Technology Action Plan

HIGH-EFFICIENCY, LOW-EMISSIONS COAL

MAJOR ECONOMIES FORUM
ON ENERGY AND CLIMATE

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Technology Action Plan: High-Efficiency, Low-Emissions Coal

Report to the Major Economies Forum on Energy and Climate

Prepared by India and Japan in consultation with MEF Partners

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PREFACE

The Leaders of the 17 partners[1] of the Major Economies Forum on Energy and Climate (MEF) agreed on 9 July 2009 that moving to a low-carbon economy provides an opportunity to promote continued economic growth and sustainable development as part of a vigorous response to the danger posed by climate change. They identified an urgent need for development and deployment of transformational clean energy technologies, and established the Global Partnership to drive such low-carbon, climate friendly technologies.

Plans were created to stimulate efforts among interested countries to advance actions on technologies including advanced vehicles; bioenergy; carbon capture, use, and storage; buildings sector energy efficiency; industrial sector energy efficiency; high-efficiency, low-emissions coal; marine energy; smart grids; solar energy; and wind energy. These plans include a menu of opportunities for individual and collective action that may be undertaken voluntarily by interested countries, in accordance with national circumstances. Further actions may be identified in support of these plans in the future.

[1] Australia, Brazil, Canada, China, the European Union, France, Germany, India, Indonesia, Italy, Japan, Korea, Mexico, Russia, South Africa, the United Kingdom, and the United States

OVERVIEW

As worldwide populations and industrial growth reach new heights over the next 20 years, electricity demand is projected to increase substantially. Fossil fuels, particularly coal, will continue to be a vital energy source for the power sector in many countries. At the same time, coal-based power generation is one of the largest sources of global CO_2 emissions. High-efficiency, low-emissions (HELE) coal technologies can help reduce the carbon emissions produced by coal-fired power generation while enabling the energy source to continue to meet growing power demand.

Sharing common interests for reducing emissions and improving energy efficiency in coal-fired power generation, several MEF countries have taken leading roles in advancing HELE coal technologies. This plan for advancing HELE coal technologies has been developed based on intensive discussion in and between India and Japan, including a Workshop on Development and Deployment of High-Efficiency and Low-Emission Coal Technologies, held in Tokyo on 15 September, 2009, with participation from public and private sector experts from around the world. Furthermore, related bilateral and multilateral activities being supported by other MEF countries, as summarized in this plan, not only support the proposed course of actions but also provide a firm base for further wide-scale cooperation.

HIGHLIGHTS OF THE HELE COAL TECHNOLOGIES TECHNOLOGY ACTION PLAN

1. GHG Emissions and Mitigation Potential
   - **Coal-fired power will remain in high demand.** In the coming decades, coal will remain the dominant fuel of the power sector, rising to 44% of the global power generation mix and accounting for 66% of the power-generation sector's emissions by 2030.
   - **HELE coal technologies can meet power demands and mitigate emissions.** 1.4 gigatonnes (Gt) of CO_2 per year can be reduced if coal-fired power plants older than 20 years (with average LHV efficiency of 29% or lower) are replaced by plants with efficiencies of 45%.

2. Development and Deployment: Barriers and Best Practice Policies
   - **Barriers** to the development and deployment of HELE coal technologies and practices include insufficient information; varying qualities of coal; the high upfront cost of advanced HELE coal technologies; lack of appropriate price, financial, legal, and regulatory frameworks; inadequate operations and maintenance skills; and insufficient research, development, and demonstration.
   - **Best practice policies** encouraging the development and deployment of HELE coal technologies include identifying research and development priorities, establishing regulatory incentives and benchmarking, and multilateral and bilateral cooperation.

3. Opportunities to Accelerate Development and Deployment

- Supporting innovation:
  - Identify HELE coal technologies prioritized for innovation, based on national circumstances.
  - Formulate roadmaps for HELE coal technologies including, where appropriate, setting nationally appropriate RD&D goals.
  - Enhance RD&D efforts for HELE coal technologies through public-private partnerships.
  - Enhance international collaboration on RD&D of HELE coal technologies.
- Accelerating deployment:
  - Identify best available technology options and best practices relevant to HELE coal technologies and practices.
  - Consider developing a Nationally Appropriate Technology Deployment Roadmap for coal-fired power plants.
  - Put in place appropriate price, financial, and regulatory incentives for the uptake of BAT and BP relevant to HELE coal technologies.
  - Consider nationally appropriate policy goals related to HELE coal technologies, where appropriate.
  - Cooperate with the private sector through public-private partnerships to effectively identify HELE coal technologies to be deployed and to design appropriate policies and measures.
  - Learn from successful joint venture experiences related to the introduction of HELE coal technologies
  - Enhance regular national measurement and monitoring for developing clear baselines, which will help to establish the cost-benefit of upgrading or making improvements to a country's or a utility's coal fleet.
  - Develop effective capacity-building measures in such areas as operations and maintenance (O&M) for improving and maintaining the energy efficiency of a coal-fired power plant.
  - Develop an effective technology transfer mechanism to promote international dissemination of clean and efficient technologies (including HELE coal technologies) and an effective mechanism to match technology needs with technology owners and financial sources.
- Facilitating information sharing:
  - Share information on best available technology options and related best practices.
  - Identify and utilize ongoing international initiatives that collaborate on HELE coal technologies (e.g., APP and IEA).
  - Develop and support a web-based repository or clearinghouse of knowledge and information for available technologies, the location of their deployment around the world, updates on new and available technologies, related work in research and technology development, pools of competence, etc.
  - Develop an international initiative for creating "international technology hubs" in key sectors (e.g., power sector) using the expertise of existing international forums (e.g., IEA).

TABLE OF CONTENTS

1. Coal-Fired Power: GHG Emissions Production and Mitigation Potential

Coal is a fossil fuel that will continue to be a vital energy source in the coming decades for the power sector in many countries. At the same time, coal-based power generation is one of the largest sources of CO_2 emissions in the world. High-efficiency, low-emissions (HELE) coal technologies can help reduce the carbon emissions produced by coal-fired power generation while enabling this energy source to continue to meet growing power demand.

GHG Emissions Production from Coal-Fired Power

Growing Demand for Fossil Energy

Due in large part to worldwide population and industrial growth, global demand for energy, and electricity in particular, is projected to increase substantially over the next 20 years. The International Energy Agency (IEA) Reference Scenario[2] estimates that electricity demand will increase by 76% from 2007 to 2030 (IEA 2009b). Currently, fossil power generation accounts for 67% of total power generation in the world and the same percentage of power generation in Major Economies Forum (MEF) countries. Over the coming decades, fossil fuel-based power will continue to produce a substantial share of the world's power as electricity demand rises.

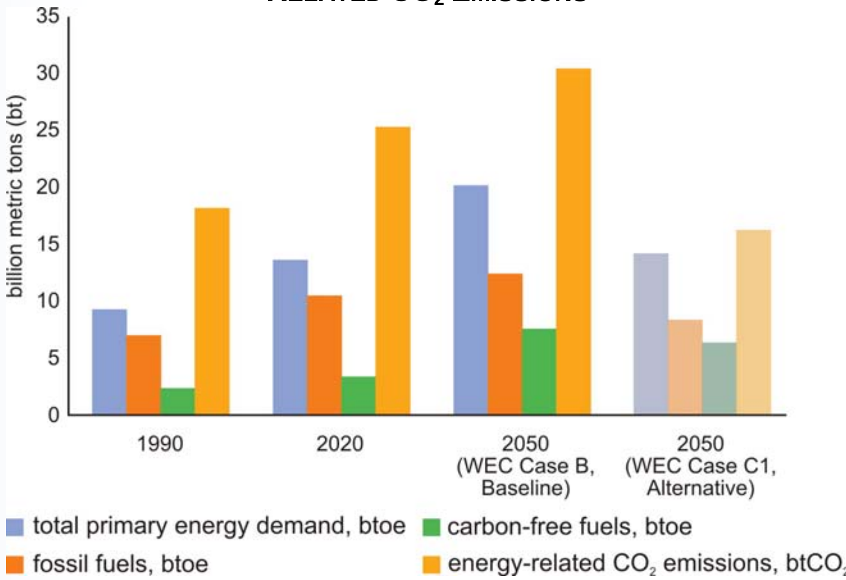
Fossil fuels have been the main source for the world's energy for more than a century; as of 2007, they represented an approximate 85% share (WEC 2007a). While this share is predicted to decline to 82% in 2030 and to 64% in 2050, the rate at which demand for fossil fuels is expected to grow over the next few decades is highly dependent on the extent to which countries adopt regulations to limit emissions of carbon dioxide and other GHG emissions. Figure 1 indicates that under the Reference Scenario with no limits on use of carbon intensive fuels, global fossil fuel demand will increase by 80% between 1990 and 2050. If caps are placed on energy-related greenhouse gas (GHG) emissions, the increase in fossil fuel demand is more likely to be around 15%–20% (Figure 1, second column in 2050). This figure also indicates the increasing emissions levels projected to accompany this growth in demand.

