CLEAN COAL AND CARBON CAPTURE AND STORAGE TECHNOLOGY ROADMAP OF TURKEY

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ABSTRACT

CLEAN COAL AND CARBON CAPTURE AND STORAGE TECHNOLOGY ROADMAP OF TURKEY

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The present study presents a draft national CCT (Clean Coal Technologies) and CCS (Carbon Capture and Storage) technology roadmap to policy makers. Various technical and non-technical (economic and social) challenges that currently prevent CCT and CCS from being a widely used commercial technology are discussed and the goals for each research pathway are defined. The process of creating the roadmap started with a review and assessment of the existing national and international technology roadmaps which represent a global picture of the state of the art and national and international plans for future on CCT and CCS research development, demonstration and deployment (R&D&D). Following this step, the national situation, capacities and priorities were examined. Finally, R&D&D actions discussed in the existing roadmaps and/or new actions were carefully selected and suggested as a draft Turkish CCT and CCS Roadmap that needs further development and discussion by the input of interdisciplinary national stakeholders. As a conclusion a number of technical and non-technical suggestions are delivered.

Keywords: Technology Roadmap, Clean Coal Technology, Carbon Capture and Storage, Climate Change Mitigation, Carbon Dioxide (CO_2), Green House Gas

ÖZ

TÜRKİYE TEMİZ KÖMÜR VE KARBON YAKALAMA VE DEPOLAMA TEKNOLOJİ YOL HARİTASI

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Mevcut çalışma politika yapıcılara taslak bir ulusal Temiz Kömür ve Karbon Yakalama ve Depolama (TKT ve KYD) Teknoloji Yol Haritası sunmaktadır. Günümüzde TKT ve KYD'nin geniş çapta ticarileşmesinin önündeki teknik ve teknik olmayan (ekonomik ve sosyal) engeller tartışılmış ve her alt teknoloji alanı için hadefler belirlenmiştir. Yol haritası oluşturma çalışmaları TKT ve KYD konusunda Ar-Ge, demonstrasyon ve uygulamasındaki mevcut durumun ve geleceğe yönelik planların küresel bir bakış açısı ile sunulduğu ulusal ve uluslararası teknoloji yol haritalarının araştırılması ve değerlendirilmesi ile başlamıştır. Bu adımı takiben ulusal durum, kapasiteler ve öncelikler incelenmiştir. Son olarak mevcut yolharitalarında tartışılan Ar-Ge, demonstrasyon ve uygulama eylemleri ve/veya yeni eylemler dikkatlice seçilerek taslak Türkiye temiz kömür ve karbon yakalama ve depolama teknoloji yol haritası olarak önerilmiştir. Bu çalışmanın disiplinlerarası ulusal paydaşlar tarafından geliştirilmesi ve tartışılması gerekmektedir. Sonuç olarak politika yapıcılara teknik ve teknik olmayan önerilerde bulunulmuştur.

Anahtar kelimeler: Teknoloji yol haritası, Temiz Kömür Teknolojileri, Karbon Yakalama ve Depolama, İklim Değişikliği Azaltma, Karbon Diyoksit (CO_2), Sera Gazları

to my family...

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ABBREVIATIONS

ASU	Air separation units
BFBC	Bubbling fluidized bed combustion
CCS	Carbon capture and storage
CCT	Clean coal technologies
CFBC	Circulating fluidized bed combustion
CHP	Combined heat and power
CLC	Chemical looping combustion
CO_2	Carbon Dioxide
CO_2e	Carbon Dioxide equivalent
CSLF	Carbon Storage Leadership Forum
DME	Dimethylether
ECBM	Enhanced coal bed Methane
ENGR	Enhanced natural gas recovery
ENRM	Energy and Natural Resources Ministry of Turkey
EOR	Enhanced oil recovery
ESP	Electrostatic precipitator
FBC	Fluidized bed combustion
FGD	Flue gas desulphurization
GDP	Gross domestic product
GHG	Green house gas emissions
Gt	Giga Tone
GW	Gigawatt
GWh	Gigawatt hour
HCN	Hydrogen cyanide
HFC	Hydrofluoracarbon
IEA	International Energy Agency
IGCC	Integrated gasification combined cycle
IPCC	Intergovernmental Panel on Climate Change
LULUCF	Land use, land-use change and forestry
mb/d	Million barrels per day
MM&V	Monitoring, Mitigation and Verification

