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Analysis of the relationship between international cooperation and scientific publications in energy R&D in China

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ABSTRACT

Energy is important for China and for the whole world. Previously, the huge investment in energy-related research and commercialisation made it possible for China to cooperate with its international partners in various channels, and programs involving international cooperation and co-published papers increased annually. In this paper, through the review of intergovernmental cooperation programs and bibliometric analysis of the top energy journals, it was found that: (1) intergovernmental cooperation and non-governmental cooperation are two effective channels for energy R&D. (2) In these two channels, most participants of international cooperation are universities and institutes, and the most important partner countries are the US, Japan, and European Countries. (3) Industries began to be involved in international cooperation gradually. (4) For different areas, the degree of cooperation is not the same. Some areas have been more fruitful in cooperation, some are just beginning hydrogen energy, fuel energy and applied energy are the main co-publication areas with Chinese involvement; while wind energy, solar energy, fuel cells and bio-energy are new areas for China and there has not been so much co-publication until now.

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1. Introduction

Previously China has faced a big challenge with regards to energy issues and the government is seeking solution in various ways. The basic themes of China's energy strategy are giving priority to energy conservation, relying on domestic resources, relying on science and technology, protecting the environment, and increasing international cooperation for mutual benefit [1]. The international science and technology (S&T) collaboration is an efficient method of combining the advantages of multiple participants and of increasing the output of research and development (R&D) investment.

At this point in time China has set up intergovernmental energy cooperation agreements with about 40 countries as well as intergovernmental S&T cooperation agreements with some 100 countries, in which energy is always a major area. China also participates in international energy projects such as International Thermonuclear Experimental Reactor (ITER).

This paper outlines the main policies and stakeholders of energy systems, and reviews all the energy-related intergovernmental agreements and the projects. The governmental websites of China and her cooperating countries are the main sources of data, in which news, the government statements, and program reports would be found. "The Annual Report of State Program of Science and Technology Development" [2] and "China Science and Technology Report" [3] launched by Ministry of Science and Technology (MOST) of China each year are also the main data source. Meanwhile academic journals are also significant sources of data.

Besides intergovernmental cooperation, there are many channels of international cooperation in China. This is demonstrated by international co-publication of bibliometric analysis. Bibliometric analysis for Chinese involved co-publication of energy areas is also presented here, which shows that international cooperation is a positive factor in improving high-quality papers and level of research.

2. The stakeholders in China's international cooperation in energy

2.1. China's energy policies and stakeholders

In previous years, the Chinese government launched a series of energy policies and strategies (see Table 1). In these policies, Chinese energy stakeholders are encouraged to develop renewable energy and new energy technologies by relying on S&T innovation and active international cooperation.

After these energy policies and strategies were launched the Chinese government began to emphasise the administration of energy. In July 2008 the National Energy Administration (NEA) was established under the supervisor of the National Development and Reform Commission (NDRC). In January 2010 the National Energy Commission (NEC) was established as a part of the State Council, which is composed of 21 ministries and administrations. It will be responsible for drafting national energy development plans, reviewing energy security and coordinating international cooperation at a higher level than the NEA. The sequential establishment of the NEA and the NEC shows the government has raised the issue of energy to an previously unprecedented level and that energy is paramount for the future development of China, the world's second-largest energy consumer.

In the Chinese central government, the S&T policy stakeholder is the State Steering Committee of S&T and Education which was established in 1998. It is composed of 10 ministries and is responsible for drafting S&T and education policies and strategies, reviewing relevant missions and projects and coordinating the main issues across different ministries. In the field of energy R&D the NEC will, in the future, cooperate with the State steering Committee of S&T and Education (see Fig. 1).

MOST and NDRC are two important ministries in the two commissions named above. In the field of energy R&D, MOST is responsible for national R&D Programs and intergovernmental S&T cooperation with about 100 countries, while the NEA/NDRC focuses on the scaling up of energy technology and the industrialisation and strategy cooperation with other countries. The NEA represents the Chinese government to maintain bilateral and multilateral energy dialogue systems with foreign countries and organisations, such as the United States, Russia, Japan, the EU, APEC and the International Energy Forum (IEF). It has set up bilateral energy cooperation systems with 36 countries.

Energy R&D is the main field in the Chinese National High-tech R&D Program (Program 863) and National Basic Research Program (Program 973) which are supported by MOST. The central governmental budget for Programs 863 and 973 has been increased over the past few years. In 2006–2008, the total financial support for energy research for Program 863 reached about YMB 2 billion; for Program 973 it was about YMB 0.45 billion (see Fig. 2).

From 2004 to 2008 the proportional number of energy projects in Programs 863 and 973 was around 5–10%, while in 2005 and 2007 the proportional funding for projects in energy in Program 863 reached 15–18% (see Fig. 3). This means that in Program 863 energy projects have received much higher financial support than the average level.

Table 1
Energy related policies and strategies in China.

Policy and strategy	Launched/ modified year	Items related to energy R&D/international cooperation
Renewable Energy Law	2005/2009	Puts R&D and the industrialisation of renewable energy as the priority of National S&T Programs
National Plan for Medium- and Long-term S&T Development (2006–2010)	2005	Reinforces R&D of the exploitation of energy resources, energy efficiency, clean energy/encourages academia and industries to be involved in international cooperation under the framework of bilateral and multilateral S&T cooperation agreements
Middle and Long Term Development Plan for Renewable Energy	2007	Promotes the industrialisation of renewable energy technologies and establishes relevant innovation systems/absorb new imported technologies and enhances the domestic capacity for indigenous innovation
Renewable and New Energy International Cooperation Program	2007	Supports basic and applied research in five priority areas/encourages international cooperation under the framework of bilateral and multilateral S&T cooperation agreement
National Chinese Program in Response to Climate Change	2007	Promotes new energies and renewable energy technology, in order to cope with climate change/ enhances international cooperation in climate change, and promotes the Clean Development Mechanism and technology transfer
Chinese Energy Law (Draft for soliciting Comments)	2007	Promotes S&T indigenous innovation in energy by relying on S&T development and guarantees national energy security/promotes international cooperation in energy on the principle of win–win situations and equal partnerships