Growing Demand for Coal

As demand for fossil fuels increases, consumption of coal, in particular, is projected to increase (Table 1). According to the IEA, the world's Total Primary Energy Supply (TPES) is expected to increase by approximately 45% from 2006 to 2030, out of which global coal consumption is expected to increase by 60% such that its share within the TPES will increase from 26% to 29% (see Figure 1 and Table 1).

[2] The IEA Reference Scenario assumes no change in government policies, resulting in 40% higher energy demand in 2030 (16.8 billion tonnes) (IEA 2009a).

FIGURE 1. WORLD TOTAL PRIMARY ENERGY DEMAND AND RELATED CO_2 EMISSIONS



btoe: billion tonnes oil equivalent
$btCO_2$: billion tonnes CO_2 equivalent
Source: WEC 1995

TABLE 1. WORLD TOTAL PRIMARY ENERGY DEMAND BY FUEL IN THE REFERENCE SCENARIO (MTOE)

	1980	2000	2006	2015	2030	2006-2030*
Coal	1788	2295	3053	4023	4908	2.0%
Oil	3107	3649	4029	4525	5109	1.0%
Natural Gas	1235	2 088	2407	2903	3670	1.8%
Nuclear	186	675	728	817	901	0.9%
Hydro	148	225	261	321	414	1.9%
Biomass and waste**	748	1045	1186	1375	1662	1.4%
Other renewables	12	55	66	158	350	7.2%
Total	7223	10034	11730	14121	17014	1.6%

mtoe: million tonnes of oil equivalent
*Average annual rate of growth.
**Includes traditional and modern uses.
Source: IEA 2008c

Among the fossil fuels satisfying growing global demand for electricity, coal will likely remain the dominant fuel of the power sector. The IEA Reference Scenario estimates that coal's share of the global power generation mix will rise by two percentage points to 44% in 2030 (IEA 2009b). This is due, at least partially, to the large number of coal-fired power plants that are expected to be constructed.

Coal also has a very favorable "reserves-to-production ratio" (Table 2), meaning that, notwithstanding recent discoveries of substantial natural gas reserves not yet reflected in these figures, at the current rate it is being produced, ample supplies of coal are likely to last longer than for any other fossil or nuclear fuel reserve. The availability and staying power of coal will likely encourage further growth in demand.

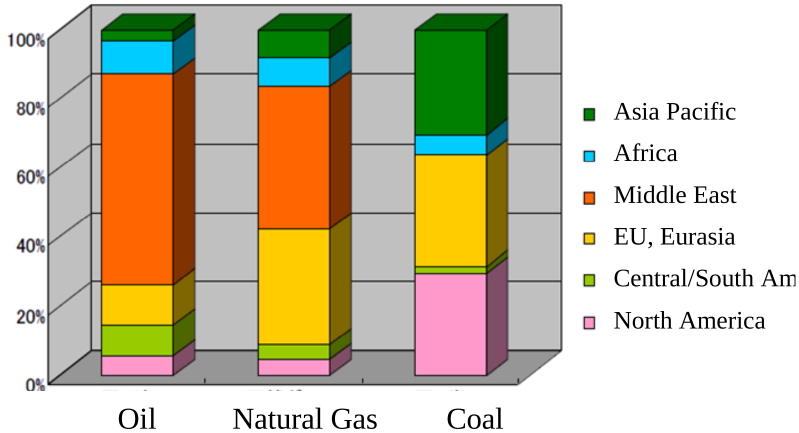
TABLE 2. RESERVES TO PRODUCTION RATIO OF FOSSIL FUELS

Fuel	Reserves-to-Production Ratio (years)
Coal	144
Oil	41
Natural Gas	62
Uranium	79

Source: WEC 2007b

Among all fossil fuels, coal is distributed more equitably across the globe (Figure 2). Hence, the development and deployment of any technology that furthers coal's clean and efficient use can contribute to energy security. Furthermore, improvement of efficiency in any phase of power supply (i.e., generation, transmission, and distribution) could have the co-benefit of addressing urgent needs to control air pollution in addition to mitigating climate change challenges.

FIGURE 2. REGIONAL DISTRIBUTION OF RECOVERABLE RESERVES



Source: BP 2009

Emissions

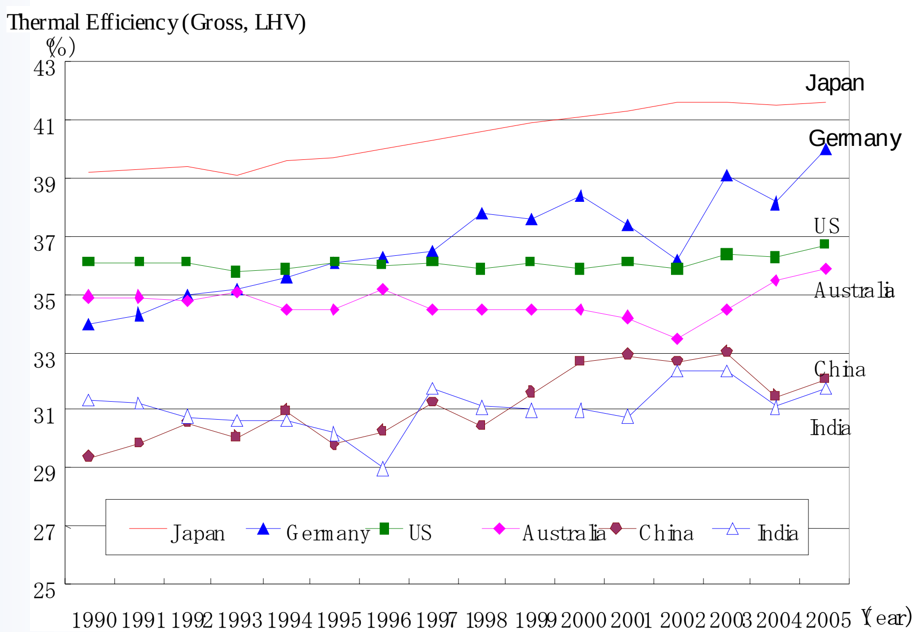
With this growing demand for fossil-based and, in particular, coal-based electricity comes an increasing production of emissions. Current levels of fossil fuel power generation account for over 40% of global energy-related CO_2 emissions (44% for MEF countries) and around 27% of the total global CO_2 emissions (IEA 2007a). The IEA Reference Scenario indicates that more than half of the power-generation sector's emissions through 2030 will be attributable to coal-fired generation, which is projected to experience a 60% increase in emissions overall (IEA 2009b).

Mitigation Potential of HELE Coal Technologies and Practices

To realize sustainable development, both electricity demand and global emissions issues need to be addressed simultaneously. According to the United Nations Framework on Climate Change (UNFCCC), clean fossil fuel power generation has the potential to reduce emissions by 1.6 gigatonnes CO_2 equivalent (Gt CO_2e) by 2030 (UNFCCC 2007).[3] Improving the efficiency of existing coal facilities or replacing them with more advanced technologies can aid in this overall reduction, providing substantial CO_2 mitigation while ensuring that power needs are met.

Currently, the average efficiency[4] of coal-fired power plants in MEF countries varies significantly from roughly 31–42% (Figure 3). This difference comes from diverse factors such as vintages of operating fleets, climatic conditions, coal quality, the operations and maintenance skills at existing plants, and uptake of advanced technologies.

FIGURE 3. COAL-FIRED POWER PLANTS



Note: Certain differences (approximately 3–4%) are due to ambient climatic condition and quality of coal available.
Source: Graus 2007

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[3] While this is a significant number, it is one of several potential interventions. For comparison, "end-use efficiency" has the potential of yielding emissions reduction of 6.0 Gt CO_2e (UNFCCC 2007).

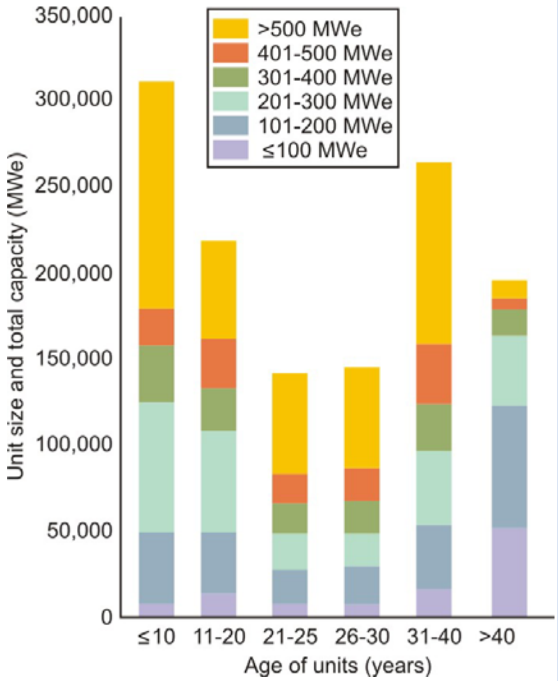
[4] Efficiency figures in this report are based on lower heating values (LHV). LHVs, unlike higher heating values (HHV), do not include the latent heat of the moisture originally present in the fuel or from combustion of the coal hydrogen. European and IEA statistics are reported on an LHV basis, while U.S. statistics are reported on an HHV basis. On these bases, HHV efficiencies are about 2% lower than LHVs for coal-fired power plants (IEA 2008).

