Prospects for Cleaner and More Efficient Coal Production and Utilization Technologies in North-East Asia

Shaping the Future of Sustainable Energy in Asia and the Pacific
The Economic and Social Commission for Asia and Pacific (ESCAP) is the regional development arm of the United Nations committed to providing a multilateral platform to its 53 member States and 9 associate members. ESCAP promotes regional cooperation to achieve inclusive and sustainable economic and social development.

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Executive Summary

Coal has been the fastest growing energy fuel since the beginning of the XXI century, and currently it accounts for around 30% of the primary energy consumed worldwide. The analysis of coal’s role in the global energy context would be incomplete without considering the context and realities of countries in North-East Asia (NEA), a sub-region consisting of China, the Democratic People’s Republic of Korea, Japan, Mongolia, the Republic of Korea and the Russian Federation.

Although encompassing “just” six countries, NEA is a vast territory covering a diversified population of 1.7 billion and a GDP that equates to 24% of the world’s total. In full tandem with the demographic and economic dimensions of the sub-region, one third of the world’s primary energy is consumed in NEA. With respect to the importance of coal in the energy mix, the picture is fairly different, with NEA countries consuming 58% of the coal produced worldwide. Given the massive demand for energy and the availability of large and affordable coal resources, it is reasonable to expect coal to continue to be as a major source of primary energy in the years to come in the sub-region.

A heavy dependence on coal has significant environmental and social costs, which include the depletion of natural resources, severe impacts on air quality, and the emission of greenhouse gases. These damaging impacts on the environment and the society have spurred the need for a more sustainable and balanced development of the coal sector. To a large extent, the development and diffusion of technologies that process coal in more efficient and less damaging ways is key to bringing countries worldwide, and those of NEA in particular, into a more sustainable pathway.

Set against this backdrop, this study aims at assessing the current status of coal technologies in NEA, with a focus on “cleaner coal”, and attempts to identify priority areas and opportunities for sub-regional cooperation on these technologies. By “international cooperation” it is meant the scope for different levels of public policy intervention, which include, among others, state-led cooperation on R&D activities and academic exchanges, the formulation of common strategies on a bilateral or multilateral basis on coal technology development, and intergovernmental cooperation on capacity building and knowledge sharing activities.

This study is primarily based on inputs provided by experts from NEA countries, and it covers a set of different areas related to the production and utilization of coal, which consist of the following: efficiency-enhancing coal technologies; coalbed methane recovery and utilization; coal gasification; coal liquefaction; and carbon capture and storage.

The assessment revealed that most countries in NEA have placed a relatively high priority to the development of cleaner and more efficient coal technologies, from the upstream to the downstream of the coal value chain. Different levels of technology development and adoption are observed in NEA countries as a whole. For example, the development of supercritical and ultra-supercritical coal combustion technologies, which in NEA has been driven by countries such as China, Japan and ROK, seems to be on par with international standards. On the other hand and also as an example, the uptake of coal drying or coalbed methane utilization technologies seems to be somewhat lagging behind developments elsewhere.

The analysis also concluded that cooperation among NEA countries on many coal technologies already exists on an inter-firm and commercial basis. On the other hand, at the R&D and demonstration stages, cooperation among NEA countries appear to be fairly limited, the same
applying to capacity building and knowledge sharing activities among these countries. Finally, at policy and regulatory level – such as the harmonization of standards or the development of common visions or strategies among countries – no joint initiatives were identified.

For each of the technology areas examined, the study came up with the following suggestions of priority areas for international cooperation among NEA countries:

### Short to Mid-Term Priorities and Recommendations

#### Advanced Coal Combustion Technologies:
- NEA countries should continue their policies of accelerating the deployment of advanced coal-fired power generation technologies by creating the necessary enabling framework, either in terms of policies, targets, regulations or a combination of these.
- NEA countries should support – or continue supporting – emerging advanced-coal combustion technologies, such as advanced-USC pulverized coal combustion, the deployment of larger CFB boilers (so as to achieve the economies of scale of the largest commercially available pulverized coal combustion boilers), and the full-demonstration of SC and USC steam conditions applied to fluidized bed combustion boilers.
- International cooperation among NEA countries could be instrumental in introducing cleaner, low-emissions and more efficient coal combustion technologies in Mongolia and DPRK, where older, more polluting and less efficient power plants continue in operation.

#### Coal Beneficiation Technologies:
- NEA countries should continue and further increase their support to accelerate the deployment of coal upgrading technologies, particularly in overcoming some of the barriers that hinder their dissemination, such as the creation of pricing mechanisms that reflect the improved quality of upgraded coal.
- International cooperation among NEA on these technologies has the potential to be further enhanced, particularly in the formulation of harmonized quality requirements for imported coal and in exploring possibilities for joint R&D and demonstration programmes. Priority areas for sub-regional cooperation are on less water intensive processes and dry separation technologies, where the know-how of countries such as Japan could be explored on commercial applications.

#### Coal Mine Methane Recovery and Utilization Technologies:
- Policymakers of NEA countries with active coal mining activities should ensure that the necessary policies, regulations and frameworks are in place to spur the deployment of the most up-to-date technologies and best practices for the recovery of CMM so as to ensure, first and above all, the safety of mining operations.
- Opportunities for cooperation among NEA countries on CMM recovery and utilization technologies and methods include the sharing of best practices on coal mining safety, CMM technology needs and technology matching assessments, and support in the design of policies and regulations.
- NEA countries could explore synergies and opportunities for cooperation on technologies that make it possible to derive economic value from low-quality CMM gas and ventilation air methane, particularly by incentivizing national R&D institutions to develop such programmes.
Short to Mid-Term Priorities and Recommendations

Coal Liquefaction Technologies:

- There is a clear scope for the utilization of CTL technologies, including those developed by organizations in China, in projects and/or initiatives in the sub-region, particularly in Mongolia and the Russian Federation, as these are the NEA countries endowed with domestic coal resources and CTL could be a means to derive a higher economic value from those resources, in particular those that are considered “stranded”.

- While CTL technologies can play an important role in enhancing energy security in the sub-region, NEA countries should ensure that the development and deployment of these technologies is based on sound technical and environmental requirements, in particular with respect to water utilization and the emission of CO₂. NEA countries could work together towards the definition of such standards or requirements.

- The market for some liquids that can be produced from coal is still incipient – if existent at all – in most countries in the sub-region. As such, policymakers of NEA countries could play an important role in the creation of those markets in articulation with each other, whereby “win-win” situations would be created by matching the supply and demand for these products.

Integrated Gasification Combined Cycle (IGCC):

- IGCC is emerging as a viable coal-conversion technology for power generation, and its deployment should be encouraged by governments of NEA countries until the technology is fully proven on a commercial basis.

- NEA countries could explore the potential for the harmonization and coordination of the different initiatives on IGCC development that are observed in the sub-region, for example through information sharing activities and the use of common methodologies.
Mid to Long-Term Priorities and Recommendations

**Carbon Capture and Storage Technologies:**
- NEA countries that are most active on CCS technologies, i.e. China, Japan and ROK, could further harmonize their R&D efforts and explore opportunities for the development of joint demonstration projects.
- NEA countries could synergize efforts in the definition of a common policy and regulatory framework for CCS development, a critical aspect for the uptake of these technologies both at national and sub-regional levels. NEA countries could also introduce requirements for the introduction of the CCS-Ready concept, in order to avoid the “lock-in” of building power-generation facilities that are unable to be retrofitted with CCS in the future.
- NEA countries could develop a vision for an integrated CO₂ transport, utilization and storage infrastructure in the sub-region, which could be developed in parallel and/or in complement to comparable regional initiatives, such as the Asian Energy Highway. Such vision could be initiated by China, Japan and the Republic of Korea due to their geographical proximity and strong interest in CCS, and possibly expanded to include other NEA countries.

**Coal Gasifier Technologies:**
- It is recommended that countries such as China, Mongolia and ROK pursue and/or continue their policies of encouraging the deployment of gasification technologies from overseas’ providers, through inward technology transfer, while building-up the know-how of national companies and organizations on these technologies.
- There is potential for exploring the competitive advantages of nationally-designed coal gasifiers of China and the Russian Federation, specifically in what concerns their cost-effectiveness vis-à-vis other commercially available models. The characteristics of Chinese and Russian models could be of interest, in particular, to DPRK and Mongolia, which have limited know-how and experience on coal gasification technologies.

**Underground Coal Gasification Technologies:**
- Government support can be instrumental in accelerating the commercial viability of UCG technologies, not only on the R&D and pre-commercial stages, but also in addressing existing gaps in legislation and regulation, such as in the definition of environmental criteria for UCG development and guidelines for site-selection. These opportunities could be explored in articulation among NEA countries, particularly the Russian Federation, China and Mongolia.

**Coal Drying Technologies:**
- NEA countries seem to be somewhat lagging in the adoption of coal drying technologies, and given their importance in deriving higher value from low-rank coals, which are abundant in countries of the sub-region, it is recommended that this can be an area of increased attention, whereupon opportunities for government induced R&D could be explored.
<table>
<thead>
<tr>
<th>Abbreviation</th>
<th>Description</th>
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<tbody>
<tr>
<td>ADMFB</td>
<td>Air-based dense medium fluidized bed separation</td>
</tr>
<tr>
<td>CCS</td>
<td>Carbon Capture and Storage</td>
</tr>
<tr>
<td>CBM</td>
<td>Coalbed Methane</td>
</tr>
<tr>
<td>CFB</td>
<td>Circulating Fluidized Bed</td>
</tr>
<tr>
<td>CFBC</td>
<td>Circulating Fluidized Bed Combustion</td>
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<tr>
<td>CHP</td>
<td>Combined Heat and Power</td>
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<tr>
<td>CLC</td>
<td>Chemical Looping Combustion</td>
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<tr>
<td>CMM</td>
<td>Coal Mine Methane</td>
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<tr>
<td>CO₂</td>
<td>Carbon Dioxide</td>
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<tr>
<td>CTL</td>
<td>Coal-to-Liquids</td>
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<tr>
<td>CRIP</td>
<td>Controlled Retractable Injection Point</td>
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<tr>
<td>DME</td>
<td>Dimethylether</td>
</tr>
<tr>
<td>DPRK</td>
<td>Democratic People’s Republic of Korea</td>
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<tr>
<td>ECNEA</td>
<td>Energy Cooperation in North-East Asia</td>
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<tr>
<td>EOR</td>
<td>Enhanced Oil Recovery</td>
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<tr>
<td>ESCAP</td>
<td>United Nations Economic and Social Commission for Asia and the Pacific</td>
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<tr>
<td>EU</td>
<td>European Union</td>
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<tr>
<td>F-T</td>
<td>Fischer-Tropsch</td>
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<tr>
<td>FBC</td>
<td>Fluidized bed combustion</td>
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<tr>
<td>GHG</td>
<td>Greenhouse Gas</td>
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<tr>
<td>Gt</td>
<td>Gigaton</td>
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<td>GW</td>
<td>GigaWatt</td>
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<tr>
<td>HRSG</td>
<td>Heat Recovery Steam Generator</td>
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<tr>
<td>IEA</td>
<td>International Energy Agency</td>
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<tr>
<td>IGCC</td>
<td>Integrated Gasification Combined Cycle</td>
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<tr>
<td>IGFC</td>
<td>Integrated Gasification Fuel Cell</td>
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<tr>
<td>IP</td>
<td>Intellectual Property</td>
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<tr>
<td>JCOAL</td>
<td>Japan Coal Energy Center</td>
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<tr>
<td>JI</td>
<td>Joint Implementation</td>
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<td>JV</td>
<td>Joint Venture</td>
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</table>
KIER  Korea Institute of Energy Research
LHV   Low-heating value
LPG   Liquefied petroleum gas
METI  Ministry of Economy Trade and Industry of Japan
MPa   MegaPascal
Mtoe  Million ton of oil equivalent
MW    MegaWatt
MWh   MegaWatt hour
NEA   North-East Asia
NDRC  National Development and Reform Commission of China
NEDO  New Energy Development Organization of Japan
NOx   Nitrogen Oxides
OECD  Organization for Economic Cooperation and Development
PC    Pulverized Coal
RMB   Renminbi
ROK   Republic of Korea
ROM   Run-of-mine
R&D   Research and Development
SC    Supercritical
SO2   Sulphur Dioxide
SOx   Sulphur Oxides
SOC   Senior Officials Committee for Energy Cooperation in North-East Asia
SOE   State-owned enterprise
t    ton
UGC   Underground Coal Gasification
USA   United States of America
USC   Ultra-supercritical
USSR  Union of Soviet Socialist Republics
VAM   Ventilation Air Methane
WG-Coal Working-Group on Coal
INTRODUCTION
1.1 Background and Context

More than 250 years passed over the onset of the Industrial Revolution, coal continues to be an abundant, well-distributed and relatively cheap energy resource. In 2012, coal accounted for 30% of primary energy consumption worldwide, and it was the fastest growing fossil fuel consumed on that year (BP, 2013). 2012 is a linchpin of recent trends, with coal meeting close to half of the increase in global energy use in the first decade of the present century (Burnard and Bhattacharya, 2011; IEA, 2012a). Despite the exponential growth of new and renewable energy technologies, the importance of coal in the world energy sector does not seem to be dwindling. On the contrary, virtually every major study analyzing energy supply and demand trends indicates that coal will remain a dominant fuel in the foreseeable future, as for instance can be observed in the “Current Policies” and “New Policies” scenarios of IEA’s World Energy Outlook (IEA, 2013d).

Any analysis on the subject of coal would be incomplete without considering the context and realities of North-East Asia, a sub-region consisting of China, the Democratic People’s Republic of Korea (DPRK), Japan, Mongolia, the Republic of Korea and the Russian Federation. In spite of comprising “just” six countries, North-East Asia is a vast territory straddling from the Western Siberian steppes to the Pearl River delta, covering a diversified population of 1.7 billion people, or 24% of the world’s total (World Bank, 2013a).

In 2012, North-East Asia accounted for 24% the world’s GDP (World Bank, 2013b), which is mainly attributed to two major economies in the sub-region, China and Japan. In full tandem with the dynamism of its economies, North-East Asia consumed around one third of the world energy on the same year (BP, 2013). With these six countries taken as a whole, coal accounted for more than 50% of the primary energy consumed. The demand for coal in the sub-region is, chiefly among all, driven by China, where coal is the cheapest and one of the few domestic fuels widely available. DPRK, Mongolia and the Russian Federation are also endowed with vast deposits of coal, although the consumption of this resource is, in absolute terms, considerably smaller than China’s. The realities of Japan and the Republic of Korea are of a different sort: both countries are heavily energy dependent, and the import of primary energy, particularly coal, has been necessary to keep up with the growth in primary energy demand. In Japan, the share of coal in the country’s energy mix is likely to increase in the foreseeable future, most in particular in the much-discussed scenario of nuclear energy being totally phased-out and if alternative fuels and measures, including natural gas and/or energy conservation, are unable to meet supply gaps.

Taking into account the availability of large and affordable coal resources and the massive demand for energy in countries in North-East Asia, it is reasonable to expect coal to continue as a major source of primary energy in the years to come in the sub-region. In full recognition of the relevance of coal in the sub-regional context, the Senior Officials Committee (SOC) of the Intergovernmental Collaborative Mechanism on Energy Cooperation in North-East Asia, established the Working Group on Coal (WG-Coal) in 2009 (please check Box 1.1 below).
Introduction

Box 1.1 – The Intergovernmental Collaborative Mechanism on Energy Cooperation in North-East Asia

Acknowledging the needs, mutual benefits and challenges in promoting energy cooperation in North-East Asia, in November 2005 the Senior Officials of four countries in North-East Asia, namely, the Democratic People’s Republic of Korea, Mongolia, the Republic of Korea, and the Russian Federation, created by consensus the Intergovernmental Collaborative Mechanism on Energy Cooperation in North-East Asia.

The Collaborative Mechanism is guided by the following vision: “By 2020, improved energy security in North-East Asia through energy cooperation in a sustainable manner”. The Mechanism aims to achieve a threefold objective: i) to increase the supply of energy in North-East Asia while lessening its dependence on energy imports from outside the sub-region; ii) to optimize the economy and efficiency of supply and use of energy; and iii) to minimize the environmental impacts of energy production and consumption through an improved energy mix and greater energy efficiency. The Collaborative Mechanism is currently implementing a Five-Year Strategy (2010-2014) in order to promote its vision and accomplish its objectives.

Since its establishment, the Collaborative Mechanism has attained some recognition as an important initiative to foster energy cooperation in North-East Asia. To date, the Collaborative Mechanism has provided information and recommendations to policymakers, conducted studies on energy issues considered relevant to the scope of work of the Mechanism, strengthened the collaboration among research institutions of countries in the sub-region, and involved energy industry representatives and experts on policy dialogues.

The participating countries to the Mechanism established a Senior Officials Committee for Energy Cooperation in North-East Asia (SOC), which is the leading decision-making and governing body of the collaborative framework. The role of the SOC is to define projects to be undertaken by the Mechanism, to approve their budgets and to monitor their implementation. The SOC also provides overall policy guidance to the Mechanism and establishes working groups, as required. The SOC comprises at least one senior government official in charge of regional energy cooperation from each of the participating countries. The meetings of the SOC are, in principle, held annually in one of the participating countries, on a rotating basis.

The SOC can establish, as necessary, task forces or working groups as subordinate organizations of the SOC. Currently there are two working groups operating under the Mechanism: the Working Group on Energy Planning and Policy, and the Working Group on Coal (WG-Coal). Working groups may be established on a temporary basis and may be mandated by the SOC for specific designated tasks. The SOC also defines the terms of reference and appoints the chairpersons of the working groups. The working groups shall conduct their tasks and report to the SOC. Chairpersons are appointed for periods of one year with a possibility of reappointment. The Russian Federation has been the Chair of the WG-Coal since it commenced operations in 2010.

The United Nations Economic and Social Commission for Asia and the Pacific (ESCAP), has been serving as the interim Secretariat to the Collaborative Mechanism since its inception. ESCAP supports the SOC in the preparation and facilitation of its meetings, as well as in the conduct of consultative processes related to the Mechanism’s working groups.

(Source: ESCAP, 2010)
The WG-Coal has the mandate to achieve two overarching and inter-related goals: i) to promote sub-regional cooperation in the production and utilization of coal in an environmentally sustainable manner, and ii) to facilitate the cross-border trade of coal resources, coal products and electricity in North-East Asia (ESCAP, 2010). To conduct its activities and appropriately substantiate its recommendations to the Senior Officials Committee, the WG-Coal is vested with the authority to consult with experts and commission studies on coal-related matters.

On its seventh session held in Gyeongju, Republic of Korea, in November 2011, the Senior Officials Committee approved for the 2012/2013 period the elaboration of the Second Joint Study of the WG-Coal, with the title “Prospects for cleaner and more efficient coal production and utilization technologies in North-East Asia” (ESCAP, 2011). This study is a follow-up to the First Joint Study of the WG-Coal, which was conducted under the title “Status and Challenges to the Coal Industry for Sustainable Development in North-East Asia and Identification of Opportunities for Sub-regional Cooperation in the Coal Sector” (ESI, 2011). The study, which was released in January 2011, presented the status of development of the coal sector in North-East Asian countries, including the role of coal on national economies as well as the national priorities in the development of their respective coal industries. The present study takes the cue from one of the main conclusions of the first Joint Study, which emphasized that the progress made in the production and utilization of coal in the sub-region was accompanied by serious environmental and social issues, which policymakers had not been able to timely and appropriately respond to. With reference made to these concluding remarks, one of the underlying motivations to conduct this study was to understand the role of coal technologies – with an emphasis on the so-called “cleaner coal” technologies – in responding to these challenges.

A heavy dependence on coal has significant environmental and social costs, which include the depletion of natural resources, sever impacts on air quality, and the emission of greenhouse gases. For example, Yushi et al. (2011) estimated that the external costs resulting from the exploration, extraction, transportation and utilization of coal in China were of 1.7 trillion RMB in 2007, equivalent to 7.1% of the country’s GDP on that year. These damaging impacts on the environment and the society have put in question the future of coal in the energy mix of countries around the globe, leading for example an institution such as the World Bank to limit the financing of coal-fired power plants only to “rare circumstances” (World Bank, 2013c). A more sustainable and balanced development of the coal sector can mitigate these negative externalities to a large extent, holding the potential of bringing North-East Asian countries into a cleaner and more sustainable energy path. The development and diffusion of technologies that process coal in more efficient and less-environmentally damaging ways, is therefore a key element for bringing countries of the sub-region into this track.

Set in this context, the aim of the Second Joint Study of the WG-Coal is to conduct an assessment of the current status of coal technologies in North-East Asia, with a focus on “cleaner coal”, and identifying opportunities for sub-regional cooperation among North-East Asian countries. In particular, this study: i) assesses selected coal technologies and development trends in North-East Asia; ii) analyzes opportunities for coal technologies developed in countries in North-East Asia to be deployed to other countries in the sub-region through international cooperation; and iii) provides policy recommendations for the selected technology sectors. It should be noted that this study does not strictly focus on the so-called “clean coal” or “cleaner coal” technologies, but rather on coal technologies that are relevant in the sub-regional context. Yet, and in line with the mandate of the WG-Coal, the analysis of all these technologies is made from the perspective of their sustainability, in other words, the accomplishing of “sustainable coal” with respect to its production and utilization.
Introduction

It is expected that this study can contribute to an improved knowledge to policymakers and practitioners of coal technologies available for countries in North-East Asia. The study also sheds light on organizations in the sub-region leading developments on these technologies as well as flagship projects where those have been applied, which could be regarded as good practices and as an inspiration to other countries in the sub-region. It is also expected that this study can guide policymakers on how they can enhance national energy security through sub-regional cooperation by fostering the development and deployment of sustainable coal technologies. The relevance of this study should also be seen in light of the fact, recognized by Ministers of countries in the Asia-Pacific, that energy efficiency improvements and the use of cleaner fossil fuel technologies are important means to mitigate the negative environmental impacts of fossil fuel consumption and reduce the emission of greenhouse gases in the region (ESCAP, 2013a).

An important aspect to reflect upon is on what is meant by “international cooperation” in the scope of this study. The adoption, development and dissemination of coal technologies depend on a set of different stakeholders, but chiefly among them national governments and commercial enterprises. On the one hand, governments play a key role due to their responsibility in the creation of the enabling conditions for the sector or industry, through the formulation of policies, programmes and regulations. On the other, commercial enterprises are usually the main engines of innovation and technology development, as they are endowed with resources and technical know-how that governments are generally not able to match.

As this study is prepared under the framework of an intergovernmental mechanism, its main focus with respect to opportunities for “international cooperation” on coal technologies is on the role that policymakers from NEA countries can play in fostering and harnessing these opportunities. There are different levels of public policy intervention that can be identified, and for the purpose of this study the following have been taken into account:

- State-led cooperation on government-sponsored R&D activities and academic exchanges;
- Intergovernmental cooperation on capacity building and knowledge sharing activities, which can be both unidirectional (if there is a clearly identified transferor and transferee of the knowledge that is shared) and bidirectional;
- Formulation of joint strategies and/or visions, which could be agreed at bilateral and/or multilateral level;
- Intergovernmental cooperation at policy level, through the harmonization of national policies and regulations;
- Inter-firm cooperation and technology transfer: the scope for policymaker intervention on this dimension can be limited, as it largely depends on the degree of decision-making autonomy of companies (private or state-owned) from the respective national governments. Examples of government-induced interventions that stimulate inter-firm cooperation and the inward transfer of technologies include national policies that require minimum content requirements for the utilization of overseas technologies, and/or requirements for the establishment of JVs with national partners.
This Joint Study is a first effort to conduct an assessment of the coal technology status in North-East Asia as a whole. Another unique feature of this study is the methodology applied, which follows the general practice of the two working groups operating under the framework of the Intergovernmental Mechanism on ECNEA. The WG-Coal has identified experts from each country in North-East Asia, who made an assessment on the status of the above-mentioned technologies in their respective countries. These studies have been prepared from May 2013 to May 2014, with an authors’ workshop being convened on 18-20 September 2012 in Kemerovo, Russian Federation, on the occasion of the Second Meeting of the WG-Coal. On this workshop, the authors shared the preliminary findings from their country research, and discussed possible opportunities for sub-regional cooperation and implications for policymakers with members of the WG-Coal and other experts who attended the meeting.

This Joint Study was prepared by a consultant identified by the ESCAP Secretariat, Mr. João Aleluia, and draws primarily from the findings and recommendations of the national country studies. Notwithstanding the fact these national studies were the primary source of data for preparing the Joint Study, other bibliographic sources were also consulted in order to complement and properly contextualize the national assessment of the experts. These sources are identified whenever used, and indicated in the reference list (Chapter 8). The Joint Study was finalized following a peer-review process with the national consultants and other members of the WG-Coal. Other experts were consulted during this peer-review process, in particular the World Coal Association. An overview of the methodology and process adopted for conducting the study is provided in figure 1.1.

The Joint Study attempts to cover different areas related to the production and utilization of coal. The identification of these technology areas resulted from a consultative process with members of the WG-Coal, with five main technology groups being analyzed on the Joint Study:

i) Efficiency-enhancing coal technologies (Chapter 2);

ii) Coalbed methane recovery and utilization technologies (Chapter 3);

iii) Coal gasification technologies (Chapter 4);

iv) Coal liquefaction technologies (Chapter 5);

v) Carbon capture and storage technologies (Chapter 6).
Chapter 2 analyzes Efficiency-Enhancing Coal Technologies. These are technologies that aim at improving the efficiency of converting coal into end-user products. In this respect, two main sets of technologies are analysed: i) technologies for the upgrading of coal, and ii) advanced coal-fired power generation technologies. These two families of technologies are closely related, with their importance in the sub-regional context being essential both as a means to derive a higher economic value from the coal resource and in the reduction of the negative environmental impacts resulting from its use.

Chapter 3 analyzes Coalbed Methane Recovery and Utilization Technologies. Methane is a gas that is found on coal seams. If released during coal mining activities it is a safety hazard for mine workers due to its explosion risk. While miners’ safety and mine productivity are the top-priorities for recovering coalbed methane, the possibility of harnessing an energy resource and the need to curb the emissions of a greenhouse gas have spurred the interest on end-uses of the methane captured from coal mines. Due to their importance on meeting these three goals, technologies for the extraction and utilization of coalbed methane are analyzed on this chapter.

Chapter 4 analyzes Coal Gasification Technologies. Coal gasification represents the “next generation” of coal production and utilization technologies. Instead of combusting coal directly for power generation, the syngas resulting from the coal gasification process can be used either as a fuel or as a feedstock for the synthesis of chemicals, while opening a different range of possibilities for minimizing negative environmental impacts, both through a cleaner combustion of the gasified coal and the capture of CO₂. Gasification technologies can therefore play an important role in fulfilling the concept and idea of “sustainable coal”.

Chapter 5 analyzes Coal Liquefaction Technologies, also known as Coal-to-Liquids. The production of liquids from coal is a further step from coal gasification, and it is also a means of deriving...
added-value products from coal. Concerns over the security of oil supplies and the possibility of harnessing abundant indigenous coal resources have been amongst the main drivers for the development of CTL technologies in the sub-region. However, there are challenges associated with the energy and water requirements of these technologies, and their large-scale deployment in NEA countries is still uncertain.

Chapter 6 analyzes Carbon Capture and Storage Technologies, which are mainly driven by concerns over climate change and the need to reduce the emissions of CO₂. With NEA countries consuming 58% of the world’s coal, whose use for power generation is the largest contributor to global greenhouse gas emissions, the uptake of these technologies in the sub-region countries will remain critical greenhouse gas mitigation solution. Their prospects are analysed on this chapter.

Chapter 7, Conclusions and Recommendations for Policymakers, draws the main conclusions of the study and prioritizes recommended actions for policymakers. Suggestions are also provided on possible directions for the future work of the WG-Coal, which are expected to be debated in the upcoming meetings convened by the group.

The following experts have participated on this project by preparing the national country studies and peer-reviewing the Joint Study: Ms. Hu Yuhong, National Center for International Cooperation of the State Administration of Work Safety, China; Mr. Keiji Makino, Japan Coal Energy Center (JCOAL); Mr. Budeebazar Avid, Institute of Chemistry and Chemical Technology, Mongolian Academy of Sciences, Mr. Byoung-hwa Lee, Pusan University Clean Coal Center (Republic of Korea); Mr. Evgeny Gorlov and Ms. Galina Agapova, the National Mining Research Center A. A. Skochinsky Institute of Mining (Russian Federation). These experts were identified with the support of the national governments of the countries involved on this study. In addition to the national experts, this study was also reviewed by the World Coal Association, in particular by Mr. Milton Catelin (Chief Executive) and Ms. Aleksandra Tomczak (Policy Manager).

Some limitations can be pointed out to this study. First and foremost, the absence of DPRK from this coal technology assessment. This is explained by the fact that the WG-Coal, with the support of the ESCAP Secretariat, was unable to identify a national expert who could assess the status of coal technologies in DPRK. Unlike the other five NEA countries, information from DPRK’s coal sector is very difficult to come by through publicly available sources, and therefore the participation of a national expert was considered essential for including DPRK on this study. Despite this limitation, implications from the analysis also included DPRK whenever clear opportunities for sub-region cooperation were identified.

More than a limitation per se, a caveat to be noted is that the study is not intended to be a comprehensive, detailed and all-encompassing assessment of coal technologies in North-East Asia and their status of development. Instead, it is expected this study can provide an informative overview of existing coal technologies and their state-of-the-art, the identification of trends both at global and sub-regional level, and the recommendation of possible areas for cooperation among NEA countries.

The remainder of this chapter provides a brief introduction to the five NEA countries focused on this study, shedding light on the importance of coal in their respective economies as well as the main policies and strategies for the development of the respective national coal sectors, including the role of cleaner coal technologies. These country briefs were prepared based on the national country studies: Yuhong and Yongxu (2012) for China, JCOAL (2012) for Japan, Avid (2012) for Mongolia, Lee (2012) for the Republic of Korea, and Gorlov and Agapova (2013) for the Russian Federation. Additional sources of information are noted whenever used.
1.2 China Country Profile

China is the world’s most populated country and its second largest economy. China’s economy is driven by the consumption of coal, which is the country’s most important energy resource, accounting for 73.8% of the primary energy mix in 2010. China holds abundant coal resources, which are widely distributed and present a good variety of coal ranks. It possesses the world’s third largest proven coal reserves, estimated at about 115 Gt (BP, 2013). Currently China is the largest coal-producer and coal-consumer country in the world. In 2012, the production of coal reached 1825 Mtoe, while consumption totaled 1873 Mtoe, around 50% of the world’s consumption of coal. China is a net coal importer of coal, a status it has acquired in 2009.

In China, four main industrial sectors are responsible for the bulk of coal consumption: the power generation, steel, construction and chemical industries. In 2011, these four industries combined accounted for around 90% of the total coal consumption, with the power sector accounting for 52.6%, steel for 15.8%, construction for 16.2% and chemical 5.8%. Following the power sector’s reforms of 2002, there are currently five main electricity production groups: Hua Energy Group, Datang Group, Guodian Group, Huadian Group and the Power Investment Group. These five groups account for around 49% of China’s installed power generation capacity.

The negative impacts of coal on the environment and the emission of GHGs caused by its extraction and utilization have been drawing increasingly more attention in China. In fact, the development of cleaner coal technologies has become a key strategic area for the sustainable energy development of China, and since the early 1990s that the country has been developing cleaner coal technology programmes.

China is guided by a five-year planning cycle, which is defined by the Five Year Plans for National Economic and Social Development. These plans set out the intended way forward for the country and provide guidelines, policy frameworks and targets for policymakers at the different levels of government (Minchener, 2011b). The development of cleaner coal technologies has been part of these plans since 1995, when the State Council ratified the “Ninth Five-Year Plan of China’s Clean Coal Technology and Development Guideline before 2010”. The need to adopt cleaner coal technologies for power generation was recognized and included for the first time in the national Eleventh Five-Year Plan in 2006. The “Notice of National Scheme in Tackling Climate Change” by the State Council, as well as the “Eleventh Five-Year Plan for Energy Development” by the National Development and Reform Commission (NDRC) in 2007, reiterated that great importance should be attached to a cleaner and more effective utilization of coal in the power generation sector. During the Eleventh Five-Year Plan period (2006-2010), China achieved noticeable progress in the research, development, construction of pilot projects and the promotion of cleaner coal technologies.