MOF	Microporous metal organic framework
Mt	Million tones
Mtc	Million tones Carbon
$MtCO_2e$	Million tones of CO_2 equivalent
Mtoe	Million tones of oil Equivalent
MW	Megawatt
MWe	Megawatt electrical
NH_3	Ammonia
NO_2	Nitrogen dioxide
OECD	Organisation for Economic Co-operation and Development
OPEC	Organization of the Petroleum Exporting Countries
OTM	Oxygen transport membranes
PCC	Pulverized coal combustion
PCFBC	Pressurized circulating fluidized bed combustion
PFC	Perfluorocarbon
PM	Particulate matter
PPCC	Pressurized pulverized combustion of coal
ppm	Parts per million
PPP	Purchasing power parity
R&D	Research and development
R&D&D	Research and development and deployment
S&T	Science and technology
SCR	Selective catalytic reduction
SH_6	Sulfur hexafluoride
SNCR	Selective non-catalytic reduction
SO_x	Sulfur oxide
TKI	Turkish Coal Enterprises
TPE	Tone petroleum equivalent
TTK	Turkish Hard Coal Enterprise
TUBITAK	The Scientific and Technological Council of Turkey
UCC	Ultra clean coal
UNFCCC	United Nations Framework Convention on Climate Change
WAG	Water alternating gas
WCI	World Coal Institute

CHAPTER 1

INTRODUCTION

1.1. The Purpose of this Technology Roadmap

The rapid pace of science and technology (S&T) growth and globalization has substantially increased the complexity of S&T management. Due to difficulty in technology forecasting under such circumstances, there is a growing need to clarify the direction of research and development (R&D), share future visions on technologies, and promote interdisciplinary collaborations among different participants both in industry and academia. In such circumstances, there is a growing need for S&T roadmaps to offer a means of communicating visions, attracting resources from business and government, stimulating investigations, and monitoring progress. In this context, Robert Galvin describes a roadmap as becoming an inventory of possibilities in a particular field, thus stimulating more targeted investigations. Although there is no standard definition of an S&T roadmap, Lewis Branscomb gives the following brief definition: "A consensus articulation of a scientifically informed vision of attractive technology futures." Similarly, Robert Galvin states "A 'roadmap' is an extended look at the future of a chosen field of inquiry composed from the collective knowledge and imagination of the brightest drivers of change in that field." Roadmaps are both forecasts of what is possible or likely to happen, as well as plans that articulate a course of action. In short, roadmaps are defined as the views of a group of stakeholders as to how to get where they want to go to achieve their desired objective. This definition of S&T roadmap originates from that of a road map. In everyday life, a road map is a layout of the paths or routes of some particular geographical space. They are used by travelers to select among alternative routes in determining how to arrive at a particular destination. Reflecting this, S&T roadmaps are typically illustrated as a time-directed representation among scientific and technological concepts. [1]

Turkey's GHG emissions, including and excluding LULUCF (land use, land use change and forestry) is the highest among 40 Annex I countries of Kyoto Protocol (i.e. industrialized countries and economies in transition). [2] During the period between 1990 and 2008, Turkey has tripled her energy demand compared to world average and it corresponds to %4.3 of world total demand. Among OECD countries, Turkey has the fastest growing energy demand in past 10 years due to her increasing population and economic development. Since 2000, Turkey has the second largest increase after China in electricity and natural gas demand. Projections performed by Energy and Natural Resources Ministry of Turkey (ENRM) showed that this trend will continue in the medium term. Signing Kyoto protocol in 2009, Turkey has to enact a series of measures in every sphere from transportation to agriculture and heating to industry to reduce carbon emissions after 2012. All these facts necessitated such a roadmap on Clean Coal Technologies and Carbon Capture and Storage.