Figure 4 shows that currently more than half of the operating coal-fired fleets in the world have been in service for more than 25 years. Additionally, more than 80% of global installed capacity is subcritical power plants (IEA 2007b), which have less thermal efficiency than supercritical, ultra-supercritical, and IGCC plants, as shown in Table 3 (IEA 2008a).

IEA suggests that 1.4 Gt CO_2e per year could be reduced if coal-fired power plants older than 20 years—of which average net efficiency is 29% or lower—are replaced by plants with efficiencies of 45% (IEA 2008a). Such measures would need to take into consideration the quality of locally available resources as well as climatic conditions, and may not be appropriate for every country, due to high gestation and investment needs. Replacing old power stations with new, highly-efficient plants may need to be financially supported due to the related high investment needs. The number of existing or planned higher-efficiency supercritical plants already in place in many countries is promising and could increase the probability of achieving this level of emissions reduction (Figure 5).

IEA also estimates that the best available coal technologies could help reduce overall coal power CO_2 emissions from 1.4–2.0 Gt CO_2e per year (including the 1.4 Gt CO_2e identified in the last paragraph), or approximately 5–7% of the current global CO_2 emissions, as shown in Figure 6 (IEA 2008d).

FIGURE 4. SIZE AND TOTAL CAPACITY OF EXISTING COAL-FIRED POWER PLANTS, BY LIFESPAN



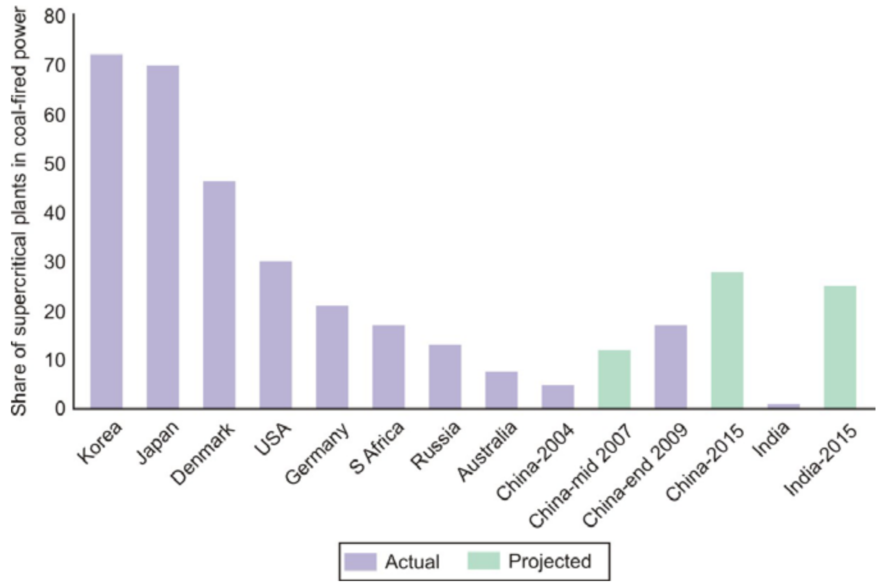
MWe = megawatt equivalent
Source: Bhattacharya 2008

TABLE 3. PERFORMANCE SUMMARY FOR DIFFERENT COAL-FIRED POWER PLANTS

Plant type*	PCC	PCC	PCC	IGCC
Steam cycle	Subcritical	Typical Supercritical	Ultra-Supercritical (best available)	Triple Pressure Reheat
Steam conditions	180 bar 540ºC 540ºC	250 bar 560ºC 560ºC	300 bar 600ºC 620ºC	124 bar 563ºC 563ºC
Gross output (MW)	500	500	500	500
Auxiliary power (MW)	42	42	44	67
Net output (MW)	458	458	456	433
Gross efficiency (%)	43.9	45.9	47.6	50.9
Net efficiency (%)	40.2	42.0	43.4	44.1
CO_2 emitted (tonnes/hour)	381	364	352	321
Specific CO_2 emitted (tonnes/MWh) net	0.83	0.80	0.77	0.74

*PCC: Pulverized Coal Combustion; IGCC: Integrated Coal Gasification Combined-Cycle.
Certain differences (approximately 3-4%) are due to ambient climatic condition and quality of coal available.
Source: IEA 2008a

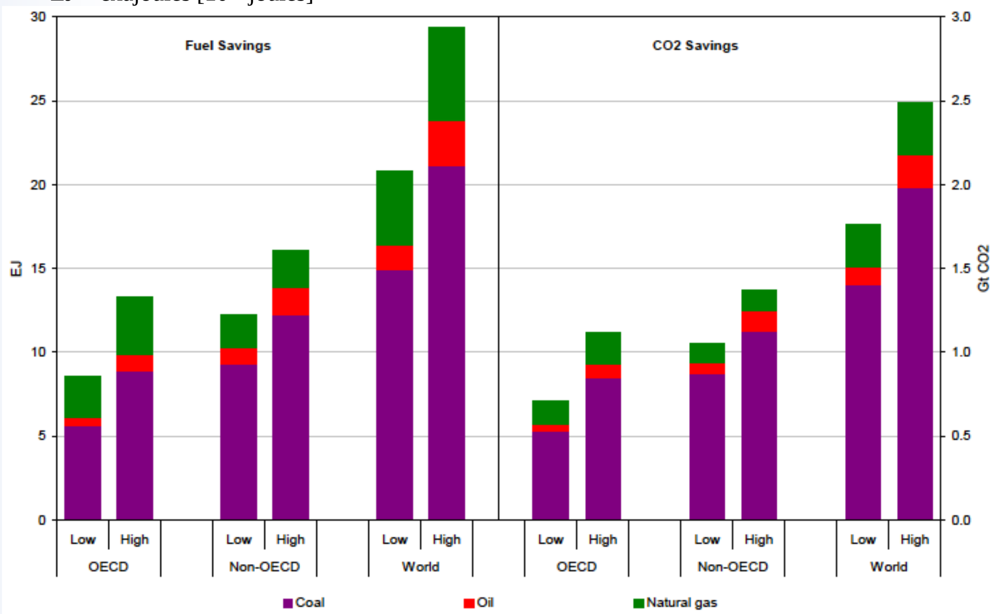
FIGURE 5. SHARE OF SUPERCRITICAL PLANTS IN COAL-FIRED POWER GENERATION BY COUNTRY



Source: IEA Clean Coal Centre et al. 2008

FIGURE 6. TECHNICAL FUEL AND CO_2 SAVING POTENTIALS FROM IMPROVING THE EFFICIENCY OF ELECTRICITY PRODUCTION

EJ = exajoules [10^{18} joules]



Source: IEA 2008d

Clean coal technologies include technologies that improve the efficiency of the power generation as well as technologies that utilize, consume, or sequester the CO_2 produced as a result of the combustion of fossil fuel. Both of these technological options serve the prime purpose of reducing the CO_2 intensity of coal-fired power generation.

Technologies for improving the efficiency of coal-fired power generation can roughly be broken down into existing plant technologies and higher-efficiency new power plant technologies, and could include the following:

Technologies for Improving the Efficiency of Existing Plant Technologies

- Renovation and modernization technologies for existing power stations
- Waste heat recovery from power plants

Higher-Efficiency New Power Plant Technologies

- Supercritical and ultra-supercritical technologies (SC and USC)
- Integrated coal gasification combined cycle (IGCC)
- Advanced ultra-supercritical technology (A-USC)
- Other innovative high-efficiency cycles (e.g., ammonia and organic Rankine cycle)

Appendix A provides detailed descriptions of these technologies. Technologies for carbon capture and storage (CCS) or for the conversion of CO_2 into useful chemicals, such as methanol, or for other industrial uses will also likely play an important role in the future in the reduction of CO_2 emissions from coal-based power plants. These technologies are fully included in the MEF Global Partnership's *Technology Action Plan: Carbon Capture, Use, and Storage*.

2. Development and Deployment: Barriers and Best Practice Policies

Coal will continue to play a major and indispensable role in meeting existing and anticipated global energy demand in the foreseeable future. Governments and industries must find a path that mitigates carbon emissions while meeting societal and developmental power needs, especially those of developing countries. Overcoming the barriers that can hinder the development and deployment of HELE coal technologies is one element to achieving this critical balance. A number of best-practice efforts to surmount these barriers are already underway, but to achieve needed or desired levels of HELE coal-fired power, they must continue to be evaluated and adjusted to address ongoing barriers in the future.

Barriers to Development and Deployment

The development and deployment of HELE coal technologies is impeded by a range of barriers. Identifying these challenges enables countries to better focus their actions going forward.

Insufficient Information

Lack of information on various suitable technologies, resources, and stakeholders prohibits wider dissemination of clean coal technologies, particularly in developing countries. The latest updates in technological advancement should be captured in a timely manner and disseminated widely.

Varying Qualities of Coal

While coal-fired power generation technologies are similar across the globe, the quality of coal differs. The differences in the quality of coal used can cause the technology to perform in unanticipated and/or unacceptable ways. For example, some countries, like India, have coal with high ash content (approximately 40%), low calorific value (approximately 2400–3300 kcal/kg) and low volatile matter. The gasification of these high ash-content coals, gas cleanup, and low-calorific value of syngas present challenges, yet to be resolved, for the adoption of IGCC or other HELE coal technologies in general. Component erosion due to high ash content can reduce the availability and reliability of power stations even in subcritical regimes in countries like India. This could be a contentious issue for the wider adoption of SC, USC, and A-USC operating regimes.