The Twelfth Five-Year Plan (2011-2015) underscores the need to utilize coal in more efficient and cleaner ways. The Plan also comes up with new objectives and requirements with regards to the development of cleaner coal technologies. In particular, the “General Planning for Technological Innovations of Industries during the 12th Five-Year Plan Period”, issued by the Ministry of Industry and Information Technology, has identified several key coal technology areas to be developed in the future, including coal-to-olefins technologies, advanced coal gasification technologies, and integrated and cleaner utilization of lignite with improved efficiencies. The Twelfth Five-Year Plan on Clean Coal Technology Development, issued by the Ministry of Science and Technology, recognized five key dimensions of cleaner coal technology application for future development. They are as follows: clean
and efficient coal-fired power generation, advanced coal conversion technologies, energy conservation, pollutants control, and carbon capture, sequestration and utilization.

With coal accounting for more than 80% of the total power generated in China, the development of advanced coal conversion technologies and related industries has become a priority in the past 10 years. During the Eleventh Five-Year plan period, and according to rough figures, around 80 billion RMB were invested in pilot projects using these technologies. However, a number of core technologies has not been fully mastered yet by Chinese organizations. To address this, in the five years of the Twelfth Five-Year Plan (2011-2015), R&D will focus on the following technologies: i) integrated processing and upgrading of low-ranking coals; ii) new gasification technologies; iii) synthetic methods to convert coal into liquids and/or chemicals; iv) integrated demonstration of advanced coal-fired power generation technologies in large scale settings.

In addition to the above, the Twelfth Five-Year Plan defines a set of objectives which are of relevance to the coal industry in China (Minchener, 2011b):

- Energy consumption per unit of GDP to be reduced by 16% from 2010 levels;
- CO₂ emissions per unit of GDP to be reduced by 17% from 2010 levels;
- Non-fossil fuel use to account for 11.4% of primary energy consumption;
- Emissions of NOx and SO₂ to be reduced by 10% and 8%, respectively, from 2010 levels;
- Expenditure on R&D to account for 2.2% of the GDP, with a focus on innovations leading to Chinese intellectual property rights;
- Water consumption per unit of value-added industrial output to be reduced by 30% from 2010 levels.

### 1.3 Japan Country Profile

Japan is an island state located to the East of the Korean Peninsula, with a population of 128 million inhabitants. Japan is a country with scarce energy resources, being the world’s third largest net importer of oil, the largest importer of liquefied natural gas, and the second largest importer of coal. As of 2010, coal accounted for 22% of the total energy consumption, with oil taking a share of 42%, natural gas 18% and nuclear energy 13%. The domestic production of coal came to an end in 2002, and most imports of coal come from Australia (EIA, 2012).

Coal is an important fuel in Japan’s energy mix, and is typically used as a base load fuel for power generation. In 2011, the power generation capacity of coal-fired power plants was of 43 GW. As a consequence of the earthquake and tsunami that hit Japan in March 2011, several coal-fired power plants were significantly damaged. But except for two units, all of them returned into normal operation soon after the earthquake occurred. Almost all coal power plants were operating at full load capacity before the earthquake, and the same situation continued after the disaster. Due to this, the total coal consumption in Japan could not increase much in the aftermath of the earthquake. On the other hand, Japan increased the operation time of natural gas combined cycles by importing more LNG on an emergency basis. At the same time, Japan made efforts to decrease the total electricity consumption through energy efficiency and conservation measures. Eventually, coal and natural gas generation were able to cover the energy gaps following the shutdown of the nuclear power generation fleet (JCOAL, 2012).
The development of cleaner coal technologies in Japan dates back to the early 1970s, as cities in the country experienced severe air pollution, mainly in industrial areas. As a response, the government issued strict air pollution control regulations, while power generation companies and equipment suppliers joined the effort by developing cleaner coal technologies. As the result of R&D activity, technologies such as low NOx combustion, selective catalytic reduction (SCR), or flue gas desulphurization equipment were developed, and nowadays they are applied in all commercial coal-fired generation units. While environmental protection and air pollution control used to be the main driver for the deployment of cleaner coal technologies in Japan, concerns over greenhouse gas emissions have shifted the attention to CCS and efficiency-enhancing coal utilization technologies.

The Ministry of Economy, Trade and Industry (METI) of Japan has the responsibility of formulating Japan’s energy policy. With respect to the development of coal technologies, the Japan Coal Energy Center and METI work in close cooperation. The figure below presents the roadmap for coal technology development in Japan up to 2050:

![Roadmap for the development of cleaner coal technologies proposed by JCOAL](Source: JCOAL, 2012)
1.4 Mongolia Country Profile

Mongolia is a landlocked country bordered by the Russian Federation in the North and China to the South. It encompasses a vast territory with a land surface of 1,565,600 km², almost three times the size of France. The population of Mongolia totals 2.87 million people, and is one of countries in the world with the lowest population density. Approximately 1.3 million people live in the capital city, Ulaanbaatar.

In the last 20 years, Mongolia has made significant progress on its transition from a centrally-planned state to a market-based economy. Overall, this transition has been successful, with the private sector currently contributing to over 70% percent of Mongolia’s GDP. The economic growth the country has experienced in recent years has also been accompanied by a rapid increase in the demand for energy.

Mongolia is a country rich in coal, with 9.8 billion tons of proven reserves and additional estimated resources totaling 162.3 billion tons. More than 300 coal deposits and occurrences are evenly distributed across the whole country, and most of these coal resources could be produced applying open-pit mining methods. Coal qualities range from lignite to anthracite. The figure below presents the location of some of the largest coal deposits in Mongolia. Among these, the most important are the Baganuur, Shiveeovoo and Tavantolgoi coal deposits.

The Baganuur coal deposit is located 110 km East of Ulaanbaatar, and it is the largest open pit coal mine in Mongolia. It has been operating since 1978, currently with the capacity to produce 3 million tons of coal per year. The coal quality is lignite with a calorific value of 3,360 kcal/kg, 31% of moisture content, 12.1% of ash content, and 0.4% of sulfur content.

Shiveeovoo is an open pit coal mine located 260 km South-East of Ulaanbaatar. It has entered operations in 1993, and currently produces 1.4 -1.5 million tons of coal per year. The Shiveeovoo coal mine is endowed with lignite with a calorific value up to 3,610 kcal/kg, 34.5-43.6% moisture, 8.7-17.3% of ash, and 0.5 -0.9% of sulphur.
Introduction

Tavantolgoi is the country’s largest coal mine, being located in the Ulaannuur coal-bearing depression in the Omnogovi Aimag, 560 km South of Ulaanbaatar and 90 km East of Dalanzadgad. This basin is unique in that it is 90 km² in size and contains high quality coal, most of it located in close proximity to the surface. Around a quarter of the coal at Tavantolgoi is high-grade coking coal, while the remainder is thermal coal.

Aduunchuluun is located near the city of Choibalsan, Dornod province, around 100 km from the Mongolia-China border. The deposit was found in 1951 and it contains an estimated 464.4 mln ton of brown coal. The mine is connected to Russian Federation’s Solovyevsk port through a 254 km railway line, and also to the Arkhasaa border point with China by road. The coal quality is lignite with a calorific value of 2500-2700 kcal/kg, 45-48% of moisture content, 18-10% of ash content, and 1-1.2% of sulphur content. There are plans to convert this coal into gasoline.

Since the first time coal was produced in Mongolia, in 1922, it has been used to meet the country’s demand for energy. At present, coal accounts for 68.5% of total energy supply, followed by oil (23.3%) and hydro (0.1%) (ESI, 2011). Currently, coal is mostly used for power generation, meeting more than 90% percent of Mongolia’s electricity and heating needs. In 2003, coal started to be exported. In 2007, one third of the coal produced in Mongolia was exported, all of it to China via the South Gobi. Exported coal mostly originates from the Tavantolgoi and Nariinsukhait deposits. The largest fraction of the coal used domestically is lignite, while exports consist of bituminous coal.

Coal is, nowadays, one of the most important exports and drivers of Mongolia’s economy. Recognizable to that, the Government proposed the “Coal Programme for 2010-2025”, which aims, among others, to support private sector’s involvement in the coal sector, the establishment of a skilled labor force for coal mining, and increased policy coordination along the whole value chain of the coal industry (ESI, 2011).

One of the most important projects conducted by the Mongolian government is the establishment of the Sainshand Industrial Complex, which is considered a centerpiece of Mongolia’s National Development Strategy. The project is being developed by the Bechtel Corporation, a US-based company, and will include a set of industrial projects, which consist of a coal gasification power plant, an oil refinery, and mineral processing facilities. The complex is planned to use coking coal from the Tavantolgoi mine, which is located around 400 km from the complex. It is expected that the project can play a key role in Mongolia’s social and economic development.

1.5 Republic of Korea Country Profile

The Republic of Korea (ROK) is a country located in the Southern part of the Korean Peninsula, with a population of 49 million people. It is the world’s thirteenth largest economy and the seventh largest exporter of goods, with an economy largely driven by energy intensive industries, such as cement, steelmaking and petrochemicals (IEA, 2012c).

ROK is the world’s third-largest importer of coal, behind Japan and China. In 2011, coal accounted for 31% of total primary energy supply and 45% of power generation. Almost all coal consumed in ROK was imported, mostly from Australia, Indonesia and the Russian Federation. However, there are still five anthracite coal mines in operation, three of which operated by the state-owned Korea Coal Corporation (KOCOAL). The production of electricity and heat from coal is the largest single source of CO₂ emissions in the country, accounting for almost 30% of total emissions in 2010 (IEA, 2012c).
In the past few years the government of ROK has designed and implemented many policies in the energy and environment fields. Amongst the most relevant of them, in August 2008 the government announced its Low Carbon, Green Growth Policy, ushering in a new paradigm for national growth to create jobs and generate economic wealth, while opening a new path for addressing the challenges posed by GHG emissions and energy security. As a follow-up measure, the Ministry of Knowledge Economy mapped out in September 2008 the Green Energy Industry Development Strategy, with a view of turning the green energy industry into the nation’s key growth engine.

The strategy was bolstered by comprehensive and detailed R&D action plans, with the Korea Institute of Energy Technology Evaluation and Planning (KETEP) unveiling the first Green Energy Strategy Roadmap. This roadmap identified 15 strategic items for R&D, which are as follows: solar energy, wind power, fuel battery, bio-fuels, clean fuels, IGCC, CCS, cleaner thermal power plant, nuclear energy, smart grids, energy storage, energy-efficient buildings, high efficiency lighting, heat pumps, and green vehicles. Among these strategic items, those related to coal include IGCC, the enhancement of energy efficiency, CCS, the production of cleaner fuels, and the deployment of cleaner thermal power plants. It should be emphasized that one the most notable features of ROK’s energy policy is the importance assigned to R&D.

In November 2009, the government announced its commitment to the reduction of GHG emissions by 30% compared to its business as usual (BAU) case by 2020, and this commitment was integrated into its Green Growth Strategy. To achieve this ambitious target, the share of GHG emissions from the utilization of coal will have to be significantly reduced, and amongst the means to meet these goals are the development of cleaner coal technologies, particularly advanced coal-fired power generation, IGCC and CCS.

Figure 1.4 below presents the general approach for developing cleaner coal technologies in the ROK since 2008. The Korea Institute of Energy Research (KIER) scope of work is on thermal efficiency improvements and on CTL technologies, while the Korea Gas Corporation (KOGAS) focuses its R&D activities on issues related to the production of DME. SK innovation (the major oil refining and petrochemical company of ROK) has as priority the gasification of low-rank coals, whereas POSCO the construction of syngas plants. These R&D efforts are supported mostly by the Ministry of Knowledge and Economy. On the other hand, the national R&D programme on CCS is being conducted under the coordination of three ministries: the Ministry of Knowledge Economy, the Ministry of Education, Science and Technology, and the Ministry of Land, Transport and Maritime Affairs.
The Russian Federation is one of the world’s largest and one of the most energy resource rich countries, with large reserves of oil, gas and coal. Coal is considered one of the country’s national assets, as it can provide long-term energy security. The Russian Federation holds the second largest coal reserves in the world, accounting for a share of almost 20% of the global total.

As of 2012, coal in the Russian Federation is produced in 121 opencast mines and 85 coal mines, which had a combined output of 354.9 million tons, the highest since the Soviet period. The Kuznetsky basin is the largest coal basin, holding 43% of Russian Federation’s proven reserves. In addition to these, opencast mines of the Kansko-Achinsky coal basin, Eastern Siberia and the Russian Far East are important and hold significant potential in terms of reserve size and coal quality, supporting infrastructure and geological conditions. Currently, work is underway to build and develop new coal centers around the Elginskoye coal deposit (Yuzhno-Yakutsky coal basin, Republic of Yakutia), Mezhegeyskoye and Elegestskoye coal deposits (Ulughemsky coal basin, Republic of Tyva), and Apsatskoye coal deposit (Zabaikalye Territory). An illustration of major coal deposit in the Russian Federation is provided in the figure below.
Russian Federation’s major coal operations are concentrated in Siberia and the Far East of the country, whereas major coal consumers are based in the European part and the Urals, resulting in significant transport and productions costs for the coal supply to meet demand. The high moisture, ash and sulphur content of most coals as well as coal fines make the transport of these coals uneconomic. In this context, one of the strategic objectives of the Federal Government is to create efficient and innovative techniques for coal beneficiation, as well as the processing of coal into added-value fuels.

In January 2012, the Government of the Russian Federation approved the Long-Term Programme for the Development of the Coal Industry up to 2030, which will be implemented on a phase by phase basis until its completion in 2030. The Programme encompasses eight sub-programmes, and it is intended to achieve a set of different objectives, among them the following:

- Introduction of new and more modern coal companies, and closure of unpromising and unprofitable coal companies;
- Increase the Russian Federation coal supply to the national power generation industry along with an increase in the share of the exports of coal;
- Decrease the energy intensity of coal production and processing by at least 1.5 times;
- Increase the production of synthetic liquid fuels up to 15-17 million ton per year;
- Increase in the share of integrated use of coal waste up to 45%;
- Decrease the injury rate and number of accidents in coal mines by at least 30%.

The actions of this Programme are harmonized with other federal and state programmes, in particular the “Development of Science and Technologies” programme, which promotes the introduction of innovative technologies for the processing and use of coal and coal waste, the commercialization of underground coal gasification, the utilization and recovery of coalbed methane, and the commercialization of technologies for the integrated use of coal waste. Adding to this, the Ministry of Energy of the Russian Federation has envisaged the implementation of R&D projects on areas that include enhanced energy efficiency processes for the production of coal, as well as the processing of synthetic liquids from coal.

In complement to the above, the Energy Strategy of Russia for the period up to 2030, approved in November 2009 by the Government of the Russian Federation, sets the overall objective of transforming the coal sector into an efficient sustainable industry, which should be accomplished by a substantial modernization of coal production and conversion processes. Several indicators are set forth on this Strategy, which include an increase in the share of coal in the electricity generation mix (from 26% in 2008 to 34-36% in 2030), as well as a reduction in the emission of pollutants into the atmosphere, waste waters discharges, and waste generation rates by energy sector companies.
2 Efficiency-Enhancing Coal Technologies
2.1 Introduction and Background

This chapter focuses on technologies that aim at enhancing the efficiency of converting coal into end-user products, such as electricity, synthetic gas or CTL liquids. As observed in the previous chapter, coal is likely to continue playing a major role on the global energy mix, especially in developing countries, where it is still the cheapest and most readily available fuel to meet the increasing demand for energy. It is therefore of central importance to maximize the utility – or efficiency – of coal use. Efficiency improvements can bring along several benefits (Burnard and Bhattacharya, 2011; IEA, 2010):

- Extending the lifetime of coal reserves and resources through the reduction in coal consumption;
- Reducing the emissions of conventional pollutants, such as sulphur dioxide (SO$_2$), nitrogen oxides (NOx) and particulates;
- Reducing the emissions of carbon dioxide (CO$_2$)$^1$;
- Increasing the power output or the yield of an end-product from a given unit of coal resource;
- Potential for reducing operational costs associated with coal-conversion processes.

In light of the benefits above, there is a generalized interest among coal consuming and producing countries in adopting and mainstreaming technologies that improve the efficiency of coal production and utilization processes. The technologies covered under this chapter encompass two distinct sets of coal conversion processes: i) coal upgrading technologies; and ii) advanced coal-fired power generation technologies. The latter is intrinsically related to the first group of technologies, as the necessary starting point for making power generation more efficient is the quality of the coal feed (Couch, 2002).

Coal upgrading technologies encompass a broad range of processes and techniques that can be applied to improve the quality of coal. These technologies are applied to produce a saleable product and add economic value to run-of-mine (ROM) coal, and usually their main goal is to recover the maximum amount possible of organic matter in the coal. As noted above, environmental benefits in the form of reduced emissions of CO$_2$ and other pollutants can also be achieved with coal upgrading. Coal can be upgraded by washing, drying or briquetting/pelletizing (Couch, 2002; Nunes, 2009).

**Coal washing**, also known as **coal preparation, cleaning** or **beneficiation**, is aimed at separating and removing impurities from coal, to the extent possible and in an economically viable manner. Coal beneficiation techniques mainly work by exploiting differences in density between the coal and its impurities. Beneficiation techniques involve physical processes, and they are carried out mainly on high-rank coals, such as bituminous coal and anthracite. Coal beneficiation technologies are analysed in sub-chapter 2.2.

**Coal drying** techniques are essentially applied to low-rank coals, such as lignites and sub-bituminous coal. Unlike high-rank coals, the challenges with low-rank coals are not with the need to remove ash or sulphur, but rather on their high moisture content, which is usually in the range of 30-70% on a dry basis. Upgrading techniques involve drying these coals as efficiently and as cost-effectively as possible (Burnard and Bhattacharya, 2011). Coal drying technologies are analysed in sub-chapter 2.3.

$^1$ A one percentage point improvement in the overall efficiency of coal-fired-power plants can result in up to a 3% reduction in CO$_2$ emissions.
**Briquetting/ pelletizing** is the process of compressing or moulding coal into a specific shape so as to make the raw material more adequately fit to an end-use, including for example to facilitate its utilization on domestic boilers or industrial processes (Nunes, 2009). This form of coal upgrading is not a focus area of this study, but given its importance in the specific context of Mongolia, this topic is briefly analyzed in sub-chapter 2.6 (Other Issues).

Table 2.1 attempts to summarize the main policy drivers in NEA countries for coal upgrading technologies. It may be observed that the two largest coal producing countries in the sub-region, China and the Russian Federation, acknowledge the importance of these technologies on some of their national level programmes and policies. NEA countries with limited domestic coal production, i.e. Japan and ROK, appear to consign lower priority to these technologies, although some noteworthy concepts have been developed by organizations based on these countries.

<table>
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<th>Country</th>
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| China                  | • The energy intensity and carbon intensity targets defined in the Eleventh (2006-2010) and Twelfth Five-Year Plans (2011-2015) are the guiding objectives for efficiency improvements in the coal industry. There is a target to cap domestic coal consumption by 2015;  
  • According to the Twelfth Five-Year Plan, the ratio of ROM preparation is required to increase from the current figure of 50% to 60% in 2015, and up to 70% in 2020;  
  • In the 12th Five-Year Plan, the Government has designated the research on technologies for the upgrade of low-rank coals as one R&D focus area. |
| Japan                  | • No specific measures were identified on coal upgrading technologies.                                                                                                                                 |
| Mongolia               | • No specific measures were identified on coal upgrading technologies. However, it is recognized the potential economic benefit derived from the production of upgraded coals.                                      |
| Republic of Korea      | • No specific measures were identified on coal upgrading technologies.                                                                                                                                 |
| Russian Federation     | • In the Long-Term Programme for the Development of the Coal Industry up to 2030, substantial attention is given to coal beneficiation, which includes the establishment of new coal-producing centres and the construction of modern coal preparation plants.  
  • The Energy Strategy of Russia for the period up to 2030 envisages the transformation of the coal sector into an efficient and sustainable industry, which is to be achieved by the substantial modernization of coal production and processing facilities. |

Table 2.1 – Main policies and strategies for coal upgrading in NEA countries.

The second family of technologies analysed on this chapter concerns those that improve the conversion efficiency of coal into electricity. It is important to analyse this set of technologies separately because coal is the most widely used fossil-fuel for power-generation, and it is remained to continue as such in the foreseeable future. As observed by Yang and Cui (2012), at the end of 2012 there were 1,199 coal-fired power plants planned at global level, with a combined capacity above 1,400 GW. The uptake of advanced-coal technologies will therefore play an important role in the average global efficiency of coal-fired power plants, as well as on their CO₂ emissions per unit of energy produced.

Within this family, two sub-sets of technologies are analysed. The first pertains to the supercritical (SC) and ultra-supercritical (USC) coal combustion technologies, which are analysed in sub-chapter 2.4. The second sub-set encompasses fluidized bed combustion technologies, examined in sub-chapter 2.5.
Pulverized coal (PC) combustion is the most predominant conversion technology for generating electricity from coal, accounting for more than 97% of the current installed coal-fired power capacity at global level. Most of these plants operate under subcritical steam conditions, with the best performing plants achieving efficiencies of 39%. However, with more advanced technology it is possible to generate steam at pressures above the critical point of water, so that there is no distinction between the liquid and gaseous phases: in thermodynamic terms, this is a “supercritical” fluid. Higher efficiencies can be achieved with supercritical steam cycle technologies (IEA, 2013a).

Fluidised bed combustion (FBC) is an alternative to pulverized coal combustion technologies for power generation. It consists in burning coal suspended in an upward flow of combustion air. It is a technology particularly suited to low-rank coals, and one of its main advantages being the considerable flexibility allowed to plant operators, as it is suitable to the utilization of a broad range of different coals (IEA, 2013a).

There is a third major group of advanced coal-fired power generation technologies which are not analysed on this chapter: integrated gasification combined cycle (IGCC). In an IGCC plant coal is first converted into a synthetic gas – syngas – through a gasification process. After the removal of impurities, the resulting syngas is utilized as a feedstock to a combined cycle gas turbine plant. As gasification technologies are an intrinsic component of IGCC plants, this coal-to-electricity technology is analyzed in chapter 4, whose focus is on coal gasification technologies.

All NEA countries have significant coal-fired generation fleets, and therefore there is a strong policy backing towards the development and adoption of advanced coal combustion technologies, as can be observed in table 2.2 below:

<table>
<thead>
<tr>
<th>Country</th>
<th>Policies and strategies of NEA countries for promoting advanced coal-fired generation technologies.</th>
</tr>
</thead>
</table>
| China           | • The energy intensity and carbon intensity targets are the guiding objectives for efficiency improvements in the coal sector;  
                  • The Eleventh Five-Year Plan mandated the closure of small and inefficient coal-fired power plants. The Twelfth Five-Year Plan mandates that all plants above 600 MW must apply supercritical or ultra-supercritical technology;  
                  • In the Twelfth Five-Year Plan, the Government has designated as one of its priorities the demonstration of advanced coal-fired power generation technology in large scale settings, as part of its policies to integrate the coal mining industry with the power generation business. |
| Japan           | • Since the 1970s that the Government of Japan has been supporting the development of advanced coal-fired power technologies. |
| Mongolia        | • There is an interest in more advanced coal combustion technologies in order to reduce atmospheric pollution and CO₂ emissions. |
| Republic of Korea| • Advanced coal combustion technologies are one the means to achieve national greenhouse gas emission reduction targets;  
                  • The Green Energy Strategy Roadmap identified clean thermal power plants as one of the 15 strategic R&D items to be prioritized. |
| Russian Federation | • In the Long-Term Programme for the Development of the Coal Industry up to 2030, it is set the objective of decreasing the energy intensity of coal production and processing at least 1.5 times  
                     • Advanced-coal processing technologies are supported by the Energy Strategy of Russia for the period up to 2030. |

Table 2.2 – Policies and strategies of NEA countries for promoting advanced coal-fired generation technologies.  
In order to better grasp the scope of this chapter, figure 2.1 below provides a representation of its structure and the technologies analyzed under each sub-chapter.

Figure 2.1 – Technologies analysed on this chapter.
(Source: own elaboration)

2.2 Coal Beneficiation Technologies
(for high-rank coals)

In the scope of this study, coal beneficiation – or coal washing – refers to methods and processes to remove impurities from high-rank coals, i.e. bituminous coals and anthracite. This type of coal accounts for around two thirds of global coal production, with one third of this amount being currently washed (Burnard and Bhattacharya, 2011). The main aim of beneficiation is to improve the quality of coal, in an economically feasible manner, by reducing extraneous matter, in particular mineral matter (ash) and sulphur. As most beneficiation methods are water-based, “coal washing” is a term often used to refer to coal beneficiation. It should be noted that on this sub-chapter dry separation methods are also analysed, not only because of their application to high-rank coals, but also due to their importance in the context of coal mining and upgrading activities in water-scarce areas, particularly in China and Mongolia. Thus, the analysis is split between water-based and dry separation methods.

For the purposes of coal beneficiation – which relies on physical processes – a set of coal properties can be explored. The first one is the relative density between the coal and the associated inorganic matter. The second is the hydrophilic nature of the mineral matter, which is in contrast with the hydrophobic nature of coal. And thirdly, the differences in size among coal particles, which are split into three different groups: coarse coal, intermediates and fines (Nunes, 2009).
Coal washing processes are usually part of coal preparation plants, and this equipment is found in major coal processing facilities across the globe. There are three main water-based processes to separate coal: jig washing, dense medium separation (DM), and froth floatation cells. Jig washing and DM are more suitable to coarse coals, while DM are used for intermediates and froth floatation cells to fines (Nunes, 2009). An illustration of these methods is provided in figure 2.2 below.

Air pulsated jig washers are amongst the most popular coal preparation equipment in the world. They rely on the different densities of materials to separate coarse coal. Figure 2.3 below provides a graphic representation of a jig developed by a Japanese company, Nagata Engineering Co. Ltd., which applies a trapezoidal wave pattern to induce the separation of the coal particles. This method is also known as vari-wave jig system.

Figure 2.2 – Water-based beneficiation methods.  
(Source: Nunes, 2009)

Air pulsated jig washers are amongst the most popular coal preparation equipment in the world. They rely on the different densities of materials to separate coarse coal. Figure 2.3 below provides a graphic representation of a jig developed by a Japanese company, Nagata Engineering Co. Ltd., which applies a trapezoidal wave pattern to induce the separation of the coal particles. This method is also known as vari-wave jig system.

Figure 2.3 – Vari-wave Jig concept of Nagata Engineering Co., Ltd.  
(Source: JCOAL, 2012)
Efficiency-Enhancing Coal Technologies

Dense Medium separation consists in the separation of coal using a water-based suspension of fine magnetite. This mixture is fed into the top of a cyclone, where the separation between the coal and the mineral matter takes place by centrifugal force. Froth flotation is the most common method of upgrading fine coals, and it is based on the different hydrophilic and hydrophobic properties of coal particles, and the ability of air bubbles to selectively adhere to specific mineral surfaces. On this process, fine particles of coal are mixed with water, and when air is blown into the mixture, the particles that adhere to the air bubbles are carried to the surface and removed, while the particles that remain wet stay in the bottom of the container in a liquid phase (Kawatra, 2009).

In China, only 50% of ROM coal is prepared, a relatively low rate compared with other major coal producing countries (Yuhong and Yongxu, 2012). In particular two reasons can be pointed out for this (Nunes, 2009): the lack of policies that provide incentives for the preparation of coal and the scarcity of water. In recent years, DM separation technologies have been put into application, and it is currently the most widespread method of coal washing in China. Companies in China apply international coal washing technologies, and it is currently at the forefront of R&D and application on DM cyclones. On new coal preparation plants, either DM shallow-slot separators or moving sieve jigging machines are used for coal beneficiation in China. Compared to the moving sieve jiggers, DM shallow-slot separators have advantages in price as well as with respect to the efficiency and precision of the separation process (Yuhong and Yongxu, 2012).

Although Japan has marginal domestic coal production, some Japanese companies have developed coal-washing technologies. In particular, the model developed by the Nagata Engineering Co., Ltd., which is presented in figure 2.3 above, has been commercially applied in Japan as well as in countries such as India, China, Viet Nam and Indonesia (JCOAL, 2012).

In Mongolia, the introduction of coal beneficiation technologies is a priority, as there is still a high utilization of raw and untreated coal for energy production. Coal-washing technologies have been gradually introduced in new projects in Mongolia, and the models deployed have been supplied by international companies. For instance, the coal preparation unit for the first phase of production of the Tavantolgoi mine, in the South Gobi, was provided by Sedgman Ltd, one of the world’s leading engineering companies in coal processing and material handling technology (Avid, 2012).

In the Republic of Korea, coal washing technologies do not appear to be a priority, which is not surprising, given the limited domestic coal production. Accordingly, no such technologies have been identified (Lee, 2012).

In the Russian Federation, and as observed in table 2.1, in the Long-Term Programme for the Development of the Coal Industry up to 2030, substantial attention is given to coal beneficiation, including the establishment of new coal-producing centres and the construction of modern coal preparation plants. The ambition is to increase the share of beneficiated from 39% now up to 60%. Coking coal is almost entirely beneficiated, while the share of beneficiated thermal coal accounts for only 35% of the total production volume. All of this is exported, so it can be observed that the increase in the volume of thermal coal beneficiated is strongly co-related to the quality requirements of overseas customers (Gorlov and Agapova, 2013).

The development of coal preparation in the Russian Federation has achieved a higher qualitative level in the past few years. Among the companies involved on the design of these plants, Coralina Engineering has been one of the most active. It should also be noted the collaboration with Germany, Australia and Poland in the development of coal beneficiation technologies. Indeed, it can be observed that both old and new coal preparation plants apply both international and Russian-made...
equipment. For the preparation of coarse coal, dense medium separators are used in several coal preparation plants, and this equipment can be provided by Russian based organizations, such as for example Spetstechmash Ltd. On the other hand, dense medium cyclones are not manufactured in the Russian Federation, and the USA-based Deister and Krebs has been one of the main providers of this equipment (Gorlov and Agapova, 2013).

**Dry coal beneficiation** methods have a number of advantages over water-based processing. First and foremost, they do not rely on water as a separation medium, which is an important aspect on water-constrained regions. A second advantage is that no moisture is introduced in the product stream with the separation process. The main drawback are the limited improvements to the quality of the coal with this process. There are different dry coal beneficiation methods, which include dry jigging, FGX, and air-based dense medium fluidized bed separation (ADMFB) (Nunes, 2009).

**Dry jigging** has been one of the most popular methods of dry coal beneficiation. It applies the technology and principles of water-based jigs, except that the separation medium is air. The **FGX separation technology** is considered to be a step ahead from dry jigging, and it consists of density coal separators that are usually placed in the mine mouth to process ROM coal. The **air-based dense medium fluidized bed separation** (ADMFB) process uses an air-solids suspension as the separation medium (which serves as the “fluidized bed”) whose operation method is similar to the water based DM systems that use fine magnetite.

Among NEA countries, China and Japan have been taking the lead in developing dry coal beneficiation technologies. In **China**, the Tangshan Shenzhou Machinery Co. Ltd. has developed and commercialized its own FGX separation technology. This technology proved to bring numerous advantages, mainly with regards to its relatively simple operating mode and low operation and investment costs. The world’s largest coal preparation plant applying this technology is located in China and is owned by the Shenhua Jinfeng Coal Subsidiary Company. This FGX separation technology has established itself at global level, and it has been used in countries such as the USA, Russian Federation, Indonesia, Philippines, DPRK, Ukraine and Mongolia (Yuhong and Yongxu, 2012). It can therefore be observed that international cooperation among NEA countries on this technology field, even if driven and established by private sector organizations, is already happening.