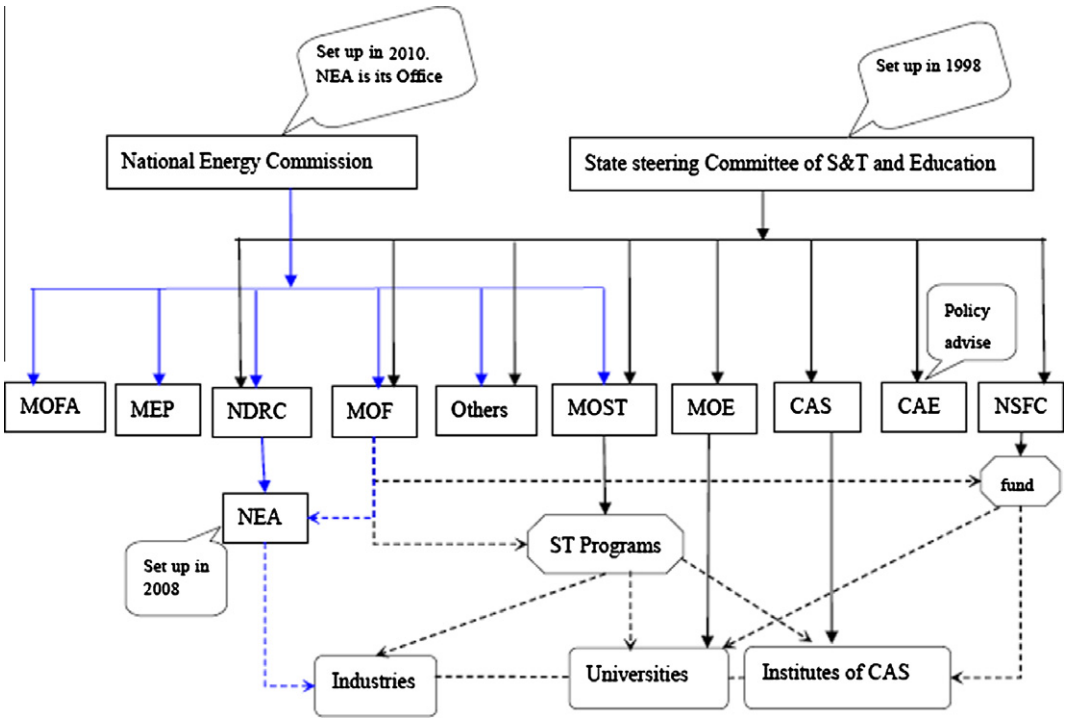

Fig. 1. Energy and S&T administration systems in China. MOC: Ministry of Commence; MOF: Ministry of Finance; MOE: Ministry of Education. MOP: Ministry of Personnel; CAS: Chinese Academy of Sciences; CAE: Chinese Academy of Engineering. NSFC: National Natural Science Foundation of China; MOFA: Ministry of Foreign Affairs; MEP: Ministry of Environment Protection; MOST: Ministry of Science and Technology.

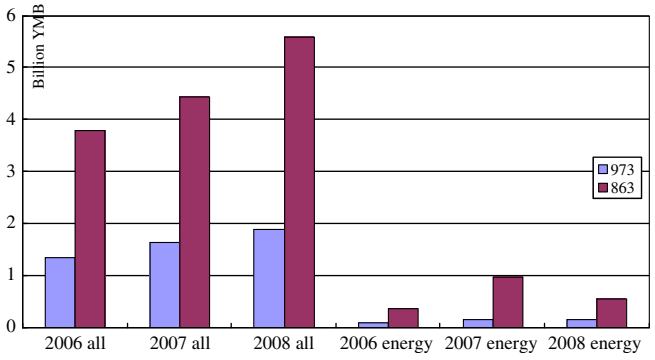

Fig. 2. The 2006–2008 budget for all areas and for energy areas of Programs 863 and 973.

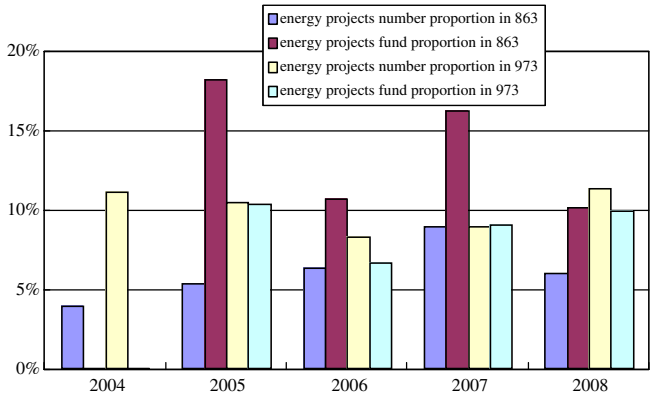

Fig. 3. Energy projects supported by Programs 863 and 973 in 2004–2008 [2].

In 2010, the central government budget for the NEA is YMB 77.6 million, of which YMB 2 million is used for S&T projects [4]. A comparison of the central budget for energy R&D between NEA and MOST shows that energy R&D is mainly supported by MOST not NEA. While in some countries the national energy agency is the main energy research sponsor, such as the Swedish Energy Agency which received SEK 61 billion of central government funding in 2008, of which 815 million SEK was expended on R&D. It is one of the main energy research sponsors in Sweden [5].

From 2009, energy efficiency, CO_2 emission reduction and renewable energy began to enter the Chinese central governmental budget as an independent item (see Fig. 4), which emphasises the commercialisation and utilisation of clean energy and new energy technologies.

S&T program funds and investment in energy related areas make it possible for Chinese researchers to cooperate with their international partners in various ways.