IEA analysis projects that energy sector CO_2 emissions will increase by %142 above 2009 levels in the absence of new policies or from supply constraints resulting from increased fossil fuel usage. Addressing this increase will require an energy technology revolution involving a portfolio of solutions: greater energy efficiency, increased renewable energies and nuclear power, and near-decarbonisation of fossil fuel-based power generation. [3] Clean coal and CCS technologies are the only technology available to mitigate GHG emissions from large-scale fossil fuel usage in fuel transformation, industry and power generation. To this end, as energy technology development on CCT and CCS represents one of the best alternatives in terms of Turkey's ability to cope during the upcoming decade, this thesis focuses on this particular aspect. The main purpose of this roadmap is to supply Turkish decision makers and policy makers with insight in to the direction which the country's strategic energy technology development should lead to.

1.2. Methodology and Sources

This roadmap was developed to provide a vision for addressing the above challenges. The process started with a review and assessment of existing national and international technology roadmaps:

- Cooperative Research Center for Greenhouse Gas Technologies, 2004, *Carbon Capture and Storage Research Development & Demonstration in Australia, A Technology Roadmap*
- CANMET Energy Technology Center, 2006, *Canada's CO_2 Capture and Storage Technology Roadmap*
- CANMET Energy Technology Center, 2006 *Canada's Clean Coal Technologies Roadmap*
- U.S. Department of Energy (DoE), Office of Fossil Energy National Energy Technology Laboratory, 2007, *Carbon Sequestration Technology Roadmap and Program Plan, Ensuring the Future of Fossil Energy Systems through the Successful Deployment of Carbon Capture and Storage Technologies*
- UK Energy Research Center/ UK Carbon Capture and Storage Consortium, 2007, *Carbon Capture and Storage Roadmap*
- International Energy Agency, 2009, *Technology Roadmap Carbon Capture and Storage*
- Carbon Sequestration Leadership Forum (CSLF), 2009, *Carbon Capture and Storage Technology Roadmap*
- The European Technology Platform for Zero Emission Fossil Fuel Power Plants (ZEP), 2009, *Strategic Research Agenda*

The roadmaps investigated are the only available comparable roadmap studies all around the world and they represent a global picture of the state of the art and national and international plans for future on CCT and CCS research development, demonstration and deployment (R&D&D).

The next step was examining the national situation, capacities and priorities. National scene is discussed in comparison with global scene throughout the thesis. Although more research is needed and suggested in the roadmap analysis for determining the exact CO_2 geological storage capacities of Turkey, current knowledge show strong evidence to continue the roadmap study. In addition, Vision 2023 Turkish National Technology Foresight Program) which was conducted by The Scientific and Technological Council of Turkey – TUBITAK (2003) and "Public Research Programs" on Environment and Energy (2005) used as a starting point.

Finally, R&D&D actions discussed in the above mentioned roadmaps and/or new actions were carefully selected and suggested as a draft Turkish CCT and CCS Roadmap that needs further development and discussion by the input of interdisciplinary national stakeholders.

CCS is the latest in a portfolio of CCT that have successfully managed emissions from coal-based generation. The CCT focus in most of the countries and international studies has moved to the development and operation of low and near-zero GHG emission technologies like CCS. In addition CCS is more than a strategy for CCT. CCS technology can also be adopted by biomass and gas power plants; in the fuel transformation and gas processing sectors; and in emissions-intensive industrial sectors like cement, iron and steel, chemicals, and pulp and paper. Therefore although CCS is a part CCT, it has been discussed as a separate part in the thesis.

Recently multidisciplinary (or interdisciplinary) research is increasingly recognized in most of the fields. It is defined as a study that relies on the knowledge of more than one traditional scientific and technological discipline. The knowledge that has been available for a long time in one discipline may be a breakthrough technology that can revolutionize the business practices of another discipline. As well, a technique being developed in a department, with a tremendous amount of time, money, and resources, may be regarded as common knowledge in another department. A big opportunity exists for the significant level of improvement, based on the learning from other disciplines. [4] Therefore throughout the thesis a holistic approach is considered which means that the links to all the related fields like hydrogen and fuel cell, landfill and coal bed methane gas utilization and other renewable sectors are covered.

