larger demand, but is low in energy resources and is rather distant (typically about 3000 km).

The conventional energy road map used to solve the uneven distribution of energy resources and economy, entails transportation of fossil fuels from west to east, and then their conversion into secondary energy through conventional energy systems. This road map is, however, currently facing many problems, such as the tremendous pressure on the transportation sector and serious pollution. In addition, this current energy road map only develops the exploration and mining industries of western China, while most of the energy utilization industries are concentrated in eastern China. It thus exacerbates the economic imbalance between the two regions. The SI paper by Jin et al. [21] recommends a new energy road map based on innovative energy systems that would deal with the uneven energy resources distribution, and at the same time promote the sustainable development of western China, based on local conversion of the western region's fossil fuels to alternative fuels (such as DME, methanol, and F-T oil) and electricity at higher efficiency, lower investment cost, and less impact upon the environment, then transportation of these fuels and electricity to eastern China; and finally comprehensive utilization of alternative fuels with high-efficiency and low pollutant emissions in eastern China. This approach is expected to promote the development of energy and related industries such as manufacturing, transportation, and construction in the western region and thus play an important role in industry upgrade and economic development. Altogether, the new road map should be of help to China's development in general and to sustainable development of western China in particular.

As one of such innovative energy conversion systems, the authors estimated that their proposed multi-functional energy systems (MES, described in more detail in SI paper [20]) can achieve 10–14% in energy conservation, 4–8% reduction of investment cost, and a 10–37% decrease of main pollutants.

The success of the proposed road map requires development of robust and economical technologies, and availability of funds for this major investment and it is thus obviously important to accelerate the relevant research, as well as to acquire the government's support in terms of technology, policy, and finance.

Related to that, Lu et al. (SI paper [24]) use a comprehensive economic model to study the effects of investments in the energy sector on economic benefits for the local population in Shaanxi province as well as effects on energy use and emissions. They found that increasing investment in the energy sector by 60% would grow the GDP and production by 9%, but also results in household consumption and total demand growth by a similar percentage, as well as 11% growth in emissions. This serves as a good reminder that economic improvement, especially when related to energy use, may be accompanied by the adverse effects of increasing resource consumption and environmental damage. Since the full rebound effect was not included in the model, it is likely that increased consumption due to increase in disposable income would have made the adverse effects even stronger.

Chinese companies could obviously use investment moneys for developing efficient clean energy systems, and one source is via the Clean Development Mechanism (CDM) that China is eligible for, and of which it is currently the largest user. The CDM was established by Article 12 of the Kyoto Protocol with two aims: to help industrialized countries meet their greenhouse gases reduction targets in a cost-effective way, and to promote sustainable development in the host developing countries. The SI paper by Teng and Zhang [25] describes the CDM system in detail, the participation of China, the benefits to its industry (and its government which levies a "tax" on the income) and ways by which it can be improved globally to meet the intended CDM aims more effectively. China has become the biggest Certificate of Emissions Reductions (CERs) supplier in the world, with a market share higher than 40%, and has the biggest number of CDM projects. The CERs can be sold on the world market, and their total number is still well below the number needed to offset GHG emissions by the industrialized countries eligible for offsetting their emissions by this program (Annex I countries). While not realized during the formulation of the CDM scheme, sellers have quickly discovered that they can earn most by focusing on reducing emissions of gases of very high global warming potential, such as HFC, PFC, and N2O, rather than those that reduce CO_2 emissions, say by implementing renewable energy use. These projects only account for 2% of the total but therefore represent 50% of the annual CERs, thus stymieing renewable energy development although they do reduce global warming gas emissions. The administrative/bureaucratic effort involved in establishing CDM projects is extensive and daunting. The analysis in [25] shows that a clear institutional setting and implementation strategy is crucial for the effective implementation of CDM projects, and that technology transfer from the developed countries to the CER sellers should be improved to ensure longer-term positive approach for meeting the CDM intended aims.

It is well known for many years that wise integration of energy conversion systems, that properly employs energy recovery and exergy principles, is likely to yield lower energy consumption than systems providing the same services independently (cf. [26–29]). Innovative design may also reduce the price of the products. In their SI paper, Xu et al. [30] demonstrated by analysis the advantages and prospects of developing combined cooling, heating, and power systems for distributed energy uses in China, employing techniques of cascade heat use and energy reuse. Two systems were analyzed, one with complementary use of fossil fuel and renewable energy, and the other integrated with desalination technology. Water desalination is regarded as one of the ways to relieve the water crisis situation in China. Energy savings of up to 30% were predicted in their system simulations. It of course remains to determine the systems' economic performance,

Along the same lines, another SI paper (Deng et al. [31]) proposes, analyzes and shows the advantages of integrating thermal systems with seawater desalination processes including combinations of the desalination process with a combined cooling heating & power system, a power plant, or a solar thermal utilization system. They emphasize the need in China for water desalination, which, as well known and employed in industry for many years, is most energy and cost economical in dual purpose plants that use exhaust heat of power plants to desalt water (cf. [28,29,32]), feasible since thermal water desalination processes need temperatures of only 80–100 °C.