The MOST and NDRC also cooperate to promote the development of energy. The NDRC and MOST co-fund several international cooperation energy projects. In 2007, the "Renewable and New Energy International Cooperation Program" was launched by the NDRC and MOST together. It focuses on large capacity wind farms, biomass power plants, transfer technology from biomass to liquid fuel, building with solar energy, photovoltaic (PV) technology, hydrogen energy and fuel cells. The NDRC and MOST are the co-chairs of the Chinese National Clean Development Mechanism (CDM) Board which consists of seven ministries, and many CDM projects are relevant to new energy and renewable energy.

2.2. The main executers of international energy cooperation projects

The institutes and universities are the main executers of international cooperation energy R&D projects (see Fig. 5).

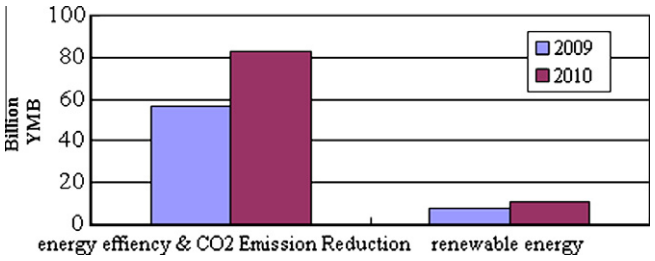

Fig. 4. Investment in energy related areas of the Chinese central governmental budget.

CAS is the most important public research organisation in China. It currently owns 91 scientific research institutes and 200 + S&T enterprises, many of which are involved in energy R&D international cooperation. Recently CAS has integrated its R&D and technology resources internally to form several energy plans. An example of this, in 2009, was when CAS initiated "Solar Energy Action" – an action aimed to promote solar energy as the primary energy source by 2050 thereby setting up five research centres focussed upon this action.

Many Chinese universities are active in implementing energy R&D international cooperation within intergovernmental agreements or inter-college agreements.

The Chinese Academy of Engineering (CAE) is also an active organisation involved in international energy cooperation. Mainly focussed on consulting and workshops, its main partners are the other countries' academies of engineering, such as the National Academy of Engineering of the US (NAE) and the Royal Swedish Academy of Engineering (IVA).

To begin with energy R&D international cooperation programs were mainly participated in by academia, however currently the leading energy industries and power plants also participate in international cooperation in certain research fields.

2.3. Main international cooperation partners of China in energy

In 1978 the Chinese government decided to implement open policy. Based on reciprocity and mutual interest, China began to carry out international S&T cooperation through intergovernmental and non-governmental channels. France, Italy, the US, the UK, Sweden and Japan were the pioneering countries which signed the bilateral intergovernmental S&T cooperation agreement with China between 1978 and 1980. Energy R&D was covered by these agreements from the beginning and since 2000 has become more and more important, with many agreements and protocols renewed during this period (see Table 2).

The US is the most important energy R&D cooperation partner for China. There are 12 agreements under the S&T framework on a wide variety of energy sciences and technologies, some of which are listed in Table 2. MOST and Department of Energy (DOE) of the US are the administrations responsible for these agreements.

European countries have a strong and lasting S&T cooperation with China on bilateral levels and multilateral levels in energy areas. The United Kingdom, France, Italy and Sweden have carried out many outstanding energy R&D projects with China. Meanwhile the European Union has signed a series of cooperation agreements related to energy R&D with China (see Table 3).

Under these MOU and agreements, China participated in 16 energy projects in FP6 and in 6 energy projects in FP 7 of EU until June 2010 as third country participants.

3. The main cooperation fields and projects

In previous years international cooperation within energy has covered clean energy, renewable energy and energy efficiency, and cooperation forms are primarily international workshops, project cooperation and joint research centres.

It is very difficult to statistic all the international program on the energy area. In this article, the criteria to select the cooperation projects is based on "Three Main Factors": (1) with main partner countries; (2) under the main cooperation governmental agreements; (3) supported by stakeholders of energy systems of China, such as MOST, NEA and CAS.

3.1. Clean energy and CCS (CO_2 capture and storage)

Coal is the most important energy source in China and the reduction of pollution from coal is a priority. In 2008 68.7% of the primary energy of China was from coal, meanwhile 50% of coal is used to produce electricity, and 80% of electricity and 90% of CO_2 emissions is from coal. True "clean" coal technology is expensive, and its commercial application is still many years away, and it is a main cooperation area.

3.1.1. The United States

The United States is the second largest coal consuming country, and 50% of electricity in the US comes from coal. China and the United States have great potential for energy cooperation since they are confronting the same issues, such as upgrades of old power plants, the commercial application of CCS technology and demonstration projects in different regions.

MOST, NDRC and several power companies of China have supported some clean and highly energy efficient technology to produce electricity from coal, including Integrated Gasification

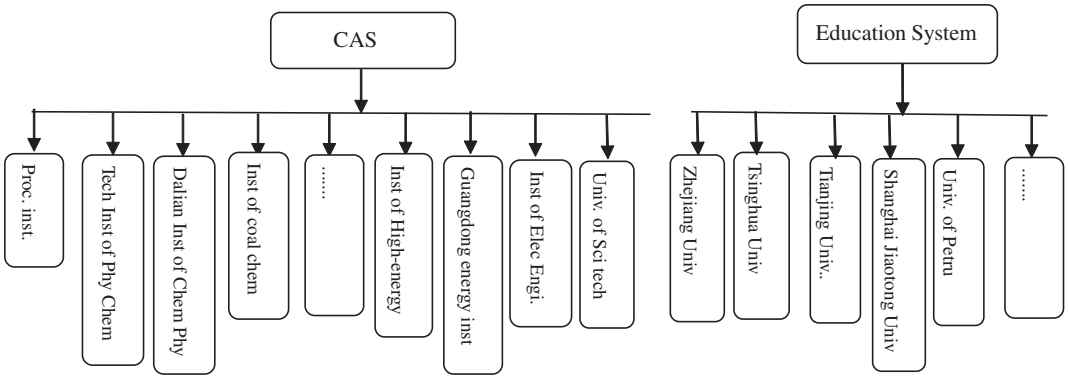

Fig. 5. The main institutes and universities of international energy cooperation projects.