High Upfront Cost of Advanced HELE Coal Technologies

The high upfront costs of HELE coal technologies are likely to be a significant challenge for utility companies. Over the course of deploying more advanced technologies (e.g., from subcritical to supercritical or from supercritical to ultra-supercritical), depending on coal prices in each country, the high upfront costs could exceed the energy efficiency benefits, especially during the early stages. This may hinder the introduction of advanced technologies, despite the significant cost advantages they offer when measured over their long expected life cycles.

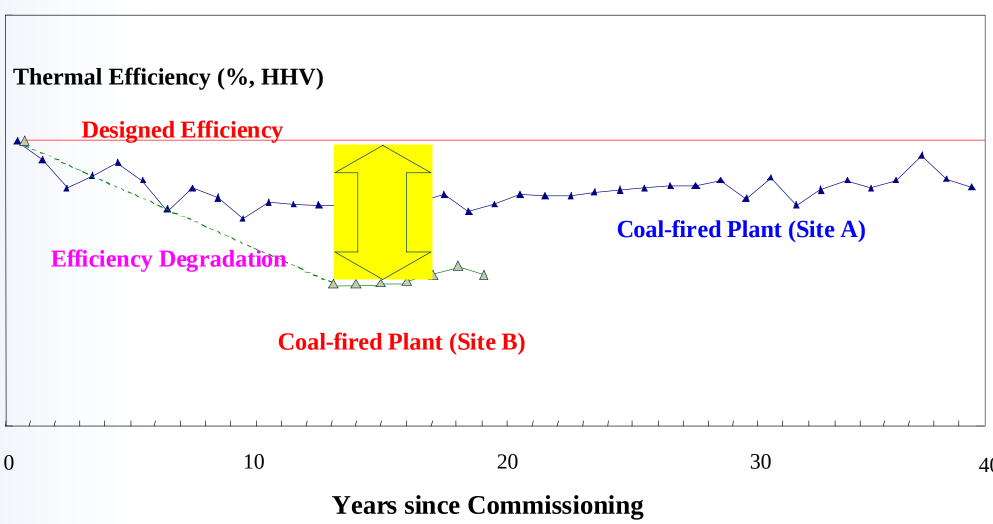
Lack of Appropriate Price, Financial, Legal, and Regulatory Frameworks (Both Domestic and International)

A number of different price, financial, legal, and regulatory frameworks impact the deployment and use of HELE coal technologies. Most HELE coal technologies belong to private manufacturing companies. Dissemination of the "know-how" associated with manufacturing and operating these technologies occurs primarily through commercial transactions between private technology companies and utility companies in host countries. The absence of an enabling environment for technology dissemination can hinder the adoption of advanced technologies. This includes insufficient price signals (in some cases, subsidized) in host countries, which reduces benefits from energy savings; weak efficiency/CO_2 abatement policies (e.g., performance standards for incoming and existing plants); weak domestic/international financial incentives for new technologies; a lengthy and uncertain process for Clean Development Mechanism (CDM) registration; and the possible unintended consequences of existing policies. In the United States, for example, the New Source Performance Standards (NSPS), which are issued by the U.S. Environmental Protection Agency, can limit the modifications that a power plant can make before stricter environmental controls are required even if the modifications result in reduced operating costs and lower emissions. The specific impacts of these policy-related challenges vary greatly by country; policies that create a barrier in one country may not impact technology deployment in another.

Inadequate Operation and Maintenance Skills

To improve the thermal efficiency of power generation, the use of adequate operation and maintenance (O&M) standards, practices, and tools, including software and training, plays a role as important as the introduction of new generation equipment (hardware). Depending on the type of plant (subcritical, supercritical, ultra-supercritical, or IGCC) different methods of O&M are needed. Currently, the actual operational efficiency of subcritical technology, in many cases across the world, is far below the designed efficiency due to inadequate O&M (Figure 7). Even with the introduction of highly efficient power generation systems in the future, it will be

FIGURE 7. COMPARISON OF THERMAL EFFICIENCIES OF COAL-FIRED POWER PLANTS: ADEQUATE O&M (SITE A) VERSUS INADEQUATE O&M (SITE B)



Source: Federation of Electric Power Companies 2009 difficult to realize and maintain the designed efficiency in the long-term without appropriate O&M technologies and the training to use them. This situation could be rectified without incurring large costs through capacity building including disseminating O&M software and training.

Insufficient Research, Development, and Demonstration

Notwithstanding recent stimulus efforts in many countries, the declining trend for energy research, development, and demonstration (RD&D) investments worldwide is a significant barrier to the development and deployment of HELE coal technologies. Recognizing the critical role of innovative energy technology RD&D in energy security and addressing climate change in the long term, a collaborative effort is necessary to increase energy RD&D, according to national circumstances. Countries that will continue to utilize coal in their energy/power mix should consider enhancing their RD&D efforts for HELE coal technologies. Cooperative RD&D might also be encouraged in the areas of efficiency enhancement, reliability, and availability improvement.

IPR Issues

One issue on which a variety of divergent views have been expressed in international forums is intellectual property rights (IPR).

On the one hand, several countries claim the following:

- Close protection of intellectual property (IP) limits the uptake of HELE coal technologies by increasing the cost of such technologies, thus making them economically unviable, especially for developing economies.
- The adoption of HELE coal technologies should be viewed as a global imperative rather than a business opportunity.
- Recognizing this imperative, the primary need is to facilitate and liberalize the use of IP to accelerate the mitigation of emissions from coal while improving the energy security of developing economies. Under this model, traditional technology transfers would be replaced by closely cooperative R&D.
- Hence, a proper internationally funded mechanism needs to be created to promote and facilitate the use of such IP, while suitably compensating the technology owner.

On the other hand, other countries claim the opposite:

- Proper IPR protection does not limit the uptake of HELE coal technologies but, on the contrary, facilitates technology transfer.
- The IPR for HELE coal technologies is owned by private companies and thus, should be transferred when an enabling business environment is ensured, including proper IPR protection and guarantee of appropriate return.
- In most cases, these companies are not getting excessive return from their IP. Prices are determined by many factors, including market competition, and pricing policies often differentiate between customers in developing and developed countries.
- If IPR protections are weakened, then private companies will not have an incentive to make costly, high-risk R&D investments, which will ultimately hinder technology transfer.

Current Best Practice Policies

While there are a number of barriers to the development and deployment of HELE coal technologies and practices, many countries have already begun implementing responsive actions. Through practice, these countries have identified best practices and policies that have been the most successful in the work that has been done so far to meet emissions reduction targets.

Identifying Research and Development Priorities

Different countries require different HELE coal technologies to meet their varying economic, regulatory, technical, and other needs. Identifying priority technologies that meet these unique needs from an early stage is an important step in maximizing the potential return on investment in the long term and in ensuring the successful adaptation of these technologies.

India, for instance, is currently involved in R&D efforts on IGCC technology suitable for Indian coal. India is also prioritizing the adoption of larger (660/800 megawatt [MW]) thermal units based on supercritical technology in capacity addition programs during its current and future five-year plans (2007–2012 and 2012–2017). Improvement in efficiency is also envisaged under the Renovation & Modernization (R&M) and Life Extension (LE) modification programs for old thermal power plants.

Japan is also accelerating the development of innovative energy technology. Japan established the "Cool Earth Energy Innovative Technology Program" in March 2008, through which it has identified 21 selected technologies that can contribute to substantial reduction in CO_2 by 2050. These technologies include HELE coal technologies (e.g., USC, A-USC, IGCC, and IGFC [integrated coal gasification fuel cell combined cycle]) and will be prioritized in government R&D spending.

In addition to numerous European Union initiatives, the German government supports science and industry by funding the R&D of HELE coal technologies. The Instituto de Investigaciones Electrica (IIE) in Mexico has also started a program on IGCC development to support utilities—first, in the adequate selection of technologies and suppliers, and then, in solving operational problems that might be encountered.

Regulatory Incentives

Regulatory incentives provide utilities with benefits for investing in higher-cost HELE coal technologies. These incentives help to encourage widespread deployment and use of HELE coal technologies and practices, which is key to significant emissions mitigation.

Japan is currently instituting regulatory incentives for improving energy efficiency through the adoption of HELE coal technologies. By revising its Energy Efficiency Law in May 2008, Japan has also introduced sectoral benchmarking to certain sub-sectors (iron and steel, cement, and electricity suppliers) to determine indicators that will enable companies to benchmark their levels of energy efficiency against others within the same sub-sector. This benchmarking effort will enable these sectors to set medium-term targets to be achieved around 2015–2020.

India's Central Electricity Regulatory Commission has adopted a nationally-appropriate tariff mechanism to promote energy efficiency based on heat rate and auxiliary power consumption with increased availability in power generation.

