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Magnetic fusion development for global warming suppression

Jiangang Li[1], **Jie Zhang**[2] **and Xuru Duan**[3]

[1] Institute of Plasma Physics, CAS, Hefei, 230031, People's Republic of China
[2] Shanghai Jiao Tong University, Shanghai 200240, People's Republic of China
[3] Southwestern Institute of Physics, CNNC, Chengdu, 610041, People's Republic of China

E-mail: j_li@ipp.ac.cn

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Abstract
Energy shortage and environmental pollution are two critical issues for human beings in the 21st century. There is an urgent need for new sustainable energy to meet the fast growing demand for clean energy. Fusion is one of the few options which may be able to satisfy the requirement for large scale sustainable energy generation and global warming suppression and therefore must be developed as quickly as possible. Fusion research has been carried out for the past 50 years. It is too long to wait for another 50 years to generate electricity by fusion. A much more aggressive approach should be taken with international collaboration towards the early use of fusion energy to meet the urgent needs for energy and global warming suppression.

1. Energy needs in the 21st century

Energy shortage and environmental pollution are two critical issues for human beings in the 21st century. There is an urgent need for new sustainable energy to meet the fast growing demand for clean energy. Future requirements of energy before 2050 are shown in figure 1 according to the IEA report. Energy consumption will double within 40 years to lift the world out of poverty. At the moment, 80% of world energy is generated by burning fossil fuels which is the main culprit in global climate change and pollution. It is anticipated that developing countries such as China and India will witness an even greater energy need and more pollution.

The Chinese economy has been enjoying 8–9% annual growth for the past 30 years, with 9% in 2008. Aiming at a moderately developed economy for China as the target in 2050, the total energy requirements will increase by a factor of three as shown in figure 2. Meanwhile, China's resources are poorly balanced. It uses 11% of world coal, 13% hydropower, but only 2.5% of the oil and 1.2% of the gas on the Earth. This means that the Chinese energy consumption structure is and will continue to be mainly based on coal, nearly 70% at the moment and around 50% in 2050. At the same time, China suffers from poor efficiency in turning fissile energy into economic output, just about one-seventh of that in Japan.

It is a disturbing picture that the Chinese coal-centred energy structure has already caused many problems, such as pollution and global warming, since China has now become the second largest CO_2 producing country. If its energy structure is not significantly changed, the CO_2 emission could increase by a factor of two within the next 20 years. This will certainly have a big impact on the global environment. Moreover, coal, oil and gas, as non-reproducible fossil fuels, will not meet our energy demand for long-term sustainable development.

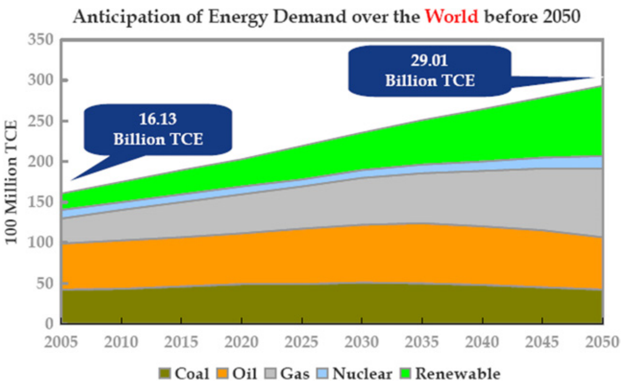

Figure 1. Anticipated energy need before 2050, IEA2005 report: TCE stands for ton coal equivalent.

China's growing reliance on imported oil, the pollution and looming water shortages pose major threats to its economic development. However, a change in the energy structure needs massive and sustained efforts. It would take 50 years and tremendous efforts to reduce the contribution of coal to 50% as shown in figure 2, and perhaps 100 years to bring the number down to 24%, the present world average level.