In **Japan**, the Nagata Engineering Co. Ltd. and NEDO have been working on ADMFB technologies. The first ADMFB separators were commercially operated in 2008, and subsequently they have been applied to seven plants in Japan. This technology has only been applied to the waste and recycling industry, but it is now ready to be deployed, at demonstration scale, to the separation of ROM coal (JCOAL, 2012).

In **Mongolia**, there are two companies that apply dry beneficiation technology on their coal preparation processes. One of them is the Mongolyn Alt Corporation (MAK), and the second one is the South Gobi Resources Ltd. (SGQ). Both companies have applied the FGX separation technology developed by the Tangshan Shenzhou Machinery Co. Ltd. on two of their most recent projects (Avid, 2012).

No dry coal beneficiation technologies have been developed or applied in the **Republic of Korea**, and the same observation is made with regards to the **Russian Federation** (Lee, 2012; Gorlov and Agapova, 2013).
All in all, it can be concluded that coal beneficiation methods and technologies are mature and commercially available. Although there is significant scope for further adoption of these technologies in coal producing countries in NEA, the share of cleaned coal is expected to increase due to policy and regulation (particularly in China and the Russian Federation), market forces (China, the Russian Federation and Mongolia), and environmental concerns (mainly China). It has also been observed that some companies based in NEA countries are already taking the global lead on some coal beneficiation technologies.

### 2.3 Coal Drying Technologies (for low-rank coals)

Around 53% of the world’s coal reserves consist of low-rank coals (BP, 2013). While these coals are inexpensive, low in sulphur and ash, they have high moisture content (30-70% on a dry basis). Currently, the largest market for low-rank coals is the power generation sector, with the utilization of coal generally occurring close to the mines from which the coal is extracted. If the moisture content of the coal is not removed, this can result in a different range of problems in a coal-fired boiler, requiring more energy per unit of power generated, and leading to higher O&M costs of the plant. On the other hand, the drying process will result on an energy penalty of the overall coal conversion process, so there is a need to dry these coals as efficiently and as cost-effectively as possible (Dong, 2011).

An important issue with respect to low-rank coals is their propensity to spontaneous combustion, which increases with the storage time of the coal and with the removal rate of its moisture. Due to this, the drying process is usually carried out shortly before the coal combustion takes place (Burnard and Bhattacharya, 2011).

There is a wide range of processes for drying low-rank coals, both in current use and under development. Table 2.3 below summarizes the key features of some of the most widely used coal drying technologies:

<table>
<thead>
<tr>
<th>Technology</th>
<th>Main Features</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tubular dryer</td>
<td>• The drying medium is steam, which is bled from power generation turbines, and then used in a tubular heat exchanger to dry the feedstock; Technology is in use in Germany, India and Australia.</td>
</tr>
<tr>
<td>WTA technology (steam fluidised bed pre-drying with internal heat utilization)</td>
<td>• Technology originally developed in Germany, which has been successfully demonstrated at commercial scale; • On this process, raw coal is milled to fine grain which is then dried in a bed of materials fluidized with steam; • This technology has proved to bring several benefits, including reduced risks of fires and dust explosions and a reduced energy penalty on the drying process.</td>
</tr>
<tr>
<td>Mechanical-thermal dewatering (MTE)</td>
<td>• Technology originally developed in Germany, which removes moisture through the application of mechanical pressure and heat (coal is heated to 150-200°C), so as to “squeeze out” the water from the coal. So far, demonstration is at pilot scale, only.</td>
</tr>
</tbody>
</table>
Most developments on coal drying technologies have been taking place in countries with sizeable reserves of low-rank coals, most in particular Germany, Australia and the USA. NEA countries appear to be lagging in the development of these technologies, with relatively few concepts or models as compared to other technology sectors examined throughout this study.

In China, research in the processing and utilization of low-rank coals started only in recent years. Despite this, several technologies for upgrading lignite have been tested as trials, which apply different drying methods and heating temperatures. The most relevant of these projects are summarized as follows (Yuhong and Yongxu, 2012):

- Processing of lignite through a pyrolysis process, developed by the Dalian University of Technology;
- Dry distillation of lignite in low temperatures, developed by the Anshan Research Institute of Thermo-Energy Co., Ltd.;
- Lignite improving technology with low temperatures, developed by the Beijing Cleanstar Technology Development Co., Ltd.;
- Drying process using high-temperature flue gas, suitable both for sub-bituminous coal and lignite, co-developed by the Shenhua Group and the China University of Mining and Technology (Beijing).

In Japan, two organizations manufacture and commercialize tubular dryer systems. They are the Tsukishima Kikai Co. Ltd. and Kawasaki Heavy Industries. The systems manufactured by the latter have been installed in major steel mills in Japan, although they are used to dry coking coal, which is a high-rank coal (JCOAL, 2012).

Coal drying technologies are one of the priority areas in Mongolia. The first coal drying plant in the country was launched in 2011, at the Shivee Ovoo coal deposit, one of the fifteen strategically significant deposits designated by the Mongolian government. The technology applied makes use of the heat from the flue gas. This process helps overcome the difficulties associated with high moisture, such as freezing in the winter period, and the high transport costs, reducing the moisture of coal in 30%. This coal processing plant can process 200 ton of coal per hour, and it has significantly improved the economics of the coal extracted from the Shivee Ovoo mine (Avid, 2012).
In the **Republic of Korea**, KIER has conducted research on coal drying technologies, with two projects currently underway. The first one consists of a fluidized bed drying reactor, and it is presently being tested at laboratory scale. The second initiative has been under development since 1996, and consists in the conversion of low-grade coals into a higher quality feedstock through the application of the heavy oil immersion method. In this process, low-grade coal is immersed into heating oil, and the moisture is removed through an evaporative process. A graphic representation of this method is provided in the table below. A pilot plant with a 5 ton/day capacity is now under construction (Lee, 2012).

In the **Russian Federation**, coal drying technologies have been applied in 19 coal preparation plants. Technologies in use include tubular and drum dryers. Thermal drying does not appear to be popular, as it considered expensive. The introduction of more efficient and less costly technologies for coal drying seems to be a priority in the Russian Federation (Gorlov and Agapova, 2013).

In summary, it can be observed that a considerable number of coal drying technologies exist and/or are currently under development. However, many of these technologies are still at demonstration or pre-commercial phases, and its potential is still far from being fully harnessed. Countries in NEA do not appear to be assigning much importance to these technologies, despite interesting developments in China and Japan. In light of this, it can be concluded there is a strong need to develop less energy intensive coal drying technologies which, once commercialized and mainstreamed, will considerably improve the economic value of widely available low-rank coal resources.

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*Figure 2.4* – Drying process for low-rank coals by means of the heavy oil immersion method developed by KIER. *(Source: Lee, 2012)*
2.4 Supercritical and Ultra-supercritical Coal Combustion Technologies

Coal is a major energy resource in NEA countries, and its main utilization is for the generation of electricity. As can be observed from the table below, four countries in NEA rank amongst the ten largest in global terms with respect to the installed coal-fired power generation capacity. Altogether these ten countries account for more than 85% of greenhouse gas emissions from coal through the production of electricity and heat (IEA, 2012d).

<table>
<thead>
<tr>
<th>Country</th>
<th>Total capacity (MW)</th>
<th>Number of coal power units</th>
<th>CO₂ emissions from power heat and heat production (Mt of CO₂)</th>
</tr>
</thead>
<tbody>
<tr>
<td>China</td>
<td>669,259</td>
<td>2,929</td>
<td>3,017</td>
</tr>
<tr>
<td>United States</td>
<td>336,332</td>
<td>1,368</td>
<td>1,929</td>
</tr>
<tr>
<td>India</td>
<td>100,540</td>
<td>809</td>
<td>663</td>
</tr>
<tr>
<td>Germany</td>
<td>51,071</td>
<td>273</td>
<td>250</td>
</tr>
<tr>
<td>Russian Federation</td>
<td>50,456</td>
<td>487</td>
<td>223</td>
</tr>
<tr>
<td>Japan</td>
<td>41,031</td>
<td>155</td>
<td>217</td>
</tr>
<tr>
<td>South Africa</td>
<td>37,500</td>
<td>114</td>
<td>203</td>
</tr>
<tr>
<td>Poland</td>
<td>32,067</td>
<td>544</td>
<td>149</td>
</tr>
<tr>
<td>Australia</td>
<td>29,971</td>
<td>109</td>
<td>203</td>
</tr>
<tr>
<td>Republic of Korea</td>
<td>26,296</td>
<td>86</td>
<td>150</td>
</tr>
</tbody>
</table>

Table 2.4 – Top-ten list of countries with the largest coal-fired capacity. NEA countries have been highlighted. (Data from 2008). (Source: IEA, 2012d)

Globally, the capacity of the vast majority of coal-fired plants is based on pulverised coal combustion (PC) technology, with a small fraction applying fluidised bed combustion (FBC) and just a few applying integrated gasification combined cycle (IGCC) technology. The average efficiency of coal-fired power generation units in major coal-using countries varies substantially, with figures in the range of 30-40%. A large number of old and low-efficiency coal power plants remain in operation, and around 75% of the power plant fleet in operation uses subcritical technology (IEA, 2012b). The figure below provides an overview of the potential for energy efficiency improvements on coal-fired power plants:

---

2 On this study, power-plant efficiencies indicated are based in the lower heating value (LHV) of the fuel, i.e. they assume that the latent heat of water in the fuel used is not recovered. Plant efficiencies are also expressed “net”, that is, the gross electricity output is subtracted from the power consumption of the facility, which typically accounts for 5-7% of gross power.
The development of SC and USC technologies dates back to the 1950s, and currently SC and USC boilers are mature technologies which are available from major international suppliers. Technology aspects related to SC and USC coal-fired generation are the boiler materials/alloys and piping, which need to withstand higher temperatures and pressures than in subcritical steam conditions. Most developments are in marginal improvements or refinements of the technologies than on major breakthroughs (Nalbandian, 2008).

SC technology is already applied in a number of countries, and it has become the norm for new coal-fired generation in industrialized nations. Currently, around 25% of the global installed PC combustion fleet uses SC technology. There are very few USC plants in operation worldwide, but its numbers are expected to increase in coming years.

Among NEA countries, in China there is a strong urge to deploy SC and USC coal-fired units, with large capacities and high operation parameters, as a means to meet the country’s increasing demand for electricity while minimizing the environmental impacts derived from the utilization of coal. The development of SC and USC technologies in China started in the 1980s, and the technological progress since then has been remarkable, with Chinese manufacturers now being on par with major international suppliers in terms of technology mastery. To this end, much has contributed to the

The efficiency of PC power plants depends on several factors, including the quality of the coal, the local climatic conditions, operating practices in the plant, and the steam conditions of the thermodynamic cycle. It is particularly on the latter where large potential for improved efficiencies exists, through the introduction of advanced coal-fired combustion technologies, which include supercritical (SC) and ultra-supercritical (USC) technologies (please check Box 2.1 below).

Figure 2.5 – Energy efficiency and CO₂ emission reduction potential on coal-fired power plants. 
(Source: VGB, 2013)

Box 2.1 – Pulverized coal combustion plants and the supercritical steam cycle

In pulverized coal (PC) combustion plants, fine-powdered coal is fed into a burner attached to the boiler, along with combustion air. Combustion takes place at temperatures in the 1,300-1700°C range, at atmospheric pressure conditions, with the residence time of the coal particles in the boiler typically being 2-5 seconds. The heat released due to the coal combustion process is absorbed by water flowing in water tubes surrounding the boiler furnace, in order to generate steam, which is subsequently used to drive a steam turbine that will eventually produce electricity. “Reheaters” and “superheaters” are frequently used to recover heat from the flue gases and add it to the steam in order to increase the efficiency of the cycle.

Typical PC combustion boilers have capacities ranging from 50 to 1300 MW. The most modern units have rated capacities above 300 MW, so as to take advantage of economies of scale. Despite the higher capital costs of supercritical plants – usually 2-3% higher than subcritical plants – these costs can be offset by lower costs incurred with the purchase of fuel.

PC combustion units are usually classified into three types, which depend on the steam conditions entering the steam turbine: subcritical, supercritical and ultra-supercritical. Higher steam conditions result in higher thermal efficiencies. “Supercritical” is a thermodynamic expression to designate that there is not distinction between the liquid and gaseous phase of a fluid. Water/steam reaches this state at the pressure of 22.1 MPa. Above this pressure level, the cycle medium is a single-phase fluid with homogenous properties and, as a result, there is no need to separate water from steam as in the boiler of a subcritical cycle. The table below indicates the major differences in steam conditions among subcritical, supercritical and ultra-supercritical boilers.
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<table>
<thead>
<tr>
<th>Steam conditions</th>
<th>Subcritical</th>
<th>Supercritical</th>
<th>Ultra-supercritical</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pressure (MPa)</td>
<td>12.4-16.5</td>
<td>24-25</td>
<td>30</td>
</tr>
<tr>
<td>Temperature (°C)</td>
<td>538</td>
<td>540-595</td>
<td>595–620</td>
</tr>
</tbody>
</table>

Table above – Steam conditions on subcritical, supercritical and ultra-supercritical boilers.

In addition to the economic benefits that can be derived from improved plant efficiency, advanced coal combustion technologies can reduce the CO₂ emissions factor of coal-fired power plants. As can be observed in the table below, high-efficiency power generation technologies hold the potential of bringing down CO₂ emissions from coal combustion to 670 g/kWh, which compares with the 1,100 g/kWh of some subcritical plants.

<table>
<thead>
<tr>
<th>Technology</th>
<th>Average Efficiency</th>
<th>CO₂ intensity factor</th>
<th>Coal consumption</th>
</tr>
</thead>
<tbody>
<tr>
<td>Subcritical</td>
<td>36 %</td>
<td>≥ 880 g CO₂ / kWh</td>
<td>≥ 380 g/kWh</td>
</tr>
<tr>
<td>Supercritical</td>
<td>up to 45 %</td>
<td>800-880 g CO₂ / kWh</td>
<td>340-380 g/kWh</td>
</tr>
<tr>
<td>Ultra-supercritical</td>
<td>&gt; 45 %</td>
<td>740-800 g CO₂ / kWh</td>
<td>320-340 g/kWh</td>
</tr>
<tr>
<td>Advanced ultra-supercritical (700°C class)</td>
<td>45-50 %</td>
<td>670-740 g CO₂ / kWh</td>
<td>290-320 g/kWh</td>
</tr>
<tr>
<td>Integrated Gasification Combined Cycle (IGCC)</td>
<td>45-50 %</td>
<td>670-740 g CO₂ / kWh</td>
<td>290-320 g/kWh</td>
</tr>
</tbody>
</table>

Table above – Efficiency indicators of advanced coal-fired power plants.

(Source: Dong, 2011; Nalbandian, 2008; IEA, 2012e; Burnard and Bhattacharya, 2011)
technology licensing and JV agreements between Chinese and major international suppliers, which was encouraged by the National Development and Reform Commission (Yuhong and Yongxu, 2012; Minchener, 2010). Currently there are four Chinese companies qualified for the design and manufacture of USC boilers: i) Harbin Boiler Company Limited; ii) Shanghai Boiler Works Co., Ltd; iii) Dongfang Boiler Group Co., Ltd.; and iv) Babcock & Wilcox Beijing Co., Ltd (Yuhong and Yongxu, 2012).

In China, the first commercial SC unit was commissioned in 1992, at the No. 2 Plant of Shidongkou. In 2004, the first 600 MW SC unit manufactured in China was successfully put in operation at the Qinbei Power Plant of Huaneng Group. The first 1,000 MW USC unit was successfully operated at the Yuhuan Power Plant of the Huaneng Group in January 2006. By the end of 2010, 33 USC units were in operation, each with a capacity of 1,000 MW. China has not officially started the research on 700 °C USC units, but this has been one of the key R&D areas defined by the Ministry of Science and Technology (Yuhong and Yongxu, 2012).

Japan has a decades’ long experience with SC and USC technologies. Amongst the leading international manufacturers of SC and USC it must be included at least three Japanese companies: Hitachi, IHI Corporation and Mitsubishi Heavy Industries. Current R&D focus is the development of advanced-USC technologies, a research initiative which started in 1998 (JCOAL, 2012).

In Mongolia, there is an interest in improving the efficiency of PC combustion mainly due to issues related to local pollution in the capital city, Ulaanbaatar, where most of the coal-fired power generation capacity is installed. There are plans to build a SC power plant within the programme of the Sainshand industrial complex, but this initiative is still at very early stages, with a feasibility study reported to have been initiated in 2013 (Avid, 2012).

In the Republic of Korea, there are two main government-driven goals with respect to the deployment of SC and USC technologies. On the one hand, the improvement of existing and outworn SC plants already in operation, and the deployment of state-of-the-art USC coal-fired power plants. On the other hand, the design and manufacture of these units by Korean companies. In ROK, Doosan Heavy Industries has the technology know-how to manufacture its own SC boilers, and is currently in the process of acquiring the know-how to achieve full technological independence with regards to the development of USC boilers (Lee, 2012).

In the Russian Federation, information on the development of SC and USC technologies is not easy to come by. However, it can be observed that these technologies do not appear to be experiencing a quick uptake in the Russian Federation, despite being one of the coal-fired power generation technologies mentioned in the Long-Term Programme for the Development of the Coal Industry up to 2030. For instance, the construction of the Petrovskaya GRES SC power plant planned in 2012, to be located in the Shatuskoy district of the Moscow region, was in the process of being reviewed due to the high costs of the project. Another project consists of a SC CFB 330 MW boiler that is planned to be constructed at the Novochehraskaya GRES power plant in 2014. The boiler will be provided by an overseas manufacturer, Foster Wheeler, through the Russian company OAO EM Alliance. Also important to note, in the Russian Federation SC and USC coal-fired boilers are being developed by OAO I.I. Polzunov CKTI, although the results of this work are not available yet in the literature (Gorlov and Agapova, 2013).

It can be concluded that SC and USC coal-fired power are proven and mature technologies, with many years of large-scale commercial experience. Technological progress has been more on incremental than on disruptive improvements. The deployment of advanced coal combustion technologies, including SC and USC, is a priority in China, Japan, the Republic of Korea and the Russian Federation.
Japanese companies have been global leaders on these technologies for years, while more recently Chinese companies have been able to catch-up with international technology providers. On the other hand, ROK manufacturing giants are expected to soon achieve a level of full technological independence on these technologies. One important observation is that these technologies, owing to their commercial viability and high-level of technological sophistication, are in the hands of large organizations, mostly private-owned, but they also include SOEs such as in the case of China.

2.5 Fluidized Bed Combustion Technologies

Fluidized bed combustion (FBC) is a combustion method to burn fossil fuels in power plants and an alternative to pulverized coal combustion. The fuel is crushed instead of pulverized, and the combustion occurs at lower temperatures than in PC units.

In FBC, coal is burnt in a reactor that contains a mass of granular solids, called “bed materials”, which may consist of sand or gravel, limestone, ash from coal or a combination of these. On a FBC reactor, a continuous stream of air is injected at high pressures from the bottom of the bed, which causes the solids to suspend and behave like a fluid. When coal is discharged into the reactor, the mixing of the fuel with the hot fluidized bed materials creates conditions for a good combustion process and an efficient heat transfer (Dong, 2011; Basu, 2006).

There are basically two main formats of boilers using FBC: i) bubbling fluidized bed; and ii) circulating fluidized bed. The main difference lies in the injection speed of the air/gas that fluidizes the bed, with higher speeds in circulating fluidized bed combustion (CFBC). In a CFBC boiler, the gas speed is high enough to push the bed materials along with the flue gases to the upper areas of the furnace. These materials are captured by a cyclone, which separates the solid particles from the flue gas, returning them to the furnace for recirculation. Because of this the process is known as “circulating fluidized bed combustion”. An important aspect of the technology is that limestone is fed into the combustion system to control the emissions of SO₂, usually achieving abatements of 95%. A simplified illustration of the process is provided in figure 2.6.

Both bubbling and circulating fluidized bed combustion may operate under either atmospheric pressure or under high pressure, with the latter being usually known as pressurized fluidized bed combustion. Non-pressurised FBC units are the most widely applied type of FBC, with efficiencies similar to those of PC combustion units. Pressurized reactors are less common, and have been considered a “dead” technology (Dong, 2011). Bubbling FBC is commonly used in industrial applications (mostly on small boilers with capacities up to 25 MW), while CFBC boilers are on their majority used for power generation. As such, they are the FBC variant examined more in detail on this section.
There are several benefits associated with CFBC vis-à-vis PC combustion (IEA CCC, 2013b; Gorlov and Agapova, 2013):

- CFBC boilers are extremely flexible, allowing a wide range of fuel qualities and sizes to be burnt. This makes them particularly suited for low-rank coals;
- Combustion temperatures are relatively low (800-900°C) compared with PC combustion (1300-1700°C), which results in considerably reduced formation of NOx;
- The fuel does not require fine grinding (crushing is sufficient) prior to feeding into the furnace, thereby eliminating the need of coal mills and improving the overall environmental impact of thermal power plants;
- Lower temperatures limit ash fouling and the corrosion of materials of heat transfer surfaces in the furnace;
- Most of the sulphur in the coal can be captured if limestone is used as bed material (up to 95% SO2 reductions can be achieved).

CFBC is considered a mature technology, and has been in use for power generation for more than 25 years. Progress on the technology continues. One of the major drawbacks associated with the technology is that almost all of the existing CFBC units are small in size (usually 200-300 MW, compared to units above 1000 MW for a PC combustion boiler), and operate with subcritical steam conditions, which makes them less efficient than SC and USC PC combustion. In addition, the use of fans to inject the air in the reactor to fluidize the bed results in an energy penalty. The poorer economies of scale and the lower efficiencies of CFBC units have limited their deployment, making CFBC accounting for just a small fraction of the global coal-fired generation capacity (Dong, 2011; IEA CCC, 2013b).

Until quite recently, CFBC was only available in subcritical technology, but the first supercritical CFBC was commissioned in 2009 at Lagisza, in Poland, with a capacity of 460 MW. The plant was designed by Foster Wheeler, a large manufacturing conglomerate, and it has a rated efficiency of 43.3%. Another major CFBC unit exists in the USA, the 320 MW plant of Jacksonville, although this is a subcritical unit (Burnard and Bhattacharya, 2011). Major international manufacturers of CFBC boilers include Alstom and Foster Wheeler. Among NEA countries there has been a significant interest on this coal combustion technology.
In **China**, CFBC technologies have been developing fast in the past two decades, due to their potential as a versatile technology that can utilize a variety of fuels and the reduced emissions of pollutant gases. Chinese organizations firstly mastered the basic principles of flow, combustion and heat transfer of circulating fluidized bed. From 2000 to 2005, a number of CFBC boilers with 135-150 MW capacity were put into operation. After 2005, the technology for a 300 MW CFBC supercritical boiler was introduced, with a pilot project at the Baima Neijing Sichuan power plant using anthracite. The technology solution was provided by Alstom. Afterwards, the technology was successfully adopted and developed by Chinese organizations, and applied to lower-rank coals. At present, 300 MW CFBC boilers (subcritical conditions) are manufactured by Chinese companies, including Harbin Boiler, Dongfang Boiler and Shanghai Boiler, which are able to compete with international manufacturers both on cost and quality. Research on 600 MW CFBC supercritical boilers was initiated in 2008, with three companies developing this technology (Yuhong and Yongxu, 2012).

In **Japan**, many CFBC boilers are in operation, mostly in industrial applications, and the technology is available from Japanese manufacturers, chiefly among them is the IHI Corporation. Worthy of note is the R&D work on pressurized FBC technology, which was conducted by the J-Power’s Wakamatsu Research Institute, with a 71 MW unit being tested. A 360 MW commercial power plant was constructed and put into operation in 2001, with a net efficiency of 41.8% (JCOAL, 2012).

In **Mongolia**, a CHP plant with a power generation capacity of 415 MW is planned to be built in Ulaanbaatar by an international consortium consisting of International Power, Sojitz Corp., Posco Energy and Newcom LLC. It will be equipped with three CFBC boilers, which are expected to significantly reduce the emissions of pollutants. The technology is fully provided by GDZ Suez, a French company, under an engineering, procurement and construction contract. No other projects or initiatives on FBC were identified with the involvement of Mongolian organizations (Avid, 2012).

In the **Republic of Korea**, at the time of writing there were 21 CFBC boilers in operation, with 6 under construction for the production of electricity and heat. All of these use coal as a feedstock. The Korean Electric Power Research Institute (KEPRI) has plans for a research initiative for developing a combustion process for fuel diversification in commercial CFBC boilers, which is supported by several power generation companies in ROK. On this project, the application of various fuels (including biomass, refuse-derived fuel, wastes and low-rank coals) will be tested. Furthermore, a national research roadmap in the field of thermal power generation is currently being developed for technology to be commercially available in 2020. The development of supercritical and ultra-supercritical CFBC boilers, associated with oxy combustion technology (please check chapter 6 for additional details), is part of this roadmap (Lee, 2012).

In the **Russian Federation** relevant activity in the field of FBC can be observed, with several companies and research organizations developing this technology. In fact, different FBC boilers have been in development and are currently used in a number of regions in the Russian Federation, which use for both hard and brown coals. Worthy of note is the development of a simpler, more reliable and cost-effective “alternative” to conventional FBC boilers. This consists in employing a high-temperature CFBC combustion technology, which minimizes the volume and cost of commercial boilers retrofit, while providing the advantages of FBC technology. On this technology, fuel is combusted in two stages: i) in the fluidized bed where 40-60% of combustion air is injected; and ii) in the freeboard of the furnace where secondary air is injected in heavy jets. The capacity of these boilers ranges between 1.5 to 50 MW, and they are particularly suitable for retrofitting existing facilities. The payback period for retrofitting is on average 1.5-2 years, which led to the successful implementation of this technology at a few boiler houses in several opencast mines across the country. These high temperature FBC boilers have been developed and are manufactured in the Russian Federation,
for example, by OAO Dorogobushkotlomash and Petrokotel-VCKS. The latter is a major product engineer and a leader on this technology in the Russian Federation (Gorlov and Agapova, 2013).

In summary, fluidized bed combustion is an alternative to PC combustion, and is particularly suitable to low-rank coals. Interest to this technology has increased in recent years, and NEA countries have not been an exception to this trend. In line with SC and USC technologies, and as observed in the previous sub-chapter, FBC these technologies are commercially available and the intellectual property is mostly owned by large corporations, some of them being companies from NEA countries.

### 2.6 Other Technologies

This sub-chapter briefly sheds light on two areas related to efficiency improvements of coal production and utilization processes, and which are of relevance in the sub-regional context: i) briquetting of coal; and ii) consumption of water in the coal industry.

Briquettes consist of blocks of solid fuel which have been compressed. The use of briquettes from coal reduces the emission of CO₂ due to the fact that the combustion process is more efficient than unprocessed coal. Further advantages can be obtained if the briquettes can be made available as a smokeless fuel, with low ash and sulphur content. This can be of great importance in countries where the access to modern cooking and heating fuels is not universal and where coal is a widely available resource. Mongolia is a case in point.

Mongolia’s capital, Ulaanbaatar, has been facing severe problems with air pollution due to the combustion of coal not only in coal fired power plants, but also in small and medium boilers and domestic stoves. Most of the coal used is untreated, with its combustion contributing to the release of CO₂ and other pollutants into the atmosphere. The introduction of smokeless fuels is therefore a priority of the Mongolian government, and several companies have been developing initiatives on this area. Among those are included the Mongolyn Alt Corporation (MAK), NAKO, Sharyngol Energy and Amore international (Avid, 2012).

MAK, for example, has built a plant that produces smokeless semi-coke from coal of the Eldev deposit, which is located approximately 200 km south-east of Ulaanbaatar. NAKO, a newly created Mongolian small company, has recently completed a semicoke-based briquette manufacturing factory in the city of Darkhan, located 220 km north of Ulaanbaatar. Similar projects are underway by Sharyngol Energy and Amore International. One of the difficulties facing these projects is the lack of domestically available binder materials for the production of briquettes, and therefore this could be an area with opportunities for technology cooperation between Mongolia and other NEA countries (Avid, 2012).

With respect to the second issue, it is important to underscore the large quantities of water that are required for the production and utilization of coal, particularly for coal beneficiation and power generation. As noted in chapters 5 and 6, the liquefaction of coal and CCS are also water-intensive processes. In NEA countries, specifically in China and Mongolia, coal production processes tend to be located in arid regions with limited water resources, and therefore the success in deploying coal upgrading and advanced coal-combustion technologies will to a large extent rely on reducing water requirements.
In the case of coal-fired power plants, a critical factor for site selection is the existence of a reliable and abundant source of water, which is required for the following operations: water to drive the turbines; cooling water for the steam turbine condensers; water to operate the flue-gas desulphurization plant; water for handling and disposing ash. For example, 1 MWh of electricity generated from coal uses 1,200-2,000 litres of water, which excludes the water required for mining and washing the coal. On the other hand, options available to significantly reduce water consumption in power generation – for example through the use of air-based cooling systems – usually lead to the reduction of plant efficiencies of 4-5% (IEA, 2013a).

In conclusion, technologies on coal upgrading and advanced coal-combustion technologies should be accompanied with progress on water consumption requirements.

2.7 Summary and Implications

This chapter has assessed coal technologies that enhance the efficiency of coal conversion processes. Two different but closely interrelated families of technologies were analysed: coal upgrading technologies and advanced-coal combustion technologies. While the former relates to the upstream of the coal-to-electricity chain, the latter pertains to its downstream.

Coal accounts for around one third of total primary energy consumed in the world, 58% of which in the North-East Asia sub-region. Therefore there is a strong need to use coal more efficiently, not only to derive a higher economic value from the coal resource, but also to reduce the negative environmental impacts resulting from its use.

This chapter reviewed a set of coal upgrading technologies, specifically the beneficiation of coal – mostly aimed at high-rank coals – and coal drying technologies, used to remove the moisture of low-rank coals. Although these technologies already exist and are encouraged in NEA coal producing countries, the analysis indicated that there is the need for further deployment and dissemination. An area which could be the focus of higher attention from policymakers in NEA countries pertains to coal drying technologies, whose uptake has been relatively slow. However, its importance in improving the efficiency of coal-fired power generation, reducing environmental impacts, and in increasing the economic value of low-rank coals, should not be overlooked. Its dissemination and mainstreaming could ultimately lead to an increase in the global reserves of lignite and sub-bituminous coal.

Pulverized-coal combustion has been the prevailing mode of firing coal for electricity generation worldwide for almost a century, and such plants remain the backbone of the power sector in many countries. Currently, there is a wide gap between the average performing coal-fired power plant (efficiencies of 33%) and the state-of-the art commercially available technologies (efficiencies of 45%). The adoption of advanced coal-combustion technologies can lead to a significant increase in the global average efficiency of coal-fired power generation. Among these, the adoption of supercritical and ultra-supercritical steam cycles have been the technology of choice for achieving improved efficiencies. Other advanced coal combustion technologies, such as fluidized bed combustion (FBC) and integrated gasification combined cycle (IGCC), are likely to remain a “niche”, but its uptake is likely to gradually increase in the next few years.
FBC technologies, in particular circulating fluidized bed combustion (CFBC), have been of great interest among NEA countries due to their flexibility in burning a wide range of fuels – including low-rank coals which would otherwise not be used due to their poor quality – and the lower emissions of pollutants, such as NOx and SO2. The technology has progressed significantly in the last 20 years and is currently considered mature. There is however scope for further technological improvements, particularly with regards to the manufacture of larger boilers, so as to achieve the economies of scale of state-of-the-art PC combustion boilers, and the application of more advanced steam conditions, i.e. SC and USC. Although the development of these technologies is to a large extent driven by the private sector, government support still plays a key role, both in terms of financing of R&D activities and demonstration projects, as well as in the creation of the necessary enabling framework.

Based on the analysis above, the key messages to policymakers and practitioners are as follows:

On coal upgrading technologies:

▶ NEA countries should continue and further increase their support to accelerate the deployment of coal upgrading technologies. This support could consist in overcoming some of the barriers that hinder their dissemination, such as the set-up of pricing mechanisms that reflect the improved quality of upgraded coal. On this aspect for example, there appears to be scope for coordination at sub-regional level.