The European Union currently has several regulatory efforts in place that are positively impacting the development and deployment of HELE coal technologies and practices. One of these efforts is the EU emission trading system (ETS). Launched in 2005, the ETS sets a cap on CO_2 emissions from the industrial and power sectors to ensure that the ambitious climate protection targets will be achieved. The system is already sending out a clear price signal to encourage the shutdown and replacement of old, higher-emission power stations with newer, more efficient ones. From 2013 onward, CO_2 emission allowances in the EU electricity sector will be fully auctioned, in general, and the cap on available emissions allowances under the ETS will decrease by 1.74% per year. This decrease will create strong incentives to improve the efficiency of the power generation system as a whole. By 2020, the ETS cap will result in a 21% decrease in emissions (compared to 2005 levels). Moreover, the EU will increase this target if Europe commits to an ambitious climate protection target under an international agreement.

To help inform regulators' decisions on large combustion plant (LCP) permit conditions throughout the European Union, the European Commission developed a reference document that describes pollution abatement techniques for all types of LCPs (i.e., greater than 50 megawatt thermal (MW_{th}) inputs) and draws conclusions as to what are best available technologies.

Under the new Combined Heat & Power (CHP) Act (2009), Germany will promote the construction and modernization of highly efficient CHP installations, including the power used by operators themselves. Grants are available to expand heat networks. The target is to double the percentage of power generated by CHP to 25% by 2020.

Mexico has established a policy to increase the efficiency of its powers plants and in this manner, reduce CO_2 emissions. This policy has led to the construction of supercritical coal-fired power plants, the first of which will begin operation in 2010. In addition, Mexico has decided to diversify its primary sources of energy for power generation, which, to date, have been primarily oil (until the early 2000s) and gas (in the most recent years). Future plans include the construction of additional high-efficiency coal-fired power plants.

Multilateral and Bilateral Cooperation

Multilateral and bilateral cooperation help to facilitate the information sharing that is critical to developing, improving, and advancing HELE coal technologies and practices.

India is actively involved in various bilateral cooperation efforts with countries like the United States, the European Union, Germany, and Japan to help improve the efficiency of thermal units, conduct thorough baseline studies, and build O&M personnel capacity. For example, India and Germany have been working together since 2006 through the German Agency for Technical Cooperation (GTZ), the Bureau of Energy Efficiency (India), and the Indian Ministry of Power to create a CO_2 Baseline Database for the Indian Power Sector under the Indo-German Energy Programme.

Asia-Pacific Partnership (APP)
Power Transmission and Generation Task Force (PG&T TF)

APP's PG&T TF maintains a "Best Practices for Power Generation" project that includes peer review activities targeting the maintenance and improvement of thermal efficiencies of existing coal thermal power plants. Participation in the Asia Pacific Partnership (APP) Power Generation and Transmission (PG&T) Task Force is considered a best practice for power generation. It includes peer review activities targeting, maintaining, and improving thermal efficiency of the existing coal thermal power plants. To date, five peer reviews have been conducted in Japan, India, the United States, Australia, and Korea, to share technologies, knowledge, and skills pertaining to the operation and maintenance management of coal-based power plants. An effort to quantify CO_2 emission reduction potential by operations and management improvement for coal power generation has also been undertaken. The task force was selected as a flagship project for its demonstrated effectiveness in the reduction of CO_2.

Japan is also actively engaged in multilateral and bilateral cooperation for improving energy efficiency in the power sector. For instance, Japan actively participates in the multilateral Asia-Pacific Partnership (APP). Its bilateral initiatives include cooperation with China, India, Indonesia, and other Asian countries through policy dialogue, dispatching experts, and conducting training in areas such as legal/regulatory systems, energy management systems, and energy efficiency auditing.

The United Kingdom has participated in this type of cooperation through its Cleaner Coal Technology (CCT) Programme. Starting in the 1990s, the CCT Programme, through the former Department of Trade and Industry, supported several inward and outward missions with China and India.

Joint venture efforts between countries could contribute to the local production of HELE coal technologies and their low-cost uptake. Recent examples of such joint ventures between Japanese and Indian companies are L&T-MHI Boilers Private Ltd. / L&T Turbine Generators Private Ltd., which covers supercritical boiler and turbine technologies, and Toshiba JSW Turbines & Generator Private Ltd., covering 500–1000 MW supercritical steam turbines and generators.

3. Actions to Accelerate Development and Deployment

This plan has outlined the potential for greatly reducing GHG emissions through the use of high-efficiency, low-emissions (HELE) coal technologies. These technologies are an essential part of the portfolio of technologies and mitigation policies needed to address climate change, while simultaneously pursuing energy security and economic growth.

However, these technologies are not based on "one size fits all" solutions. Specific country and regional factors will determine the appropriate set of technologies, applications and solutions for each geographic area and country that wishes to implement effective HELE coal policy. Nonetheless, all countries seeking to catalyze progress on these technologies should consider similar categories of action. Countries can also work together to expedite their programs and develop standards that enable the wider dissemination of HELE coal technologies.

The MEF Global Partnership discussions, including the Workshop on Development and Deployment of High Efficiency and Low Emission Coal Technologies (Tokyo, 15 September), have identified many areas of common ground to promote the further development and deployment of HELE coal technologies. To achieve transformational gains in HELE coal globally, MEF countries have developed a menu of opportunities for individual and collective action. Many of these actions rely on, or can be effectively leveraged through, coordinated action among countries, including support for existing international forums on coal technologies. This chapter discusses both opportunities for individual country action as well as opportunities for cooperative action among MEF countries.

Menu of Opportunities for Individual and Collective Action

Chapter Two illustrates multiple best practices that point to specific individual and collective country actions that can help to reduce market barriers and realize the full potential of HELE coal technologies and practices. Key categories of action for consideration include the following:

- Support innovation:
  - Develop new technologies.
  - Demonstrate new technologies.
- Accelerate deployment:
  - Establish appropriate domestic and international policy environments for strengthening deployment.
  - Build deployment capacity.
- Facilitate information sharing:
  - Share best practices and knowledge.
  - Enhance public awareness.

The following section outlines a menu of actions within each category. Interested countries should consider the actions in each category to identify those that may be appropriate to their unique circumstances.

Supporting Innovation

- Identify HELE coal technologies to be prioritized for innovation, based on national circumstances.
- Formulate roadmaps for HELE coal technologies including, where appropriate, setting nationally appropriate RD&D goals.
- Enhance RD&D efforts for HELE coal technologies through public-private partnerships.
- Enhance international collaboration on RD&D of HELE coal technologies to distribute the high risks inherent to new technology development and reduce investment burdens, particularly for developing countries.

Accelerating Deployment

- Identify best available technology (BAT) options and best practices (BP) relevant to HELE coal technologies and practices.
- Consider developing a Nationally Appropriate Technology Deployment Roadmap for coal-fired power plants.
- Put in place appropriate price, financial, and regulatory incentives for the uptake of BAT and BP relevant to HELE coal technologies.
- Consider nationally appropriate policy goals related to HELE coal technologies, where appropriate.
- Cooperate with the private sector through public-private partnerships to effectively identify HELE coal technologies to be deployed and to design appropriate policies and measures.
- Learn from successful joint venture experiences related to the introduction of HELE coal technologies.
- Enhance regular national measurement and monitoring for developing clear baselines, which will establish the cost-benefit of upgrading or making improvements to a country's or a utility's coal fleet.
- Develop effective capacity building measures in such areas as operations and maintenance (O&M) for improving and maintaining the energy efficiency of a coal-fired power plant.
- Develop a technology transfer mechanism that enables effective matching among technology needs, technology owners, and financial sources. While this issue is being discussed intensively in the UNFCCC negotiations, because such technologies belong to the private sector, any mechanism to be developed needs to incorporate public-private cooperation and include an effective mechanism to match up technology users, technology owners, and diverse financial resources, including international financial mechanisms created under the UNFCCC. Developed countries should take a lead in such endeavors.