Table 2
The main intergovernmental cooperation agreements related to energy R&D.

Partners	Signed/ renewed time	Cooperation agreement	Energy areas
US	1979	Bilateral S&T cooperation	Energy
	2000/2005	Fossil Energy Protocol	Clean energy, coal liquefaction, enhanced oil recovery
	1995/2006	Energy Efficiency and Renewable Energy Protocol	Industrial energy efficiency; energy efficient building technologies
	2007	Next-generation efficiency vehicle technologies	Electric, hybrid-electric, fuel cell, and alternative fuel technologies.
France	1978	Bilateral S&T cooperation agreement,	Nuclear
	2007	Joint statement on Climate Change	Energy efficiency and infrastructure, nuclear energy and low carbon technology
	2008	China–France Sustainable Energy Joint Laboratory Cooperation Agreement	Sustainable energy
UK	1978	Bilateral S&T cooperation agreement and protocol	Energy
	2007	Renewable energy cooperation program	Renewable energy, hydrogen/fuel cell
	2006	China–UK Energy Working Group	Overall energy cooperation system
	2001/2008	CAS and BP energy cooperation	Clean energy
Japan	1980	Bilateral S&T agreement, Bilateral Environment Protection agreement, Bilateral Nuclear Cooperation Agreement, Joint statement about Climate Change	Energy, nuclear
Sweden	1978/2004	Bilateral industry and ST cooperation agreement	Energy
Italy	1978	Bilateral S&T agreement	Energy

Table 3
The EU-Chinese cooperation agreements related to energy.

Signed/renewed time and organisation	Cooperation agreement	Energy areas
2005 MOST/TREN	EU–China Energy Conference	Clean coal, energy efficiency, transport and energy
2006 EC/MOST	MOU on "Co-operation on Near-Zero Emissions Power Generation Technology through Carbon Capture and Storage"	CCS
2004 NDRC/EC	EU–China Energy and Environment Programme	Energy saving, renewable energy, natural gas
1999/2009 EU/China	EU–China S&T Cooperation Agreement	Including energy
2005 EU/MOST	Action Plans on clean coal technologies; Action Plan on Industrial Co-operation on Energy Efficiency and Renewable Energies	Clean coal, energy efficiency and renewable energies
2005 NDRC/TREN	MOU on EU–China Dialogue on Energy and Transport Strategies	Energy policy and strategy
2003	ITER	Nuclear

Combined Cycle (IGCC) projects. China Huadian Corporation has developed 1000 MW ultra-supercritical coal-fired generating units with low NO_x emission, which was successfully operated commercially [6]. These domestic R&D projects not only would support large thermal power plant constructions, but also set up the groundwork for international cooperation.

Under the China–US Fossil Energy Protocol, from 2001 to now, several R&D projects have been done by bilateral Institutes. The National Power Plant Combustion Engineering Research Centre (NPCC) of China began to cooperate in research of "Low NO_x Combustion, Low CO_2 Emission and Denitrification Technology for Coal-Fired Power Plants" [7], with State Energy Technology Laboratory of DOE. State Key Laboratory of Clean Energy Utilisation of China in Zhejiang University and National Energy Technology Laboratory of US carried out the "Mercury Emission and Control research of Coal combustion in China" [8]. Based on this research, MOST was initiated to build "China–US Low CO_2 Emission and Pollutants Integrated Control Joint Key Laboratory" in NPCC.

In 2003, DOE launched the FutureGen project which is the most attractive clean coal project in the world and the anticipated financial contribution for the project from DOE is $1073 billion. In 2005, with the support of Chinese government, Huaneng Group joined the FutureGen Alliance, a milestone for Chinese energy companies in participating in the bilateral S&T cooperation program. China became the third international partner of FutureGen. Once completed the technology to build first-of-its-kind coal-fuelled, near-zero emissions power plant will be used by member countries to reduce emissions around the globe.

Meanwhile, the DOE cooperated with the NEA and CAS of China in the field of CCS technologies focussing on policy and basic and applied research. From 2008 until now, Shenhua Group, one of the top energy groups of China, and West Virginia University began to cooperate to carry out preliminary feasibility studies of CCS and coal-liquefaction project in Inner Mongolia [9].

Besides the cooperation projects, China and the US have established two energy research centres. Compared with the joint R&D projects, the joint research centres could provide a stable platform for long term cooperation and personnel training. One is the US-Chinese Energy & Environmental Technology Centre, set up in 1997 between Tulane University and Tsinghua University, supported by the DOE, the Environmental Protection Agency of US, some US private organisations in the US, and MOST. The other is the "China–US Clean Energy Joint Research Centre" set up in July 2009, by MOST, NEA, and the DOE with the priorities of energy efficient building, clean coal and clean vehicles. Afterwards, the development of clean and efficient energy and the guarantee of energy security became immediate and long-term strategic and economic interests for both sides during the first US-Chinese Strategic and Economic Dialogue.

3.1.2. EU and European Countries

Clean Coal and CCS technology is also an important area in EU–China cooperation. In FP 6 and FP7, China involved seven projects in the CCS (see Table 4).

In these projects, Chinese research groups have cooperated with top researchers on CCS from all over the world, aimed at establishing broad cooperation between China and the EU in the field of CCS. These projects will be the foundation for the Chinese implementation of large-scale polygeneration energy facilities with options for coal based electric power generation as well as production of hydrogen and synthetic fuels. Not only academia, but the biggest oil company of China, Petrochina participated in these projects.