In SI paper [20] Cai et al. propose innovative Multi-functional Energy Systems (MES) for the conversion of coal to liquid fuels, which have both energy efficiency and environmental impact advantages over conventional liquefaction and gasification methods. One of the approaches, polygeneration, produces at least one liquid fuel as well as electricity and cleverly integrates the different types of fuels as inputs. Several MESs with multi-fuels input and multi-products output have been proposed and investigated. These include a system combining coal and natural gas, a system with a co-input of coke oven gas and syngas, and a solar thermal power cycle integrating liquid fuel and solar energy. Preliminary analysis shows not only higher energy efficiency but also some economic advantages over single product systems such as the IGCC. Proof of feasibility and competitiveness of these promising innovative approaches requires additional R&D.

Liquefied natural gas (LNG) is a world-common way to transport gas, usually by LNG tankers, from the supplier to the customer's gas distribution site. Natural gas is liquefied in the sellers' facilities to reduce its volume about 600-fold for transportation, When ready for distribution the customer vaporizes the LNG. The LNG industry is relatively new in China, and its status, technological aspects, and future prospects are discussed in the SI paper by Lin et al. [33]. There are many novel features in China's LNG industry, and key topics such as small-scale liquefiers, LNG cold energy utilization, coal-bed methane liquefaction, LNG plant on board (FPSO - floating production, storage, and off-loading), and LNG price are introduced and analyzed. While some of these have been used in industry, the others may be useful for future LNG practice. LNG codes and standards are being established in China. These standards must be referenced as much as possible to corresponding international equivalents. While LNG is contributing to China's multi-energy resource structure to promote energy security of the nation, the LNG supply itself must be secure. The authors of [33] recommend that it is wise to avoid politically sensitive areas and to choose suppliers situated not too far away from China when deciding on LNG suppliers. Safety is an important issue even if the LNG industry has a rather good safety record. Public education is also very important for acceptance of LNG and related facilities. To meet the increasing demand for natural gas, China needs to build about 10 large LNG receiving terminals, and to import LNG at the level of more than 20 Bm^3 per year by 2020.

5. Renewable energy

Increased introduction of renewable energy to replace fossil fuels has many obvious advantages and depends on its cost and need to occupy large areas when diffuse energy sources such as solar and wind are used. Intermittency of solar and wind sources also poses problems that must be resolved by additional investment in energy storage and backup systems. Furthermore, some renewable energy sources, such as hydropower, which is the dominant renewable energy component in China and many other countries, often have negative environmental and social impacts. Use of renewable energy in China in 2005 was about 18%, dominated by biomass (10.7%) and hydropower (6.2%) with much smaller share of solar, wind and biofuels energy.

A thorough review and study of the role played by renewable energies in China's sustainable energy supply at present with forecasts for the future is presented in the SI paper by Zhang et al. [34]. To attain the necessary large contribution of renewable energy to China's energy supply, they point to important risks that must be dealt with. These include financial risks due to the high cost, some performance uncertainties, and insecurities associated with the government role in taxation, incentives and equitable accounting for externalities (which at this time strongly favor fossil fuel producers and users), technological due to the novelty of some of the technologies, and market entry ones due to competition from large established fossil fuel companies, They describe the important role of the "China Renewable Energy Law" (2006) that presents a comprehensive renewable energy policy framework, and that institutionalized several policies and instruments for China's renewable energy development and utilization, but they also note that the enabling environment for its implementation has not been well established yet. For example, specific mechanisms and methods for premium transfer and grid-connection cost management aren't in place and arguments over feed-in tariff and public bidding persist, leaving risks for renewable energy power generation development. Suggestions for alleviating some of the risks are proposed.