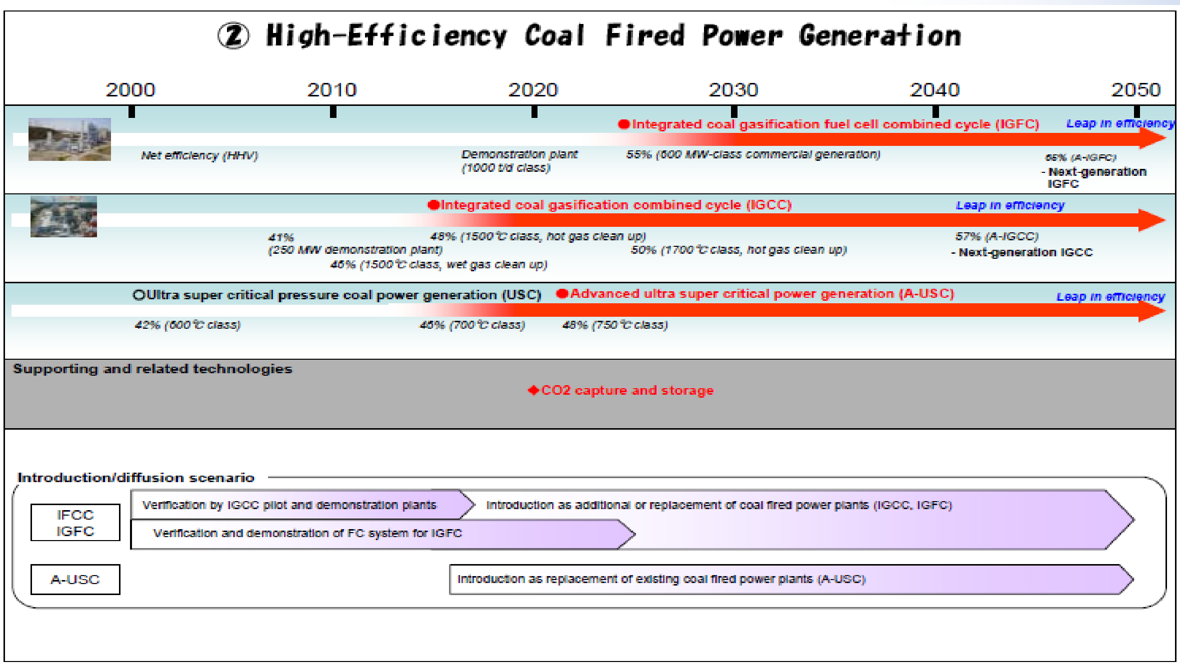
Facilitating Information Sharing

- Share information on best available technology (BAT) options and related best practices (BP)
- Identify and utilize ongoing international initiatives that collaborate on HELE coal technologies (e.g., APP and IEA).
- Develop and support a web-based repository or clearinghouse of knowledge and information for available technologies, the location of their deployment around the world, updates on new and available technologies, related work in research and technology development, pools of competence, etc.
- Develop an international initiative for creating "international technology hubs" in key sectors (e.g., the power sector) using the expertise of existing international organizations (e.g., IEA). Adoption of HELE coal technologies will be facilitated by bringing down the cost of technology in a manner that minimizes its impact on the cost of power.
- Share information with other MEF technology initiatives in the Global Partnership.

Actions by Individual Countries

To accelerate the development and deployment of HELE coal solutions, countries should consider adopting some of the actions in each of the categories outlined above as appropriate to their goals and unique national circumstances. More generally, countries may wish to start by developing a Nationally Appropriate Technology Deployment Roadmap for coal-fired power plants in the broad context of their energy and climate change policies and reflecting specific national circumstances (see Figure 8 for an example). This may include roadmaps for renovation and modernization or replacement of aged and low-efficiency coal-fired power plants

FIGURE 8. EXAMPLE OF TECHNOLOGY ROADMAP (JAPAN)



Source: Agency for Natural Resources and Energy 2008 with more advanced technologies, while keeping in view the energy availability, security, and affordability of such technologies, in particular, for developing countries. The IEA's recommendations in *Towards a Sustainable Energy Future*, which cover improving the operating efficiency of the global fleet of coal-fired power plants, provide one possible input to such consideration (see Appendix B for excerpt).

A Nationally Appropriate Technology Deployment Roadmap would ideally identify and appropriately sequence high-impact actions, including focusing national HELE coal RD&D portfolios and fostering the development of comprehensive legislative and regulatory frameworks. It is crucial that these roadmaps are backed by appropriate price, financial, and regulatory incentives. Such policy frameworks could include robust carbon prices, phasing-out of energy price subsidies, elimination of import tariffs for related goods and services, low interest or concessional loans, and/or minimum efficiency standards for new plants.

These roadmaps could also entail cooperation between the public and private sectors to effectively enhance the identification of technologies to be deployed and the design of policies and measures. Learning from successful joint venture experiences, which could contribute local production of HELE coal technologies and their low-cost uptake, is one example. This information could provide valuable inputs to governments in designing enabling price, financial, and regulatory incentives to foster private investment (among other things).

In some cases, countries may further wish to define nationally appropriate policy goals for the deployment of specific HELE coal technologies and practices. Central to attaining the objective is broad engagement with relevant stakeholders to build capacity. Certain countries may also choose to translate these goals into minimum standards for new coal-fired power plants.

In any case, countries should assess progress against their own action plan and implement course corrections as desired. At a minimum, they may want to ensure that they are establishing policies or taking other enabling actions on the schedule envisioned in their roadmap. Similarly, they may consider establishing a matrix of projects, product announcements, and similar actions, categorized by solution type, to ensure they are addressing the full range of promising technologies.

To establish the costs and benefits of upgrading or making improvements to a country's or a utility's coal fleet, a clear efficiency baseline is important. To this end, countries should have more regular national measurement and monitoring.

Coordinated or Cooperative Actions

Beyond the individual efforts described above, countries should consider the vital role of international coordination and cooperation for the deployment of HELE coal technologies and practices. As MEF countries currently take the lead on developing and deploying many low-carbon technologies, HELE coal among them, the Global Partnership can play an active role in overcoming common barriers faced by all countries to accelerate their development and deployment. Global Partnership initiatives would not replace ongoing work in existing forums, but rather enhance cooperation globally.

Individual countries may lack the resources needed to develop the legal, regulatory, and technical capacity to deploy, operate, and maintain HELE coal technologies. Hence, for effective deployment and dissemination of HELE coal technologies, best available technology options and best practices need to be identified and shared internationally. While the actual choice among identified BAT and BP will be affected by specific national circumstances, such information sharing is crucial. Developing an international initiative for creating "international technology hubs" in key sectors (e.g., the power sector) using the expertise of existing international organizations (e.g., IEA) warrants consideration.

In addition, MEF countries should consider creating a web-based knowledge repository to catalogue information such as available technologies, the places of their deployment around the world, updates on new and available technologies, the status of technology R&D, and pools of competence. Once created, such a knowledge repository could be a valuable resource for the world community. The repository could enable more efficient and effective technology absorption and open the pathway for much more collaborative RD&D than is currently taking place.

Since best practices are continually improved, effective capacity building measures are crucial for widely sharing their benefits. For example, given the important role of O&M in improving and maintaining the energy efficiency of a coal-fired power plant, training and knowledge-sharing at the plant level is essential. Since O&M skills and knowledge often belong to private companies, such capacity building could be accelerated through public-private partnerships, with the Asia Pacific Partnership (APP) providing one successful example.

An effective technology transfer mechanism needs to be set up to promote international dissemination of clean and efficient technologies, including HELE coal technologies. While this issue is being discussed intensively in the UNFCCC negotiations, because such technologies belong to the private sector, any mechanism to be developed needs to incorporate public/private cooperation and entail an effective matching mechanism between technology users, owners, and diverse financial resources, including international financial mechanisms created under the UNFCCC. Developed countries should take a lead in such endeavors. Streamlining the Clean Development Mechanism (CDM) process should also be explored to facilitate technology transfer while ensuring environmental integrity.

Currently, there is almost no internationally agreed upon mechanism or framework to confirm or promote the progress of technology development that each country or region has achieved. Formulating and internationally sharing technology roadmaps will lead to solid progress of technology development by confirming the status and progress of such efforts in each country or region, and help to secure investments through international cooperation to accomplish the goal. It is also beneficial to take a comprehensive and panoramic view of various technology development efforts being carried out in each country and region, which will facilitate identification and accelerate the progress of specific technological areas to be addressed under international collaboration. The IEA's work on international roadmaps is among a number of good starting points for this effort.

A major advantage of cooperative RD&D efforts is the distribution of the high risks associated with new technology development that require long-term investments that one country alone, particularly a developing country, could not meet. Enhancing this cooperation, through existing or new forums, could accelerate RD&D by using technology seeds and human resources that one country cannot sufficiently provide and could improve the efficiency of R&D by rapidly distributing leading-edge technical trends and findings to other countries through strong information exchange. Cooperative RD&D could also allow for the smooth market introduction of outcomes by the promotion of international standardization. In this regard, developed countries should take the lead in such international collaborative RD&D efforts.

In general, the instances where researchers from several countries gather at one or several sites to collectively conduct RD&D are limited to undertakings that need large funding, such as the ITER fusion research collaboration. More often, international RD&D efforts to which funding and resources are assigned simply have the participants gather the R&D outcomes from each nation. Thus, information exchange must be facilitated at a wide range of stages of RD&D (e.g., through the Implementing Agreements of the IEA). Given that, it may be appropriate to build upon existing international partnerships, such as the APP and the IEA Implementing Agreements, to enhance information exchange and explore new areas for cooperation based on the technology status and needs of both developed and developing countries.

MEF countries take the lead on many kinds of low-carbon technologies under the MEF technology initiatives of the Global Partnership. Some technologies are closely related to other technologies (e.g., CCUS, which may be considered, if nationally appropriate, a HELE coal technology, or wind energy, solar energy, or smart grid). Best practices and experiences from other MEF technology initiatives could be shared. Information sharing among MEF technology initiatives could be beneficial for further technology RD&D.

Appendix A. Key HELE Coal Technologies

Technologies for Improving the Efficiency of Existing Power Plants

Renovation and Modernization Technologies for Existing Power Stations

Many older coal-fired power plants do not perform to their design efficiency level. Innovative renovation and modernization (R&M) techniques can not only revive the plants to their design efficiency levels, but also improve them to higher levels and, thereby, reduce CO_2 intensity. This can be achieved by retrofitting efficient plant components in a short time, ensuring plant availability. In boilers, the economizers are good candidates for retrofitting. Economizers are heat exchange devices that heat fluids (usually water) up to, but not typically beyond, its boiling point. Economizers use the exhaust gases from the boiler to preheat the cold water used to fill it (i.e., the feed water). Economizers are so named because they can make use of the otherwise wasted energy in flue gas exhaust, which is hot but not hot enough to raise high-temperature steam. This heat recovery improves boiler and overall plant efficiency. Another example of a modernization technology for existing plants is the air pre-heater. An air pre-heater uses the heat in flue gas from the boiler to heat the required combustion air before it enters the boiler, thus improving efficiency. In addition, new boilers with more efficient designs can be retrofitted to existing power plants.