▶ There is a wide variety of commercially available coal beneficiation technologies, with cooperation among NEA countries already existing to some extent on a commercial basis. This cooperation has the potential to be further enhanced, particularly among coal producing countries. Opportunities exist for example in the formulation of harmonized quality requirements for imported coal and in the possibilities for initiating R&D and demonstration programmes on priority areas among countries, which could include less water intensive processes or dry separation technologies.

▶ NEA countries seem to be somewhat lagging in the adoption of coal drying technologies. Given the high energy efficiency penalty associated with the direct utilization of low-rank coals and their abundance in countries in the sub-region, it is recommended this to be an area of increased attention. The formulation of policies and regulations to encourage the uptake of these technologies should be considered, whereas opportunities for sub-regional cooperation could be in the joint development of some of the most promising coal drying technologies and their application in joint demonstration projects.

On advanced coal-fired power generation technologies:

▶ NEA countries should continue their policies of accelerating the deployment of advanced coal-fired power generation technologies by creating the necessary enabling framework, either in terms of policies, targets, regulations or a combination of these. NEA countries could further exchange their experiences and approaches in encouraging energy efficiency in the power generation sector and, in specific areas, there may be the potential for harmonizing policies and/or targets at sub-regional level, for example in coming up with common targets for CO2 emissions from coal-fired power plants per unit of electricity produced. Such cooperation should also consider the potential to include carbon capture and storage (CCS) in coal-fired power plants as well as less water-intensive processes.

▶ R&D and demonstration of advanced “next-generation” coal-fired combustion technologies should be proactively promoted and supported by policy-makers of countries in NEA. Emerging technologies where support from public funds would be most necessary include
advanced-USC steam conditions for PC combustion, larger CFB units (i.e. on par with the largest commercially available models for PC combustion), and the full-demonstration of supercritical and ultra-supercritical steam conditions applied to fluidized bed combustion boilers. Given the strong interest of NEA countries on advanced coal combustion technologies, there is a potential for these countries to work together to further accelerate deployment, for example through knowledge sharing networks and the set-up of specific technology platforms where different areas of technical expertise could be integrated and synergized.

International cooperation among NEA countries could be instrumental in introducing cleaner and more efficient coal combustion technologies in Mongolia and DPRK, where older, more polluting and less efficient power plants continue to be in operation. With the support of policymakers of related NEA countries, who could use the framework of the intergovernmental collaborative mechanism on ECNEA, the transfer of advanced coal combustion technologies could be enabled and accelerated. For both countries, and given their status of low-middle income and least developed countries, respectively, the introduction of these technologies could be supported by international climate financing mechanisms and, for example, be framed in the context of Nationally Appropriate Mitigation Actions, which could also leverage support in terms of technology transfer and capacity building.
3.1 Introduction and Background

Coalbed methane (CBM) is a generic term used to designate the methane found in coal seams. Large quantities of methane are produced during the coal formation process (“coalification”) and adsorbed on the pores of the coal matrix. In general, the amount of methane in a coal seam increases with the depth of the seam and the rank of the coal. If the seam is disturbed in some way, CBM can be easily released either when the mining activities occur or during the drilling and construction works that precede the coal mining. The gas then escapes through fissures in the rock until it eventually reaches the surface and is released into the atmosphere (Sloss, 2005).

Four main categories of CBM can be identified (Sloss, 2006):

- **Coal mine methane (CMM)**, usually known in the literature as coalbed methane (CBM), is the methane drained from mines either before or during mining activities;
- **Ventilation air methane (VAM)**, is diluted methane which reaches the surface through the mine ventilation system;
- **Virgin coal bed methane (VCBM)**, refers to the methane from coal seams that have not been mined for the extraction of coal;
- **Abandoned coal mine methane (ACMM)**, refers to the methane extracted from previously worked mines.

Coal mine methane has always been considered a hazard for underground coal mining due to its explosion risk, which can be a serious threat to the safety and productivity of mining activities. Methane is an explosive gas in the range of 5-15% in air on a volumetric basis, and therefore one of the main duties of ventilation systems is to keep methane levels well beyond the explosive limits. The diagram in figure 3.1 presents the combination ranges of methane with air that make it a hazardous explosive gas.

To reduce the risks to coal miners, the minimization of CMM concentrations in mines has been the main driver for recovering CMM, with the primary and most straightforward method consisting in diluting and venting the gas into the atmosphere. On the other hand, CBM is a potential source of energy and can be used as a natural gas resource, for example for the production of electricity in a gas turbine. In addition, methane is a greenhouse gas 20 times more potent than CO₂, and concerns over climate change have increased the interest in recovering this methane instead of venting it into the atmosphere.

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3 For the purposes of this study, CBM and CMM are used interchangeably.
Table 3.2 provides a summary of the main policy drivers for the adoption of CBM recovery and utilization technologies in NEA countries: This chapter provides an overview of technologies used to recover and utilize coalbed methane. Sub-chapter 3.2 focuses on technologies associated with the recovery of CBM, in particular ventilation and degasification systems. Sub-chapter 3.3 sheds light on technologies that can be employed to utilize CBM as an energy resource, which primarily depend on the availability and concentration of the methane extracted from coal mines. Sub-chapter 3.4 reflects on other important relevant technologies related to the handling of CBM, while sub-chapter 3.5 draws the main conclusions and implications from the analysis.

There are two main methods to control and recover methane from coal mines: i) ventilation systems and ii) degasification systems (IEA, 2009b). Ventilation systems are utilized to move large volumes of air into the mine in order to dilute and remove hazardous gases – among and above all methane – from the mine’s working front. The resulting ventilation air methane (VAM), whose methane concentrations are usually less than 1% in volume of air, is generally released into the atmosphere, although methods exist to utilize this gas (analysed in sub-chapter 3.3).

In the North-East Asia sub-region, interest on CBM is primarily driven by those countries with active and sizeable mining industries, i.e. China and the Russian Federation. The Russian Federation, for instance, holds the largest resources of hard coal in the world, which are also amongst the most gas-rich, with an average of 11.6 m³ of methane per ton of coal, as can be observed in table 3.1. On the other hand, China has extensive coal deposits and derives most of its primary energy needs from coal, with methane emissions from mining activities corresponding to around half of all global CMM released (IEA, 2013a).

![Figure 3.1 – Diagram with the explosion ranges of methane in the air. (Source: UN ECE, 2010)](image)

Table 3.1 – Average methane content per ton of coal in selected countries. (Source: Gorlov and Agapova, 2013)

<table>
<thead>
<tr>
<th>Country</th>
<th>Methane content (m³/t)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Russian Federation</td>
<td>11.6</td>
</tr>
<tr>
<td>United Kingdom</td>
<td>10.3</td>
</tr>
<tr>
<td>China</td>
<td>9.3</td>
</tr>
<tr>
<td>USA</td>
<td>7.0</td>
</tr>
<tr>
<td>Germany</td>
<td>5.0</td>
</tr>
</tbody>
</table>
Table 3.2 provides a summary of the main policy drivers for the adoption of CBM recovery and utilization technologies in NEA countries:

<table>
<thead>
<tr>
<th>Country</th>
<th>Policies and strategies</th>
</tr>
</thead>
</table>
| China              | • A comprehensive number of policies are in place in the areas of planning, development and safety on coal mine methane recovery and utilization;  
|                    | • In April 2008, the Ministry of Environmental Protection issued an Emission Standard of CBM/CMM, which prohibits CMM drainage systems to emitting CMM. |
| Japan              | • No specific measures identified on CBM recovery and utilization, given the limited coal mining activities in the country. |
| Mongolia           | • A government-action plan emphasizes the importance of CBM and there is the intention of using it as an energy resource, as well as possible feedstock for liquid transportation fuels. |
| Republic of Korea  | • No specific measures identified on CBM recovery and utilization, given the limited coal mining activities in the country. |
| Russian Federation | • Since 2011, degasification is compulsory in mines where the methane content of coal is above 13 m³/t;  
|                    | • Extensive legal and regulatory measures exist to promote the safe application of high-tech equipment in methane-rich mines, such as the “Guidelines on Ventilation Design for Coal Mines” (1989). |

Table 3.2 – Policies and strategies on coalbed methane recovery and utilization on NEA countries.  
(Source: own elaboration based on IEA, 2009a; JCOAL, 2012; Avid, 2012; Lee, 2012; and Gorlov and Agapova, 2013)

This chapter provides an overview of technologies used to recover and utilize coalbed methane. Sub-chapter 3.2 focuses on technologies associated with the recovery of CBM, in particular ventilation and degasification systems. Sub-chapter 3.3 sheds light on technologies that can be employed to utilize CBM as an energy resource, which primarily depend on the availability and concentration of the methane extracted from coal mines. Sub-chapter 3.4 reflects on other important relevant technologies related to the handling of CBM, while sub-chapter 3.5 draws the main conclusions and implications from the analysis.

3.2 Coalbed Methane Recovery Technologies

There are two main methods to control and recover methane from coal mines: i) **ventilation systems** and ii) **degasification systems** (IEA, 2009b). Ventilation systems are utilized to move large volumes of air into the mine in order to dilute and remove hazardous gases – among and above all methane – from the mine’s working front. The resulting ventilation air methane (VAM), whose methane concentrations are usually less than 1% in volume of air, is generally released into the atmosphere, although methods exist to utilize this gas (analysed in sub-chapter 3.3).
Degasification systems are techniques used to drain methane from coal seams in order to maximize CBM capture and utilization. The main purpose of methane drainage is to capture high purity gas before it can enter the mine airways. These techniques can be divided into two main groups (IEA, 2009b; UN ECE, 2010):

- **Pre-mining drainage**: consists in draining the gas from coal seams prior to the start of mining operations, either from the surface or from inside the coal mine; and

- **Post-mining drainage**: consists in capturing the gases released from surrounding coal seams after coal is extracted as a result of movements on adjacent strata to a longwall face and increased permeability of the seam due to the mining activity. These regions of fractured material are known as “gob” or “goaf”, and post-mining drainage techniques recover the gas that is found on these areas, the so-called “gob gas”.

The selection of degasification system depends on factors such as the source of methane, the coal type, the permeability of the coal seam, and the coal extraction method. The permeability of the coal is an important factor to take into account. Indeed, the lower the coal permeability, the more time is required to drain the gas from the coal seam. A low permeability may imply a higher number of boreholes to achieve the desired methane levels prior to the start of the mining operations, which would result in increased costs. The time required for degasification and the costs associated with the operation are factors that determine the feasibility of pre-mining drainage. A combination of pre and post-mining drainage techniques may eventually be applied (UN ECE, 2010).

There are many different gas drainage techniques in use across the globe, and the main methods are summarized in the table below. In essence, four pre-drainage methods and three post-drainage methods are applied:

<table>
<thead>
<tr>
<th>Technique</th>
<th>Description</th>
<th>Advantages</th>
<th>Disadvantages</th>
</tr>
</thead>
</table>
| Vertical drilling from the surface (pre-drainage) | • Well drilled from the surface  
• Involves fracturing one or more coal seams using high-pressure fluids | • High-purity gas is usually obtained           | • High costs 
• Arrangements at the surface can be difficult in terms of land ownership, visual impact and “nimbyism” |
| Horizontal (directional) drilling from the surface (pre-drainage) | • A vertical hole is first drilled, and then directional drilling is initiated in order to reach the target seam | • High-purity gas usually obtained 
• More effective gas recovery than through vertical wells 
• Drilling location is flexible due to the directional drilling | • High costs 
• Specialist drilling equipment and skills are necessary |

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4 Longwall mining is an underground mining method where a long wall of coal is mined in rectangular blocks with the support of mechanical shearsers. Coal recovery rates can achieve 75%. Once coal is extracted from a certain area, the roof is allowed to collapse in a controlled way (IEA, 2013a).
The methods and technologies presented in the table above are, in most of their variants and applications, fully demonstrated and commercially available. In NEA countries, and as much as in other countries around the globe, the introduction of ventilation and drainage technologies is compulsory on underground coal mining. Coal safety is the main driver for the deployment of these technologies.

In China, the drainage of CMM from underground coal mines dates back to the 1950s, but it has been since 2005 that CMM drainage has quickly developed. While in 1994 the quantity of CMM drained was of only 564 million m³, in 2010 it reached 7.35 billion m³. Presently, China has entered into a stage of extensive gas drainage, that is, the application of multiple drainage methods in a mining area so as to maximize the quantity of gas recovered (Yuhong and Yongxu, 2012).

<table>
<thead>
<tr>
<th>Technique</th>
<th>Description</th>
<th>Advantages</th>
<th>Disadvantages</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Horizontal drilling from within the mine</strong></td>
<td>Boreholes are drilled from roadways located in the mine underground</td>
<td>High-purity gas usually obtained</td>
<td>The coal seam needs to be highly permeable</td>
</tr>
<tr>
<td>(pre-drainage)</td>
<td></td>
<td></td>
<td>Boreholes need to be drilled prior to the mining operations start</td>
</tr>
<tr>
<td><strong>Superjacent borehole drilling</strong></td>
<td>Used to pre-drain methane from over and under-lying gassy strata adjacent to the target coal seam</td>
<td>Low-cost method to reduce risks from gas that is adjacent to coal seams</td>
<td>Low gas flows</td>
</tr>
<tr>
<td>(pre-drainage)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Cross-measure boreholes</strong></td>
<td>The gas is drilled from mine entries adjacent to the longwall face</td>
<td>High capture of gas is possible</td>
<td>The productive life of boreholes is usually short</td>
</tr>
<tr>
<td>(pre-drainage)</td>
<td></td>
<td>Effective in low-permeability coal seams</td>
<td>Trained underground team is required</td>
</tr>
<tr>
<td><strong>Vertical and deviated gob wells</strong></td>
<td>These wells are drilled from the mine surface</td>
<td>Gas drainage operations independent of underground activity</td>
<td>Costly option for deep coal seams</td>
</tr>
<tr>
<td>(pre-drainage)</td>
<td></td>
<td>Well-proven and cost effective method</td>
<td>Risk of water inflow</td>
</tr>
<tr>
<td><strong>Superjacent methods</strong></td>
<td>The degasification takes place from overlying and/or underlying mining galleries</td>
<td>Potentially higher gas capture than cross-measure boreholes</td>
<td>High costs</td>
</tr>
<tr>
<td>(pre-drainage)</td>
<td></td>
<td></td>
<td>Fire risk in spontaneous combustion-prone coal seams</td>
</tr>
</tbody>
</table>

Table 3.3 – Overview of gas drainage methods.
(Source: UN ECE, 2010; EPA, 2009)
Among the technologies and techniques developed by Chinese organizations for recovering CMM, it is worth emphasizing the research work conducted by the Huainan Mining Group. One of these techniques consists in the co-production of coal and gas, whereby the pre-drainage of gas is made in coordination with the coal mining activities, maximizing the productivity of the mine. With this method, an order for the extraction of coal and gas is scientifically defined, which includes the geological assessment, surface pre-drainage of gas, mine construction works, coal mining, drainage of gas while mining coal and post-drainage of gas (Yuhong and Yongxu, 2012). The Huainan Mining Group has also researched and developed a “pillarless” continuous mining technique. This technique consists in introducing an “Y-ventilation” system along the gateway of a mine, and then recovering gas from the adjacent seam using high angle upper (or lower) cross-measure boreholes. This technique can greatly improve the recovery rate of the gas, saving costs, and effectively improving the working environment of the coal mine working face (Yuhong and Yongxu, 2012).

With respect to pre-drainage technologies, there are several different methods being applied in coal mines in China. At present, technologies to extract CBM from the surface are mature, and successful results have been obtained in many basins with different geologic structures. The Qinshui Blue Flame Co. Ltd, subsidiary of the Jincheng Coal Mining Group, is a leader in these technologies in China (Yuhong and Yongxu, 2012).

An initiative worthy of note is a project jointly developed by China and Canada for the injection of CO2 to enhance coal mine methane recovery rates. The purpose of the project, which was launched in January 2008, is to test a new CO2 injection technology in deep unworkable coal seams and to effectively ensure the geological storage of CO2 in the seam. This is, in reality, a means of utilizing and storing captured CO2. The partners of the project are the China United Coalbed Methane Company Limited, Petromin Resources Ltd, and the EnviroEnergy International Holding Ltd. The test site is in the Qinshui Basin, Jincheng city, Shanxi Province (Yuhong and Yongxu, 2012).

In Japan, several companies and organizations have developed cutting-edge technologies for the recovery of CMM. These technologies have been developed when Japan had several coal mines in operation. Currently, only one underground coal mine is active in Japan, mainly for keeping and testing Japanese technologies for CMM recovery and utilization, as well as for the training of miners from other countries on these technologies, including on mine safety issues (JCOAL, 2012).

Some Japanese organizations have been developing enhanced CMM utilization technologies. These technologies are of relevance and particularly suited to address challenges related to the gas drainage on CO2-rich low permeability coal seams, and in the drainage of shallow coal seams with low pore pressures. One method developed by JCOAL consists in the injection of a low adsorbing gas through boreholes from the surface until it reaches the target coal seams. The injected gas penetrates into the coal and displaces CMM that can then be recovered through normal gas drainage boreholes. This technique has been trialled in the US and in Japan, where nitrogen was the injected gas. Another gas that could prove suitable for injection is exhaust or flue gas, including CO2, as illustrated in the figure below (JCOAL, 2012):
In **Mongolia**, there is a dearth of technological know-how both on CBM recovery and utilization technologies. The first project on CBM in Mongolia has been conducted in the Nalaikh mining site, which is an underground mine located 40 km southwest of Ulaanbaatar with more than 70 years of activity. The first phase of the project consists in drilling test boreholes in the projected mining area in order to determine its CMM potential. The recovered gas will be used for power generation to support the mine’s electricity needs (Avid, 2012).

In the **Republic of Korea**, KOCOAL is producing anthracite from three coal mines. KOCOAL is reputed for its underground mining technological skills, which can reach 1,000 meters below the surface level. These drilling technologies are presented in the table below:

<table>
<thead>
<tr>
<th>Drill Type</th>
<th>Data</th>
<th>Advantages</th>
<th>Disadvantages</th>
</tr>
</thead>
<tbody>
<tr>
<td>Auger</td>
<td>Geochemical sampling, top few metres of unconsolidated material</td>
<td>• Portable, usually Landcruiser mounted; &lt;br&gt; • Uncontaminated sample, &lt;br&gt; • Quick and cheap.</td>
<td>• Poor penetration</td>
</tr>
<tr>
<td>Rotary Air Blast (RAB)</td>
<td>Geochemical sampling until the base of regolith</td>
<td>• Large sample volume; &lt;br&gt; • Quick and cheap.</td>
<td>• Does not penetrate hard rock; &lt;br&gt; • Sample contamination; &lt;br&gt; • Limited depth; &lt;br&gt; • No structural data.</td>
</tr>
</tbody>
</table>

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*Figure 3.2 – Simplified illustration of the enhanced coal mine methane process for underground coal mines. (Source: JCOAL, 2012)*
While the top priority for the recovery of CMM is mine workers’ safety and increased mine productivity, the methane extracted from coal mines is a resource that can be harnessed into some productive use. In addition, if untapped this resource will be released into the atmosphere and contribute to global warming, as methane is a greenhouse gas. Thus there are two potential avenues for NEA countries to derive value from the recovery of CMM: i) utilization of the methane as an energy resource; and ii) generation of carbon credits from the avoidance of methane emissions (please check Box 3.1 below).

There are several possible utilizations for the methane captured from mining activities, although two main uses can be distinguished: utilization as a fuel or as feedstock in the chemical industry. The utilization of CMM depends first and foremost on the concentration and quality of the gas drained from the mine. For example, VAM is difficult to use as a source of energy because methane is in small and variable concentrations. For utilization in the chemical industry, the concentration of methane in the feedstock usually needs to be very high (>85%), such as for the production of methanol or dimethyl ether (both analysed in detail in chapter 5, on coal-liquefaction technologies). Other criteria to take into account are the projected gas flow rate, the proximity to markets for end-products, and the estimated duration of the gas production.

In the Russian Federation, the degasification of underground coal mines is usually carried out either by stationary centralized suction systems or mobile gas pumps. Mines without degasification equipment frequently use fans to move air from working areas towards goaf areas. While these are much cheaper and simpler technologies than proper degasification systems, Russian experts have considered them to be very dangerous, as they lead to the accumulation of explosive concentrations of methane and dust. Despite this, the situation has been changing considerably in the past few years with greater use of degasification systems, whose primary goal is to ensure workers’ safety and achieve higher mining productivity (IEA, 2009b; Gorlov and Agapova, 2013).

The introduction of degasification technologies is encouraged and, above certain thresholds of methane concentrations in the coal seams, made compulsory by regulation in the Russian Federation. However, the adoption of these technologies has been slow and limited, mainly due to their high costs and the limited technical expertise of Russian coal companies, particularly on cutting-edge drilling technologies. Despite this, Russian coal companies have gradually started to adopt foreign technologies and adapt them to the characteristics of Russian coal mines (IEA, 2009b).

In conclusion, the analysis indicates the different levels of adoption of CMM recovery techniques and technologies among NEA countries. While the uptake of these technologies has been relatively quick in China, predominantly in the last 10 years, their adoption has been somewhat slower in the Russian Federation. Yet, in China there is still a high potential for further dissemination and uptake of these technologies, whereas in a country like Mongolia their introduction is still at an early stage. On the other hand, Japan appears to be at the forefront on a few cutting-edge CMM recovery technologies, specifically on enhanced CMM recovery techniques, and this know-how and expertise could be utilized and transferred to other countries in the sub-region.

<table>
<thead>
<tr>
<th>Drill Type</th>
<th>Data</th>
<th>Advantages</th>
<th>Disadvantages</th>
</tr>
</thead>
<tbody>
<tr>
<td>Air Core</td>
<td>Geochemical sampling into bedrock</td>
<td>• Minimal sample contamination;</td>
<td>• Small sample size.</td>
</tr>
<tr>
<td></td>
<td></td>
<td>• Quick and cheap;</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>• Some core recovery.</td>
<td></td>
</tr>
<tr>
<td>Reverse Circulation</td>
<td>Geochemical sampling in hard and soft rocks at depths above 200m</td>
<td>• Large and uncontaminated sample;</td>
<td>• Large and heavy rig;</td>
</tr>
<tr>
<td></td>
<td></td>
<td>• Rock chip returns;</td>
<td>• No structural data;</td>
</tr>
<tr>
<td></td>
<td></td>
<td>• Relatively quick and cheap.</td>
<td>• Possible sample contamination below water table.</td>
</tr>
<tr>
<td>Diamond</td>
<td>High quality sampling to greater than 1000 m deep</td>
<td>• Maximum geological information;</td>
<td>• Site preparation and water supply required;</td>
</tr>
<tr>
<td></td>
<td></td>
<td>• Uncontaminated high quality sample;</td>
<td>• Small sample size;</td>
</tr>
<tr>
<td></td>
<td></td>
<td>• Accurate hole positioning</td>
<td>• Slow operation;</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>• High costs.</td>
</tr>
</tbody>
</table>

Table 3.4 – Drilling technologies available in the Republic of Korea (i.e. KOCOAL).
(Source: Lee, 2012)
3.3 Coalbed Methane Utilization Technologies

While the top priority for the recovery of CMM is mine workers’ safety and increased mine productivity, the methane extracted from coal mines is a resource that can be harnessed into some productive use. In addition, if untapped this resource will be released into the atmosphere and contribute to global warming, as methane is a greenhouse gas. Thus there are two potential avenues for NEA countries to derive value from the recovery of CMM: i) utilization of the methane as an energy resource; and ii) generation of carbon credits from the avoidance of methane emissions (please check Box 3.1 below).

Box 3.1 – Coal Mine Methane and Climate Change Mitigation

The release of methane from coal mines is one of the largest anthropogenic sources of methane emissions. However, these emissions can be significantly reduced through the implementation of good practices and appropriate technologies. Despite the fact that global CMM emissions are comparatively small vis-à-vis other GHG emission sources (such as, for example, those released from the combustion of coal), these are not insignificant per se.

Emission reduction credits which can be claimed from the reduction of GHG released into the atmosphere, can provide an additional source of financing of CMM projects in some countries, and thus be a complement to the possible end-uses of the coal methane utilized. There are different options for this so-called “carbon financing”, with the Clean Development Mechanism and Joint Implementation, under the Kyoto Protocol, being the most popular vehicles for tapping such support. In China, for instance, there were nearly 90 CMM projects registered by the CDM Executive Board, with the CDM being a vehicle for additional finance and the transfer of technologies to these projects.

(Source: UN ECE, 2010; UNFCCC, 2013)

There are several possible utilizations for the methane captured from mining activities, although two main uses can be distinguished: utilization as a fuel or as feedstock in the chemical industry. The utilization of CMM depends first and foremost on the concentration and quality of the gas drained from the mine. For example, VAM is difficult to use as a source of energy because methane is in small and variable concentrations. For utilization in the chemical industry, the concentration of methane in the feedstock usually needs to be very high (>85 %), such as for the production of methanol or dimethyl ether (both analysed in detail in chapter 5, on coal-liquefaction technologies). Other criteria to take into account are the projected gas flow rate, the proximity to markets for end-products, and the estimated duration of the gas production.
Table 3.5 – Possible utilization of CBM/CMM as fuel.
(Source: own elaboration based on Sloss, 2005)

<table>
<thead>
<tr>
<th>Gas Quality</th>
<th>Utilization Options</th>
<th>Brief Description / Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>High-quality gas</td>
<td>Injection into a natural gas pipeline</td>
<td>Depends on the proximity to a natural gas pipeline network, as well as the investment requirements for gas cleaning technologies.</td>
</tr>
<tr>
<td></td>
<td>Local distribution</td>
<td>For the heating and cooking needs of towns located in proximity to the extraction site.</td>
</tr>
<tr>
<td></td>
<td>Vehicle fuel</td>
<td>If properly treated, CBM/CMM may be used in an internal combustion engine as vehicle fuel.</td>
</tr>
<tr>
<td>Medium-quality gas</td>
<td>Power generation and combined heat and power</td>
<td>CBM/CMM may be used as a replacement for natural gas in power generation and/or CHP, particularly when the generator is located in relative proximity to the coal mine.</td>
</tr>
<tr>
<td></td>
<td>Coal drying</td>
<td>Captured gas utilized for drying purposes. Practiced in countries such as the USA and Poland.</td>
</tr>
<tr>
<td></td>
<td>Industrial applications</td>
<td>CBM/CMM may be used in industrial boilers.</td>
</tr>
<tr>
<td>Low-quality gas and VAM</td>
<td>Combustion Air</td>
<td>The captured gas is fed into the furnace of a coal-fired power plant boiler as combustion air.</td>
</tr>
<tr>
<td></td>
<td>Oxidation technologies</td>
<td>Consists in the reaction of oxygen with methane aimed at generating heat or power.</td>
</tr>
<tr>
<td></td>
<td>Lean-burn turbines</td>
<td>Turbines that burn fuel with an excess of air.</td>
</tr>
</tbody>
</table>

Among the options listed above, it is of relevance to emphasize the CBM/CMM utilization technologies related to medium and low-quality gases, as these are the most difficult to derive economic value from their utilization. It should be noted that the utilization of CMM in methane concentrations of 2% to 25-30% (allowing for a margin from the 5-15% explosive range of methane in air) is not considered safe, due to the explosion risk (IEA, 2009b).

For the production of electricity with methane from mines, both internal combustion engines and gas turbines can be utilized. Turbines are more suitable to use gas with 35-75% of methane. Internal combustion engines require relatively high methane concentrations (>45%), although more recent developments with membrane systems have enabled the combustion of gases with concentrations in the 25-40% range. One of the challenges associated with the combustion of methane from coal mines is that the concentration of methane may fluctuate significantly throughout the operation period, which affects the overall performance of the engine. To address this potential shortcoming, some gas engines allow the combination of coal mine gas with natural gas in order to ensure that the operation is kept relatively constant (Sloss, 2006).
An important technology for the combustion of low-quality gas and VAM has been the developments on **lean-burn gas turbines**. These are turbines that can run and burn a fuel – in this case, VAM – with an excess of air. There are different concepts for such turbines, mostly in pilot or trial scale (Sloss, 2006; UN ECE, 2010).

There are two other important possible uses to medium and low-quality gases. One is to use CMM as an additional fuel to the combustion of a solid fuel (**co-firing**), such as pulverized coal, which can reduce the emissions of pollutants and increase the efficiency of combustion. Another possible utilization – particularly of VAM – is as **combustion air** in conventional coal-fired power plants.

Finally, another relevant option is the application of **oxidation technologies** for the generation of heat or power, particularly methane from coal mines with very dilute concentrations of methane. For example, thermal flow reverse reactors (TFRR) can work with concentrations of 0.2% of methane, while catalytic flow reversal reactors can operate with concentrations as low as 0.1% (Sloss, 2005). Commercial-scale applications of these technologies have been demonstrated in CMM projects in Australia, China and the USA (UN ECE, 2010).

In **China**, the utilization of CBM is of around 30% of the total generated from coal mining activities, while the remainder is vented into the atmosphere. This is a comparatively low rate, which is to a large extent explained by the low concentration of methane coming from coal mines, suggesting an enormous potential for the utilization of technologies that use low-quality gas as feedstock, as well as for degasification systems instead of ventilation equipment that dilutes the methane underground. CBM/CMM that is captured is mainly used as a fuel for domestic and industrial purposes, and many of these projects can be developed (and a few have already been) under the Kyoto Protocol’s Clean Development Mechanism (Yuhong and Yongxu, 2012).

Amongst the considerable number of CBM/CMM recovery and utilization projects currently in operation in China, the one developed by Jincheng Anthracite Mining Group at the Sihe coal mine should be emphasized. This project utilizes coal methane to run 60 sets of gas turbines, which have a combined capacity of 120 MW, making it the largest power project in the world using CMM. The gas turbines are supplied by Caterpillar. Another project of note in China is the Hongkong China CBM liquefaction project, which is co-funded by the Shanxi Jincheng Anthracite Mining Group and the Hongkong China Coal Gas Company. This was the first and currently is the largest CBM liquefaction project in China (Yuhong and Yongxu, 2012).

In **Japan**, and notwithstanding the cessation of underground coal mining activities since 2002, several technologies for the utilization of CBM/CMM have been developed by Japanese organizations. An example in case is the MACH gas engines of Mitsubishi Heavy Industries, which are particularly suited to CMM fired power generation. This engine is commercially available and demonstrated, and has been in use in projects in China. Another concept worthy of note is the world’s first gas turbine generator utilizing VAM, which is being developed by Kawasaki Heavy Industries. Furthermore, the Osaka Gas Co. Ltd. has been developing a system to upgrade the low-concentration CMM to higher methane concentration gases by applying a material technology to selectively absorb methane in the air-methane mixture. This technology can make low-concentration of CMM available in various forms, such as in fuel for gas engines and gas boilers, and as city gas for domestic and industrial purposes. An illustration of the concept is provided in the figure below (JCOAL, 2012):
Both in Mongolia and the Republic of Korea, no CMM utilization technologies have been identified or are currently in use (Avid, 2012; Lee, 2012).

In the Russian Federation, currently only relatively small amounts of CMM are recovered and used, with cutting-edge technologies being applied in just a few coal mines. This CMM is primarily used for heat and power generation purposes, and as fuel for vehicle engines. Projects on the industrial utilization of drained methane have recently started in the Kuzbass region under the initiative of coal companies that include OAO SUEK-Kuzbass, OAO SDS-Ugol, OAO Yuzhkuzbassugol and OAO UK Yuzhny Kuzbass (Gorlov and Agapova, 2013). A few of these projects have been supported by the Joint Implementation framework, under the Kyoto Protocol.