Hydropower has a very important role in China's energy scene, and the SI paper by Chang et al. [35] reviews the situation and future plans, and offers some suggestions. China's gross amount of hydro resources ranks first in the world, and only about 27% of the technically exploitable resource is presently used. The hydropower development is presently at its peak period and ever since the gross installed hydropower capacity of China broke through 100 million kW it remains the highest in the world. Water resources and hydropower development are intimately connected, and China has a strong geographic nonuniformity in its water resources availability and water and electricity demand: western China has 75% of the water resources while eastern China has only 7%, but most of the demand. National development of hydropower would thus require the creation of a proper infrastructure for water and power projects construction in the west, that does not interfere with plans for water transfer to the east and north, alongside with the development of an adequate west-east electricity transmission grid. Development of pumped storage power stations is recommended, which would also be important for the development of solar and wind energy.

This paper presents a general popular and government attitude in China that hydropower development is an unalterable way for advancing economy and society, yet that at the same time emphasis must be placed on the relevant adverse impacts on society and environment, and exploitation and management of water resources should be sustainable. We note that a very important component of the method to effectively deal with these adverse problems is to properly include all the environmental and social externalities, including those of the huge embodied energy and emissions and construction, in the price of the produced electricity.

China has very large solar energy resources, especially in the sparsely populated west, and its use and development plans are described in the SI papers by Wang and Zhai [36], Wang [37] and Guo et al. [38]. The first of these papers deals with building energy systems, which offer a good opportunity for the integration of solar thermal collectors that could become multi-functional in serving both for energy collection and for some part of the building envelope. The use of solar water heaters is increasing rapidly and has in 2008 reached about 100 million m^2, the largest in the world, and the plans are for an increase to 150 million m^2 in 2010. Various solar heating and cooling demonstration projects, new construction as well as retrofit, are described. To learn from the extensive experience of solar retrofit development and demonstration conducted in the 1970s and 1980s in the US, the reader is referred to [39]. The government role in encouraging solar energy use is discussed.

The second SI paper on solar energy [37] reviews the status of solar thermal power development and its road map in China for the next 15 years. It points out that Tibet, Qinghai, Xinjiang, the southern parts of Inner Mongolia, and northern Shanxi, Hebei, western Jilin, and the middle- and southwest parts of Yunnan receive relatively large amounts of solar radiation, with areas on the Qinghai-Tibetan Plateau receiving the most. As mentioned above, many of those areas are far from demand centers, and large investment into a suitable transmission infrastructure will thus be required. Various solar power generation methods using concentrators are being examined, and an important conclusion is that significant cost reductions will be required to secure market acceptance: Wang [37] estimates that by 2025 the average 2006 solar power system cost should be lowered by 50% to reach a price that is 1.3 times the price of coal-fired power (0.030–0.042 $/kWh) at that time. Such cost reductions are to come from technical improvements, larger plant sizes, and large volume production. It is noteworthy that solar thermal power generation using concentrators is currently considered the most economical and practical solar power generation technology and has thus seen much renewed worldwide activity from about 2005, and many demonstration systems were built and are planned.

Hydrogen is considered to be a very good energy carrier, useful for energy storage, transmission, fuel cells and combustion. In the last two processes, where it is used for generating power or heat, only water is emitted rather than polluting gases. One important disadvantage of using hydrogen is that it must be manufactured, and the manufacturing energy requirement is large. If the energy comes from fossil fuels, the hydrogen manufacturing process depletes the fuel resources and is accompanied by undesirable emissions. Using renewable energy, such as solar, reduces these negative effects. The third SI paper on solar energy, by Guo et al. [38] describes methods for using solar energy to produce hydrogen, based on the plans outlined by the project of the Chinese national project “Basic Research on Large Scale Hydrogen Production Using Solar Energy”, which emphasizes understanding and exploration of fundamental theories of hydrogen production by use of solar energy, especially visible light using thermo-chemical decomposition of biomass and water, or/and using photolysis of water. The authors point out that for all solar hydrogen production processes there is a need for great improvement in conversion efficiencies, reduction of capital costs, and enhanced reliability and operating flexibility, before these technologies can become commercially viable.

The wind energy resource is very abundant in China (a recent study estimated, perhaps optimistically, that for a guaranteed price of 7.6 U.S. cents per kilowatt-hour for delivery of electricity to the grid over an agreed initial average period of 10 years, it could accommodate all of the demand for electricity projected for 2030 [40]), is a relatively mature and robust renewable power generation technology, and its use is being developed rapidly: The SI paper by Xu et al. [41] shows that the installed capacity has increased from nearly zero in 1996 to 2.7 GW in 2006. Some assessments show that 25.8 GW were installed by the end of 2009 [42], but with only 8.9 GW connected to the grid. Assuming generously a total installed capacity of about 10 GW (including off-grid) and a capacity factor of 0.3, the total wind electricity supplied to users is only 0.12% of China’s primary energy use, or 0.89% of the electricity, in 2009. The Chinese government plan is to have 50 GW installed by 2030.