Waste Heat Recovery from Power Plants

In conventional power plants, more than 60% of the heat produced by the combustion process is not converted to useful energy, which is the main reason for the low efficiency of those thermal power plants. Even a slight reduction in this waste heat or increase in its use for other purposes can have a major impact on improving the power plant's efficiency and reducing its CO_2 intensity. Therefore, technologies that use waste heat should also be considered for deployment. One example of such a technology is cogeneration (also known as "combined heat and power" or CHP), which is the simultaneous generation of both electricity and useful heat. CHP has efficiencies of up to 90%. Conventional power plants emit the heat created during combustion into the environment through cooling towers, flue gas, or other means. CHP captures much of this heat for domestic or industrial heating purposes, either very close to the plant, or—especially in Scandinavian countries and Eastern Europe—as hot water for heating. This heat may also be used for coal-drying, which further closes the energy loop, yielding increased net heat (Btu) value of the coal, improved boiler efficiency, and reduced air emissions. Early results of a U.S. DOE project underway at Great River Energy's Coal Creek Station in Underwood, North Dakota, are showing an estimated increase in efficiency of about 5%, reductions of sulfur dioxide emissions by 25%, and reductions of nitrogen oxide and mercury emissions by 7% (Great River Energy 2005).

Higher-Efficiency New Power Plant Technologies

Supercritical and Ultra-Supercritical Technologies

According to the IEA, 85% of the global installed power generation capacity is "subcritical power plants," which have lower thermal efficiency, around 35% to 36% (IEA 2007b). On the other hand, supercritical (SC) and ultra-supercritical (USC) technologies have higher operational efficiency compared to most widely adopted subcritical power plants, and thus have lower fuel consumption and CO_2 emissions. Current state-of-the-art supercritical steam power generation plants operate at up to 4350 psi (~300 atm) and 1100°F (~600ºC), with net efficiencies (firing coal) of around 45%, depending on coal type and plant location. USC power plants have the potential for even higher efficiencies (approaching 50%). Much work has been carried out over the last 20 years to develop new steels for these plants, both for the boiler and the steam turbine. A number of new steels are currently being tested, which could allow steam temperatures up to 1200ºF (~650ºC) for USC power plants–these steels are among the technologies that can improve power generation efficiency by increasing the steam temperature and pressure of pulverized coal-fired power generation. SC and USC power plants can make a major contribution toward mitigating CO_2 emissions from the power sector. They are suitable for new builds and the possibility of retrofitting them may be explored for pulverized coal-fired power plants, because they have a system structure and operability similar to that of most existing plants.

Integrated Coal Gasification Combined Cycle (IGCC)

Integrated gasification combined cycle (IGCC) is a technology that turns coal into a synthetic gas (syngas). Impurities are removed from the syngas before it is combusted, resulting in lower emissions of sulfur dioxide, particulates, and mercury. The primary combustion exhaust is then passed to a heat recovery steam boiler to recover the heat in a steam cycle. This process results in improved efficiency compared to conventional pulverized coal-fired power generation technologies.

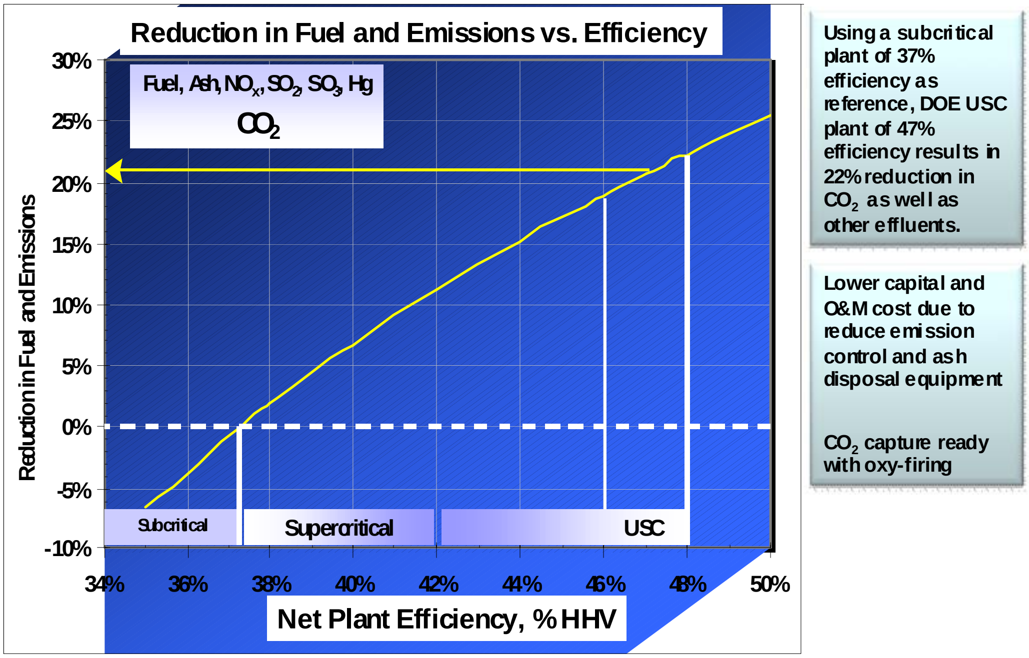
IGCC is currently being pursued in several locations around the world, although it has yet to be fully developed and commercialized for various coals, including high ash coals. In addition to its potential to significantly raise the efficiency of coal-fired power plants, IGCC also provides opportunities for poly-generation. It offers the prospect of using the syngas for chemicals and transportation fuels and a comparatively easier way to separate CO_2, which is emitted as a concentrated gas stream at high pressure—in this form, it can be captured and sequestered more easily and at lower costs. By contrast, when coal burns in air (79% of which is nitrogen), in a conventional power plant, the resulting CO_2 is dilute (~12%) and thus more costly to separate.

With efficiencies currently approaching 50%, IGCC power plants use less coal and produce much lower emissions of CO_2 than conventional power plants.

Advanced Ultra-Supercritical Technology

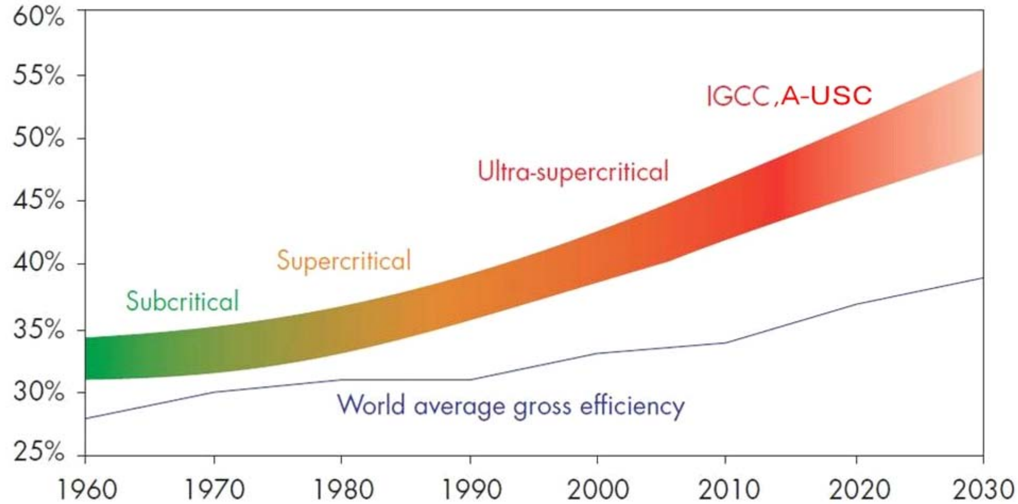
Advanced Ultra-Super Critical (A-USC) technology has an even higher thermal efficiency than that of USC. This technology has not yet been commercially available yet but is predicted to be introduced in the middle of the next decade. Steam temperatures of 1400°F (760°C) and 5,000 psi (340 atm) can reduce CO_2 emissions by over 20% compared to the current fleet average (Figure 9). There is a clear and urgent need to identify, evaluate, and qualify the materials needed to build the extreme high-temperature steam boilers to operate in these advanced steam regions. Such developments are currently ongoing in the United States, through the U.S. Department of Energy, and in Europe, through the European Commission's Thermie Project, which is exploring the economic viability of such plants. Through projects such as these, candidate alloys applicable to various temperature ranges have been identified and stress rupture tests have been completed on the base metals and on welds for a number of alloys. Steamside oxidation tests have also been completed, and fireside corrosion tests have been conducted under conditions simulating those of waterwalls and superheater/reheater tubes; the weldability and fabricability of the alloys have also been examined. The successes of these developments hold the promise of maintaining coal-based electric generation as a cost-competitive, environmentally acceptable option.