It can be observed from the analysis above that although CMM utilization technologies are in use in NEA’s largest coal producing countries, i.e. China and the Russian Federation, there is still a great potential for the deployment of these technologies on both countries. The utilization of methane from coal mines not only has the potential to reduce the emissions of methane into the atmosphere, but it can also result in a financial benefit to the project developer. Indeed, many of these technologies are already commercially viable, and thus there is a significant opportunity for building a strong business case on many CMM recovery and utilization projects, which could be of interest to these countries as a complement to the drainage of CMM for safety purposes.

### 3.4 Other Technologies

CBM reservoirs are difficult to characterize due to small-scale heterogeneities in the coal seams, which can differ significantly from seam to seam (Sloss, 2005). Due to this, modelling and simulation technologies are of significant relevance in the context of CBM recovery and utilization projects. Japan has been very active in the development of techniques for modelling CMM. In particular, JCOAL has developed different gas simulation software packages which are commercially available, in particular the following:
There are three main drivers for the recovery and utilization of methane in coal mines. First and foremost concerns over mine workers’ safety and mine productivity, as methane is an explosive gas in the range of 5-15% concentrations in volume of air, and these risks need to be minimized. A second motivation is that methane is a resource that can be made into productive use, while a third motivation is the need to curb the emissions of methane due to its global warming potential as a greenhouse gas.

Two main methods exist to recover CMM: through ventilation systems, and through degasification systems. Ventilation systems move large volumes of air into the mine in order to dilute methane, with the resulting mixture – named ventilation air methane (VAM) – being usually released into the atmosphere. Degasification systems refer to techniques that drain methane from coal seams in order to maximize CMM capture and utilization.

Several different technologies exist to utilize CMM, for a whole range of different concentrations of methane per volume of air. Gas with high concentrations of methane can be used to replace natural gas in gas pipelines for utilization in power plants or vehicles, while medium-quality gas can be used to run internal combustion engines and turbines, and low-quality CMM can be co-fired with natural gas and pulverized coal. CMM with very low concentrations of methane, such as VAM, may be used in power production through oxidation technologies, or as combustion air in furnaces.

The assessment presented on this chapter suggests that the uptake of CMM recovery and utilization technologies in NEA countries has been, at best, moderate. In China, the recovery of CMM has sharply increased in the last 10 years, driven by policy and regulatory measures as well as the introduction of modern methods and technologies. Yet, only 30% of the methane recovered from mines is utilized, indicating the potential for a broader dissemination of both degasification systems and CMM utilization technologies. In the Russian Federation progress on the adoption of these technologies has gradually increased in recent years, but the potential for introducing cutting-edge technologies and best practices, both for the recovery and utilization of CMM, is still quite significant. With respect to other countries in the sub-region, Japan has mastered a set of CMM handling technologies and is prepared to transfer these technologies to other countries. In Mongolia there is a lack of know-how and experience on CMM recovery and utilization technologies, while in the Republic of Korea these technologies are not a priority due to the relatively small coal mining activities. Although DPRK has not been analysed on this study, it is reasonable to assume that current technologies and practices are a far cry from the best available internationally.
Based on the assessment above, the key messages to policymakers and practitioners are as follows:

- Mine safety has been and should continue to be the top priority and the main driver for the recovery and utilization of coal mine methane. Policymakers of NEA countries, in particular those with active coal mining activities, play an important role in the design and enforcement of policies and regulations that minimize the risks posed by CMM. CMM recovery technologies are one of the enablers to the effective application of these regulations, and thus it is important to ensure that such technologies are available to coal mine developers. Potential for cooperation exists among NEA countries that have know-how and experience on CMM technologies, such as China and Japan, and those that are more in need of them, in particular Mongolia and DPRK. The framework for cooperation could consist in the sharing of best practices on coal mining safety, CMM technology needs and technology matching assessments, and support in the design of policies and regulations.

- There is a large potential for mainstreaming and further accelerating the deployment of cutting-edge coal mine methane degasification technologies in NEA countries. Notwithstanding the progress observed in countries on the adoption of these technologies, particularly in China, there is significant scope for further headways, most specifically in the Russian Federation. Policymakers of countries in NEA should therefore ensure that national policies and regulations support the adoption of these technologies and, whenever feasible, R&D activities by domestic organizations. On the other hand, opportunities for cooperation seem to exist for the transfer of technologies between Japan, and other countries in the sub-region, in particular on enhanced CMM recovery and combustion technologies for gases with low concentrations of methane.

- A potential area of interest for cooperation among NEA countries is on technologies that make it possible to derive economic value from low-quality CMM gas and ventilation air methane, including lean-burn gas turbines and oxidation technologies. The deployment and mainstreaming of these technologies could help building up the business case for many CMM methane recovery projects in NEA countries. In this connection, policymakers of NEA countries could consider making this an area of focus for R&D of national research institutions, which could also include the assessment of opportunities for cooperation with similar organizations of other countries in the sub-region.

- Methane is a greenhouse gas and the capture and utilization of CMM can make a significant contribution to climate change mitigation. International climate finance, through the CDM and JI, has played a role as an additional source of funding and as a means to the transfer of technologies to the development of CMM projects, particularly in China and, to a lesser extent, in the Russian Federation. The collapse in global carbon prices and the non-ratification of the Kyoto Protocol by the Russian Federation have significantly weakened this carbon financing vehicle. Therefore, countries in NEA countries should work together in the international arena in the overhaul of existing mechanisms (i.e. the CDM and JI) and, both as alternative and complement to each other, in the design of new frameworks to tap from the climate benefit of recovering and utilizing CMM, such as Nationally Appropriate Mitigation Actions (NAMAs) and the so-called New Market Mechanisms.
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4.1 Introduction and Background

Technologies for the gasification of fuels have been commercially available for more than a century. Gasification consists in the process of converting a carbonaceous material into a synthetic gas – usually designated as “syngas” – which can be used as an energy source or as a feedstock for the production of other fuels and chemicals. The focus of this study is on gasification technologies that process coal, although it should be noted that other feedstocks, such as petroleum coke and biomass, can also be gasified and converted into syngas.

In general, gasification involves the reaction of a fuel with a combination of air, oxygen, steam, carbon dioxide or a mixture of these gases, at temperatures above 700ºC, to produce the syngas. The resulting syngas is a mixture of gases that consist essentially of carbon monoxide (CO) and hydrogen (H₂), but which also include light hydrocarbons and other impurities that need to be removed. In the gasification of coal the supply of oxygen is controlled so as to create the conditions for an incomplete combustion. While the gases resulting from a complete combustion cannot be further processed to produce energy, syngas can be used to generate energy or chemically converted into other products (Rezaiyan. and Cheremisinoff, 2005).

The main goals to achieve with the gasification of coal are to convert the entire non-ash fraction of the feedstock into a gas, and to produce a syngas that preserves, to the extent possible, the heating value of the coal processed. Interest on coal gasification has increased significantly in the last 10-15 years, not only in light of concerns over the security of oil supplies, but also because it is a relatively cost-effective means for using coal while holding the potential for minimizing GHG emissions. Also important, gasification is particularly suitable for the processing of low-rank coals due to the high gasification reactivity of such coals. This interest has spurred remarkable progress in the science and technology of gasification, and countries in NEA are not an exception to this trend.

Figure 4.1 below provides an overview of gasification and related technologies, and puts the analysis on this chapter in perspective vis-à-vis the whole study. As can be observed, different feedstocks can be used for gasification, and after syngas is generated, a clean-up process to remove undesired gases and impurities follows suit. CO₂ is one of the gases that need to be removed from the syngas stream, which opens opportunities for carbon capture and storage (analyzed in chapter 6). As for the products that can be generated, the cleaned up syngas may be used for generating electricity in a gas turbine, in a process known as Integrated Gasification Combined Cycle (IGCC), or further processed for the synthesis of products like methanol and dimethyl ether (DME), or other liquid fuels through the Fischer-Tropsch process (all analysed in chapter 5).

Figure 4.1 – Coal gasification and related processes. Note: the water gas shift reaction consists in reacting the carbon monoxide which is part of the syngas with water in order to obtain carbon dioxide and hydrogen.
(Source: own elaboration based on Bell et al., 2011)
This chapter first sheds light on the fundamentals and state-of-the-art technologies for gasification systems, including the development and trends at global level and in NEA countries. As one of the main interests in the production of syngas from coal is the generation of electricity and heat from operating an IGCC plant, this subject is analysed in a separate sub-chapter (4.3).

Gasifiers and IGCC plants are usually installed in industrial facilities where a feedstock is delivered, either raw coal or syngas, respectively. However, there is one gasification approach which is considerably different from this: underground coal gasification (UCG). In UCG, un-mined coal seams are reacted underground in order to produce syngas. There has been interest on these technologies in NEA, particularly in the Russian Federation and China, with the former having acquired considerable know-how and experience on this area due to pioneering initiatives dating back to the USSR period. UCG is covered in sub-chapter 4.4.

Table 4.1 summarizes the main drivers in NEA countries for coal gasification technologies:

<table>
<thead>
<tr>
<th>Country</th>
<th>Policies and strategies on coal gasification</th>
</tr>
</thead>
</table>
| China           | • The national government has encouraged the build-up of a coal-to-chemicals industry based on coal gasification, with the overarching goal of reducing China’s growing dependence on oil imports.  
                   • The national government has encouraged the introduction of cutting-edge gasification technologies from overseas, while stimulating the development of indigenous technologies.  
                   • The closure of small and inefficient coal-fired power plants in the Eleventh Five-Year Plan (2006-2010) and the issuance of more stringent emissions for SO₂, NOₓ and particulates in 2012, are driving the interest on cleaner and more efficient coal-conversion technologies, including IGCC. |
| Japan           | • Although there are no specific guidelines on coal gasification, IGCC is one of the power generation technologies whose R&D and commercial development is being prioritized, both in the short and mid-term. |
| Mongolia        | • No specific policies or strategies for coal gasification exist, but there is a strong interest in developing added-value products from coal, in association with CTL technologies, as well as in modernizing the coal-fired power generation fleet. |
| Republic of Korea | • The development of IGCC is one of the 15 strategic items defined on the first Green Energy Strategy Roadmap (2009). For the reduction of GHG emissions from the coal-fired power generation, energy efficiency, IGCC and CCS are the technological solutions envisioned to achieve GHG emission reductions below business-as-usual.  
                      • The government aims at achieving a level of “self-reliance” on IGCC, with the view of exporting the technology overseas in the mid-term. |
| Russian Federation | • As part of the Energy Strategy for Russia up to 2030, all new coal-fired generation facilities will have to be based on clean coal technologies including coal gasification (i.e. IGCC).  
                        • The Long-Term Programme for the Development of the Coal Industry up to 2030, which was approved by the Russian Federation government in 2012, includes the commercialization of underground coal gasification as one of the priority areas. |

Table 4.1 – Policies and strategies on coal gasification on NEA countries.  
(Source: own elaboration based on Yuhong and Yongxu, 2012; JCOAL, 2012; Avid, 2012; Gorlov and Agapova, 2013; and Lee, 2012)
4.2 Coal Gasifier Technologies

Despite the existence of many different gasification reactors – “gasifiers” – all are based on three generic types:

a. Moving bed gasifiers (sometimes called fixed-bed gasifiers);
b. Fluidized bed gasifiers;
c. Entrained flow gasifiers.

Moving bed gasifiers were the earliest type of gasification reactor developed. In a moving bed gasifier, coal is fed from the top of the reactor, and while it moves slowly downward due to gravity, it is gasified by reacting with gases that move up the reactor bed. A mixture of oxygen and steam is usually introduced at the bottom of the reactor, and it is this upward flow of gases, in counter-current, that reacts with the coal and produces the syngas. This type of gasifier is only suitable for solid fuels with relatively large dimensions. Depending on whether the gasification temperatures exceed the ash melting point or not, moving bed gasifiers can be classified as “dry bottom” or “slagging” (Fernando, 2008; Higman and van der Burgt, 2008).

In a fluidised bed gasifier, coal is gasified in a bed of hot non-combustible particles which are in suspension due to an upward flow of fluidized gases, consisting of steam and either air or oxygen. These gasifiers can use bubbling bed or circulating bed technology. The bed consists of a mixture of sand, char, coke or ash. The gasifier operates at temperatures below ash melting temperatures in order to prevent the formation of slag. Fluidised bed gasifiers differ among each other with respect to ash conditions, being classified as “dry ash” or “agglomerating”. This type of gasifier is more suited for gasifying reactive feedstocks, such as low-rank coals and biomass (Fernando, 2008).

In an entrained flow gasifier, the coal feedstock reacts concurrently with steam and oxygen or air. Coal is fed into the gasifier” dry” or “wet” in a slurry of water. On this type of reactor, coal must be fed in very fine particles and, as the reaction time is very quick, it operates at very high temperatures, which are above the ash melting point. Entrained flow gasifiers are the most versatile type of gasifier as they are suitable to every type of coal, although coals with high moisture or ash content are less favourable for this type of gasifier (Fernando, 2008; Higman and van der Burgt, 2008).

Table 4.2 summarizes the main characteristics of these gasifiers, while figure 4.2 provides an illustration of their operating process.

<table>
<thead>
<tr>
<th>Gasifier Type</th>
<th>Moving bed</th>
<th>Fluidized bed</th>
<th>Entrained-flow</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ash Conditions</td>
<td>Dry-bottom</td>
<td>Dry Ash</td>
<td>Slagging</td>
</tr>
<tr>
<td>Feed-size characteristics</td>
<td>6-50 mm</td>
<td>6-10 mm</td>
<td>&lt;0.1 mm</td>
</tr>
<tr>
<td>Preferred coal rank</td>
<td>Any</td>
<td>Low</td>
<td>Any</td>
</tr>
<tr>
<td>Preferred ash melting temperature</td>
<td>&gt;1200</td>
<td>&gt;1100</td>
<td>&lt;1300</td>
</tr>
<tr>
<td>Exit gas temperature (°C)</td>
<td>425–650</td>
<td>900–1050</td>
<td>1250-1600</td>
</tr>
<tr>
<td>Typical Gasifier manufacturers</td>
<td>Sasol-Lurgi</td>
<td>KBR, Rheinbraun</td>
<td>Siemens, Shell</td>
</tr>
</tbody>
</table>

Table 4.2 – Gasifier characteristics. (Source: Fernando, 2008; Higman and van der Burgt, 2008)
For a project developer, the choice of gasifier depends on several factors, such as the properties of the coal to be used as feedstock, its reactivity, and the utilization purpose of the syngas. For example, if the syngas is to be used to manufacture chemicals, the CO/H₂ ratio of the syngas is important, while for an IGCC turbine this issue is not as important.

The main technology providers of gasifier systems are international/multinational corporations. As of 2008, three main technologies dominated more than 90% of the market, all owned by private companies: Sasol-Lurgi, GE and Shell. Sasol-Lurgi holds the license for the most widely used moving bed gasifier, while GE and Shell have successfully developed entrained flow gasifiers. Other companies have developed and/or commercialized gasifier models which have been adopted worldwide, including Siemens, ConocoPhilipps and Mitsubishi Heavy Industries (Fernando, 2008; Bell et al., 2011).

In China there has been an active and significant programme encouraged by the national government to develop coal gasification technologies. While the introduction of technologies from abroad has been actively pursued – with many licensing agreements from OECD companies, including GE Energy and Shell Global Solutions – China has been exploring gasification technologies with its own intellectual property rights, having achieved noteworthy breakthroughs in some areas. In fact, some technologies have surpassed their counterparts in other countries, with a few being utilized overseas (Yuhong and Yongxu, 2012).

Through its own companies and research organizations, China has developed a few coal gasifier variants, which are presented in table 4.3 below. Among those presented, the technology that seems more promising is an entrained gasifier consisting of a coal-water slurry gasification system, which was developed by the East China University of Science and Technology in partnership with the Yankuang Group.
In Japan, the interest on coal gasification has been closely associated with the development of IGCC. With regards to the development of coal gasifiers, there are two concepts to note developed by Japanese organizations. The first one is a fluidised bed gasifier named “TIGAR”, which is developed by IHI, and which is particularly suitable to gasifying lignite and biomass. A 6t/d pilot plant was built, and next step is the construction of a 50t/d demonstration plant (JCOAL, 2012). The second concept is of a gasification technology named “Hydrogen-from-Coal Process” (HYCOL), which is an entrained flow gasifier (JCOAL, 2010).

In Mongolia, the development of coal gasification technologies has been associated with the interest in deriving high-value products from coal. Relevant initiatives are covered in the CTL chapter, as projects involving coal gasification have been associated with the synthesis of liquid products.

In a somewhat similar standing as Japan, coal gasification technologies in the Republic of Korea have been closely related to the development of IGCC. Despite the fact that R&D on coal gasification dates back to the late 1950s, almost all technologies used have been imported from other countries and/or international organizations. Despite this, there have been a few initiatives developed by ROK organizations worthy of note. KIER has been conducting research on entrained flow gasifiers using a

<table>
<thead>
<tr>
<th>Organization</th>
<th>Gasifier Type</th>
<th>Technology features</th>
</tr>
</thead>
</table>
| East China University of Science and Technology & Yankuang Group | Entrained flow | • The innovative features are the development of an entrained flow gasifier with opposed multi-burners, which is based on a design by GE/Texaco;  
• There has been a relatively significant deployment of this option at reasonably large scale. |
| Xian Thermal Power Research Institute | Entrained flow | • Consists of a two-stage dry feed entrained flow gasifier, which is based on a design by Shell;  
• The conversion efficiency is 1-2 percentage points higher than other gasification technologies;  
• A demonstration facility with a capacity of 2000t/d has been used in Huaneng’s Power Group “Green Generation” project. |
| Research Institute of China Aerospace Science and Technology Corporation | Entrained flow | • Consists of a pulverized coal pressurized gasification technology;  
• It is applicable to a wide range of coals, and it is clean, highly efficient and low-cost;  
• The technology is being demonstrated at the Fuyang Methanol Plant, and if the results are positive, a fast deployment is expected. |
| Tsinghua University | Entrained flow | • Consists of a two stage entrained flow gasifier based on a design by Shell;  
• Limited deployment to date, with the scale of operation below 500 tonnes of coal per day. |
| Institute of Coal Chemistry (Chinese Academy of Sciences) | Fluidised bed | • Consists of an ash agglomerating fluidised bed coal gasifier;  
• Limited deployment to date, with the scale of operation below 500 tonnes of coal per day, either for ammonia or methanol production. |

Table 4.3 – Coal gasifier technologies developed by Chinese organizations.  
(Source: Yuhong and Yongxu, 2012; Minchener, 2010)
wet gasification process. This project started in 1994 and served to improve knowledge on the suitability of different coals to gasification. Another project involving entrained flow gasifiers has been conducted by the Institute for Advanced Engineering of Korea, in partnership with the Ajou University. This initiative studied dry coal gasification techniques, and led to the construction of a 20 ton/day test bed. This project also started in 1994. Last but not the least, since 2000 SK Energy has been developing a pilot project for a fluidised bed gasifier applying a floating layer gasification technology (Lee, 2012).

In the **Russian Federation**, a number of processes based on entrained-flow gasification have been developed, as well as some applying the fluidised bed approach. A summary of the main technologies is provided in table 4.4 below:

<table>
<thead>
<tr>
<th>Organization</th>
<th>Gasifier Type</th>
<th>Technology features</th>
</tr>
</thead>
</table>
| ZAO Karbonika-F | Entrained flow | • Technology based on the process of coal-bed gasification in the “reverse heat wave” mode;  
• ZAO Karbonika-F has been implementing this technology for 6 years and processes up to 30 thousand ton of lignite per year;  
• The technology does not generate wastewater for disposal nor solid waste from partial gasification;  
• A pilot unit has been installed in the town of Sharypovo in the Krasnoyarsk Territory. |
| Federal State Unitary Enterprise Research and Production Center Moscow | Entrained flow | • A gasification technology consisting on a two-stage thermal processing of solid fuels by a steam air heating method;  
• The gasification process operates at around 1100°C with a limited amount of oxygen;  
• A facility processing 15,000 ton of coal per year is in operation. |
| OAO All-Russian Thermal Engineering Institute (VTI) | Moving bed | • Developed a test bench consisting of a fixed bed gasifier, dry gas clean-up and a gas-turbine combustion chamber;  
• A variety of fuels were tested for this technology, and the test results demonstrate that this technology can be successfully used. |
| ZAO Kompomash-TEK & FSUE IGI | Fluidised bed | • Simple in design and easy to operate gasifier based in the process of concurrent gasification of a fine-dispersed coal-water slurry, prepared from brown and hard coals of any grade;  
• This gasifier can handle any type of solid fossil fuels and bulk waste of wood-processing industry or agriculture. |
| OAO GIAP | Fluidised bed | • OAO GIAP has been successfully developing a low-rank fine-grained coal fluidised bed gasification to produce gas used for ammonia synthesis;  
• This is a technology that dates back from the USSR period. |
| ZAO SibCOTES | Plasma gasification | • ZAO SibCOTES has designed a novel microwave-induced plasmatron which is currently under development. Unlike plasma torches powered by an electric arc, microwave-induced plasmatrons coal particles can be crushed more efficiently. |

*Table 4.4 – Coal gasifier technologies developed by Russian organizations.  
(Source: Gorlov and Agapova, 2013)*
As can be observed, considerable R&D and commercialization efforts on gasifier technologies have been conducted in the Russian Federation. One of the aspects to underscore from Russian technologies is their high economic competitiveness vis-à-vis similar developments in other countries, enabling the conversion of coal into gaseous fuels at competitive prices compared with petroleum feedstocks (Gorlov and Agapova, 2013). More recently, Russian organizations have been engaged in the development of “less conventional” gasifier technologies, based on plasma gasification, such as the ZAO SibCOTES’ model indicated above.

To sum it up, technologies on coal gasifier systems are mostly dominated and owned by private sector organizations, with relatively few developments in North-East Asia countries. Countries such as China and the Republic of Korea have encouraged inward technology transfer from overseas providers, while at the same time stimulating R&D efforts led by national organizations. In the case of China, a few variants of coal gasifiers have been successfully developed and, step by step, Chinese organizations start to export their technologies. The Russian Federation seems to be some sort of an exception among NEA countries, with several gasifier models both at development stage and commercial operation. However, there appears to be limited international recognition and/or awareness about these technologies.

4.3 Integrated Gasification Combined Cycle (IGCC)

One of the possible applications of the syngas from gasified coal is the production of electricity and heat through an integrated gasification combined cycle (IGCC). Compared with conventional pulverized coal (PC) fired power plants, IGCC has a number of advantages (Barnes, 2011; IEA, 2013a):

- High thermal efficiencies, on a par with the most efficient PC plants. Thermal efficiencies approaching 50% are achievable. In particular, the introduction of more advanced, higher temperature gas turbines (of the 1500ºC class) will result in the increase of IGCC plant efficiencies;
- Good environmental performance: the emissions of SO\textsubscript{x} and other particulates are significantly reduced, as the syngas is cleaned-up before being used in the turbine. Technically, CO\textsubscript{2} can be captured, although additional costs will be significant given existing technologies (please refer to chapter 6). Even without CCS, existing IGCC plants are amongst the lowest emitting coal fired power plants per kWh of electricity generated;
- Reduced water consumption: IGCC uses less water per kWh generated than an equivalent PC fired power plant, both due to the different thermodynamic cycle and the reduced need for flue gas desulphurization, which is a water-intensive process.
- The development of IGCC dates back to the 1970s, and it was initially motivated by a surge in natural gas prices, which stoked the interest in the production of syngas from coal and other solid fuels that could substitute natural gas to run a gas turbine. More recent interest in IGCC has been spurred by increasingly stringent emission regulations and concerns over the security of natural gas supplies (Mills, 2006).

A simplified representation of a coal-fuelled IGCC cycle is presented in figure 4.3. In essence, there are three main processes to take note in IGCC: i) the gasification of coal and the clean-up of syngas; ii) the operation of the gas turbine for power generation; and iii) the operation of a steam turbine for power generation with the heat from the syngas and the exhaust of the gas turbine (Fernando, 2008).
Worldwide, only a small number of IGCC plants are in operation, all of them either at demonstration or pre-commercial stage. The relatively low uptake of this technology is attributed to its higher capital and operating costs for power generation. Besides, if an air separation unit is needed to produce oxygen for the gasification process, this may consume 10-15% of the gross power generated. Additionally, the technical differences between a conventional PC fired-power plant and an IGCC plant, with the latter resembling somewhat to a chemical plant, has also been pointed out as an obstacle to the adoption of this technology (IEA, 2012b; Fernando, 2008).

Unlike conventional PC fired-power plants and other advanced coal combustion technologies, IGCC is not a technology at maturity stage yet. Currently, only six IGCC plants are in operation in the United States, Europe and Japan, although several other plants are planned or under construction. Despite this, the immediate future of the technology is still uncertain, with several projects been cancelled or put on hold since 2007 due to cost escalations and uncertainties in regulations for GHG emission reductions (Burnard and Bhattacharya, 2011).

With regards to the technology-edge of NEA countries on IGCC, it is important to understand their know-how and capabilities on the following components of a typical IGCC plant:

- Coal gasifier;
- Syngas cleaning system;
- Air separation unit;
- Gas turbine system;
- Heat recovery steam generator (HRSG);
- Steam turbine cycle.

**China** initiated the study on IGCC technology in 1978. Currently, Chinese institutes possess the ability to design IGCC projects, specifically in what concerns the combined cycling facility, balance of plant control, coal gasification system, gas cleaning system, and air separation unit. With regards to the gas turbines, overseas technologies have dominated, particularly those of GE, Mitsubishi Heavy Industry and Siemens. However, independent development of gas turbine models with low heat value is currently underway in China (Yuhong and Yongxu, 2012).
In Japan there is another IGCC project of note, whose development is being conducted by the Osaki CoolGen Corporation. The objective of this project is to build an oxygen-blown IGCC, and the next step to add a CO2 capture equipment and a fuel cell. This concept is known as Integrated Gasification Fuel Cell (IGFC). This technology differs from IGCC in that part of the syngas exiting the gasifier is diverted into a high temperature fuel cell. It can be said that IGFC consists of a “triple combined cycle”, in that three power generation systems are combined: gas turbine, steam turbine and fuel cell. IGFC is expected to achieve efficiencies up to 65% (JCOAL, 2012). An illustration of this concept is provided in figure 4.4 below:

In Mongolia, no specific plans or projects to develop IGCC have been identified, although there is a widely recognized need to introduce modern coal conversion technologies for power generation (Avid, 2012).

In the Republic of Korea, IGCC is regarded as one of the key technology routes to reduce GHG emissions from the power generation sector. The government of ROK has been promoting R&D on IGCC technologies, while at the same time encouraging the establishment of technology transfer agreements with companies from Japan and the USA since the early 1990s. The goal is to achieve a level of technology development that allows domestic organizations to design, fully build and operate an IGCC plant, with the mid-term goal of exporting overseas this technological know-how. At this point, ROK organizations have secured 40% to 60% of fundamental technology for fully developing an IGCC facility on their own (Lee, 2012).

A 300 MW IGCC demonstration project is now underway in ROK, which was initiated in December 2006. A consortium consisting of the national government, 20 academic-research institutes and seven participating corporations was set-up. The government is supporting the project through the Ministry of Knowledge Economy and the Korea New & Renewable Energy Center, by providing 30% of the total investment requirements. The consortium is led by the Korea Electric Power Corporation, KEPCO. Shell was selected as the technology provider of the coal gasification system. The project was planned to be completed by the end of 2012 (Lee, 2012).

In the Russian Federation, the most important initiative on IGCC is being carried out by the Federal State Unitary Enterprise Institute of Fossil Fuels (FSUE IGI), in partnership with the ZAO Kompomash-TEK. This project, which has the support of the Federal government, aims to create the conditions for the industrial use of innovative technologies on IGCC. The implementation of this project was approved by the Ministry of Science and Technology as a key scientific research programme in the period of the Eleventh Five-Year Plan. The project also includes a CCS component, for pre-combustion carbon capture (Barnes, 2009; Yuhong and Yongxu, 2012; Minchener, 2011b).

One of the most recent IGCC projects coming online at global scale is the Nakoso IGCC demonstration project, a 250 MW plant developed under the auspices of Japan’s Ministry of Economy, Trade and Industry (METI). An overview of this project is presented in Box 4.1.

Among coal combustion technologies, IGCC is one of Japan’s priorities in the short and mid-term. One of the most recent IGCC projects coming online at global scale is the Nakoso IGCC demonstration project, a 250 MW plant developed under the auspices of Japan’s Ministry of Economy, Trade and Industry (METI). An overview of this project is presented in Box 4.1.

Box 4.1 – The Nakoso IGCC plant

Based on several years of accumulated experience with a 200t/d IGCC pilot plant, the construction of a 250 MW demonstration plant in Nakoso, Iwaki City, was initiated in 2004 by the Clean Coal Power R&D Company. The plant initiated operations in 2007.

The plant consists of an IGCC system developed by Mitsubishi Heavy Industries, which includes an air-blown dry feed entrained flow gasifier, a gas clean-up unit, and a gas turbine combined cycle power. The plant processes approximately 1,700 ton of coal per day, and has a gross thermal efficiency of 48% and a net efficiency of 42%. An overview of the plant layout is presented in the figure below.

As of January 2012, the plant had operated, cumulatively, for 14,122 hours. A full-load of 250 MW was achieved with a stable and safe operation. The net thermal efficiency achieved was of 42.9%, i.e. above the design target of 40%. As the demonstration phase was very successful, the plant was converted into a commercial unit, officially starting operations on 28 June 2013. The plant was renamed as “Jyoban Kyodo Nakoso Unit 10”.

(Source: JCOAL, 2012; Barnes, 2009)
In Japan there is another IGCC project of note, whose development is being conducted by the Osaki CoolGen Corporation. The objective of this project is to build an oxygen-blown IGCC, and the next step to add a CO₂ capture equipment and a fuel cell. This concept is known as Integrated Gasification Fuel Cell (IGFC). This technology differs from IGCC in that part of the syngas exiting the gasifier is diverted into a high temperature fuel cell. It can be said that IGFC consists of a “triple combined cycle”, in that three power generation systems are combined: gas turbine, steam turbine and fuel cell. IGFC is expected to achieve efficiencies up to 65% (JCOAL, 2012). An illustration of this concept is provided in figure 4.4 below:

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IGCC is considered to be a priority technology for the Serafimovsky cluster project on coal processing, which is currently underway in the Kuzbass region. Another IGCC project in the Russian Federation is under development in the Kuzbass by the I.I. Polzunov CKTI company. This project will utilize a steam-air blown fluidized bed gasifier to be applied to a 250 MW power generating unit (Gorlov and Agapova, 2013).

IGCC is a coal-conversion technology for power generation which is not yet on a par, technologically and economically, with other commercially-available technologies. Despite this, there is a strong interest on this technology among NEA countries, with Japan, China and the Republic of Korea at the forefront. There seems to be the potential for harmonization efforts among NEA countries both on R&D and demonstration projects on IGCC, but also to address some of the challenges that preclude a more widespread uptake of the technology vis-à-vis other alternatives.

4.4 Underground Coal Gasification

Underground coal gasification (UCG) is a method to convert coal located in underground seams into a combustible gas, i.e. syngas. The concept of UCG is relatively simple and is illustrated in figure 4.5. A mixture of air or oxygen, possibly with steam, flows through an injection well until it reaches the coal seam. Once in the seam, the oxygen and water react with the coal to produce syngas, which is brought to the surface through a production well. The gas is then cleaned up from coarse silt and particulate matter usually using cyclones. The gas is then brought to scrubbers for additional removal of impurities, while electrostatic precipitators ensure final gas clean-up (Gorlov and Agapova, 2013).

There are significant differences between surface and underground gasification. On surface gasifiers, the reactions leading to the production of syngas take place in a contained vessel where the temperature and pressure can be measured and controlled with considerable accuracy, as well as the coal feed and the injected gas. Under these conditions the quantity and composition of the syngas can be predicted and controlled with reasonable precision. In underground gasification, the shape and location of the reaction zone will be continually changing and it is not possible to measure or control the operating conditions in the same way as in a gasifier (Couch, 2009).