Some of the main problems with more massive introduction of wind power are (a) the inadequacy of the national transmission power grid in general and in its capacity to manage the intermittency of the wind in particular, leading to much waste, (b) government incentives that encourage capacity increase but not the amount of actual useful power delivered to customers [17], (c) electricity cost that is higher than that generated by coal, in part because of the established experience with coal use, and importantly, the inequitable cost comparison due to the traditional long and short term subsidies that have been invested into coal use. An important aspect and advantage is that since wind power generation is basically well within China’s technological capacity, its industry is gearing up to become a major manufacturer and exporter of such systems, especially after it starts manufacturing wind turbines with capacity larger than 1 MW.

Biomass is a widely available energy resource in China: its total quantity, including the portion that peasant households in rural areas consume directly, is second only to the amount of coal. As reviewed in the SI paper by Wu et al. [43], the development of bioenergy is an important measure to improve energy structure, safeguard energy security, protect the environment, and assist in the sustainable development of rural economy. Bioenergy technology application is therefore playing an important role in China’s energy market, and it is one the fastest growing renewable energy resources, with much additional potential for the future. The Chinese government renewable energy plan emphasized industrialization of biomass electricity, biogas, biomass briquettes, and biomass liquid fuels.

It is noteworthy that China is a world leader in the development of anaerobic digestion for the production of biogas. By the end of 2005, more than 17 million household biogas digesters generating 8 billion m^3 of biogas annually were in operation. Importantly, this technology not only produces fuel but also serves to treat industrial organic wastewater and animal wastes and thus reduces greenhouse gas emissions significantly. Evaluation of family benefits of China’s family size biodigesters is given in the SI paper by van Gronendaal and Wang [44].

In their SI paper [43], Wu et al. also analyze the current research progresses of ethanol derived from lignocellulose, sweet sorghum and cassava, biodiesel from jatropha, biomass briquetting, synthesized fuels and pyrolysis technologies at the fundamental research and demonstration stages. The authors conclude that the key areas for developing bioenergy for China’s future are the exploitation of new biomass resources, R&D in biofuels from non-food biomass resources, and commercialization.

All biofuels have to compete with fossil fuels, and an important obstacle in rapid increase of bioenergy is their high cost. Economic feasibility of bioenergy is related to various factors, such as incentive policies and equitable accounting of externalities for all competing fuels, economies of scale, technical feasibility, cost-effective feedstock, local resource conditions, and suitable commercialization methods. Bioenergy should also get financial credits for its important role in assistance to China's rural economy in ways such as providing new jobs, increasing agricultural output, and reducing pollution-related health problems. Effective methods of reducing cost include the reduction of feedstock cost, increase in conversion efficiency and the reduction in investment in plant and equipment.

In their SI paper [45], Li et al. address bioenergy feedstock increase aspects, pointing out that no more than about 2.5% of the total feedstock growing potential is used and that China's huge amounts of available marginal land ($\sim$453 million ha) have significant potential for growing bioenergy resources, with co-benefits such as carbon sequestration, water/soil conservation, and wind erosion protection. Suitable plant species include some species of Salix, Hippophae, Tamarix, Caragana, and Prunus and could produce feedstocks of 100 million tce/year in 2020, and 200 million tce/year in 2050. Li et al. feel that is a win–win situation of realizing an eco-society through an expected 4–5% reduction of total CO_2 emission in China in 2020–2050, with bioenergy development. To move towards this goal, they recommend an urgent systematic assessment of biomass resources and marginal lands, breeding of energy crops with high rate of productivity and high heating capacity for bioenergy use, and development of new high technologies of energy conversion.

Planting of marginal lands tends to protect soil surface, improve soil structure, reduce wind erosion and sand storms, and increase rainfall retention, and protects wildlife and biodiversity. At the same time, a worldwide argument among scientists is ongoing about possible environmental damages due to conversion of marginal land to agricultural. One of the objections is that such processes creates a "biofuel carbon debt" by releasing 17–420 times more CO_2 than the annual greenhouse gas (GHG) reductions that these biofuels would provide by displacing fossil fuels (cf. [46–48]).

Other concerns about massive use of biomass (summarized in [49,50]) include the fact that bioenergy production and policies have mostly not been based on a broad cost-benefit analysis at multiple scales and for the entire production chain, which is particularly true for bioenergy's impact on land and water use, on food production, and on agriculture. It is often ignored that greenhouse gases are emitted due to the associated agricultural harvesting, transportation and energy conversion processes, and fertilizer and pesticide use. Effects of water use and contamination (e.g. by fertilizer and pesticide runoff) are also often undervalued. To avoid unexpected and unacceptable negative outcomes and waste of investment funds, and to reduce risk, it is extremely important to apply rigorous sustainability analysis and planning, with adequately sized system boundaries and time scales if massive use of biomass is sought.