Furthermore, in 2007, China and the UK launched the Near Zero Emissions Coal Initiative (NZEC) which was funded by the DTI and MOST, with 3 million Pounds of funding from the UK. Thirty-one Chinese and European partners worked with the themes of (1) knowledge sharing and capacity building; (2) future technology perspectives; (3) case studies for carbon dioxide capture, storage and transport, and (4) policy assessment. In the summary report of NZEC, it was concluded that CCS could provide a key low carbon option for coal-based industry in China, particularly for power generation applications and the various development and deployment approaches considered within NZEC have provided valuable experience while also establishing the basis for further UK–China cooperation [10].

Among all the European countries, Italy has been involved in outstanding energy cooperation with China. Until 2007 Italy had supported more than 20 projects in China, including Energy Efficiency Building at Tsinghua University, solar energy village in Inner Mongolia, a biomass energy CDM demonstration project in Ningxia, etc. In 2008 MOST and the Ministry of the Environment of Italy signed "The plan for CO_2 emission Control for Building in China", aimed to promote the advanced build energy efficiency standard and demonstration in China. MOST also signed the "MOU of Clean Coal Technology with CCS and Supercritical Thermal Power Technology" with the Ministry of the Environment of Italy and Enel (Italian National Agency for Electric Energy) to promote the transferring of European clean technology to China.

Meanwhile, under CDM, Canada, Japan, France and the Netherlands carried out the several clean energy technology projects in China. "China–Netherlands CDM Capability Construction Project " which was initiated in 2007 by ING bank and MOST, provided funds support to five provincial governments of Jiangxi, Chongqing, Heilongjiang, Fujian and Guangdong to set up CDM technology service centres in the fields of wind power, hydro power, coal bed methane exploration, etc. [11].

Australia is also an important partner with China in clean energy and CCS. On December 17 2010, NEA of China signed MOU of "Post-Combustion CCS feasibility study" with Department of Resources, Energy and Tourism of Australian. Commonwealth Scientific and Industrial Research Organisation (CSIRO) of Autrilian and the China Huaneng Group will establish through their groundbreaking collaboration on the Gaobeidian post-combustion capture project, the first carbon capture demonstration project in China.

3.2. Renewable energy and new energy

Usually new energies, including solar energy, wind energy, biomass energy and hydro power will first be transformed into electricity before being accessible to its customers, so the transfer technology and cost is vital to new energies. In the previous years, perspective of renewable energy systems [12] and the Utilization and the deployment of renewable energies in China have been summarized [13,14]. In each area, there are typical international cooperation agreements and projects.

3.2.1. Solar power

Between 2003 and 2007, with support from NSFC and the Japanese Science and Technology Agency (JST), the State Key Laboratory of Advanced Technology for Materials Synthesis and Processing (Wuhan University of Technology) and the Japanese Aerospace Exploration Agency carried out the joint research on nanostructures and enhanced thermoelectric properties in Ce-filled skutterudite bulk materials [15] and research on thermoelectric transport properties of high-performance p-type Bi2Te3 with layered nanostructures [16]. This explored new methods of transferring the solar energy spectrum highly efficiently. Based on the research results, the Chinese group received support from "Program 973" for further basic research on thermoelectric transport materials and units of high performance.

In April 2007 MOST and the Italian Ministry of the Environment and Oceans initiated the demonstration project of 1 MW thin film solar cells on the Chongming Island in Shanghai and interconnected this with the grid in June 2008. The main part of this project is monocrystalline silicon PV components combined with heterojunction with intrinsically thin layers which produces about 1 GW h electricity annually, the largest commercial PV project in China [17].

The Institute of Electrical Engineering of CAS (IEECAS) is the leading research organisation in various new electrical and energy engineering in China. Solar power generation is one of its domains. In 2001 IEECAS established the joint laboratory with Himin Solar Group, the leading solar thermal company in China. In May 2008 IEECAS and Spanish Inceisa S. A. signed to set up a Chinese–Spanish Joint Centre for solar thermal power generation in Spain. This joint centre will promote the recruitment of experienced Spanish experts to work for IEECAS and increase bilateral competitiveness in the future. This is a model for cooperation between research institutes and companies.

The United States government also regards solar power as a strategic area. The Solar America Initiative (SAI), a presidential initiative, is projected to result in a cumulative installed base of about 24 GW of PV in the US by 2015, while at the end of 2006

Table 4
China's participants in FP6 and FP7's CCS projects.

Project	Title	Acronym	Chinese participants
FP6	Cooperation Action within Carbon Capture and Storage China–EU	COACH	China Agenda 21, CAS, Tsinghua Univ. Zhejiang Univ. PetroChina, et al.
FP6	CO_2 Capture using Amine Processes: International Cooperation and Exchange	CAPRICE	Tsinghua Univ.
FP6	Monitoring and Verification of CO_2 Storage and ECBM in Poland	MOVECBM	China United Coalbed methane corp., Petrochina
FP6	Assessing European capacity for geological storage of carbon dioxide EU	GEOCAPACITY	Tsinghua Univ.
FP6	Support to Regulatory Activities for Carbon Capture and Storage	STRACO2	CAS, China Agenda 21
FP7	Innovative CO_2 Capture	ICAP	Tsinghua Univ.
FP7	Quantitative Failure Consequence Hazard Assessment for next Generation CO_2 Pipelines	CO2PIPEHAZ	Dalian Univ. of Tech.

the cumulative installed base in the US is only about 480 MW of grid-connected PV [18]. In April 2010 the DOE announced that it will invest more than $200 million over 5 years to expand and accelerate the development and commercialisation of solar and water power technologies throughout the United States. This will provide a potential cooperation opportunity between China and the US in solar power.

In FP7 China involved one project on PV/solar power "Improved material quality and light trapping in thin film silicon solar cells" (SILICON_LIGHT)". Shanghai Jiaotong University is involved in this project.