In order to conserve the holistic approach, terrestrial sequestration of CO_2 is also discussed in another section of the roadmap. This subject was usually left out and only the geological storage is included in most of the above mentioned roadmaps, but the USA.

Since many non-CO_2 greenhouse gases (e.g., methane, nitrous oxide, and certain refrigerants) have significant economic value and emissions and their capture and storage also plays an important role in the mitigation activities of Turkey. According to UNFCC Greenhouse Gas Inventory Database, growth in methane and nitrous oxide emissions in Turkey is the largest among 42 Annex I countries. Therefore *Non-C02 Greenhouse Gas Control* section is included as a separate section in the roadmap.

In addition in order to foster the innovative potential of academy and industrial, a specific part in the roadmap is devoted to *breakthrough concepts*. The actions discussed in this section are basically the collections of ideas which are considered as breakthrough concepts all around the world.

CHAPTER 2

BACKGROUND INFORMATION

2.1. Definition of CCT and CCS

The technologies employed and being developed to meet coal's environmental challenges, collectively referred to as clean coal technology (CCT), represent a continuously developing range of options to suit different coal types, different environmental problems, and different levels of economic development. [5] CCT has been developed and deployed to reduce the environmental impact of coal utilization over the past 30 to 40 years. Initially, the focus was upon reducing emissions of particulates, SO_2, NO_X and mercury. The coal sector (producers, consumers and equipment suppliers) as well as governments and agencies in countries where coal is essential, have a long experience of stimulating clean coal technology deployment. Experience continues to grow as the technologies are introduced and spread in developing countries. The clean coal technology focus in most of the countries has moved to the development and operation of low and near-zero GHG emission technologies like CCS. Deployment of CCS, as part of an effort to reduce GHG emissions, has been endorsed by G8 leaders, the IEA, The Stern Review and the IPCC. [6]

Clean coal technologies can be categorized and summarized as following:

- Coal Beneficiation
- Technologies for Reducing Emissions of Pollutants
- Efficient Combustion Technologies
- Gasification Technologies
- Carbon Capture and Storage
- Cross cutting Issues (CHP, polygeneration, biomass co-firing)