China has significant geothermal resources but we failed to include in the SI a paper on this important topic, so some general editorial comments are made here. More than 100 geothermal fields are used in China, mostly for low temperature heat use, with total thermal installed capacity of 3.7 GWt, and those for electricity production generate only about 25 MWe (in Tibet) [51]. It was reported [52] that in June 2010 the Icelandic company Geysir Green Energy signed an agreement with China's Sinopec Star Petroleum Company to help develop geothermal energy resources in Northern China. The agreement will create a new company: Sino-Icelandic Green Energy Geothermal Development Corporation, which intends to be a launching point for developing geothermal power in China. The agreement includes developments in Shaanxi Province, Hebei Province, Beijing, Tianjin and other locations in Northeastern China. It's estimated that the projects will eventually cover 30–40 million square meters.

Geothermal energy does not receive nearly the interest and investment that other renewable forms of energy do, despite some unique advantages. Besides being "renewable", geothermal energy is abundant, with a long-term potential that is more than 200,000-fold of current world energy demand [50,53–55], it is available at a steady supply rate and is thus much more usable than the intermittent and unsteady wind and solar, its land use is very low: smaller 3-fold than that of wind power generation and 10-fold smaller than solar or coal, and it can have very low or zero emissions of any kind with proper system design [54]. At the same time, issues of liquid and gas discharges, proper recharge (to maintain reservoir productivity, dispose of undesirable geothermal fluids and prevent land subsidence), water management, and risk reduction (induced seismicity, etc.) must be taken carefully into consideration in design and operation.

Its current and future use is for heating (including low temperature ground heat heat-pumps), combined heat and power generation (CHP), and power generation. 10 GWe are produced worldwide from geothermal energy, and more than 100 years of experience have been accumulated. The electricity currently produced is typically competitive in price, at about 7–10 ¢/kWh, and readily reducible by half [53,55].

Commercial geothermal wells are currently 60 to 3000 m deep, with the drilling technology borrowing from the extensive experience of drilling for oil and gas (that reach depths of around 6000 m). Since the temperature of the geothermal heat source, whether hydrothermal, dry rock, or magma, increases with the depth, access to massive amounts of high temperature geothermal energy depends on drilling technology. Currently aiming at 10,000 m, the temperatures there are 400–600 °C at pressures around 1000 bar thus having a very high power generation potential, but economical drilling to these depths and conditions is still under development.

6. Environmental aspects and technology

Starting the comparison say from 1990, shortly after the economic system started changing significantly, China had a very low Nominal GDP/capita of 1633 CNY, it has grown it by an annual rate somewhat higher than 10%, reaching 22,640 CNY in 2008 [1]. This growth was accompanied by a similar growth rate of energy use, and since much of the hardware was outdated and inefficient, and the main fuel is coal, emissions of CO_2 and other pollutants were growing very rapidly. Furthermore, China's modernization and growth from a basically rural economy require industrialization at a much faster rate than in developed countries that are industrialized already. This industrialization is also encouraged by developed countries because China is increasingly serving as the low cost manufacturer for the world. This energy use creates severe environmental problems for China's air, water and land, which have direct and immediate detrimental impact on its citizens and on the nation's ability to improve its citizens' quality of life. Until global warming was recognized as a problem, just in the 1990-s, China was focusing its environmental work on other pollutants, a serious problem that requires a great effort and investment and is far from being complete. The perceived global warming risk, and international pressures, especially from developed counties, to reduce its huge greenhouse gas emissions (now the largest in the world) are facing China not only with additional investments but also with having to consider fossil fuel use reductions, both very formidable tasks that clearly need much help from the developed countries.

In their SI paper [56]. You and Xu state that coal combustion is the greatest source of air pollution in China and describe the problem of coal combustion emissions and their control by some commonly used technologies for removing the pollutants from coal combustion, and compare their utilization efficiency, engineering investment, and operating expense. They recommend that advanced industrial cost-effective pollution control techniques should be implemented, especially in the power sector and the thousands of small boilers spread throughout China. Coal washing- and sieving regulations should be implemented and enforced in all sectors of the coal industry in China to reduce SO_2 emission and increase combustion efficiency. The development of cost-effective, low water-consuming FGD technologies, cost-effective de-NOx technologies, and cost-effective technologies for inhalable particle emission control, must be simultaneously undertaken. The investment required is very high, but the damage to the environment and to human health is much higher.