Figure 4.5 – Representation of the Underground Coal Gasification process. (Source: IEA, 2012b)
The earliest developments on UCG technologies date back to the 1930s in the Soviet Union. The motivations were more ideological than economic, as underground coal mining was a hazardous and dirty work, resulting in many casualties and injuries among miners (Bell et al., 2011). Nowadays the interest on UCG is mainly economical, which is also aligned with the unique benefits that can be drawn from the process of producing a combustible gas directly from underground coal seams (Lauder, 2011):

- **Increase in coal reserves**: most known coal resources are too deeply buried to be economically mined in the near future with conventional methods. The development of UCG technologies can be a game-changer, and if successfully developed and widely deployed, it may significantly increase world’s coal reserves.

- **Less environmental impacts at the surface**: natural landscape remains largely untouched, as there is no active mining and thus a reduced need for rail and road infrastructure.

- **Lower emission of pollutants**: UCG leaves many pollutants underground, significantly reducing the emissions of NOx, SOx, particulates and methane. It also leaves coal ashes and other process wastes below the ground, eliminating the costs of handling and disposing these by-products. In favourable geological conditions, UCG may offer a relatively low-cost solution for capturing and storing CO2.

- **Syngas production at potential lower economic and social costs**: UCG produces in-situ and in-seam a combustible gas which is ready to be utilized by the end-user, eliminating the need for often harmful underground working conditions and the need for the transportation of raw coal for further processing. Low capital and operating costs are also possible to achieve, as no surface gasifiers are required.

There are **three primary methods for conducting UCG projects** (UCG Association, 2013):

- The vertical well method (also known as Soviet method);
- The enhanced vertical well method, with in-seam horizontal boreholes;
- The Controlled Retractable Injection Point (CRIP) method.

The vertical well method has been the most widely used, and consists in drilling two vertical wells that are linked underground, by using either a high pressure mixture of air/oxygen and steam or by reverse combustion, which opens an internal pathway in the coal seam that allows the gas to flow between the wells. This is based on technology developed originally in the USSR. In demonstration or production-scale operations, series of holes are drilled in parallel rows. This method is considered by some experts to be most suitable to relatively shallow coal seams, i.e. below 300 m deep (Couch, 2009).

The second method draws on the progress made in directional drilling technologies. The principle involved is illustrated in figure 4.6b below, where an in-seam hole establishes a physical link between vertical holes, which allows the gas to flow to a production well.

The third method, CRIP, makes use of a vertical production well and a lateral well drilled directionally into the coal seam. The lateral well is used for injecting the air/oxygen mixture and steam, while the injection point (i.e. the point where the injected gas first comes into contact with the coal) can be moved so as to control where the underground reaction takes place. As the coal reacts with the oxidant gas, the injection point is moved along the coal seam liner. There are two variants of this technique,
the “linear” and “parallel” method, which are illustrated in figure 4.6 below. The CRIP method has potential advantages over the two other methods, as it can provide a much higher control over where the gasification reaction takes place, and hence it can improve resource recovery. This method also involves the drilling of far less wells from the surface, significantly reducing the costs of syngas production (Couch, 2009).

![Diagram of underground coal gasification methods](source: Couch, 2009)

The application of UCG and the choice of method require a thorough understanding of key aspects that include the coal properties (such as coal permeability, “caking” characteristics of the coal, etc.) and the geological characteristics of the coal seam (such as thickness, inclination angle, depth, etc.).

Notwithstanding its potential benefits, UCG is still an emerging technology area, several years behind commercial viability (Couch, 2009). Among the challenges to commercial application and broader deployment, are the need for increased characterisation of the geology around potential coal seams and legislation for extracting these underground resources (IEA, 2012b). In particular, the environmental and geological impacts of an UCG development should not be overlooked, and can be put in the same footing as the challenges arising with the shale gas boom, namely gas leakages, water contamination, etc.
There is a wide range of countries and locations across the globe where UCG projects are being considered and assessed. Most UCG initiatives are being developed in what are generically considered “favourable” or “desirable” conditions, i.e. fairly thick coal seams (5–20 m) located at depths between 150 and 500 m. Outside the NEA sub-region, Australia, South Africa and the USA are the countries where UCG projects and technologies are at a more advanced stage. In Australia there are a number of companies conducting trials and/or feasibility studies. Among them is Linc Energy, one of the leading companies on UCG, which is developing its own technologies and actively investing in projects overseas, namely in China, Viet Nam and Uzbekistan. The USA has a long history on UCG, with several projects in the pipeline, including one in Alaska which is expected to become commercial by 2015. In South Africa there have been several pilot UCG facilities in operation, the most promising of which having the involvement of the national energy giants Sasol and Eskom (Couch, 2009; UCG Association, 2013).

Among NEA countries, the interest on UCG has been confined, essentially, to three countries: China, Mongolia and the Russian Federation. In the Russian Federation, substantial practical, technical and research experience on UCG has been accumulated that could be used in the power generation and chemical industries. The National Mining Research Center A.A. Skochinsky Institute of Mining, VNIMI and the Institute of Coal of the Siberian Branch of the Russian Academy of Sciences are the organizations in the Russian Federation possessing know-how on UCG technologies (Gorlov and Agapova, 2013). On the other hand, Promgaz has been the main Russian-based company promoting UCG development (Couch, 2009).

There has been a continued interest on UCG in the Russian Federation, in particular because UCG-fired power stations are expected to achieve efficiencies of 45%, while current efficiencies of coal-fired power plants operating in Russia average 30%. Besides, the implementation of UCG technology has the potential to substantially reduce pollution, while at the same time enhancing the efficiency and profitability of coal conversion operations (Gorlov and Agapova, 2013).

UCG in the USSR was carried out on coalfields of the platform type (lignite and humic coal of the Moskovsky and Dnepropetrovsky basins) and geosynclinal type (bituminous coals of Donbass and the Kuzbass). The longest running UCG operation has been at the Angrenskaya station, which is now in Uzbekistan. On all these projects, the syngas produced was consumed in the boilers of companies, plants, factories, and state district power stations. A summary of the main UCG projects conducted in the Russian Federation is presented in the table below:

![Table 4.5](source: Gorlov and Agapova, 2013)

<table>
<thead>
<tr>
<th>Gasification station</th>
<th>Coal seam thickness (m)</th>
<th>Coal seam depth (m)</th>
<th>Inclination angle (degree)</th>
<th>Coal type</th>
<th>Lower calorific value (MJ/kg)</th>
<th>Results achieved</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lisichanskaya</td>
<td>0.44-2</td>
<td>60-250</td>
<td>38-60</td>
<td>Bituminous coal</td>
<td>20.1-23</td>
<td>• Produced about 700 million m³ of gas with a heating value of 3.26 MJ/m³</td>
</tr>
<tr>
<td>Yuzhno-Abinskaya</td>
<td>2.06-9</td>
<td>130-220</td>
<td>35-56</td>
<td>Bituminous coal</td>
<td>28.9-30.7</td>
<td>• Produced annually 0.46 billion m³ of gas;</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Lignite</td>
<td>11.8</td>
<td>• Over 23 years of operation, the heating value of the gas was of 3.56-4.61 MJ/m³</td>
</tr>
<tr>
<td>Podmoskovnaya</td>
<td>2.5</td>
<td>30-80</td>
<td>0</td>
<td>Lignite</td>
<td>11.0</td>
<td>• Heating value of the gas from 3.0 to 3.5 MJ/m³</td>
</tr>
<tr>
<td>Shatskaya</td>
<td>2.6</td>
<td>30-60</td>
<td>0</td>
<td>Lignite</td>
<td>11.0</td>
<td>• Heating value of the gas from 3.0 to 3.5 MJ/m³</td>
</tr>
<tr>
<td>Angrenskaya</td>
<td>3-20</td>
<td>120-200</td>
<td>7</td>
<td>Lignite</td>
<td>15.1</td>
<td>• Heating value of the gas from 3.0 to 3.5 MJ/m³</td>
</tr>
</tbody>
</table>
Russian experiences confirm the potential for UCG to be an economic and efficient means for energy production. Among the main disadvantages and challenges identified with these experiences are the lack of process control, which results in an unstable syngas composition. Another challenge is the poor management of the oxidant (injected gas) and the syngas underground flow, resulting in the burnout of the latter (Gorlov and Agapova, 2013).

According to Gorlov and Agapova (2013), most international UCG pilot programmes were run on just a few production wells and, for this reason, they should be viewed as pilot trials of in-situ coal gasification. On the other hand, the Russian experience shows that there is a long way from experiments on a few wells to a full-fledged UCG production plant.

In China, trials on UCG technologies date back to the end of the 1950s, and the interest is driven by the enormous potential for energy recovery from coal located in very deep seams. Currently, the ENN Group Co. Ltd is taking the lead in UCG development in China. A pilot UCG project started in October 2007 in the city of Wulanchabu, Inner Mongolia province, with injection and production wells drilled into a previously un-mined coal seam located 200 m underground, using a Chinese version of the CRIP technology. R&D work has been concentrated on the China University of Mining and Technology, Beijing, which has a dedicated research centre on UCG (Couch, 2009). The ENN Group works closely with this research centre, as well as with universities and private companies in Uzbekistan, USA, Australia, South Africa and the EU (ENN, 2013).

In Mongolia, until now the exploitation of coal reserves has been mostly on surface deposits through open-pit mining, and therefore the development of UCG does not appear to be a priority. However, there have been some trials with UCG in Mongolia. In 2011, the Neo Matrix Consulting Limited initiated a project named Syngas Energy Hub, which was intended to produce syngas from coal seams. The drilling technology applied by Neo Matrix has been in use in the oil and gas industry. There are also plans for using UCG in a brown coal deposit located 300 km from Ulaanbaatar (Avid, 2012).

There have not been any programmes or studies on underground coal gasification neither in Japan nor in the Republic of Korea (JCOAL, 2012; Lee, 2012).

All in all, UCG is a very promising approach to harness coal resources which are difficult to reach or economically unfeasible to exploit with conventional mining methods. Although there has been an increasing interest on UCG technologies in several countries around the globe, the commercial viability of UCG is still unproven. There are several challenges hindering the large-scale commercial development of UCG, including the lack of short-term competitiveness with other low-cost alternatives, such as mined coal or natural gas, operational risks from unproven large-scale performance, and uncertainties related to its environmental soundness (Couch, 2009). Among NEA countries, there is scope for international cooperation to overcome these barriers.

4.5 Summary and Implications

The gasification of coal consists in reacting the fuel with a combination of air, oxygen and steam at high temperatures and pressures in order to produce a gas, commonly known as “syngas”, which can be used either as an energy source or as a feedstock to the production of fuels and chemicals. The interest on coal gasification has increased recently due to concerns over energy supply and the need to harness nationally-available resources, and as a means to produce cleaner fuels.
There is a strong interest among NEA countries in coal gasification technologies, and this chapter analysed three areas: coal gasification systems (gasifiers), integrated gasification combined cycle (IGCC), and underground coal gasification (UCG).

Most coal gasifiers are based on three generic designs: moving-bed, fluidized-bed and entrained flow gasifiers. Existing technologies for gasifying coal are considered mature and commercially-proven. For a project developer, the choice of gasifier depends on a set of different factors, including the properties of the coal to be gasified, its reactivity, and the utilization purpose of the syngas. Technologies on gasifiers have been dominated by private sector organizations, with relatively few developments in North-East Asia countries. Countries such as China and the Republic of Korea have encouraged inward technology transfer from overseas providers, while at the same time stimulating R&D from national organizations. China and the Russian Federation have developed their own gasifier models, although there seem to exist limited international recognition and awareness about such technology developments.

IGCC is a technology which uses syngas to run a gas turbine in order to generate electricity. The interest on IGCC has been driven by the higher efficiencies that can be achieved and the reduced emissions of CO₂. Besides, IGCC facilities have the potential to provide a cost-effective method for capturing and storing CO₂. IGCC is a promising technology but has not achieved its full potential yet. Its relatively high costs and lower availability and operating experience, particularly when compared with SC and USC PC combustion, have hindered the full commercial deployment of IGCC. Notwithstanding this, there is a strong interest on this technology among NEA countries, with Japan, China and the Republic of Korea at the forefront. Since 2007, Japan has been operating one of the few existing IGCC pre-commercial demonstration projects in the world, which became fully commercial in June 2013.

Applying a significantly different approach from gasification processes that occur at the surface, in gasifiers, UCG has seen a resurgence of interest in the last few years. UCG is best suited to deep, inaccessible coal deposits, and has the potential to significantly increase global coal reserves and turn these into syngas in a safe, economic and environmentally sensitive manner. Among NEA countries, the interest on UCG has been driven mainly by China and the Russian Federation, with the latter having accumulated decades of experience. While there are technology aspects that can be considered “proven”, UCG is still an emerging technology field, years behind full-commercial viability and wide-spread deployment.

Based on the analysis above, the key messages to policymakers and practitioners are as follows:

On coal gasifier technologies:

- For China, Mongolia and the Republic of Korea, it is recommended that they pursue and/or continue the policies of encouraging the deployment of gasification technologies from overseas’ providers, through inward technology transfer, while building-up the know-how of national companies and organizations on these technologies.

- Russian Federation-based companies and R&D institutions appear to have developed coal gasifier technologies, although with limited international recognition. It is recommended to conduct a thorough assessment of Russian coal gasifier technologies, which would include an analysis of their suitability to the context of other NEA countries, as well as the potential for harmonizing research efforts among R&D organizations in the sub-region, particularly on emerging areas (e.g. plasma-gasifier technologies).
There is potential for exploring the competitive advantages of nationally-designed coal gasifiers of China and the Russian Federation, specifically in what concerns their cost-effectiveness vis-à-vis other commercially available models. The characteristics of Chinese and Russian models could be of interest, in particular, to DPRK and Mongolia, which have limited know-how and experience on coal gasification technologies.

On IGCC technologies:

- IGCC is emerging as a viable coal-conversion technology for power generation, and its deployment should be encouraged by governments of NEA countries until the technology is proven on a commercial basis. Policies to foster IGCC development should target both the R&D and the demonstration phases, and instruments that policy-makers could apply include, among others, the establishment of public-private partnerships involving the national government or publicly-owned power utilities, government guarantees and long-term power purchase agreements.

- Several initiatives related to IGCC can be observed among NEA countries, including pre-commercial demonstration projects in all countries except for Mongolia and DPRK. To a large extent, these initiatives appear to be unrelated and unconnected, and thus there seems to be the potential for harmonizing and coordinating some of these efforts. Information sharing activities through workshops and joint studies could be a first step to foster international cooperation. On specific areas where there is scope for joint cooperation, joint ventures involving technology providers should be considered whenever feasible, as they are one of the most effective mechanisms to support the transfer of technologies.

- Among NEA countries, Japan is at the forefront on IGCC development, with several years of accumulated experience from operating one of the few existing pre-commercial demonstration projects in the world. Japan is also leading R&D efforts, at global level, on IGFC. These experiences could be of significant interest to countries in the sub-region, and Japan could take the lead in the development of a sub-regional knowledge sharing and transfer centre, for instance through JCOAL or NEDO, for supporting the dissemination of these experiences and know-how.

- IGCC facilities are well-positioned to embrace CCS, as the gasification of coal makes it technically feasible the capture of CO₂ before the combustion of syngas. In this context, it is recommended that R&D and IGCC demonstration projects in NEA countries can be developed alongside the technical developments necessary to ensure CCS is ready to be deployed.

On underground coal gasification technologies:

- The Russian Federation has accumulated significant practical, technical and research experience on UCG, and it can position itself both as a sub-regional and global leader in these technologies. It is recommended that the know-how and technical expertise of Russian Federation organizations are properly documented and “marketed” so that their applicability and potential benefits vis-à-vis other technologies could reach non-Russian organizations.

- There is the perception that UCG technologies could benefit enormously from a greater exchange of knowledge and experiences among the companies and the institutions involved on their development, despite difficulties related to this know-how being privately owned or protected by IP rights. Government-sponsored R&D could significantly address these
challenges, particularly if conducted in the framework of international cooperation, as resources and efforts could be harmonized and maximized. In NEA, opportunities for cooperation in the sub-region could be first explored between Russian and Chinese organizations, as these are the two countries that have accumulated more experience on UCG, then with Mongolia, because of its recent interest on UCG, and possibly with DPRK.

Government support can be instrumental in accelerating the commercial viability of UCG not only on the R&D and pre-commercial stages, but also in addressing existing gaps in legislation and regulation. Notorious gaps are on environmental criteria for UCG development and on guidelines for site-selection. In this connection, it is suggested that governments of NEA countries, particularly those of China, Mongolia and the Russian Federation, can work together in coming up with common guidelines for UCG development.

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Coal Liquefaction Technologies
5.1 Introduction and Background

Coal is a solid fuel rich in carbon and relatively low in hydrogen content that can be converted into liquid fuels, either by the removal of carbon or the addition of hydrogen. Technologies for converting coal into liquids (CTL), or coal liquefaction, have been applied as early as the 1930-40s, when coal-rich Germany needed to secure the supply of fuels for transport. In the 1950s, concerns over an oil boycott due to its apartheid policy led South Africa to subsidize the production of transportation fuels from its abundant coal resources. The oil shocks of the 1970s stimulated OECD countries such as the USA, Japan or Australia in earmarking funds for R&D on CTL technologies, although many projects were later discontinued due to a sustained decrease in oil prices (CIAB, 2006). China has also been conducting research on CTL since the 1970s, due to the relative paucity of oil (the country became a net oil importer in 1993) and the abundance of coal reserves. Concerns over the security of supply and economic considerations (i.e. the low price of raw coal) have therefore been the main drivers for developing CTL technologies. In 2010, only 0.5% of the global demand for coal was used for CTL purposes. Under the IEA’s New Policies Scenario, this share is expected to increase to 3% by 2035, which underpins the growing importance of CTL in the global energy picture even if its share remains relatively small (IEA, 2012a).

For coal to replace oil or any products derived from oil, the coal feedstock must be converted into liquids with similar properties to those of oil, in particular the hydrogen content. This can be achieved either by adding hydrogen or removing carbon, while it also needs to be ensured that “impure” elements, such as nitrogen and sulphur, are removed from the final product (Minchener, 2011a).

In essence, there are two alternative approaches for obtaining liquid fuels and other products from coal: the direct and direct coal liquefaction routes. A third route should also be mentioned, the pyrolysis or carbonization of coal, which consists in the thermochemical decomposition of coal yielding three semi-finished products: gas, liquid tar and char. This technology has however been considered a “dead-end”, with comparatively low yields of liquid products and therefore with low economic viability (Gorlov and Agapova, 2013). Its analysis has thus been left out of the scope of this study.

The first step in the indirect CTL approach is the gasification of coal so as to produce a syngas which, as observed in chapter 4, is a mixture consisting essentially of carbon monoxide and hydrogen. After clean-up and purification, the syngas is condensed through a catalyst and converted into liquids. The syngas can be treated either by the Fischer-Tropsch synthesis (which mostly yields diesel), or the methanol synthesis (whose main product is petrol/gasoline).

The alternative CTL approach is direct liquefaction, also known as “hydroliquefaction”. This process consists in dissolving coal in a solvent at high temperatures and pressure in a vessel containing hydrogen and an appropriate catalyst. Under these conditions, the solid organic material in the coal gets dissolved, and when reacted with hydrogen it breaks down into smaller molecules. The two process routes for converting coal into liquids are represented, in a simplified manner, in figure 5.1 below.
This chapter examines current technology developments in NEA countries along these two CTL routes: indirect liquefaction (through the Fischer-Tropsch synthesis) in sub-chapter 5.2 and direct liquefaction in sub-chapter 5.3. Other CTL approaches and relevant initiatives in the NEA sub-region are presented in sub-chapter 5.4. In line with the other technology sectors, each sub-chapter provides a brief description of the technology(ies) and their global status, developments in NEA countries, and sheds light on opportunities for sub-regional cooperation. Sub-chapter 5.5 concludes and provides recommendations on the way forward.

As can be observed in figure 5.1, in the indirect liquefaction route, and after the gasification of coal occurs, there are two different CTL producing methods: the Fischer-Tropsch (F-T) synthesis and the methanol synthesis. As the F-T is the best well-known and most common indirect CTL method, it is the focus of this sub-chapter. Alternative indirect liquefaction routes are considered in sub-chapter 5.4.

The indirect coal liquefaction route involves two main processes. The process is initiated with the gasification of coal, in a process previously described in chapter 4. Once it leaves the gasifier, the syngas needs to be cleaned up, with CO₂ and other gases being separated from the syngas. An outcome of the gas cleaning process is the production of a highly concentrated stream of CO₂, which in the absence of a GHG emission abatement programme, is eventually released into the atmosphere.

Once cleaned up, the syngas is sent to a reactor (usually called an F-T reactor), where it is converted into a mixture of hydrocarbons in the presence of a catalyst. This mixture of hydrocarbons is then separated, primarily based on differences in boiling points. Typically, in a F-T process, diesel and jet fuel oil are the resulting products. It should be noted that the conversion process is highly exothermic (i.e. it releases heat), and this heat is usually captured to generate power in the facility. A simplified representation of the indirect liquefaction process, through the F-T route, is presented in the figure below.

Table 5.1 below provides a snapshot on the main policies, programmes and strategies of North-East Asian countries in developing CTL technologies.

<table>
<thead>
<tr>
<th>Country</th>
<th>Description</th>
</tr>
</thead>
</table>
| China   | - The Eleventh Five-Year Plan (2006-2010) set the ground for the development of a series of pilot CTL projects;  
- In 2008, concerns over the business risks and environmental impacts of CTL, led the central government to exert a stricter control over new CTL projects in China. Many CTL projects have been put on hold or suspended due to concerns over the use of scarce water resources. |
| Japan   | - After the first oil crisis, the government unleashed the “Sunshine Programme” in 1974, which encouraged the development of CTL technologies “unique” to Japan. The programme finished in 2002;  
- No specific policies or strategies currently exist on CTL, but national interest on these technologies may be rekindled if oil prices remain high or further increase. |
This chapter examines current technology developments in NEA countries along these two CTL routes: indirect liquefaction (through the Fischer-Tropsch synthesis) in sub-chapter 5.2 and direct liquefaction in sub-chapter 5.3. Other CTL approaches and relevant initiatives in the NEA sub-region are presented in sub-chapter 5.4. In line with the other technology sectors, each sub-chapter provides a brief description of the technology(ies) and their global status, developments in NEA countries, and sheds light on opportunities for sub-regional cooperation. Sub-chapter 5.5 concludes and provides recommendations on the way forward.

### 5.2 Indirect Coal Liquefaction (Fischer-Tropsch synthesis)

As can be observed in figure 5.1, in the indirect liquefaction route, and after the gasification of coal occurs, there are two different CTL producing methods: the Fischer-Tropsch (F-T) synthesis and the methanol synthesis. As the F-T is the best well-known and most common indirect CTL method, it is the focus of this sub-chapter. Alternative indirect liquefaction routes are considered in sub-chapter 5.4.

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It should be noted that a Chinese company, Synfuels China, has been the technology provider to the Yitai and Lu’an Groups’ projects. This company was established in 2006 as a spin-off from the Institute of Coal Chemistry under the China Academy of Sciences, which has been conducting R&D on the F-T process since 1980. This company aims at developing projects on CTL, including the necessary technologies (Minchener, 2011a).

Another important point on China’s CTL development is that most of the planned CTL projects in China are located in water-scarce provinces. As the liquefaction of coal is a water-intensive process, one of the reasons underpinning the decision of suspending or abandoning some of the CTL projects in the pipeline were concerns over the heavy burden put on scarce water resources. Box 5.1 sheds some light on the main environmental concerns associated with CTL projects.

Commercial experience with F-T CTL is fairly limited, with only one large-scale commercial plant in operation in the world by Sasol in South Africa. However, the technology has considerably progressed in the last 20 years, as an indirect liquefaction plant uses much the same technology as do other systems that involve coal gasification (such as IGCC). Global leaders in F-T conversion include multinational companies such as Shell, Sasol, Chevron or Exxon Mobil, as well as smaller firms such as Rentech and Syntroleum Corporation, both US-based firms (Bartis et al., 2008).

Among North-East Asian countries, China is leading the way on F-T indirect liquefaction technologies. Although it has been a relatively late comer vis-à-vis countries which have traditionally been ahead on these technologies, such as the US, Germany and Japan, China has been able to gradually catch-up, eventually becoming one global leader.

The development of CTL should be seen in the context of China’s industrialization programme which, in parallel with concerns over energy security, led the government to develop technologies on coal-to-liquids and coal-to-gases in order to take advantage of its large coal reserves. Under the Eleventh Five-Year Plan (2006-2010) there was a drive to develop CTL projects, if possible integrated upstream with coal mines, and downstream with the markets for oil products. This drive was considerably cooled down in the 2006-2008 period, with a different set of policy measures issued by NDRC restraining the development of such projects, mainly due to concerns over technical and economical issues (Minchener, 2011a).

Among the restrictions imposed, NDRC defined minimum processing capacities of 3 Mt per year for CTL projects, and the favouring of low-grade and lower calorific value coals as feedstock. Apart from a few exceptions, NDRC decided to suspend approvals of new CTL projects. In spite of these restrictions, several indirect coal liquefaction projects are in operation in China, with five main companies interested in these technologies: Shenhua Group, Yitai Group, Lu’an Group, Jingcheng Mining Group and Yankuang Group (Yuhong and Yongxu, 2012). A brief overview of the main projects in indirect CTL in China is presented in table 5.2:

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**Figure 5.2** – Simplified representation of the indirect coal liquefaction method, through F-T synthesis. *(Source: adapted from CIAB, 2006)*
It should be noted that a Chinese company, Synfuels China, has been the technology provider to the Yitai and Lu’an Groups’ projects. This company was established in 2006 as a spin-off from the Institute of Coal Chemistry under the China Academy of Sciences, which has been conducting R&D on the F-T process since 1980. This company aims at developing projects on CTL, including the necessary technologies (Minchener, 2011a).

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### Table 5.2 – Key indirect coal liquefaction projects in China.
(Source: Yuhong and Yongxu, 2012; Minchener, 2011a)

<table>
<thead>
<tr>
<th>Company</th>
<th>Project Location</th>
<th>Start-up date</th>
<th>Notes</th>
</tr>
</thead>
<tbody>
<tr>
<td>Yitai Group</td>
<td>Inner Mongolia</td>
<td>March 2009</td>
<td>• Project developed in partnership with the Institute of Coal Chemistry under the China Academy of Sciences (now Synfuels China);</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>• Capacity: 160,000 ton per year;</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>• 1 ton of liquid products can be produced with approximately 4 tons raw coal.</td>
</tr>
<tr>
<td>Lu’an Group</td>
<td>Shanxi</td>
<td>July 2009</td>
<td>• This was the first demonstration plant in China following the indirect CTL route;</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>• Technology provided by Synfuels China;</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>• Capacity: 160,000 ton per year.</td>
</tr>
<tr>
<td>Shenhua Group</td>
<td>Shaanxi</td>
<td>March 2010</td>
<td>• Demonstration project associated with the direct liquefaction project developed by the same company;</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>• Capacity: 180,000 ton per year;</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>• Start-up and operation were successfully conducted,</td>
</tr>
<tr>
<td>Yankuang Group</td>
<td>Inner Mongolia</td>
<td>December 2009</td>
<td>• Yankuang has intellectual property rights on the technology used on this project;</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>• The project obtained environmental clearance, but construction had not started at the time the research was conducted;</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>• Capacity: 1 million ton per year.</td>
</tr>
</tbody>
</table>

Box 5.1 – The environmental footprint of coal-to-liquids

The conversion of coal into liquids is associated with potential environmental challenges. They include the high emission levels of CO₂ (in comparison with liquids derived from oil or natural gas), as well as the higher energy usage and water requirements for unit of product obtained.
The production of liquids from coal is a carbon intensive process, and implies a substantial increase of GHG emissions compared with equivalent oil-based alternatives. On the other hand, CTL facilities produce concentrated streams of CO₂, which are readily available for capture and/or utilization.

The amount of water required to operate a CTL plant depends on a set of variables, including the design of the unit, the type of gasifier, the coal characteristics and the local atmospheric conditions. For both direct and indirect liquefaction, between 5 and 8 litres of water are necessary per litre of liquid fuel produced. Water is required for several processes, but the cooling needs of the plant tend to be the largest source of water consumption. Therefore, the management of water supplies and the reuse of effluents should play an important role in a CTL plant.

Other environmental challenges include the treatment of effluents and unwanted by-products, such as gases from the refining of products, solid residues associated with catalysts, etc.

(Source: Couch, 2008)

Due to its limited energy resources and the relative proximity of coal-rich countries, such as Australia, China and Indonesia, Japan considered that CTL could play an important role in enhancing energy security by reducing the imports of oil. The first oil crisis in 1973 led the Japanese government to initiate a programme aiming at devising liquefaction technologies “unique” to Japan. This programme was called the Sunshine Project, and was mainly focused on direct liquefaction technologies (more details provided in the next sub-chapter).

Mongolia has been a net exporter of raw coal, and in the past few years there has been a growing interest in the development of industrial projects that could generate high-value products from coal. A few international companies have assessed the economic and technical feasibility for coal liquefaction with coal from Mongolia’s mines. Among those, a study was carried out by QGX, a Canadian mining company, which showed there was potential for a CTL plant using coal from the Baruun Naran reserve. There was also a positive screening conducted by Nexant. However, none of these projects had moved forward at the time of writing, possibly due to financial considerations (Avid, 2012).

On a recent development in Mongolia, the Baganuur Energy Corporation, a joint venture between MCS (Mongolia) and POSCO (ROK), is planning to build a plant at the Baganuur mine for the production of 456,000 ton of diesel, 90,000 ton of gasoline and 100,000 tons of DME. The plant plans to use 4.2 million ton of Baganuur and 3.1 million ton of Ukhakhuagt coal per year. The total investment is of around 2 billion USD. The pre-feasibility study of the project was approved by the Mongolian Mineral Resources Professional Council in June 2013, and, currently work is being conducted on the implementation of the project. The Engineering, Procurement and Construction work will be carried out by POSCO E&C and MCS International. The construction is expected to be completed by 2018. Details about the DME component of this project are provided in sub-chapter 5.4.

In the Republic of Korea, the interest on CTL has been related on coal gasification development. From 2007 to 2011, KIER has conducted a pilot project entitled “syn-oil manufacturing technology by means of coal”, which consisted of a 15 barrel/day device. There is the perception that CTL technology should be independently developed, due to difficulties in obtaining such technologies from private companies (Lee, 2012).
In the Russian Federation there has been extensive academic research in the Fischer-Tropsch synthesis approach, resulting in the development of the scientific process fundamentals. However, the development of Russian technology is somewhat limited by the lack of experimental base for the continuous testing of catalysts (Gorlov and Agapova, 2013), even though notable progress has been made by some research institutes affiliated with the Russian Academy of Sciences. Despite this, a few Russian Federation companies are considering the development of CTL projects:

- Mechel has plans to build a CTL facility, using a variation of the F-T indirect liquefaction technology, in the Sakha (Yakutia) Republic for the production of synthetic fuels (diesel fuel) from the coal of Elginsky coal deposit.
- SUEK plans to build a demonstration unit and then a CTL plant in the vicinity of one of the company’s coal fields, which is located far away from oil refineries. The fuel produced would be used to meet the company’s own energy needs.

It can be observed that the most active country in NEA in developing indirect coal liquefaction technologies has been China. It is yet to be seen whether the demonstration projects are technically and economically feasible, but the experiences and technological edge obtained by Chinese companies have the potential to be disseminated to other countries in the sub-region and even beyond. It may also be observed that CTL technologies may play a role in deriving economic value from “stranded” coal resources, particularly in countries with vast territories such as China, Mongolia and the Russian Federation.