To realize the long-term sustainable economic development, it is necessary for China to exploit renewable energy

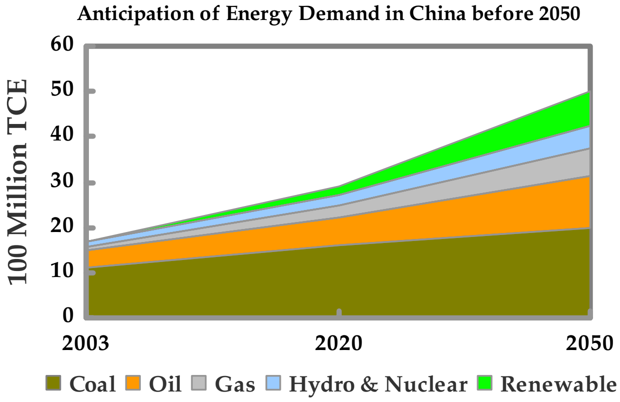

Figure 2. Energy demand in China before 2050, IEA2005 report.

and operate thousands of gigawatts non-CO_2 producing power plants.

2. Revolution of energy sources

Tremendous efforts have been made in China to suppress CO_2 emission and develop strategic and sustainable energy. Figure 3 shows the roadmap for renewable energy technology development for the next 50 years, aiming at 20% of total energy consumption. Before 2020, 10–100 MW scale demo plants for solar, wind and biomass will start operation. Gigawatt level renewable power plants will start after 2030. This challenge needs both new technologies and great efforts.

According to the proposed development roadmap, nuclear fission power generation will be boosted for the next 40 years, commercializing the third and fourth generation technologies and meeting 15% of total energy consumption untill 2050, as shown in figure 4. It is obvious that if 15% of the whole energy were to come from nuclear fission, the number of fission power plants in China would be 460–500, almost equal to the number of all power plants in the world at present. China is poor in fission fuel resource; the fuel shortage problem must be addressed and a means of processing the long-life radioactive waste must be found before 2050. These two tasks are very challenging and no good solution is available now.

With the use of other technologies, such as energy saving and improving energy efficiency, CO_2 emission will significantly decrease over the next 20 years, as shown in figure 5. However, if controls are not adopted, China would be the largest CO_2 producing country in the world in the very near future. If China's economy maintains 7–9% annual growth for another 20–30 years together with its population rise from the present 1.3 billion to 1.5 billion, the estimated energy demand would jump to 4 billion TCE in 2050 instead of the 3 billion TCE shown in figure 1. 20% renewable power and 15% nuclear fission power would be the upper possible limits, thus leaving a large energy demand gap to be filled.

3. Contribution by fusion energy development

It seems at present that we, humankind, do not have many choices in energy. To our delight and relief, fusion is at hand. Fusion has been proved to be a potential source of secure, inexhaustible and environment friendly energy. Fusion research started 50 years ago and significant progress had been made since then. More than 16 MW fusion power has been produced in JET, the world largest tokamak. Equivalent Q is over unity in the JT-60U tokamak. High performance hot plasma has been kept for more than 1 h in the Large Helical Device. EAST and KSTAR, the new generation of fully superconducting tokamaks, have been put into operation. Fusion research has entered a new era with joint efforts from China, Europe, India, Japan, Korea, Russia and the United States on the International Thermonuclear Experimental Reactor (ITER). ITER is now being constructed in Caderache, and it will fulfil our dream—to build an artificial sun on the earth.

Still, we are often asked 'How long will it take to use the fusion energy?', 'Can fusion play a role in this century?'. People have begun to consider DEMO more seriously than before. With both theoretical and experimental knowledge from the past 50 years, a detailed gap analysis has been done in the US [1] and EU [2] for achieving steady-state operation of a commercial fusion power plant. There are still many technical difficulties in plasma performance, enabling technologies, material and component performance and safety issues, and time is needed for further development of a fusion power plant. According to the input requirement of DEMO and the power plant as shown in figure 6 (r-solution is desirable, R-solution is requirement), some key scientific and technical issues will be addressed in ITER as shown in the column under ITER. There are still many issues which can only be eventually solved with DEMO and the power plant, as shown in the right 3 columns. Most people would agree that about 30 years are needed for DEMO and 50 years towards a commercial fusion power plant.