Analysis of impacts of energy consumption on environment and public health in China are reviewed in the SI paper by Wang [57]. It is pointed out that the pollution and GHG emissions that result from fossil energy combustion have seriously impacted on the environment and on health. With the rapid development of the economy, and China's pace of industrialization and urbanization, energy consumption was projected to increase rapidly, and the paper presents an analysis of the impacts of energy consumption on the environment and on public health under different scenarios. Focusing on the effects of sulfur dioxide (SO_2) and Inhalable Particulate Matter of $\leq$10 μm size (PM10), were introduced to calculate the emission caused by energy consumption in various sectors and regions in China.

While the damage to public health, and any mortality, are socially much more significant than barely their associated economic magnitude, calculation of the economic value of such consequences is an in important step, which allows assessment of externalities and an ability to evaluate the costs of energy use and pollution in a sustainable development context. Raising the price of energy activities to reflect full externalities would then tend to reduce energy use and foster pollution reduction. It is therefore very significant that Wang [57] analyzed the economic value of the damage to public health caused by the changes of pollutant concentration related to energy consumption, and does it for various scenarios, for different regions and sectors in China.

The results predict that the PM10 and SO_2 emissions and consequent health damage will increase significantly in the next 12 years, and that the public health economic damage would be 1% of GDP in 2010, and reach 1.06% in 2020. As steps towards the alleviation of these problems it is proposed to reduce coal use by increased efficiency and substitution for renewable energy, to reduce population density, and to reduce pollution created by biomass use for cooking and heating in rural areas. The need for government legislation and regulation in these actions is emphasized.

Airborne particulate matter (PM) now exceeds sulfur dioxide and nitrogen oxides to become the principal urban pollutant in most major cities of China. The SI paper by Yao et al. [58] gives an overview of fundamental studies on the formation and control of combustion PM from various sources, primarily coal combustion and vehicle engines. PM emissions from coal-fired power plants accounts for 44.6% of the total PM. The R&D of emission control technologies of PM10 including combustion modification, electrically enhanced fabric filtration and novel agglomeration approaches is reviewed in detail.

An overall review of CO_2 Emission from China Energy Sector and Its Control Strategy is given in the SI paper by He et al. [59]. They also estimate China's future energy consumption and CO_2 emission in 2010 and 2020 based on a scenario analysis approach. Assuming that China will implement a sustainable development strategy that attempts to alleviate climate change, the analysis results estimated that China's carbon production growth rate will be 5.4%/year in the period between 2005 and 2020, to rise by 40% overall, and that the CO_2 emission intensity per output of Nominal GDP will decrease by about 50%. The strategy emphasizes "energy conservation first", active development and deployment of renewable energy and advanced nuclear technology, readjustment of the economic structure, formulation and issuance of the needed laws and regulations, and establishment of institutions for energy conservation and renewable energy development. They conclude that the international drive to mitigate CO_2 emission will limit world fossil fuel consumption, but that China cannot copy the developed countries' modernization model and has to harmoniously coordinate economic development and carbon dioxide emission control in the process of its industrialization and modernization towards sustainable development. They note that extension of the study to 2050 or even 2100, as well as analysis of the interaction of China's energy system with those in other countries, would be useful for strategic planning.

Since China's most available fuel is coal, coal, alongside with some other fossil fuels, is going to remain the main source of China's energy for decades to come. There are various approaches to prevent emissions of CO_2 to the atmosphere, and so far all increase energy use and generated power cost. Chinese scientists are intensely engaged in the solution of these problems, and the SI paper by Jin et al. [19] reviews the progress of CO_2 capture-and storage technology, and identifies the main obstacles and the potentials of greenhouse gas control in China. Their review of the state of the art concludes that innovative energy systems, in addition to the simple implementation of existing technology, are needed for CO_2-emission control in China. Establishing a principle of integration of energy consumption and CO_2 separation, several innovative energy systems—including chemical-looping combustion with CO_2 capture, partial gasification with O_2/CO_2 cycle, and a polygeneration system with post-synthesis CO_2 capture, are introduced. With synergetic integration of CO_2 into chemical-energy conversion and exploitation processes, these systems may achieve a breakthrough in CO_2 capture with lesser, or even zero, energy penalty. Finally, according to the specific conditions of China, a new scheme of an Energy Network, which integrates energy sources, the transportation chain, and end-users, is recommended for sustainable development in China. A new technical road map for that network is proposed, which may also lead to a new way for the development of sustainable energy and environment technologies in general.