### 5.3 Direct Coal Liquefaction

A simplified overview of the direct CTL route was provided in the introduction to this chapter. In a little bit more of detail, in direct liquefaction pulverized coal is first treated at high temperatures and pressures, with a solvent consisting of a coal-derived oil slurry resulting from the liquefaction process. The feedstock is broken down in smaller molecules, and then hydrogen is added in order to increase the hydrogen/carbon ratio of the mixture. Catalysts are usually added to speed up the reaction and, as a result, the process yields a product which can be described as synthetic crude oil. This product is highly aromatic, and it needs to be upgraded in order to obtain high quality transport fuels (Couch, 2008; Minchener, 2011a). An overview of the process is provided in the figure below:

![Figure 5.3 – Simplified representation of the direct coal liquefaction process.](Source: adapted from Deutsche Bank, 2007)
There are two main variants of the direct liquefaction process, depending on whether the initial treatment of coal is separate from its conversion into liquid distillable products. Direct CTL processes have been developed to process coals ranging from low-rank lignites to high volatile bituminous coals, while higher-rank coals appear to be less reactive. Overall, conversion efficiencies from solid coal to liquids average 60%, on a dry and mineral-matter free coal input (Couch, 2008).

Compared with indirect liquefaction, the direct route is less complex, and potentially provides a higher yield of liquid products. Although it is a relatively simple process, it requires reactors that can withstand high temperatures and pressures.

Direct coal liquefaction is a technology yet to be proven at full commercial scale, but China is one of the few countries in the world leading the way, with a major demonstration project in operation since the end of 2008. This plant is owned and developed by the China Shenhua Energy Company, a large state-owned energy conglomerate with around 150,000 employees (please check Box 5.2 below).

**Box 5.2 – The world’s first industrial-scale coal direct liquefaction project**

China’s Shenhua Group is developing the largest direct CTL demonstration project in the world, which is located in Erdos, Inner Mongolia Autonomous Region. The initial approval of the project was granted in 2002, with the construction initiated in 2005. The plant was commissioned in December 2008. The first phase of the project has three liquefaction process lines, with a combined capacity to produce 3.2 Mt of oil products. Each line consists of a coal processing unit, a coal-based hydrogen production plant, facilities for liquid production and upgrading, a solvent recovery facility and a catalyst preparation plant.

Each line has the capacity to process about 3.4 Mt of coal per year, with the capacity to produce 1.068 Mt of oil products. An overview of the expected products from the facility is provided in the table below:

<table>
<thead>
<tr>
<th>Product</th>
<th>Annual Production (ton per year)</th>
</tr>
</thead>
<tbody>
<tr>
<td>LPG</td>
<td>70,000</td>
</tr>
<tr>
<td>Naphta</td>
<td>321,000</td>
</tr>
<tr>
<td>Diesel</td>
<td>621,000</td>
</tr>
<tr>
<td>Liquid Ammonia</td>
<td>12,000</td>
</tr>
<tr>
<td>Sulphur</td>
<td>41,000</td>
</tr>
<tr>
<td>Phenol</td>
<td>3,000</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>1,068,000</strong></td>
</tr>
</tbody>
</table>

Table above – Projects output of the Shenhua direct coal liquefaction plant, on each production line.

The plant is equipped with a CCS unit. During the trial phase, 100 ton of CO₂ were injected into an underground saline aquifer at a depth of 2000 m.
The technology used in the facility incorporates elements from German, Japanese and American technology providers, which have been integrated into a new plant design developed by Shenhua. The technology developed by Shenhua for this CTL plant has been applied for patent protection in 13 countries, and a patent license has already been obtained in the Russian Federation and Ukraine.

Since its commissioning in December 2008 until August 2010, the plant had operated for more than 5,000 hours, and in accordance with the design parameters and requirements. It is estimated that the total cost per ton of product generated is of 3,058 Yuan (around 495 USD), which takes account of an annual total output of liquid product of 1.068 Mt from the plant’s first production line.

Some attention has been paid to the minimization of the environmental impacts resulting from the plant’s operation. With respect to the utilization of water, for example, the facility requires close to 8t of fresh water to synthesize 1t of liquid products. The water for the project is piped from 100 km away, while all wastewater is treated and recycled in situ.

(Source: Minchener, 2011a; Yuhong and Yongxu, 2012; IEA, 2013a)

Few other countries in the world have been developing direct coal liquefaction technologies. Outside the NEA sub-region, the USA has been one of the countries at the forefront on this technological route, with significant government-funded R&D programmes in the 1970s and 1980s, which were stimulated by the two oil crisis. These programmes were discontinued due to several reasons, including the significant cost escalation of the programmes, some technical problems with the pilot plants, and the lack of evidence showcasing that direct liquefaction was a more advantageous route than indirect liquefaction (Bartis et al., 2008). Despite this, US-based firms have developed proprietary technology on direct CTL, particularly the so-called “two-stage” liquefaction process. With the onset of the shale gas revolution and the increasingly stricter environmental constraints towards the production and utilization of coal (LA Times, 2012), the role of CTL technologies in the coming years is, at best, uncertain. The UK and Germany are other countries outside NEA that have conducted projects with the direct liquefaction route.

In 1974 Japan initiated its Sunshine Project, which encouraged the development of liquefaction technology (JCOAL, 2010). This led to the development of two direct coal liquefaction processes: i) the NEDOL process, and ii) brown coal liquefaction.

The NEDOL process consisted in the “amalgamation” of three routes for the liquefaction of bituminous coal: i) solvolysis, ii) solvent extraction, and iii) direct hydrogenation\(^5\). A 150 t/d pilot unit was built at Kashima in Japan, which processed bituminous and sub-bituminous coals. The plant operated from 1996 to 1998 (Couch 2008; JCOAL, 2010).

On a different track, a brown coal liquefaction technology was developed in the framework of a cooperation agreement between the Japanese and Australian governments. This was a direct coal liquefaction process that comprised four stages, and which was being tested for 4 years (1987-1990) on a 50t/day pilot plant in Australia (Couch 2008; JCOAL, 2010).

Research under the Sunshine programme continued until 2002, when it was halted due to the global economic environment and the relatively low oil prices. However, based on this extensive work, NEDO has been able to advise both China and Indonesia in the development of their own CTL programmes. For instance, a pilot unit in Beijing for testing coals and process conditions was transferred from Japan, with NEDO being instrumental in sharing appropriate technology in support of China’s CTL programme.

In Mongolia, experiments with direct coal liquefaction technologies date back to the Soviet period, with different small-scale pilot projects being conducted, mainly in the 1980s. More recently, in 2008, feasibility studies have been conducted for applying the direct CTL route having as feedstock the coal from the Baganuur and Tavantolgoi mines. The project using the Baganuur coal would generate 25,000 barrels of liquids per day, and apply the H-Oil technology owned by Axens, a French firm (which also licensed this technology to the Shenhua CTL demonstration project) (Avid, 2012).

In the Russian Federation, experiences with direct coal liquefaction hark back to Soviet times, with unoxidized brown and low-grade metamorphosed hard coals used for hydrogenation, which involved a great number of R&D, design and engineering companies. There were plans for a CTL production plant in the Kansk-Achinsk basin with a capacity from 3.0 to 4.0-4.5 million tons, which eventually was not implemented due to funding issues (Gorlov and Agapova, 2013).

Currently, the company OAO INTER RAO UES has plans for jointly building a CTL plant in the Russian Federation with the Shenhua Group. In the first stage, a 1 million t/year direct CTL plant would be built, while on the second phase of the project a 1 million t/year indirect CTL plant was planned. Another area of potential interest in the Russian Federation is the utilization of nuclear reactors as the energy source of coal hydrogenation plants, which could help improving the technical, economic and environmental performance of such plants (Gorlov and Agapova, 2013).

In the Republic of Korea, no projects or initiatives have been identified using the direct route for coal liquefaction.

All in all, among NEA countries China is taking the lead on direct coal liquefaction technologies. Despite a dwindling interest in the last 10 years, Japan also possesses a technological edge on direct coal liquefaction, as a result of the research efforts conducted in the 1970-90s under the Sunshine programme. The technical cooperation among China and Japan on CTL technologies, which could be of interest to the sub-region as a whole should be noted as well.

5.4 Other Technologies and Processes

In addition to the main CTL routes analysed above – the indirect liquefaction via F-T synthesis and direct liquefaction – it is important to shed light on other processes and/or projects being considered or pursued in NEA countries. It is given special attention to ongoing initiatives on coal-to-methanol and coal-to-DME.

It has been observed earlier in the chapter that an alternative to the F-T indirect liquefaction is the methanol synthesis. Through this route, after the gasification of coal, the syngas obtained is converted into methanol in a reactor at moderate temperatures and pressures. As a third step, methanol can be converted into gasoline, in a process that was initially developed by Exxon Mobil.
In alternative, preceding the production of gasoline, DME can be obtained from the methanol (please check figure 5.1 for an illustration).

The relevance of both methanol and DME is related to its application as alternatives to conventional fuels. The traditional use of methanol is in the production of pharmaceutical and agricultural chemicals. However, methanol can be used as a fuel to be blended with gasoline/petrol, and can also be converted into DME through dehydrating methanol.

**China** has a relatively developed methanol market, with 180 companies reported to be commercializing this product as of the end of 2009. Feedstocks from methanol production include coal, coke, natural gas and heavy oil. The use of methanol to produce DME is potentially attractive, but the market for DME is still at an early stage (Minchener, 2011a).

The production of DME in **Japan** has been led by the JFE Corporation, which has built a 100 ton/day demonstration plant with the support of METI. The market for DME is still in its infancy in Japan, but activities towards the development of such market are being undertaken by DME International Co. Ltd. While current plants synthesizing DME have natural gas as feedstock, the utilization of coal for DME production is expected to gradually increase (JCOAL, 2010).

In **Mongolia**, DME has been considered with special interest due its potential to replace coal as a domestic fuel for heating and cooking purposes, particularly in traditional gers. The use of DME as a clean fuel could make considerable strides in improving access of populations to modern energy services, while reducing local air pollution in large urban settlements (Avid, 2012).

MCS Holding LLC, the largest private enterprise in Mongolia, made a decision to build a methanol to DME plant with a capacity of 100,000 t per year. The company has agreed with the government of Mongolia to implement this project. The roadmap for this plant consists of three main phases: i) import of DME from China for initial build-up of a market for DME; ii) construction of a methanol-to-DME plant in Ulaanbaatar having as feedstock coke oven gas; and iii) production of DME via the indirect liquefaction of coal from the Ukhaahudag mine. At the time of writing, it was reported the existence of delays in the implementation of the project. An illustration of the roadmap for this project is presented in figure 5.4 below:

**Figure 5.4** – Roadmap for a large DME project in Mongolia. *(Source: Avid, 2012)*
On a recent development, the MAK company has started a project to produce 400,000 ton of gasoline and 17,000 ton of LPG at the Aduunchuluun coal mine using the methanol-to-gasoline technology of Exxon Mobil. The plant will consume 3.4 million ton of lignite per year from the Aduunchuluun deposit. A pre-feasibility study was prepared by Fluor (USA), and it was submitted to the Mongolian Mineral Resources Professional Council for approval. The construction of the CTL plant is expected to be completed by 2018 (Avid, 2012).

5.5 Summary and Implications

The development of CTL technologies dates back to the first half of the 20th century, with its interest as an alternative route to petroleum-derived products being driven by concerns over the security of oil supply, and the existence of large and untapped indigenous coal reserves.

There are two main routes for converting coal into liquids: the direct and indirect liquefaction routes. A brief overview of these routes is provided in the table below, which also summarizes the main benefits and potential issues associated with the process of converting coal into liquids:

<table>
<thead>
<tr>
<th>Coal-to-Liquids</th>
<th>Benefits</th>
<th>Potential Challenges and Issues</th>
</tr>
</thead>
<tbody>
<tr>
<td>Benefits</td>
<td>• Enhanced energy security: countries endowed with large coal reserves have the opportunity to diversify their energy resource base, particularly with the reduction of imported oil. • Opportunities for developing “stranded coal”: coal resources that are not economical due to their location or quality could have their business case improved. • Liquid fuels from coal are clean: liquids synthesized from coal are on par with those generated from oil or natural gas, and therefore are fungible and easy to market, as far as the plant is not too far from consumption centres. • Economic and social benefits: local economies can contribute to an increase in regional GDP, while providing increased employment opportunities.</td>
<td>• Capital requirements: CTL projects are highly capital intensive projects, which require technology know-how, qualified manpower as well as significant supporting infrastructure. • Environmental Issues: studies have proved that, on a lifecycle basis, GHG emissions from coal-liquids are twice as much as those from their petroleum-based equivalent, unless CO₂ is captured and stored. • Water resource depletion: the liquefaction of coal is a water-intensive process, requiring 8-10 tonnes of water to produce 1 ton of synthetic oil. • Exposure to oil prices: the economic viability of CTL facilities strongly hinges on oil prices, as products from coal directly compete with refined products from oil. • Characteristics of coal: the coal available in large deposits may not be adequate for being processed into liquids with the available proven technologies.</td>
</tr>
</tbody>
</table>
CTL technologies have not proved yet to be entirely successful from a technical and economical standpoint. This is further compounded by concerns over the environmental sustainability of such projects, particularly with respect to water consumption and CO2 emissions.

Among North-East Asian countries different levels of interest and technological development on CTL technologies can be observed. China is taking the lead, both on direct and indirect liquefaction. On indirect liquefaction, China has positioned itself as a global leader with three reasonably-scaled industrial units, while on direct liquefaction it is operating the only large-scale facility in the world. Japan has pursued R&D on CTL for many years under its “Sunshine Programme”, which came to an end in 2002. Significant progress has been made on direct CTL technologies, with Japan cooperating with other countries in the development of their own CTL programmes, in particular China. Persistently high oil prices and the phase out of nuclear power may rekindle the interest of Japan on CTL technologies.

In Mongolia, there is a strong interest in the production of liquid fuels from coal both due to the high reliance on oil as well as the need to produce value added products from low-rank, cheap and abundant coal. It is also deemed important the production of cleaner fuels, such as DME from coal, which can be used as a substitute to raw coal for heating and cooking purposes at household level.

In the Russian Federation, CTL has been considered with some interest, particularly as a means to derive economic value from stranded coal reserves. Large coal companies, such as SUEK and Mechel, have plans for developing CTL facilities with technologies from overseas providers. In the Republic of Korea, the interest on CTL has been associated with developments on coal gasification, particularly of low-rank coals.

### Table 5.3 – Summary chart of coal-to-liquids technologies, including the direct and indirect routes.
(Source: own elaboration based on Deutsche Bank, 2007; Couch, 2008)

<table>
<thead>
<tr>
<th>Conversion Routes</th>
<th>Indirect CTL Process</th>
<th>Direct CTL Process</th>
</tr>
</thead>
<tbody>
<tr>
<td>Technology status</td>
<td>Mature and proven technology</td>
<td>At demonstration stage</td>
</tr>
<tr>
<td>Product yield</td>
<td>Diesel / Naphtha / LPG = 64:29:7</td>
<td>Diesel / Gasoline = 70:30</td>
</tr>
<tr>
<td>Comparative Advantages</td>
<td>- The gasification of coal allows for the elimination of undesired elements and allows flexibility on the feedstock used (which can be coal, natural gas, petroleum or biomass); - The CO2 produced can, in principle, be easily captured for subsequent underground storage.</td>
<td>- Less complex liquefaction process; - Lower water consumption per unit of liquid product synthesized; - Lower coal consumption, per unit of liquid product synthesized.</td>
</tr>
</tbody>
</table>

The development of CTL technologies dates back to the first half of the 20th century, with its interest as an alternative route to petroleum-derived products being driven by concerns over the security of oil supply, and the existence of large and untapped indigenous coal reserves.

There are two main routes for converting coal into liquids: the direct and indirect liquefaction routes. A brief overview of these routes is provided in the table below, which also summarizes the main benefits and potential issues associated with the process of converting coal into liquids:
In light of the analysis above, the key messages to policymakers and practitioners are as follows:

- CTL holds great potential as an alternative to oil-derived products, and it may play an important role in increasing the resilience of NEA countries to oil price volatility. However, NEA countries should not overlook the challenges related to the development of such projects, in particular with respect to their impact on the environment. The development of CTL projects in NEA countries should therefore be based on sound technical and environmental requirements, in particular with respect to fresh water utilization and effluent treatment.

- China is spearheading technological development on CTL technologies, and the know-how and experiences acquired from ongoing projects and R&D activities could be of great interest to countries in the sub-region. More specifically, there is scope for cooperation among Chinese organizations and their counterparts in Mongolia and the Russian Federation for the development of CTL projects, as these countries share some common characteristics (e.g. extensive untapped coal resources, similar weather patterns, etc.).

- The market for some liquids that can be produced from coal is still incipient – if existent at all – in most countries in the sub-region, as for example in the case of methanol and DME. North-East Asian countries could play a role in the creation of those markets, through policies and mandates, and they could do so in articulation with each other. In the case of methanol, it could be assessed the potential for its use in complement or as a substitute to gasoline as a transportation fuel. With regards to DME, its role as a substitute to raw coal or LPG could be driven by national governments, including the establishment of international markets for such products. In light of this, it is recommended that a thorough study could be conducted to assess the potential for synthetic fuels in the sub-region and the establishment of regional and sub-regional markets for these products.

- The production of liquids from coal can turn economically viable the development of “stranded” coal reserves, particularly those in China, Mongolia and the Russian Federation. These countries, through their “national champions” and R&D organizations, could establish a research team to study the joint development of such reserves, with the long-term vision of developing a knowledge-hub on CTL in the sub-region.

- Developments on CTL technologies should be articulated with progress on other technology areas, including coal gasification and CCS. Given the high carbon footprint of CTL plants, governments of NEA countries should ensure that plans for new CTL facilities should contemplate the possibility of being CCS retrofitted (i.e. the so-called “CCS ready”). Countries in the sub-region could synergize efforts in the preparation of guidelines and regulations for CCS retrofitting, as well as in setting up limits for GHG emissions associated with CTL plants.
Carbon Capture and Storage (CCS) Technologies
6.1 Introduction and Background

It is widely accepted that the dependency on fossil fuels is not expected to significantly decline in the short to mid-run, despite efforts to deploy and mainstream alternative means to reduce this dependency, such as renewable energy technologies, nuclear power, and energy efficiency and conservation measures. One of the negative externalities associated with the utilization and consumption of fossil fuels, and coal in particular, is the release of carbon dioxide, a greenhouse gas whose increased concentrations in the atmosphere contribute to the warming of the global climate system. According to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change, the consequences of a global temperature increase can be devastating, including a rise in sea levels and a higher likelihood of extreme weather events, such as prolonged heat waves and violent storms (IPCC, 2007).

The increased dependency on fossil fuels and the need to reduce greenhouse gas emissions are in completely divergent tracks unless carbon capture and storage technologies, or CCS, are deployed in large-scale. CCS is considered as a crucial component of global efforts to limit climate change through the reduction of GHG emissions, along with other abatement technologies, such as energy efficiency and renewable energy technologies (see for example IEA, 2012a).

CCS consists in a set of technologies and techniques that enable the capture of CO₂ from fuel combustion or industrial processes and its transportation for storage on underground reservoirs. CCS comprises three integrated stages (Minchener, 2011b):

1. Capture and subsequent compression of CO₂;
2. The transport of CO₂ in a supercritical/dense phase;
3. The injection of CO₂ into a geological formation.

A representation of the CCS chain is presented in the figure below:

Figure 6.1 – The CCS Chain.
(Source: IEA, 2013b)

CCS is not exclusively associated with the utilization of coal, and any industrial processes that are large point sources of CO₂ emissions are liable to CCS application. However, taking into account that the global coal-fired power plant fleet accounts for more than 8 Gt of CO₂ emissions annually, i.e. roughly a quarter of total anthropogenic CO₂ emissions (IEA, 2012e), the role and deployment of CCS is inextricably related to its application to the coal industry.

Along the CCS chain presented in figure 6.1, there are individual technology components that are in general well understood and, in many applications, they can be considered technologically mature. For instance, the production of hydrogen in industrial facilities (which implies the separation and removal of CO₂) is a technically mature process, while the pipeline transportation of CO₂ has been
CCS consists in a set of technologies and techniques that enable the capture of CO\textsubscript{2} from fuel and renewable energy technologies (see for example IEA, 2012a). The development of CCS will ultimately lead to the abatement of CO\textsubscript{2}. Thus the main driver to CCS is climate policy and the existence of a price on carbon. However, current prices of CO\textsubscript{2}, regardless of the jurisdiction they respect to, are not high and stable enough to drive the development and deployment of CCS technologies\textsuperscript{6}. In order to drive the necessary investments for the large scale deployment of CCS, it is necessary that governments provide funding for R&D and demonstration, as well as policy incentives for further deployment beyond demonstration, which will only be possible with private sector involvement. The role of governments is therefore of crucial importance for the future of CCS.

The increased dependency on fossil fuels and the need to reduce greenhouse gas emissions are in short to mid-run, despite efforts to deploy and mainstream alternative means to reduce this dependency, such as renewable energy technologies, nuclear power, and energy efficiency and consumption of fossil fuels, and coal in particular, is the release of carbon dioxide, a greenhouse gas. Along the CCS chain presented in figure 6.1, there are individual technology components that are in roughly a quarter of total anthropogenic CO\textsubscript{2} emissions (IEA, 2012e), the role and deployment of CCS is inextricably related to its application to the coal industry. CCS comprises three integrated stages (Minchener, 2011b):

1. Capture and subsequent compression of CO\textsubscript{2};
2. The transport of CO\textsubscript{2} in a supercritical/dense phase;
3. Removal of CO\textsubscript{2}.

A representation of the CCS chain is presented in the figure below:

With NEA countries consuming close to 60\% of the world’s coal and being major GHG emitters (China, Japan and the Russian Federation are in the top ten of the world’s largest emitters), CCS is a key CO\textsubscript{2} abatement technology. Table 6.1 below provides a snapshot of the main policies, programmes and strategies of North-East Asian countries on developing CCS technologies.

<table>
<thead>
<tr>
<th>Country</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>China</td>
<td>• CCS is an R&amp;D priority: the Twelfth Five-Year Plan on Clean Coal Technology Development, issued by the Ministry of Science and Technology, has singled-out CCS as one of the cleaner coal technologies to be developed in the future.</td>
</tr>
<tr>
<td>Japan</td>
<td>• There are several R&amp;D initiatives on CCS, although there is no legal or regulatory framework in place.</td>
</tr>
<tr>
<td>Mongolia</td>
<td>• No plans exist to develop or implement CCS.</td>
</tr>
<tr>
<td>Republic of Korea</td>
<td>• An R&amp;D programme on CCS is being conducted by three ministries, and the government has been investing in the development of core technologies and pilot projects. The budget for R&amp;D on CCS has been increasing steadily over the years, and a research infrastructure is now in place.</td>
</tr>
<tr>
<td>Russian Federation</td>
<td>• No plans exist to develop or deploy CCS technologies, as GHG emissions in the Russian Federation have been below the quota defined by the Kyoto Protocol. However, there is an interest in separating and/or utilizing CO\textsubscript{2} if required by specific industrial processes if some economic value can be derived from it.</td>
</tr>
</tbody>
</table>

Table 6.1 – Policy measures and/or programmes on CCS in NEA countries. (Source: own elaboration based on IEA, 2012c; Minchener, 2011b; JCOAL, 2012; Avid, 2012; Lee, 2012; and Gorlov and Agapova, 2013)

This chapter is structured as follows: sub-chapter 6.2 provides an overview of the main carbon capture technologies and sheds light on the most relevant initiatives among North-East Asia countries on these technologies. In sub-chapter 6.3 the focus turns to the stages of transport and storage of CO\textsubscript{2}.

\textsuperscript{6} Since the beginning of 2013 that CO\textsubscript{2} prices have been trading below 10 USD in the EU Emissions Trading Scheme (Point Carbon, 2013), the world’s largest carbon market, while the abatement costs of CO\textsubscript{2} for a coal-fired power plant equipped with current CCS technology ranges from 23-92 USD per tonne of CO\textsubscript{2} (Global CCS Institute, 2011).
In addition to these, it is reflected upon the utilization of CO₂ as an “end-product” and thus as an alternative to its abatement in underground storage sites. Finally, on sub-chapter 6.3 the importance of the “CCS-ready” or CCS-retrofitting” concept in the context of NEA countries is underscored. Sub-chapter 6.4 closes with a summary and the main implications for policymakers.

6.2 Carbon Capture Technologies

There are several different ways of capturing CO₂ in large industrial processes, and they are generally characterized as first and second generation technologies. First generation technologies consist of the following methods: i) pre-combustion, ii) post-combustion, and iii) oxyfuel combustion.

Pre-combustion capture systems are intrinsically related to the gasification processes and technologies examined in Chapter 4. In pre-combustion capture coal is first gasified and converted into syngas, a mixture of carbon monoxide and hydrogen. Then steam is added to the syngas in a second reactor (the so-called “shift reactor”), where the carbon monoxide is converted into CO₂ and (additional) hydrogen. The resulting gas mixture can then be split into separate streams of CO₂ and hydrogen by means of a physical solvent process. The CO₂ can thus be captured and, after compression and dehydration, it is ready for transport and storage. If the coal is used for power-generation purposes, pre-combustion capture would very likely be associated with IGCC (please check sub-chapter 4.3 of this study) (Minchener, 2011b; Global CCS Institute, 2013). A simplified illustration of the pre-combustion process is provided in figure 6.2 below.

![Figure 6.2 – Pre-combustion carbon capture.](Source: Adapted from Minchener, 2011b)

Pre-combustion capture is already commercially used in industrial processes that gasify coal for the production of hydrogen, which is subsequently used as feedstock for the manufacture of chemicals. However, pre-combustion has not yet been commercially demonstrated on large power generation plants.

Post-combustion capture systems separate CO₂ from the exhaust gases that result from combusting coal. At present, separation is typically carried out by the use of a liquid solvent, such as an amine solution, which would result in the formation of an amine–CO₂ complex, which is afterwards decomposed through the supply of heat to release a concentrated stream of CO₂. The solvent amine solution can be recycled and reused in the capture process (Minchener, 2011b; Global CCS Institute, 2013). An illustration is provided in the figure below:
Post-combustion technology could be applied in both existing and new coal-fired power plants, although as of now there have not been any large-sized applications of the technology. Challenges with this technology are the high capital requirements to handle large quantities of flue gas, and the energy penalty associated with the capture process. A possible advantage is that post-combustion systems do not require the fuel to be processed before it is combusted, potentially making it more feasible for deployment on existing facilities. It should also be noted that R&D has been targeting the development of alternative post-capture techniques, such as membranes or solid sorbents, to replace the solvent-based systems that are currently applied in the industry (Minchener, 2011b; Global CCS Institute, 2013).

Oxyfuel combustion systems use oxygen instead of air for combusting the primary fuel. This would result in a flue gas consisting essentially of CO$_2$ and water vapour, in addition to other impurities. The water vapour would then be removed from the flue gas, so as obtain a high-concentration stream of CO$_2$ that could subsequently be transported and stored. Oxyfuel systems require the separation of oxygen from nitrogen through an air separation unit. Another feature of this technology is the need to recirculate the flue gas, in order to control the combustion temperature. The main advantage of this CO$_2$ capture method is that the separation of CO$_2$ from the flue gas is relatively simple. The main drawback is the high costs associated with the air separation process (Minchener, 2011b; Global CCS Institute, 2013).

Pre-combustion, post-combustion and oxyfuel combustion are the dominant carbon capture technologies, and they are usually lumped together as “first generation technologies”. There are also several promising CO$_2$ capture concepts, which have been mostly tested in laboratory conditions or small demonstration units (below 1 MW capacity). They are of interest because of their potential to significantly reduce the energy penalties associated with first generation technologies. These “second generation technologies” include, among others, post-combustion carbonate looping or chemical looping combustion (Minchener, 2011b).
**Chemical looping combustion** (CLC) is amongst the most promising of second generation technologies. It basically consists of a variation of the oxyfuel combustion process whereupon the separation of oxygen from air is integrated into the combustion process. CLC works in a relatively simple manner: instead of combusting the fuel in a single reaction stage, two reactions are used. For this purpose, an additional “component” is required, which re-circulates between the two reactions carrying oxygen atoms. This additional “component” consists of an oxygen carrier and is, in general, a metal. A boiler applying CLC technology would be similar to a circulating fluidized bed (CFB) system consisting of two interconnected CFB units, where the metal would be employed as bed material. Chemical looping combustion holds promise as a more economically and energy efficient alternative to first generation technologies (ZEP, 2011; Imperial College, 2013).

According to IEA’s “Tracking Clean Energy Progress 2013” report (IEA, 2013c), 13 large-scale CCS demonstration projects were in operation or under construction in 2013. However, most of these projects are either on natural gas processing or in the industrial sector, indicating that significant progress still has to be made if CCS is to be applied to the coal industry, particularly on coal-fired power plants, and mainstreamed in the mid to long-term. Most developments on carbon capture technologies for application in the coal industry are taking place in OECD countries, particularly in the EU, USA, Australia, Japan, and Canada. In North-East Asia, in addition to Japan, initiatives on carbon capture technologies are being conducted in China and the Republic of Korea.

In **China** there are several on-going industrial-scale activities involving carbon capture and utilization which are being conducted by the major national power generation companies. These include the post-combustion trials of the Huaneng Power Group in coal-fired power plants in Beijing and Shanghai, as well as the GreenGen IGCC project, which will include a CCS component using pre-combustion technology (please check sub-chapter 4.3). It should be noted that Huaneng Power Group Shidongkou No.2 Power Plant CCS project in Shanghai is one of the largest CO₂ capture facilities in coal-fired power plants in the world. A summary of the major carbon capture projects in China is presented in the table below:

<table>
<thead>
<tr>
<th>Company</th>
<th>Project Name</th>
<th>Capture Process</th>
<th>Notes</th>
</tr>
</thead>
</table>
| Huaneng Power Group     | Gaobeidian PC CHP plant (Beijing)   | Post-combustion | • The plant applies a CO₂ absorption scrubber designed by the North China Power Engineering Co Ltd., following the cooperation with Australia’s Commonwealth Scientific Industrial Research Organisation;  
• Capacity: capture of 3000 t of CO₂ per year;  
• Operation started in mid-2008;  
• Recovery rate of CO₂ was of 85 %, with 99.9 % purity;  
• The captured CO₂ is utilized in the beverages industry. |
| Huaneng Power Group     | Shidongkou No.2 Power Plant (Shanghai) | Post-combustion | • This project retrofits two ultra-supercritical power generation units, with an annual CO₂ capture capacity of 120,000 tonnes;  
• All of the captured CO₂ is sold to industrial enterprises in and around Shanghai;  
• It has been reported that the cost for capturing the CO₂ is below 30 US$/t, rising to 35 US$/t when the gas has to be purified for use in the food and beverage industry. |
China is presented in the table below:

<table>
<thead>
<tr>
<th>Company</th>
<th>Project Name</th>
<th>Capture Process</th>
<th>Notes</th>
</tr>
</thead>
<tbody>
<tr>
<td>China Power Investment</td>
<td>Shuanghuai Power Plant</td>
<td>Post-combustion</td>
<td>• Capacity: 10,000 tons CO₂ per year (with 99.5% concentration); 50 million m³ of flue gas can be processed annually (equates to less than 1% of the power plant’s throughput); The CO₂ recovery rate has been above 95%; The CO₂ captured is sold to the food and beverages industry, and a profit is reported to be made.</td>
</tr>
<tr>
<td>GreenGen Consortium</td>
<td>GreenGen</td>
<td>Pre-combustion</td>
<td>• Phase 3 of the project is expected to include a pre-combustion carbon capture component (construction expected to start in 2015).</td>
</tr>
</tbody>
</table>

Table 6.2 – Major carbon capture projects in coal-fired power plants in China.
(Source: own elaboration based on Yuhong and Yongxu, 2012, and Minchener, 2011b)

The initiatives above have been supported by R&D activities in China, as well as by international technological cooperation programmes on CCS. These technological cooperation programmes have, indeed, been instrumental to the progress on CCS technologies among Chinese organizations. Under bilateral or multilateral frameworks, higher institutes, academies and companies have conducted extensive cooperation and exchange of information with their counterparts in the EU, Australia, Japan, Italy and the USA (Yuhong and Yongxu, 2012).