3.2.2. Bioenergy

In 2007, MOST and the Italian Environment Protection Foundation initiated the "Demonstration and Industrialisation Project of Producing Biodiesel from Jatropha curcas L. in Sichuan" and has established several pilot plantations of Jatropha curcas L. in the Sichuan province. The Department of Biological Science of Sichuan University is the executive organisation. They have implemented the international cooperation project of "Key Technology Research of Producing Biodiesel from Jatropha curcas L" and developed the series of B20, B30 and B100 biodiesel from Jatropha as well as piloting 15,000 km of driving tests in diesel vehicles in the past 10 years [19] .

In FP6 China only joined the project "Development of co-firing power generation market opportunities to enhance the EU biomass sector through international cooperation with China" in the field of bioenergy (total 72 projects). Henan province, the Chinese Electricity Council and Tsinghua University were involved in it.

3.2.3. Wind power

Based on the statistics of the Chinese Wind Energy Association [20], the installation of wind turbines increased quickly in China during these years, from 5.906 GW in 2007 to 12.13 GW in 2008, about 61.8% of which was manufactured by domestic and joint venture companies and produced about 12 TWh of on-grid electricity. According to the "Middle and Long Term Developing Plan for Renewable Energy" the total number of installed wind turbines to 2020 will reach 30 GW and will set up six GW-level wind farms in China. The main national S&T programs have supported several projects of "Large capacity wind turbine research and demonstration" and "Key technology of wind turbine blades made by carbon fibre composites". These are aimed to improve the intellectual property rights of key technology of wind turbine and technology transferring.

The S&T Environment Protection company of State Grid Group of China and Aerodyn Company of German cooperated to design a 1.5 MW-level wind turbine jointly and signed the technology sharing agreement with Mingyang wind power company. Based on this a 1.5 MW typhoon-resistant wind turbine was produced in Mingyang in June 2007 Subsequently Mingyang and Aerodyn carried out Super Compact Drive (SCD) Wind Turbine R&D activities in July 2008. To further develop R&D cooperation, in August 2009, Mingyang signed the agreement with Risoe Wind Power Institute of Denmark to implement strategic cooperation and set up a research centre in Europe focussing on providing engineering and technology service to the 3 MW near-shore SCD wind turbine [21].

In FP6, China was only involved in one project "Integrated Wind Turbine Design" and this was via the Chinese University of Mining and Technology.

3.2.4. Hydrogen/fuel cell

In the United States, FreedomCAR and the Hydrogen Fuel Initiative are two complementary government-industry R&D policy initiatives that promote the development of hydrogen fuel and fuel cell vehicles. They were announced in 2002 and 2003 sequentially and have got $2.27 billion of funding until 2009 [22]. There is no substantial progress between China and the US in hydrogen/fuel cell R&D cooperation.

In 2007, China and Canada signed the S&T cooperation agreement and initiated the "China–Canada Hydrogen and Fuel Cell Joint Research Centre". In 2008 MOST and the National Research Council of Canada (NRC) initiated the China–Canada Hydrogen Fuel Cell Research Centre, and attracted Tongji University, Shanghai Jiaotong University, relevant Chinese Companies, the NRC Institute for Fuel Cell Innovation, and Ballard Power Systems company to work together to strengthen the cooperation of bilateral cell and hydrogen technology clusters. The NRC focuses on securing Canada's competitive edge in Hydrogen/Fuel Cell commercialisation [23].

For EU-Chinese Cooperation hydrogen and fuel cells are important areas. In FP6 and FP7, there are 8 projects (see Table 5).

Meanwhile, MOST also hosted workshops with ASEAN, Japan and Korea which aimed to find suitable ways to cooperate with Asian countries in the areas of new and renewable energy. India also has done a lot of cooperation with China in the field of renewable energy which was summarised by Huang [24].

3.2.5. Gas hydrate

The resource potential of natural gases caged in hydrates are estimated as about 600–700 million ton of oil equivalent in the south China sea [25] and about 1.2×10^{11}–2.4×10^{14} m^3 in Qinghai-Tibet Plateau permafrost [26].

In previous years, the Centre of Gas Hydrate Research in Guangzhou Institute of Energy Conversion (GIEC) of CAS, has set up the cooperation agreements with University of British Columbia, Korea Institute of Industrial Technology and other international institutes in the areas of fundamental theories on gas hydrate [27], natural gas hydrate production technologies [28] and hydrate-based application technology [29]. GIEC also implemented bilateral National Natural Science Foundation program with the Moscow University, and held the bilateral symposiums with Canada and United Kingdom. In 2009, GIEC and the Earth Sciences Centre of Lawrence Berkeley National Laboratory of US jointly carried out the investigation into the numerical simulation on the exploitation of natural gas hydrate in the northern slope of South China Sea, and finished the comprehensive evaluation for the exploitation potential of the region [30].

3.3. The best cases of international energy R&D projects

In the past 30 years, there have been many successful international energy R&D projects between China and other countries, especially in the area of clean energy and nuclear power plants.

CAS and BP have cooperated in the area of clean energy for about 10 years and the cooperation model extends from joint projects, to a joint research centre and a commercial centre. Early in 2002 BP, CAS and Tsinghua University initiated a joint R&D project "Clean Energy – Facing the Future" which focuses on the basic research of natural gas and hydrogen energy and set up the "CAS-BP China research centre" in the Dalian Chemistry and Physics Institute. In November 2008 BP and CAS addressed the Clean Energy Commercialisation Centre (CECC) in Shanghai They jointly invested around $73 million to commercialise Chinese clean energy technologies. CECC's joint venture will integrate individual energy-related technologies – such as coal gasification and conversion, CCS, coal bed methane and underground gasification – developed by CAS institutes and other organisations, both within and outside China, into competitive integrated manufacturing systems and products.

Nuclear power is an outstanding cooperation area for French–Chinese energy R&D cooperation. In 1984, Electricite de France

Table 5
China's participants in FP6 and FP7's hydrogen and fuel cell projects.