7. Possible paths for China's sustainable energy development

As requested by the Guest Editors when the SI was planned, most of the authors also proposed possible paths for sustainable energy development in China in the specific category of their papers. The paths described below address major opportunities and issues, in some cases to emphasize or summarize what the SI authors wrote, and often beyond those directly pointed out in the SI papers. The readers would benefit from examining both the individual papers and the following material.

We start by a disclaimer, qualifying the precision of planning into the future. While planning is needed, it is also recognized that proposals for paths to the future suffer from the impossibility to even approximately know what the future will bring, especially when we need to consider planning periods of more than about 5 years. The magnitude of the problems associated with energy and its impacts requires in fact much longer-term planning. Forecasting is fraught with uncertainties, which have especially plagued the energy field, with many examples shown by Smil [60], and presently punctuated by the unforeseen rapid and large fluctuations in energy prices that are unjustified simply by supply and demand economics, by the precipitous worldwide economic downturn, by unforeseen international conflicts, by environmental effects (especially those that are energy-related) such as global warming that wasn't even considered a couple of decades ago, by new unaccounted energy demands, such as those associated with the worsening situation of water and food supply, and by rapid improvements in technology. A few examples of the latter are the rapid improvements in energy conversion efficiency, which has nearly doubled over the past three decades, to reach about 60% with gas-fueled combined power cycles, and about 55% by advanced diesel engines, and perhaps even higher by future fuel cells, by the maturation/improvement of wind power generation through improved efficiency and reliability and lower cost, by the current trend to replace much of the fuel-powered vehicle fleet by electric or hybrid ones, and by the more distant (at least 50 years in the future) possibility of commercial use of fusion power and of power generated in space [61], and of superconductive electricity transmission. Forecasting by scenaria analysis, if the number of scenaria and the parameters' range are broad enough, slightly improve prediction.

The first step in any path to the future is wiser use of the energy resources, also referred-to as conservation. This would include elimination of obvious waste, higher energy conversion efficiency, substitution for lower energy intensity products and processes, recycling, and more energy-modest lifestyles. Benjamin Franklin's famous adage "a penny saved is a penny earned" takes in the energy area the form "a Joule saved is worth significantly more than a Joule earned": it takes significantly more than 1 J of energy to generate 1 J of power. This is amplified several fold when one considers the resources and environmental impact associated with the construction and operation of a power plant or even a vehicular engine. At the same time, conservation should not be implemented in a way that would deprive large fractions of humanity of basic comforts of life.

Conservation may also lead to forecasting errors: for example, following the oil embargo of the 1970s, and the resulting rise in energy prices, the world energy consumption during the period between 1979 and 1983 has reversed trends from continuous increase to a small decrease, due to major decreases in OECD consumption and despite the growing energy demand in the developing countries. Among other consequences of this unforeseen trend change, it has frustrated the power generation utilities in the U.S. (for example) that have based their generation expansion to the relatively constant >5% growth rates that preceded 1979, and caused significantly negative economic impacts.

While increasing energy conversion and use efficiency are vitally important steps in the path to sustainability, measures must also be taken to prevent energy efficiency "rebound", the frequent outcome in which higher efficiency and lower costs lead to increased consumption (cf. [62,63]) and thus at least partially negate the positive outcomes Such measures may include demand-side management.

The promising paths to electricity generation are amply discussed in several SI papers, and China appears to be headed in the correct direction in adopting and developing advanced technology. "Clean coal" would be the major goal for many decades. Development of an extensive efficient and smart grid is of critical importance, and ways must be found for government-industry-customer partnerships that would make the necessary investments. Significant regulatory improvements are needed for electric generation and transmission sectors, including permission of sale of energy to large utilities by small producers and in general structuring the electric industry so that it allows commercial development and sale of renewable energy, especially the intermittent types like wind and solar, appropriate enforcement power and effective action over the energy industry and users, fair market practices, and proper resolution between China's national and local conflicts related to such problems. The government should promote energy price reform to gradually create an equitable pricing mechanism that reflects all externalities, such as resource scarcity, market demand and supply, and the cost for pollution control, which would thus be effective in demand control, efficiency and environment improvements, and also be the basis for a more equitable comparison between different energy resources and conversion systems.

The pursuit of more efficient and less polluting transportation must include not only vehicular improvements (with preference for the plug-in electric or hybrid car) but also traffic management, significant development of efficient public transit, and redesign of cities. The power generation industry must be prepared for the additional electricity demand with increased introduction of electric vehicles (cf. [64]). Battery and electric car development are a major national need, as well as an opportunity for China's industry.