FIGURE 9. "ADVANCED" ULTRA SUPERCRITICAL POWER PLAN OPERATING UP TO 5,000 PSI AND 1,400°F



Source: EPRI 2008 (modified)

FIGURE 10. THERMAL EFFICIENCY OF COAL-FIRED POWER GENERATION



Note: The multi-colored line shows efficiencies for state-of-art plants on a net electrical output, lowering heating value basis.

Note: "A-USC" to the figure by the authors.

Source: IEA 2007b

Development and Deployment of Other Innovative High-Efficiency Cycles (e.g., Ammonia and Organic Rankine Cycle)

A Rankine-cycle engine that contains a binary working fluid (ammonia + water) and a recuperative heat exchanger is an example of an advanced high-efficiency cycle. This approach would allow additional power generation from the exhaust heat of a gas turbine, such as in an IGCC plant. The binary-fluid Rankine cycle has a higher efficiency and smaller volume than Rankine cycles with single-component working fluids.

The Organic Rankine Cycle (ORC) is named for an organic, high-molecular mass fluid with a liquid-vapor phase change, or boiling point, occurring at a lower temperature than the water-steam phase change. The fluid allows Rankine cycle heat recovery from lower temperature sources, such as flue gas from a coal-fired power plant. The low-temperature heat is converted into useful work to generate electricity, thus improving the overall plant efficiency.

Appendix B. IEA Policy Recommendations for Coal-Fired Power Plants

Excerpt from *Towards a Sustainable Energy Future* (IEA 2008)

"To improve the operating efficiency of the global fleet of coal-fired power plants—and thereby significantly reduce CO_2 emissions—it is recommended that governments focus on the following policy approaches.

- Ensure that all newly built coal-fired units are state-of-the-art supercritical or ultra-supercritical units with efficiency of no less than 40%, depending on coal quality, site conditions and grid capacity. Consideration should also be given to Integrated Gasification Combined Cycle (IGCC) plants as these become more commercially available. Developers should consider what might be required for retrofit with CCS, avoiding steps that might make this unnecessarily difficult.
- Ensure that all coal-fired units of below 300 MW capacity using subcritical technology and aged 25 years be gradually replaced by larger units, preferably using supercritical or ultra-supercritical technology. When applying these criteria, the performance records of the units and the country-specific power supply/demand situation should be taken into account. In choosing technologies, both pulverized-fuel (pf) fired and circulating fluidized bed (CFB) units should be considered, depending on coal quality, site conditions and grid capacity. Consideration should also be given to IGCC plants as these become more commercially available. Governments should consider urgent action to ensure substantial progress by 2015, and complete replacement by 2020.
- Consider assessing for upgrading or replacement—preferably to 40%-efficiency—all subcritical units even less than 25 years old which have efficiencies of under 30%, subject to appropriate country-specific techno-economic assessment, including CCS readiness.
- Foster international co-operation to diffuse advanced technologies in developing countries to replace or upgrade older units, as recommended in the two preceding paragraphs. This co-operation should also be extended to the adoption of best practice in power plant operation and should involve international financial institutions.
- Together with utility owners in national jurisdictions, address the financial gaps and incentives needed for the replacement or upgrading of older units, as identified above. Full use should be made of existing methodologies for high-efficiency coal-fired plants under the Clean Development Mechanism (CDM) and support should be given to the development of new CDM methodologies for the retrofit of existing plants and for CCS." (IEA 2008b)

REFERENCES

Agency for Natural Resources and Energy 2008. Agency for Natural Resources and Energy. *Establishment of the Cool Earth Energy Innovative Technology Plan*: *Technology Development Roadmap*. Tokyo, Japan: Ministry of Economy, Trade, and Industry. http://www.meti.go.jp/english/newtopics/data/pdf/CE_RoadMap.pdf (accessed November 2009).

Bhattacharya 2008. Bhattacharya, S. *IEA Activities in Cleaner Fossil Fuels.* Presentation at IEA Day COP14 in Poznan, Poland (December 9, 2008). http://www.iea.org/speech/2008/sb_poznan.pdf (accessed December 2009).

BP 2009. BP plc. *Statistical Review of World Energy 2009.* London, United Kingdom: BP plc (June 2009). http://www.bp.com/productlanding.do?categoryId=6929&contentId=7044622 (accessed December 2009).

EPRI 2008. Electric Power Research Institute (EPRI). *Advanced Coal Power Systems with CO_2 Capture: EPRI's Coal Fleet for Tomorrow Vision.* Interim Report 1016877. Palo Alto, California, United States: EPRI.

Federation of Electric Power Companies 2009. Federation of Electric Power Companies. *Possible MRVable Indicators for Power Sector*. Bonn, Germany: Workshop on Mitigation Potentials, Comparability of Efforts and Sectoral Approaches (March 24–25, 2009). http://ec.europa.eu/environment/climat/pdf/bonn09/fepc.pdf (accessed December 2009).

Graus 2007. Graus, W. *International Comparison of Fossil Power Efficiency*. Utrecht, The Netherlands: ECOFYS (August 2007). http://www.ecofys.com/com/publications/documents/Ecofys-Comparisonfossilpowerefficiency_August2007.pdf (accessed December 2009).

Great River Energy 2005. Great River Energy. Great River Energy Selects Headwaters Incorporated to Market Coal Drying Technology. News release (March 14, 2005). Underwood, North Dakota, United States. http://www.greatriverenergy.com/press/news/archive/031505_headwaters_coal_dry.html (accessed December 2009).

IEA 2006. International Energy Agency (IEA). *Focus on Clean Coal*. Paris, France: Organisation for Economic Cooperation and Development (OECD)/IEA. http://www.iea.org/work/2006/gb/papers/focus_on_coal.pdf (accessed December 2009).

IEA 2007a. International Energy Agency (IEA). *CO_2 Emissions from Fuel Combustion 2007*. Paris, France: Organisation for Economic Cooperation and Development (OECD)/IEA.

IEA 2007b. International Energy Agency (IEA). *World Energy Outlook 2007.* Paris, France: Organisation for Economic Cooperation and Development (OECD)/IEA. http://www.iea.org/textbase/nppdf/free/2007/weo_2007.pdf (accessed December 2009).

IEA 2008a. International Energy Agency (IEA). *Energy Technology Perspectives 2008: Scenarios and Strategies to 2050.* Paris, France: Organisation for Economic Cooperation and Development (OECD)/IEA.

IEA 2008b. International Energy Agency (IEA). *Towards a Sustainable Energy Future*. Paris, France: Organisation for Economic Cooperation and Development (OECD)/IEA.

IEA 2008c. International Energy Agency (IEA). *World Energy Outlook 2008.* Paris, France: Organisation for Economic Cooperation and Development (OECD)/IEA. http://www.worldenergyoutlook.org/2008.asp (accessed November 2009).

IEA 2008d. International Energy Agency (IEA). *Worldwide Trends in Energy Use and Efficiency*. Paris, France: Organisation for Economic Cooperation and Development (OECD)/IEA.

IEA 2009a. International Energy Agency (IEA). The time has come to make the hard choices needed to combat climate change and enhance energy security, says the latest IEA World Energy Outlook. News release (November 10, 2009). Paris, France: Organisation for Economic Cooperation and Development (OECD)/IEA. http://www.iea.org/press/pressdetail.asp?PRESS_REL_ID=294 (accessed December 2009).

IEA 2009b. International Energy Agency (IEA). *World Energy Outlook 2009: Fact Sheet*. Paris, France: Organisation for Economic Cooperation and Development (OECD)/IEA. http://www.worldenergyoutlook.org/docs/weo2009/fact_sheets_WEO_2009.pdf (accessed December 2009).

IEA Clean Coal Centre et al. 2008. IEA Clean Coal Centre, China Electricity Council, and Ministry of Power, India. *Share of Supercritical Plants in Coal-Fired Power Generation*. Cited in Burnard, K. *Clean coal and CCS at the IEA*. Beijing, China: ETTiC Workshop (June 13–14, 2009). http://www.iea.org/work/2009/ett_beijing/burnard.pdf (accessed December 2009).

UNFCCC 2007. United Nations Framework Convention on Climate Change (UNFCCC). *Investment and Financial Flows to Address Climate Change*. Bonn, Germany: Climate Change Secretariat (UNFCCC). http://unfccc.int/files/cooperation_and_support/financial_mechanism/application/pdf/background_paper.pdf (accessed December 2009).

WEC 1995. World Energy Council (WEC). *Global Energy Perspectives to 2050 and Beyond.* London, United Kingdom: World Energy Council.

WEC 2007a. World Energy Council (WEC). *Carbon Capture and Storage: a WEC "Interim Balance."* London, United Kingdom: World Energy Council. http://www.usea.org/programs/CFFS/FINAL_CCS_Brochure_English.pdf (accessed December 2009).

WEC 2007b. World Energy Council (WEC). *2007 Survey of Energy Resources*. London, United Kingdom: World Energy Council. http://www.worldenergy.org/documents/ser2007_final_online_version_1.pdf (accessed December 2009).

Workshop on Development and Deployment of High-Efficiency and Low-Emission Coal Technologies (Tokyo, 15 September 2009).