Title	Acronym	Chinese participants
New Methods for Superior Integrated Hydrogen Generation System	NEMESIS	Nanjing Univ. of Tech.
Carbon Dioxide Capture and Hydrogen Production from Gaseous Fuels	CACHET	Dalian Inst. of Chem. Phy, CAS.
International Partnership for a Hydrogen Economy for generation of New Ionomer membranes	IPHE-GENIE	Shanghai Jiaotong Univ.
Demonstration of SOFC stack technology for operation at 600 °C	SOFC600	Dalian Inst. of Chem. Phy, CAS. Shanghai Jiaotong Univ.
Handbook for Approval of Hydrogen Refuelling Stations	HYAPPROVAL	Tech. Inst. of Phy and Chem, CAS
Hydrogen for clean urban transport in Europe	HYFLEET:CUTE	China FCB Demonstration Project Management Office
Fuel Cell Testing, Safety, Quality Assurance	FCTESQA	Dalian Inst. of Chem. Phy., CAS,
Carbon dioxide capture and hydrogen production with membranes	CACHET II	Dalian Inst. of Chem. Phy., CAS, Inst. of Metal res., CAS.

Table 6
The main cooperation projects in energy fields.

Countries	US	Ca.	EU	UK	Italy	France	Sp.	DK.	Ge.	Swe.	Japan
General	●		□	○		●					
Bio-Hydrogen/			□		■					○	
Fuel cell		●	□								
Solar			□		■		●				□
Wind			□					●	☼		
Clean energy	□	●	□	□	●						
	◇			☼							

□ – R&D project, ○ – workshop, ● – joint centre/laboratory, ■ – demonstration, ◇ – strategic and economic dialogue, ☼ – commercialisation.

(EdF) began to get involved in China's first commercial nuclear station (Dayawan nuclear station) and were responsible for the overall design the monitoring of the manufacturing process and the engineering and commissioning of the plant. In the past 20 years the Chinese nuclear industry expanded quickly and drew on high-level R&D skills through their cooperation with France and other foreign partners. Based on this background, EdF Group's strategy is to develop a long-term partnership with China, based on the successful nuclear program in France, helping the Chinese nuclear industry move towards autonomy. Now that China has the basic ability and experience to design and manage nuclear power plants [31] the localisation of electrical instrumentation and controlling equipments is now feasible [32].

All the above cooperation projects are summarized in Table 6. It can be stated that R&D projects and joint centres are the most popular cooperation forms nowadays, but that commercialisation may be a trend for international cooperation in the future. The EU, the UK and the US are the most important cooperation partners for China with which to implement many projects.

4. Chinese and international co-publication in energy journals

One important result of S&T international cooperation is the co-publication of papers. Bibliometrics is an invaluable tool with which to analyse international cooperation, especially academia's cooperation [33]. In general international co-publication would reflect the main factors of international cooperation, such as the partner countries, organisations and authors, trends and models for cooperation. Bibliometrics would also provide statistical databases for policy-makers to evaluate the cooperation achievement and mark out an international cooperation roadmap for the future.

The SCI database is one of the best statistical and analysis tools for bibliometrics. From all the energy journals in the SCI database, the following 20 journals were chosen according to a 5-year impact factor and influences from the areas of hydrogen energy, biomass bio-energy, solar energy, wind energy and fuel cell journals as well as applied energy (see in Fig. 6). All the papers from these 20 journals (from 2005 to 2009) were obtained from the Web of Science of SCI, a total of 22,146 papers. The papers' quantities differed from 90 to 3135 and the 5-Year Impact factor differed from 1.072 to 8.844.

From 2005 to 2009 the papers published increased by more than half annually, which shows that the R&D of new energy is active and developing faster than in previous years (see Fig. 7). Correspondingly, the number of co-published papers increased sharply in the same period. 500 papers are co-published by China and international partners, see Fig. 8.

For these 20 journals the co-published papers with Chinese involvement varied from 1 to 107 (see Fig. 9). Meanwhile, the ratio of co-published papers with Chinese involvement to all the papers varied from 0.48% to 5.89%. The Applied Energy Journal has the highest ratio and Journal of Solar Energy has the lowest ratio. As for the different areas; hydrogen energy, fuel energy and applied energy are the main co-publication areas with Chinese involvement; while wind energy, solar energy, fuel cells and bio-energy are new areas for China to co-publish with its partners, and there has not been so much co-publication until now.

The top countries which have co-published papers with China are shown in Fig. 10, most of these countries have listed energy as priority areas in bilateral cooperation, with the exception of Singapore. The United States and Japan have had the highest rates of co-publication with China, much higher than other countries. Although energy is not an intergovernmental S&T cooperation area between Singapore and China, Nanyang Technology University and the National University of Singapore have many PhD candidate cooperation programs with Chinese universities which resulted in fruitful co-published papers. There are 13 co-published papers between Nanyang Technology University in Singapore and Huazhong University of Science and Technology (HUST), which is the highest of all the institutes.

India scholar Apama Basu's bibliometrics research shows that international cooperation would increase co-publication and that the citation of the involved institute, correspondingly would bring

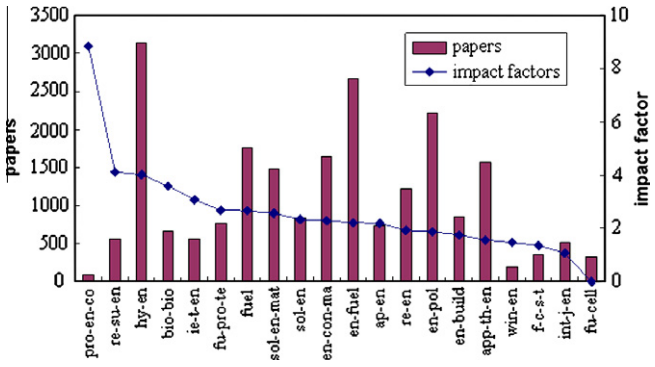

Fig. 6. The 20 energy journal in SCI database.