4. Accelerating the development of fusion energy

Do we really need another 50 years to build a commercial fusion power plant? The answer is 'No' if we take a bold way to speed up the development of fusion energy despite the technical difficulties. How fast fusion energy can be used depends mainly on how urgently human beings need it. It took only 8 years for a US astronaut to land on the moon in the 1960s. If we can carry out the fusion research in the same way as the Apollo project, fusion development will be much faster than it was.

'Fusion has always been 50 years away, and always will be', as the old joke goes. If fusion is a dream, it has been dreamed for generations, never has the dream become this clear and this realistic as today when we have already started the construction of ITER. Fusion development has made remarkable progress over the past decades and is now at the turning point towards realizing reactor-size burning plasmas. To speed up fusion development, four essential steps must be taken simultaneously:

(1) Ensure a successful ITER project via very good international cooperation.
(2) Start the International Fusion Materials Irradiation Facility (IFMIF) engineering activities as soon as possible.
(3) Start DEMO design with strong industry involvement now.

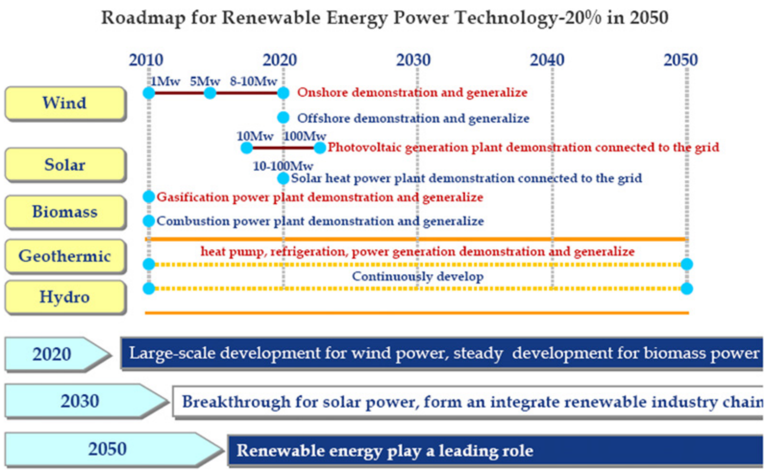

Figure 3. Roadmap for renewable energy in China before 2050.

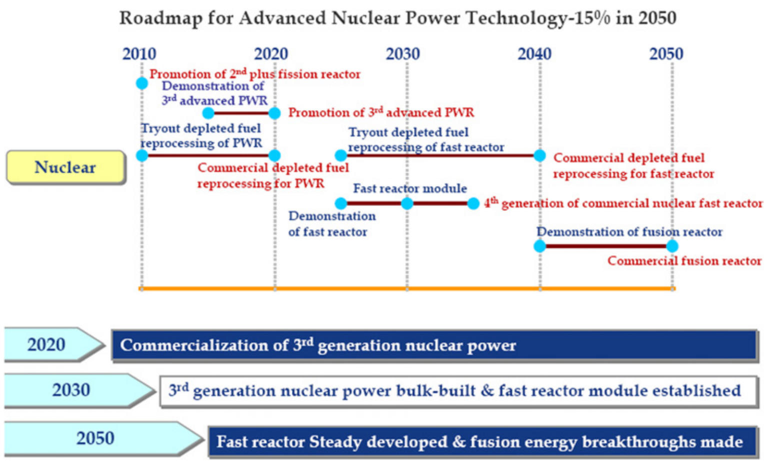

Figure 4. Roadmap for nuclear fission power plant in China before 2050.

(4) Demonstrate fusion power generation within 20 years with moderate mission.

ITER brings fusion research to a state where most of the tasks will be achieved through international cooperation. For the coming 10 years, the major tasks for the world fusion community are to accomplish ITER key component manufacturing and its assembling, to resolve ITER physics issues which might limit its performance by modelling and using the existing devices, such as JET, DIII-D, ASDEX_U, KSTAR, EAST and other devices. The successful construction of ITER without delay is the first priority of magnetic confinement fusion (MCF) development.