Buildings and household energy use (regrettably omitted in this SI) are estimated to be ~30% of China's energy consumption [65] and about 25% of its greenhouse gas emissions [66]. An excellent and practically attainable way to reduce this problem is the design and retrofit of buildings and appliances to such that consume less energy (including embodied energy) over their life time, with and without incorporation of renewable energy sources, and further with an extension to "Eco-efficient" buildings that not only reduce their negative environmental impact but also help heal and improve the environment. A broader method is to design residential communities in a way that reduces also indirect use of energy and emissions by reducing the need for transportation and resources by the residents.

It is important to understand that buildings' energy consumption (that also generates the associated emissions) is often the major (and increasing) fraction of a building's life cycle annual cost, but it typically still constitutes a relatively small fraction of their residents'/owners' income [67,50] and is in China often subsidized by employers or government. The users/owners thus don't have a strong incentive to make energy-related improvements. Financing practices that monetize long-term energy costs in near-term investment decisions, to also include relevant externalities, can make a major contribution to the effort to reduce building energy consumption and emissions. Obvious actions in that direction would be to charge the real cost of environmental effects, from cradle to cradle, which is in turn going to result in lower consumption and in preference for more energy efficient buildings. A number of such initiatives have been implemented in several countries, including the European Union and the United States.

As to sustainable paths related to energy resources, the need to vigorously pursue "clean coal" was already mentioned as a key goal. The renewable energies of biomass, wind and solar are, currently employed to only a small fraction of their potential, could, and should when they are proven to be economical and sustainable, developed to their potential. Wind energy systems development also offers an excellent opportunity for China's manufacturing industry. In [35] it is claimed that hydropower, and important part of China's energy supply already, had much development potential. Based on lessons from China and the rest of the world, this should be developed sustainably.

China leads the world in greenhouse gas emissions, and all the above-discussed measures for reducing energy consumption, use of fossil fuels, and renewable energy employment, will also reduce GHG emissions. Reasonable cost technology is also available for carbon capture when fossil fuels are used in power generation, yet practicality of technologies for sequestration of the captured carbon is still very uncertain (cf. [68]). If and when sequestration become practical it may be economically wise to attempt to cluster large coal power generation plants at a relatively short distance from sequestration sites as it was proposed for India [69].

In its relatively recent rapid development and industrialization, China has the opportunity to learn from the longer-term experience of developed countries that have been going through this process much longer. The learning should be both from the good experiences, which resulted in advanced technology and high standard of living, but also to carefully learn to avoid the bad experiences that in many cases resulted in severe long-term environmental damage and in excessive consumption and waste. Some of these poor experiences are the recent wild high amplitude fluctuations in world oil price. The peak price is about one to two orders of magnitude higher than the cost of extraction, possibly meaning that financial speculation is overwhelming supply and demand, and all technical improvements. A great concern at this time is that these huge, rapid, unregulated price fluctuations seriously threaten the development of renewable energy, and of all energy systems that do not use oil as the fuel for that matter. It is impossible to plan, establish, and maintain an energy business while the price of the conventional business competition can vary in this manner. It is a sad observation for scientists, engineers and for everyone who believes in the vital need for sustainable development that all their efforts to meet the energy predicament can be easily set back due to immoral greed and lack of regulation. While governments' role in subsidizing certain energy systems is not always useful, government is best suited to enact and enforce wise legislation and promote education, which encourage economic integrity of the energy field.

Energy conversion and use are associated with major environmental, economical and social impacts, and all large energy projects should therefore be designed and implemented sustainably. Such development, for example, requires efforts to raise GDP without a commensurate increase in energy consumption. Sustainability is only emerging as a science, and thus must be developed and applied urgently to provide analysis and evaluation tools. China has an excellent opportunity to advance, promote and foster this field in its educational and research system.

Although shorter term problems and solutions dominate, China's huge and rapidly growing economy, energy use and environmental emissions, alongside with its world-class and rapidly rising science and engineering, should increase its involvement in longer-term high potential-higher risk national and international energy projects, such as development of an extensive advanced, efficient and smart electric grid that would allow effective power transfer throughout China and especially for transferring power from energy rich regions to regions where the demand is high, and that would enable adequate grid storage for accelerating commercial use of renewable energy, methods for safe and economical CO_2 sequestration, nuclear fusion power, and power generation in space for terrestrial use (cf. [61,70–72]).

Sustainable development is founded on the three pillars of economic, environmental and social impacts. While the first two pillars are discussed in the SI more extensively, it is very important to address the social pillar too, without which sustainable development cannot succeed. Many of the papers in this SI point out that together with the affected people and objective experts, the government should create a simple, transparent, decisive, and enforced legislation to promote China's sustainable development.

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