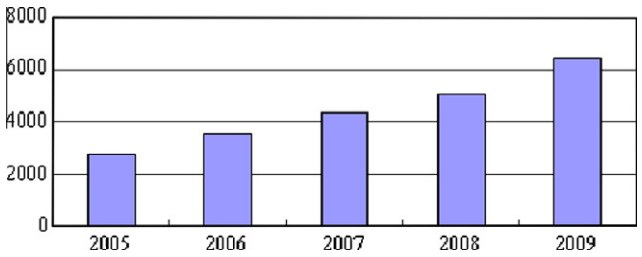

Fig. 7. All the papers of 20 journals in 2005–2009.

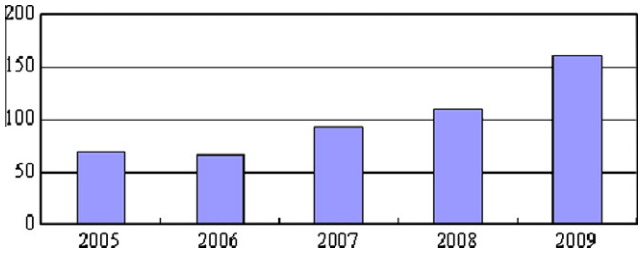

Fig. 8. Co-published papers with Chinese involvement of 20 journals in 2005–2009.

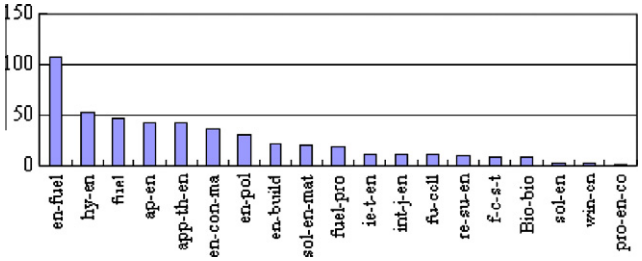

Fig. 9. Co-published papers with Chinese involvement of 20 journals in 2005–2009.

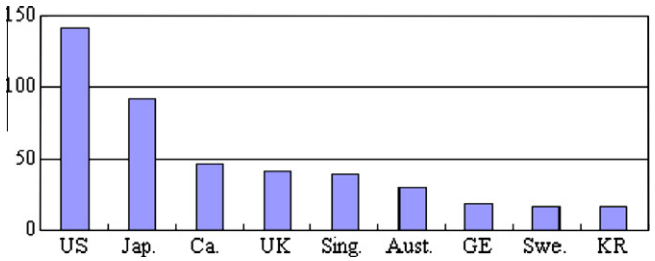

Fig. 10. The top countries with co-published papers with China.

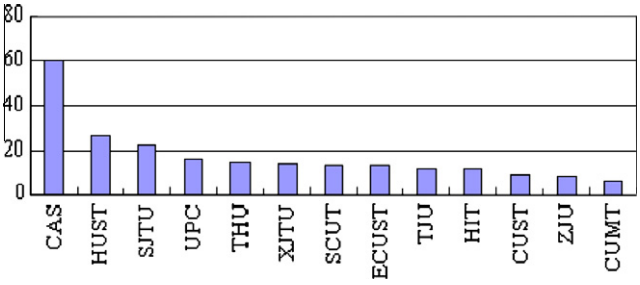

Fig. 11. The main Chinese institutes with co-published papers.

more cooperation opportunities in the future [34]. CAS and the Universities of China are the main participants in international S&T cooperation, as well as being the main responsible parties for international co-publication in China. The Chinese institutions with the most co-authored papers are shown in Fig. 11.

5. Conclusion

Energy has been an important area for China's S&T international cooperation from 1978 and now becomes a highlight in China's economic strategy and dialogue with other countries. The cooperation forms have extended from mutual visiting, technology training and forums to joint research, technology transferring and joint research centres.

In the beginning, only government, academia and universities were involved, however now the energy industries have begun to participate in international cooperation. The traditional energy state-owned enterprises and new emerging energy companies implemented different kinds of cooperation activities with foreign partners, which will benefit intellectual property rights and technology transference for China and their foreign partners.

The achievements of international energy cooperation include co-publications, demonstration projects and consulting reports. Through international cooperation the level of academic R&D and high-quality papers has increased. Consultation reports and demonstration projects are a valuable reference and experience for the Chinese government and relevant stakeholders.

Abbreviation of 20 journals

Hy-en	Int. Journal of Hydrogen Energy
Bio-bio	Biomass and Bioenergy
Sol-en	Solar energy
F-c-s-t	Journal of Fuel Cell Science and Technology
Ap-en	Applied energy
Fuel	Fuel
Fu-cell	Fuel Cells
Fu-pro-te	Fuel Processing Technology
Ie-t-en	IEEE Transactions on Energy Conversion
Int-j-en	International Journal of Energy Research
Pro-en-co	Progress in Energy and Combustion Science
Re-su-en	Renewable and Sustainable Energy Reviews
Sol-en-mat	Solar Energy Materials and Solar Cells
App-th-en	Applied Thermal Engineering
En-build	Energy and Buildings
En-con-ma	Energy Conversion and Management
En-fuel	Energy and Fuels
En-pol	Energy Policy
Re-en	Renewable Energy

(*continued on next page*)

Abbreviation of Chinese Universities:

HUST	Huazhong Univ. of Sci. and Tech.
SJTU	Shanghai Jiao Tong Univ.
UPC	Univ. of Petroleum of China.
THU	Tsinghua Univ.
XJTU	Xi'an Jiao Tong Univ.
SCUT	South China Univ. of Tech.
ECUST	East China Univ. of Sci. and Tech.
TJU	Tianjing Univ.
HIT	Harbin Institute of Tech.
CUST	China Univ. of Sci. and Tech.
ZJU	Zhejiang Univ.
CUMT	China Univ. of Mining and Tech.

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Professor Wu Yishan and Professor Pan Yuntao of the Institute of Scientific and Technical Information of China (ISTIC) have provided much help and advice for this paper. Supported by China's National Social Science Fund Project: 09CTQ017.

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