Significant results and understanding in MCF research have been achieved on the existing facilities through national and/or international efforts. To speed up the development of fusion energy, efforts must be concentrated on the facilities with a clear ITER or DEMO physics mission. The facilities that are aged and with low priority for ITER should finish their mission as soon as possible and more experts should move to the major activities aimed towards successful ITER construction and ITER physics operation by joint international cooperation.

Meanwhile, a materials irradiation facility must be built in parallel with ITER to enable the validation of the necessary materials in time. ITER and IFMIF should proceed in a coordinated way. The engineering design for IFMIF should be finalized as soon as possible. An extensive programme for construction, testing and validating materials is required. The construction of IFMIF is essential since it will be impossible to license the plasma facing and structural materials for DEMO construction without relevant irradiation validation.

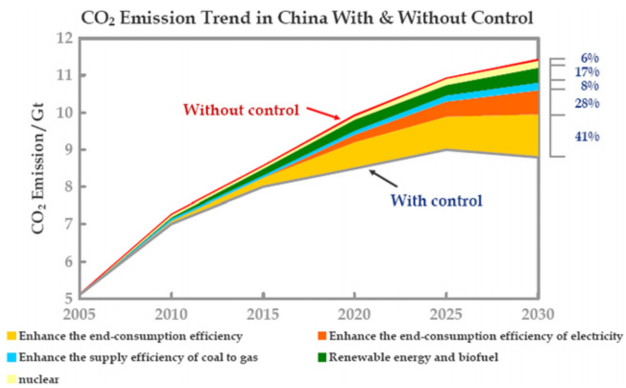

Figure 5. Comparison of CO_2 emission with/without control in China.

	Issue	Approved devices	ITER	IFMIF	DEMO Phase 1	DEMO Phase 2	Power Plant
Plasma performance	Disruption avoidance	2	3		R	R	R
	Steady -state operation	2	3		r	r	r
	Divertor performance	1	3		R	R	R
	Burning plasma (Q>10)		3		R	R	R
	Start up	1	3		R	R	R
	Power plant plasma performance	1	3		r	R	R
Enabling technologies	Superconducting machine	2	3		R	R	R
	Heating, current drive and fuelling	1	2		3	R	R
	Power plant diagnostics & control	1	2		r	R	R
	Tritium inventory control & processing	1	3		R	R	R
	Remote ha ndling	1	2		R	R	R
Materials, Component performance & lifetime	Materials characterisation			3	R	R	R
	Plasma -facing surface	1	2		3	4	R
	FW/blanket/divertor materials		1	1	3	4	R
	FW/blanket/divertor components		1	1	2	3	R
	T self sufficiency		1		3	R	R
Final Goal	Licensing for power plant	1	2	1	3	4	R
	Electricity generation at high availability				1	3	R

Figure 6. Present state and gap analysis towards a fusion power plant [3]. Input: r—solution is desirable, R—solution is requirement. Output: 1—will help to solve the issue, 2—may solve the issue, 3—should solve the issue, 4—must to solve the issue.

A Components Test Facility (CTF) would be desirable and necessary for risk reduction towards DEMO. Since some of the key issues required for DEMO, such as reliability of the major components inside the vacuum chamber like the divertor with DEMO heat flux, the tritium breeding blanket, ICRF antenna and structure materials cannot be fully tested in the ITER late D–T phase, a CTF can fill this gap and play an important role in establishing a solid base for successful DEMO operation. The feasibility of this option should be explored further. A ST type device, with the same configuration as MAST and NSTX, can play a key role for a cost effective approach.

The next major step beyond ITER will be DEMO which will demonstrate the commercial viability of a fusion power plant. A DEMO design with strong industry involvement will be important for focusing on crucial issues for the feasibility of a future power plant. Although the full burning plasma physics can be comprehensively addressed when ITER begins its long-pulse high-power DT experiments, many efforts for such an integrated DEMO design are still required for advanced plasma control, steady-state operation, heating and current drive, fuel cycle, remote handling and maintenance, tritium breeding, electrical power generation, etc. In particular, reliability, availability and maintainability are important to minimize the maintenance time. Industry must play a major role in this work to ensure the feasibility and standards, in particular in the area of nuclear technologies, and to become acquainted with the system requirements of a fusion power plant. A joint team with fusion scientists and engineers, professionals from the nuclear industry and safety is essential for the realization of future commercial fusion power plants under a full industrial leadership.