Among these programmes, it should be noted a joint China-Japan industrial scale cooperation project, which aimed at capturing 3-4 Mt of CO₂ from two power-plants in China and utilize the recovered CO₂ for EOR in China’s North-Eastern province of Heilongjiang. This project involved the Ministry of Economy, Trade and Industry (METI) of Japan, JCOAL and several leading Japanese companies. From China’s side, NDRC, Petro China and other major organizations were taking part in the project. However, at the time of writing there was limited information about the status of the project (Minchener, 2011b). Notwithstanding this fact, this project is a good example of cooperation among NEA countries on CCS, with the strong backing of national governments.

There are several R&D initiatives in China in the field of CCS. Amongst the most relevant, it should be noted the work on oxyfuel combustion being conducted by the Huazhong University of Science and Technology in Wuhan, which has conducted extensive research on oxygen-fired coal combustion, which led to the construction of a 400 kWth test unit. A pilot scale system with 3 MWth industrial pilot has been established with the capacity to capture 1t/h of CO₂. Now, the team is carrying out an industrial pilot project in Yingcheng, Hubei Province, with the capacity to capture up to 100,000 t/y of CO₂ (Yuhong and Yongxu, 2012; Minchener, 2011b).

In Japan, all first generation carbon capture technologies have been developed by Japanese manufacturers and research organizations. Among these, it should be emphasized the Osaki CoolGen “triple combined cycle” IGCC project (gas turbine, steam turbine and fuel cell), which was referred to in sub-chapter 4.3, and which is planned to include a pre-combustion carbon capture unit (JCOAL, 2012).
Research on oxyfuel combustion started in Japan in the mid-1990s. Based on the results achieved, the technology was applied in a demonstration project in Australia that retrofits an existing coal-fired power plant. This demonstration project – the so-called Callide-A Oxyfuel Project – consists of a joint venture of organizations from Australia and Japan, and it is the world’s first demonstration project on oxyfuel carbon capture. The project is designed to capture 70t of CO₂ per day for a period of 2 years, and it started operations in December 2012 (JCOAL, 2012). Another noteworthy demonstration project is being developed in the United States of America at the Barry Power Station. This project applies post-combustion carbon capture, and is a cooperation between Mitsubishi Heavy Industries and Southern Company. The separation capacity is of 500 ton of CO₂/day and the captured CO₂ is injected into an aquifer. The injection process started in June 2011.

In Japan, there are also two main studies/programmes on chemical looping combustion. One of them is studying an iron based oxygen carrier, while the other consists of a calcium-based oxygen carrier, this latter being developed by JCOAL (JCOAL, 2012).

The Republic of Korea has an extensive CO₂ capture R&D programme, which includes ambitious plans to scale-up post-combustion capture technologies on 10 MW-sized demonstration units on coal-fired power plants. In ROK, the short-term goals on CCS (i.e. to be achieved by 2014) include demonstrating credibility and optimizing plant operation on post-combustion technologies, supported by domestic absorbent manufacturing, absorption process verification, as well as plant construction and operation experience. The long-term plans (i.e. up to 2030) include the development of various indigenous technologies, including IGCC in application with pre-combustion CO₂ capture (Lee, 2012; IEA CCC, 2013a). A summary of the carbon capture demonstration projects in ROK is presented in figure 6.6.
On-going work in post-combustion capture technologies has been focused in testing advanced amine solvents and solid sorbents. In particular, ROK is developing the world’s first CO$_2$ dry absorption technology, and is taking the lead on this technology at international level. While post-combustion carbon capture technologies appear to be the R&D priority in ROK, there are noteworthy developments on both pre-combustion and oxyfuel carbon capture. With regards to the latter, there have been plans to construct a 100 MW oxyfuel thermal power plant in 2015, with the objective to capture 1 Million ton of CO$_2$ per year. On second generation carbon capture technologies, the development of chemical looping combustion started in year 2000. The major research activities are on oxygen carrier development, and on the process of design and scaling-up of these processes. At present, a 50 kWth chemical looping system which uses iron and nickel-based oxides as oxygen carriers has been designed, installed and operated continuously for 25 hours (Lee, 2012).

In the Russian Federation, carbon capture only holds interest if the carbon dioxide is an intrinsic component of the production process, such as in hydrogen production or CTL applications (Gorlov and Agapova, 2013). In Mongolia, no activities on carbon capture have been identified (Avid, 2012).

As can be observed from the analysis above, there have been several initiatives on carbon capture technologies in three countries in NEA: China, Japan and the Republic of Korea. In some areas of technology development, the three countries are assuming international leadership, such as for example the world’s largest post-combustion demonstration project at Shanghai’s Shidongkou power plant, the Callide-A oxyfuel project applying Japanese technology in Australia, and the work on post-combustion absorbents in ROK. On their majority, these developments have involved some sort of international cooperation, and there appears to be potential for further articulation of research efforts among organizations in NEA, including the development of joint demonstration projects.
6.3 Technologies for the Transport, Storage and Utilization of Carbon Dioxide

Technologies for the transport of CO₂ are amongst the most well-known and mature along the CCS value chain. Transporting CO₂ consists in compressing and cooling the captured CO₂, and transporting it in ultra-supercritical or liquid state to a storage site. There are three main ways of transporting CO₂: by pipeline, ship or truck.

For the scale of operation envisaged with the capture of CO₂ from large point sources, the most likely option for transport is through a pipeline infrastructure (please check Box 6.1). For smaller-scale applications, such as in demonstration projects (i.e. those that capture tens to hundreds of tonnes of CO₂ per day), road trucks may be the most suitable means of transport. This is the case, for example, of Huaneng Power Group’s post-combustion projects in Beijing and Shanghai (please check table 6.2 above), which transport the CO₂ captured from the power plant to the facilities where it is consumed (i.e. in the food and beverages industry). If the CO₂ is to be transported to an offshore storage location, either pipelines or ships would be the most suitable option. There is some experience, but mostly limited, with both options (Minchener, 2011b; IEA, 2013b).

The choice of the most suitable transport option depends to a large extent on the final destination of the CO₂ captured: it will either be stored on underground geological formations, or be utilized as a feedstock for a specific end-use. In the case of the latter, instead of carbon capture and storage, this would be a situation of carbon capture and utilization (CCU).

Box 6.1 – Building a CO₂ transport infrastructure

The large-scale deployment of CCS will imply the establishment of a potentially large CO₂ transport infrastructure, which in some circumstances may have to go across national borders. There is decades’-long experience in long-distance CO₂ pipelines, particularly in the United States, where CO₂ is transported from source points to selected end-user sites, mainly for enhanced oil recovery purposes. An illustration of the transport network in the USA is presented in the figure below:

The development of a CO₂ infrastructure is likely to be subject to long lead times. First of all, laws and regulations need to be in place to establish the legal framework for the development of such infrastructure. These should address aspects related to the development, ownership and operation of the infrastructure to lay out, as well as health, safety and environmental issues. International coordination on planning issues and regulatory harmonization can be instrumental in facilitating and accelerating the large-scale deployment of a cross-border transport and storage infrastructure.

(Source: IEA, 2013b; ZEP, 2013)
The geological storage of CO₂ involves injecting the captured CO₂ stream into an appropriate geologic formation, typically located between one and three kilometres below the surface, taking advantage of the natural trapping mechanisms of such formations. The CO₂ needs to be injected at sufficiently high pressures and temperatures so that the fluid remains in supercritical state. High pressure at sufficient depths keeps the CO₂ as a supercritical fluid, as illustrated in figure 6.7. Another important component of the storage process is that it must involve the regular monitoring of the injected CO₂ (DOE, 2013).

Underground formations include saline aquifers, depleted oil and gas fields, and unmineable coal seams. Saline aquifers are considered to hold the greatest potential for CO₂ storage. These aquifers contain salt water and typically have no commercial use. Potential drawback is the relatively limited information about their geological characteristics, including their capacity to store large quantities of CO₂. In contrast, depleted oil and gas fields are usually well-characterized and well-known reservoirs, although they may be distant from large point sources of CO₂ emissions. The characterization of storage sites may take 6 to 10 years (IEA; 2013b; Minchener, 2011b; ZEP, 2013).

As an alternative to underground storage, in recent years there has been an increased interest in improving the economics of CCS through the commercial utilization of the CO₂ captured (in the literature often known as carbon capture and utilization, or CCU). Instead of a cost, CCU would be a means to derive value out of CO₂ that would otherwise be stored underground or released into the atmosphere (if CCS was not in place). It would also be a means to address some of the shortcomings associated with underground storage, such as the limited availability of suitable underground reservoirs for CCS, and public resistance to storage on geological formations (i.e. “nymbism”). However, the utilization of CO₂ cannot, in itself, be a substitute to carbon storage due to its limited applications as an end-user product, and relatively small market requirements (Styring et. al, 2011). Despite this, its potential importance should not be overlooked. As observed earlier on this report, one of the drivers for ongoing CCS demonstration projects on coal-fired power plants in China is the end-use of the CO₂.
One of the most important commercially-viable end-uses of CO2 is for the purposes of enhanced oil recovery (EOR), which consists in the injection of CO2 in oil reservoirs in order to improve resource recovery rates. CO2 is one of the gases that can be used for EOR, and on the fields where it is utilized, costs incurred with CO2 are usually the largest operational expense. CO2 can also be used for enhancing the recovery of natural gas and coal mine methane, as for example the project jointly developed by Chinese and Canadian companies mentioned in chapter 3.

EOR has been commercially practiced in the USA since the 1970s, which led to the establishment of a 6,000 km pipeline network for transporting CO2 (see Box 6.1). As of 2010 there were around 140 EOR projects in operation or under development worldwide. Projects in the USA inject underground over 60 Mt CO2 per year, with the majority of it expected to be stored in the reservoir at the end of the project lifetime. However, most of these projects utilize CO2 not from anthropogenic point sources but rather from natural geologic accumulations. Besides, only few of these projects have sufficient measuring, monitoring and verification systems in place, a necessary requirement for any CCS project to be considered as such. Despite its drawbacks and limitations, in the short-run EOR is one of the most important means to stimulate the development of a CCS infrastructure (IEA, 2013b).

In addition to EOR, other possible uses of CO2 as an end-user product are as follows (Stybring et al., 2011):

- **Chemical industry**: as a feedstock to the synthesis of chemicals, such as for example fertilizers;
- **Food and beverages industry**: in the carbonation of soft drinks, decaffeination of coffee, etc.;
- **Bio-renewable fuels and materials from algae**: CO2 streams can be utilized as a nutrient to the cultivation of algae in open ponds or bio-reactors;
- **Others**: enhanced crop growing, by utilizing CO2 streams in greenhouses.

Among NEA countries, China has showcased special interest in the possibilities for CO2 utilization. In fact, China has stressed that it will pay special attention to the R&D of new and innovative methods and technologies to use captured CO2 as a resource. An overview of representative initiatives is presented in the table below:

<table>
<thead>
<tr>
<th>Project Name</th>
<th>Description</th>
</tr>
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<tbody>
<tr>
<td>Petro China CO2 EOR Project</td>
<td>• With the support of the Ministry of Science and Technology, Petro China initiated a programme for enhancing the recovery of oil and natural gas fields through the injection of CO2. Since 2006, Petro China has been undertaking China’s first major project for CO2 EOR at the Jilin oilfield.</td>
</tr>
</tbody>
</table>
| Xin’ao Group’s Biological Pilot Project           | • Xin’ao Group has developed a “carbon assimilation with micro-algae” technology and has established a pilot system in Hebei province;  
  • The project is underway, and the algae produced can yield 20 tons of biological diesel and 5 tons of protein per year;  
  • Xin’ao Group plans to establish a pilot project named “Daqi CO2 assimilation with micro-algae” with an assimilation capacity of 320,000 ton of CO2 per year. |
| Chemical production by the Jiangsu Jinlong-Gas Chemical Co. Ltd. | • A production line was established for the production of polypropylene carbonate with captured CO2. This product can be used in heat insulation materials;  
  • On this pilot project, the utilization is of 8000 ton of CO2 per year. However, there are plans to expand the production line in the period up to 2016. |

*Table 6.3 – Major CO2 capture and utilization initiatives in China.*
(Source: own elaboration based on Yuhong and Yongxu, 2012; Minchener, 2011b)
In the Republic of Korea, there is a national-led R&D programme and strategy for CO₂ storage, which is being promoted by the Ministry of Land, Transport and Maritime Affairs as well as the Ministry of Education, Science and Technology. The research work focuses on numerical modelling for the characterization of underground reservoirs, monitoring of CO₂ behaviour underground, and environmental impacts of underground storage. Some of these initiatives have involved cooperation with research organizations overseas (Lee, 2012).

Figure 6.8 below presents the scenarios for CO₂ storage technology in the ROK context. As can be observed, one of the main challenges in ROK is whether to store CO₂ in the densely-populated mainland, where space is limited and with considerable scope for public opposition, or if in marine geological formations, which are located offshore, potentially in international waters. It is clear that there is no available space to store large quantities of CO₂ onshore (Lee, 2012). Therefore, there is clear scope – and the need – for cooperation among NEA countries, particularly with China and Japan, if the large-scale deployment of CCS is to become a reality in ROK.

Now that an overview of the whole CCS value chain has been provided, including the possible CCU route, it is important to reflect on an important concept of this family of technologies: **CCS-ready**.

It has been observed earlier in the chapter that one of the main drivers to the large scale deployment of CCS is climate change policy and the existence of a price on carbon, implicit or explicit, that gives an incentive for private sector led investments. However, current carbon prices are not sufficient to drive the deployment of CCS and, in line with this reality, most coal-fired plants in the pipeline are not planned to be fitted with CCS equipment. Being assets with long lifetimes (>30 years), once these plants are commissioned, they become stranded assets and a “lock-in” effect is created which can last for decades.

It is in light of this context that “CCS-ready” comes to the fore. A CCS-ready facility consists of a large source of CO₂ emissions which is intended to be retrofitted with CCS technology once the necessary regulatory and economic drivers are in place, and which has been designed and conceived in order to ensure that the retrofitted plant would be as competitive as possible with other newly built CCS-equipped plants. These measures would include, among others, ensuring that enough space is available on the plant site for the installation of capture-related equipment; allowing for additional cooling and heating needs for the CO₂ capture process; and ensuring that an appropriate supporting infrastructure is in place for the transport of CO₂ for subsequent storage. CCS-ready is, in essence, a means to ensure that new facilities can be retrofitted with CCS equipment – and hence making them “ready” – when the necessary drivers for CCS are in place. This concept is also related to the fact that to CCS retrofit existing plants has proved to be, in most cases, a complex and very expensive industrial operation (Finkenrath et al., 2012)
6.4 Summary and Implications

Carbon capture and storage, or CCS, encompasses a family of technologies and techniques that enable the capture of CO\textsubscript{2} from large point sources of emissions, and its transportation for storage on an underground geological formation. On some of its components, CCS has proven to be a mature and commercially viable technology, such as in the separation of CO\textsubscript{2} as a requirement of some industrial processes, or the transportation of CO\textsubscript{2} through pipelines for the purposes of enhanced oil recovery. However, CCS is not yet cost competitive with other low-carbon technologies, and many aspects of CCS still need to be fully demonstrated, particularly on large scale applications. In the current context of insufficiently high carbon prices, the development and deployment of CCS strongly relies on the existence of government support.

Among North-East Asia countries, most progress on CCS technologies has been observed in China, Japan and the Republic of Korea, while in Mongolia and the Russian Federation CCS does not seem to be a priority. These three countries have a significant number of government-funded R&D programmes on CCS in place, with a few demonstration projects already in operation and/or under construction. On a few technology elements, NEA countries are already taking the lead at a global scale, such as the largest post-combustion demonstration project on coal-fired plants which is being conducted in China, Japan’s leadership on oxyfuel combustion technology, or the developments on post-combustion absorbents in the Republic of Korea. On many of their activities on CCS these countries, particularly China, have worked under the framework of international programmes, and/or at a minimum some degree of international cooperation and coordination has been observed. On the other hand, it is also observed that cooperation among NEA countries on CCS has been scattered and somewhat disconnected, and therefore there appears to exist the potential for cooperation activities.

In light of the analysis above, the key messages to policymakers and practitioners are as follows:

- Countries in North-East Asia most active on CCS technologies, i.e. China, Japan and the Republic of Korea, could further harmonize R&D efforts and explore opportunities for the development of joint demonstration projects. Based on the analysis, areas of possible technology cooperation include the geological storage of CO\textsubscript{2}, and oxy-fuel and post-combustion carbon capture technologies. Knowledge sharing and the use of common methodologies is crucial for the early uptake and full-demonstration of CCS as a commercially viable technology, and policymakers of NEA countries could support and drive these efforts through appropriate policies and enhanced coordination at sub-regional level.

- The definition of a policy and regulatory framework for CCS is a critical aspect for the uptake of these technologies. While very few countries or regions in the world have such frameworks in place, there is an opportunity for NEA countries, through sub-regional cooperation, to harmonize and synergize national laws and regulations along the whole CCS value chain.

- NEA countries could develop a common vision for an integrated CO\textsubscript{2} transport and storage infrastructure in the sub-region. This vision could be developed in parallel and/or as a complement to comparable regional initiatives, most in particular the Asian Energy Highway\textsuperscript{7}. This vision could first come under the initiative of China, Japan and the Republic of Korea, not only because these are the countries that are leading efforts on CCS development in the sub-region, but also due to their potential to share common transport and geological storage infrastructure in the sub-region.
In light of the analysis above, the key messages to policymakers and practitioners are as follows:

- In view of ongoing developments in international climate change negotiations, it is difficult to expect the emergence of global or regional CO₂ prices that could trigger the large-scale deployment of CCS at the scale required to prevent the worst impacts of climate change. While government-led support will play a major role in the interim, the commercial-viability of these technologies will be contingent on the existence of end-user markets for the CO₂ captured. In this connection, NEA countries could jointly conduct a market assessment study on CO₂ utilization in the sub-region, which would examine present and future sources of supply and demand for CO₂, and analyse the potential for commercial opportunities within and beyond national borders. Such study could also identify emerging and promising high-tech areas that require CO₂ as a feedstock, such as for instance the large-scale production of algae or chemicals, and analyse the feasibility of establishing these new markets for CO₂ in the sub-region.

- Coal-fired power plants equipped with CCS are currently not competitive with conventional non-CCS plants, with the implication that these power plants continue to be constructed at a rapid pace without consideration for CCS. To a large extent, these power plants are built in a way that makes it difficult and expensive their retrofitting with a carbon capture component at some point in the future. To avoid this potential “lock-in”, governments of countries in NEA, particularly those with a considerable fleet of plants in the pipeline, could require through national laws and regulations that newly built coal-fired power plants are constructed in a way that allows for the addition of a CCS component at a future stage, making them “CCS-ready”.

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7 The development of an integrated energy infrastructure in the Asian continent, which would connect sources of energy supply and demand across Asia, has been promoted by UN-ESCAP as a means of advancing regional energy cooperation (ESCAP, 2013b).
Conclusions and Recommendations for Policymakers
7 Conclusions and Recommendations for Policymakers

This study has reviewed a set of technologies for the utilization and processing of coal, and tracked their status of development and uptake in North-East Asia countries. The analysis included a wide-range of technologies along the coal industry value chain, and attempted to identify opportunities for cooperation among NEA countries. The analysis also attempted to formulate recommendations to policymakers for accelerating the development and deployment of cleaner and more efficient coal production technologies, both in the national and sub-regional contexts.

Table 7.1 is an attempt to summarize the main findings of the study for each group of technologies analysed. The table provides a qualitative assessment of their status in NEA countries, taken as a whole, vis-à-vis global developments on these coal technologies. Five-levels were taken into account for the assessment: “low”, “low-medium”, “medium”, “medium-high” and “high”. The table also sheds light on the potential for cooperation in the joint development of these technologies among NEA countries, classified from “low” to “high”.

A few observations can be made from the table:

- Most countries in NEA have placed a high priority to the development of cleaner and more efficient coal technologies, from the upstream to the downstream of the coal value chain; China is the only NEA country that is active in the development of all coal technology families covered;
- Different levels of technology development and adoption are observed in NEA countries as a whole. If on the one hand, technology progress on SC and USC seem to be on par with international developments, on the other the uptake of coal drying technologies or CBM utilization technologies seems to be somewhat lagging behind developments outside the sub-region;
- Cooperation among NEA countries on many coal technologies already exists on an inter-firm and commercial basis. For example, the utilization of Japanese developed gasifiers in coal processing facilities in China, or the utilization of coal beneficiation equipment manufactured in China in coal mines in Mongolia;
- At the R&D and demonstration stages, cooperation among NEA countries seems to be fairly limited. Few joint projects or initiatives were identified, although it should be noted that, for example, Japan and China have cooperated to a certain extent on a few technology areas, such as CTL and CCS;
- Cooperation among NEA countries on capacity building and knowledge sharing also appears to be somewhat limited. Exceptions exist, including for example the cooperation between China and Japan on several initiatives on CMM recovery and utilization projects;
- At policy and regulatory level – such as in the alignment of standards or the development of common visions or strategies – no joint initiatives were identified among any NEA countries on the development of coal technologies.
In order to prioritize the recommendations from this study, which were presented at the end of each technology chapter, the matrix presented in figure 7.1 was prepared. This matrix attempts to co-relate the development status in NEA of the technology groups analysed with their importance in the sub-regional context, as defined on national policies and strategies of countries in the sub-region. Technologies that appear in the upper-right side of the matrix are those whose development should be given priority, while they are also the technologies where opportunities for sub-regional cooperation could be first harnessed. In the lower-left side of the matrix are the technology groups that have been ranked less higher. The recommendations of this study are therefore aggregated into two different groups: short to mid-term recommendations and mid to long-term recommendations.

**Figure 7.1 – Coal technology development and level of importance in NEA countries.** (Source: own elaboration)

### Short to Mid-Term Priorities and Recommendations

#### Advanced Coal Combustion Technologies:

- NEA countries should continue their policies of accelerating the deployment of advanced coal-fired power generation technologies by creating the necessary enabling framework, either in terms of policies, targets, regulations or a combination of those.
- NEA countries should support – or continue supporting – emerging advanced-coal combustion technologies, such as advanced-USC pulverized coal combustion, the deployment of larger CFB boilers (so as to achieve the economies of scale of the largest commercially available pulverized coal combustion boilers), and the full-demonstration of SC and USC steam conditions applied to fluidized bed combustion boilers.
- International cooperation among NEA countries could be instrumental in introducing cleaner, low-emissions and more efficient coal combustion technologies in Mongolia and DPRK, where older, more polluting and less efficient power plants continue in operation.

#### Coal Beneficiation Technologies:

- NEA countries should continue and further increase their support to accelerate the deployment of coal upgrading technologies, particularly in overcoming some of the barriers that hinder their dissemination, such as the creation of pricing mechanisms that reflect the improved quality of upgraded coal.
Conclusions and Recommendations for Policymakers

International cooperation among NEA on these technologies has the potential to be further enhanced, particularly in the formulation of harmonized quality requirements for imported coal and in exploring possibilities for joint R&D and demonstration programmes. Priority areas for sub-regional cooperation are on less water intensive processes and dry separation technologies, where the know-how of countries such as Japan could be explored on commercial applications.

Coal Mine Methane Recovery and Utilization Technologies:

- Policymakers of NEA countries with active coal mining activities should ensure that the necessary policies, regulations and frameworks are in place to spur the deployment of the most up-to-date technologies and best practices for the recovery of CMM so as to ensure, first and above all, the safety of mining operations.
- Opportunities for cooperation among NEA countries on CMM recovery and utilization technologies and methods include the sharing of best practices on coal mining safety, CMM technology needs and technology matching assessments, and support in the design of policies and regulations.
- NEA countries could explore synergies and opportunities for cooperation on technologies that make it possible to derive economic value from low-quality CMM gas and ventilation air methane, particularly by incentivizing national R&D institutions to develop such programmes.

Coal Liquefaction Technologies:

- There is a clear scope for the utilization of CTL technologies, including those developed by organizations in China, in projects and/or initiatives in the sub-region, particularly in Mongolia and the Russian Federation, as these are the NEA countries endowed with domestic coal resources and CTL could be a means to derive a higher economic value from those resources, in particular those that are considered “stranded”.
- While CTL technologies can play an important role in enhancing energy security in the sub-region, NEA countries should ensure that the development and deployment of these technologies is based on sound technical and environmental requirements, in particular with respect to water utilization and the emission of CO₂. NEA countries could work together towards the definition of such standards or requirements.
- The market for some liquids that can be produced from coal is still incipient – if existent at all – in most countries in the sub-region. As such, policymakers of NEA countries could play an important role in the creation of those markets in articulation with each other, whereby “win-win” situations would be created by matching the supply and demand for these products.

Integrated Gasification Combined Cycle (IGCC):

- IGCC is emerging as a viable coal-conversion technology for power generation, and its deployment should be encouraged by governments of NEA countries until the technology is fully proven on a commercial basis.
- NEA countries could explore the potential for the harmonization and coordination of the different initiatives on IGCC development that are observed in the sub-region, for example through information sharing activities and the use of common methodologies.
Mid to Long-Term Priorities and Recommendations

Carbon Capture and Storage Technologies:
- NEA countries that are most active on CCS technologies, i.e. China, Japan and ROK, could further harmonize their R&D efforts and explore opportunities for the development of joint demonstration projects.
- NEA countries could synergize efforts in the definition of a common policy and regulatory framework for CCS development, a critical aspect for the uptake of these technologies both at national and sub-regional levels. NEA countries could also introduce requirements for the introduction of the CCS-Ready concept, in order to avoid the “lock-in” of building power-generation facilities that are unable to be retrofitted with CCS in the future.
- NEA countries could develop a vision for an integrated CO₂ transport, utilization and storage infrastructure in the sub-region, which could be developed in parallel and/or in complement to comparable regional initiatives, such as the Asian Energy Highway. Such vision could be initiated by China, Japan and the Republic of Korea due to their geographical proximity and strong interest in CCS, and possibly expanded to include other NEA countries.

Coal Gasifier Technologies:
- It is recommended that countries such as China, Mongolia and ROK pursue and/or continue their policies of encouraging the deployment of gasification technologies from overseas’ providers, through inward technology transfer, while building-up the know-how of national companies and organizations on these technologies.
- There is potential for exploring the competitive advantages of nationally-designed coal gasifiers of China and the Russian Federation, specifically in what concerns their cost-effectiveness vis-à-vis other commercially available models. The characteristics of Chinese and Russian models could be of interest, in particular, to DPRK and Mongolia, which have limited know-how and experience on coal gasification technologies.

Underground Coal Gasification Technologies:
- Government support can be instrumental in accelerating the commercial viability of UCG technologies, not only on the R&D and pre-commercial stages, but also in addressing existing gaps in legislation and regulation, such as in the definition of environmental criteria for UCG development and guidelines for site-selection. These opportunities could be explored in articulation among NEA countries, particularly the Russian Federation, China and Mongolia.

Coal Drying Technologies:
- NEA countries seem to be somewhat lagging in the adoption of coal drying technologies, and given their importance in deriving higher value from low-rank coals, which are abundant in countries of the sub-region, it is recommended that this can be an area of increased attention, whereupon opportunities for government induced R&D could be explored.
The WG-Coal, as the only group of experts and policymakers working on the coal industry at sub-regional level in NEA, is in a privileged position to support the implementation of these recommendations and attempt to make more specific the identified areas for synergies and mutual benefits. The WG-Coal can serve as an important vehicle to the dissemination of knowledge and best practices on coal technologies, in garnering political support for state-led technology cooperation at sub-regional level, and in setting the ground for accelerating technology development among NEA countries.
### Conclusions and Recommendations for Policymakers

#### Notes and Observations
- Coal beneficiation are mature and commercially available technologies; there is significant scope for further adoption of these technologies in coal production countries in NEA.
- The level of development on these technologies is in general low in NEA countries, but their role should not be overlooked due to their importance in enhancing the efficient utilization of low-rank coals.
- These technologies are mature and commercially available; Japanese companies are global leaders on these technologies, while more recently Chinese companies are global leaders on these technologies, while more recently Chinese companies have been able to catch-up with international technology providers. ROK manufacturing giants are expected to soon achieve a level of full technological independence on these technologies.
- Fluidized bed combustion is particularly suited to low-rank coals, and hence the interest on these technologies among all NEA countries.
- Cooperation already exists on a commercial basis:
  - Possible cooperation on less water intensive processes and dry separation technologies.

#### Major opportunities for cooperation among NEA countries
- Cooperation potential difficult to assess.
- NEA countries that have developed these technologies would compete with international technology providers for their transfer.
- Some potential for cooperation on R&D and demonstration on advanced USC technologies.
- Some potential for technology cooperation and transfer may exist in concepts developed by China, Japan, ROK and the Russian Federation.
- Most circulating FBC technologies are owned by private-sector organizations.

#### Potential for sub-regional cooperation
- Medium
- Medium
- Medium
- Medium

#### Technology Development Status in NEA
- Medium
- Low
- Medium-High
- Medium

#### NEA Countries that Prioritize the Technology(ies)
- China, Mongolia and the Russian Federation
- China, Mongolia and the Russian Federation
- China, Japan, ROK and the Russian Federation
- All NEA countries

### Technology Area

<table>
<thead>
<tr>
<th>Efficiency-Enhancing Coal Technologies</th>
<th>Technology Area</th>
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<tr>
<td>Coal beneficitation technologies</td>
<td>1.1</td>
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<td>Coal drying technologies</td>
<td>1.2</td>
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<tr>
<td>Super-critical and ultra-supercritical PC combustion technologies</td>
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<tr>
<td>Fluidized bed combustion technologies</td>
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- Notes and Observations:
  - Some potential for technology cooperation and transfer may exist in concepts developed by China, Japan, ROK and the Russian Federation.
  - Most circulating FBC technologies are owned by private-sector organizations.
Conclusions and Recommendations for Policymakers

- Uptake of these technologies in China has been swift in the past 10 years, although there is still a significant potential for further dissemination and uptake.
- In other NEA countries with active coal mining industries, the adoption of these technologies has been slow.
- There is great potential for the deployment and mainstreaming of these technologies on NEA countries with active coal mining industries, although it should be emphasized that the technological progress of China in this area in the past 10 years.
- Some technologies developed in Japan have the potential for application on other NEA countries.
- Technologies on gasifiers have been dominated by private sector organizations, with relatively few developments in NEA countries. China and the Russian Federation have developed their own gasifier models, although there seems to exist limited international recognition on these technology developments.
- Chinese and Russian coal-gasifier models could be of interest to Mongolia and DPRK due to their cost competitiveness.
- Chinese and Russian Federation coal-gasifier models could be of interest to Mongolia and DPRK due to their cost competitiveness.
- Potential to synergize and harmonize efforts on IGCC technology development among China, Japan, ROK and the Russian Federation.

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<td>2.1 Ventilation and degasification technologies</td>
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<td>2.2 CBM utilization technologies</td>
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<td>3.2 Integrated Gasification Combined Cycle (IGCC)</td>
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</table>

China, Mongolia and the Russian Federation

- All NEA countries

- All NEA countries, but mostly China, Japan, ROK and the Russian Federation

- Medium-High

- Medium-High

- Medium-High
Conclusions and Recommendations for Policymakers

Technology developments on UCG only existent in China and the Russian Federation, with the latter being one of the global leaders on this field; Still an emergent technology, years behind full-commercial viability and wide-spread deployment.

Cooperation potential among China and the Russian Federation could be further assessed; Possible interest on these technologies in Mongolia and DPRK when these technologies become fully demonstrated.

China is a world leader on CTL technologies. The world’s first industrial-scale direct liquefaction project is currently in operation in China; CTL technologies with regards to the energy penalty, as well as the high water and carbon footprint of these processes.

Several initiatives on carbon capture technologies in China, Japan and ROK; In some areas of technology development, the three countries are already assuming international leadership.

High potential for cooperation in the development of a joint infrastructure and vision for the transport, utilization and storage of CO₂.

Table 7.1 – Summary on technology status. *(Source: own elaboration)*
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