Another option to accelerate fusion development has also been proposed in conjunction with this plan involving an additional early DEMO (eDEMO) device with the moderate mission of DEMO. An eDEMO will demonstrate electricity generation by fusion energy. It would be desirable to have it constructed in parallel with the ITER first phase of operation based on the present available technology and already largely developed physics scenarios. An eDEMO will be a multi-function device, addressing not only DEMO plasma physics, such as burning plasma control and steady-state operation, but also some key engineering issues, such as electricity generation, tritium breeding and hydrogen production. There will be no need for it to achieve real steady-state operation required in DEMO, but it should be able to deal with some key issues for DEMO which cannot be fully tested in ITER, such as tokamak system availability, reliability and maintainability. A scenario with an eDEMO is also believed to strongly assist in minimizing the risk of a fast track scenario.

There could be different ways to approach this eDEMO via either pure fusion or the fusion–fission hybrid concept. By pure fusion, either the tokamak or the stellarator approach can play a role. The optimized stellarator concept can play a role in avoiding a number of unsolved issues in the tokamak concept, namely steady-state and disruption-free operation [4]. This type of machine could be of a few hundred megawatt fusion power and last from several hours to weeks. It can be realized based on the existing technologies and a few further R&D efforts. There are a few concept designs for such a device, such as the Fusion Development Facility (FDF) [5] and CTF based on ST configuration [6]. Via the fusion–fission hybrid approach, core plasma could be of a few mega-amperes (bigger than JET and smaller than ITER) and fusion power about 50–100 MW. The energy gain in the fission blanket could be 10–20 which could be fulfilled by the existing technology. This will give a total thermal energy of 1–2 GW, which is sufficient to generate electricity in the power plant scale [7].

Either DEMO or eDEMO approaches must be carried out with very strong industry involvement from the very beginning. Industry, which today acts mainly as a build-to-print supplier in fusion, will have to become deeply involved in fusion, starting with substantial contributions to the ITER construction. Its role in DEMO/eDEMO must be evolved towards taking over further development of commercial fusion power plants as its own responsibility. Licensing is also a key issue which requires all major elements of physics and technology to be proven before the construction starts.

5. Summary

Amid the fast development of the world economy, we are facing a huge energy challenge, in particular in the developing countries. A bolder approach is needed for fusion energy development since fusion is one of the very few perspective options and easily accepted by the public. ITER starts its construction in Caderache, with very strong efforts through multi-parties cooperation. Fusion needs in developing countries, particularly in China and India, have aroused both public and governmental concerns.

Chinese fusion research started 50 years ago and has remained on a relatively small scale, yet has always been oriented towards energy development. Significant progress has been achieved over the past decade, especially with joining the ITER project. The world's first fully superconducting tokamak EAST was successfully constructed in 2006 and its operations started to address the advanced high performance steady-state plasma which is one of the most important key issues for ITER and DEMO. The Chinese government and leaders strongly support fusion research. A national MCF-ITER programme started in 2007. This programme consists of ITER-CN components construction and domestic MCF development. The main thrust of Chinese domestic MCF development in the next 10 years will be on establishing good research facilities for the advanced steady-state plasma research, enhancing the education and basic plasma research in universities, developing reactor materials and starting DEMO design.

Energy is a global problem, as it is central to economic development, climate and environment, and international stability and sustainability. New sustainable energy is urgently needed to meet the fast growing demand for clean energy in the 21st century. The change of world energy structure needs normally 50–100 years. Fusion is one of the few options to satisfy the requirement of large scale generation of sustainable energy and suppression of global warming, and therefore must be developed as quickly as possible. Fusion research has been carried out for 50 years. It is too long to wait for another 50 years to generate electricity by fusion. A much more aggressive approach should be taken with international collaboration towards the early use of fusion energy to meet the urgent needs for energy and global warming suppression.

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