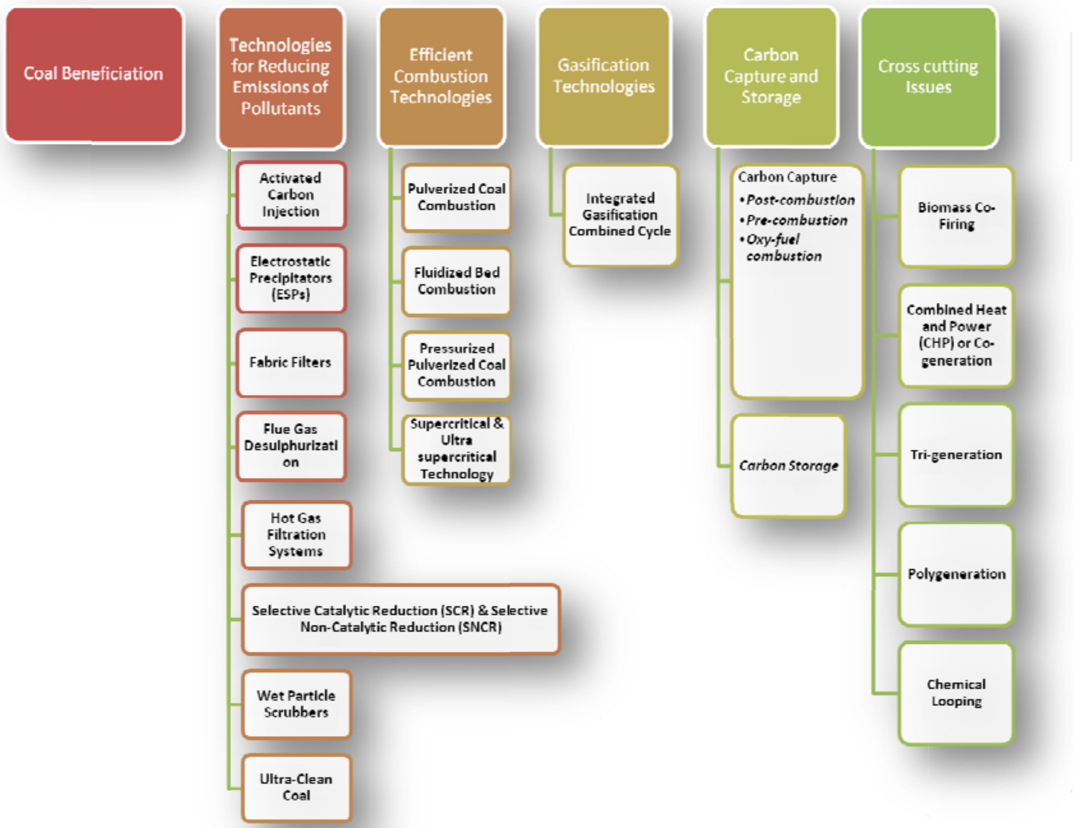

Figure 1: Portfolio of Clean Coal Technologies

2.1.1. Coal Beneficiation

Mined coal is of variable quality and contains substances such as clay, sand and carbonates. Coal beneficiation – also known as coal preparation or coal washing/cleaning – is the cleaning process in which this mineral matter is removed from mined coal to produce a cleaner product. The coal is also sized and blended to meet customer specifications. Coal washing increases the heating value and the quality of the coal, by lowering the level of sulphur and mineral constituents.

The coal preparation process involves characterization, liberation, separation and disposition. Characterization identifies the composition of the different raw coal particles. Liberation involves crushing the mined coal and reducing it to very fine particles. Separation is the partitioning of the individual particles into their appropriate size groupings and separating the mineral matter particles from the coal. Finally the disposition stage involves the dewatering and storage of the cleaned coal and the disposal of the mineral matter. [5]

2.1.2. Technologies for Reducing Emissions of Pollutants

2.1.2.1. Activated Carbon Injection

Activated carbon injection involves activated carbon being injected into the flue gas stream exiting the boiler and absorbing pollutants such as mercury onto particulate matter, which is then removed in existing particulate control equipment. [5]

2.1.2.2. Electrostatic Precipitators (ESPs)

Electrostatic precipitators are the most widely used particulate emissions control technology in coal-fired power generating facilities. Particulate/dust laden flue gases are passed horizontally between collecting plates, where an electrical field creates a charge on the particles. The particles are then attracted towards the collecting plates, where they accumulate. In dry electrostatic precipitators the agglomerated particles are then removed in a dry form by mechanical rapping or vibration to create a powder for disposal. In wet electrostatic precipitators the particles are sprayed and washed off as slurry. [5]

2.1.2.3. Fabric Filters

Fabric filters, also known as bag houses, collect particulates from the flue gas on a tightly woven fabric by sieving and other mechanisms. The choice between electrostatic separation and fabric filtration depends on coal type, plant size, and boiler type and configuration. Fabric filters are useful for collecting particles with resistivities either too low or too high for collection with electrostatic precipitators. [5]

2.1.2.4. Flue Gas Desulphurization

Flue gas desulphurization (FGD) technologies are used to remove sulphur emissions post-combustion. FGD technologies can be classified into six main categories: wet scrubbers; spray dry scrubbers; sorbent injection processes; dry scrubbers; regenerable processes; and combined SO_2/NO_x removal processes. Wet scrubbers tend to dominate the global FGD market. The technology uses alkaline sorbent slurry, which is predominantly lime or limestone based. A 'scrubbing vessel' or scrubber is located downstream of the boiler and flue gas cleaning plant, in which the sulphur dioxide in the flue gases reacts with the limestone sludge, forming gypsum. [5]

2.1.2.5. Hot Gas Filtration Systems

Hot gas filtration systems operate at higher temperatures (500-1000°C) and pressures (1 - 2 MPa) than conventional particulate removal technologies, eliminating the need for cooling of the gas. A range of technologies such as cyclones, ceramic barrier filters, high-temperature fabric filters, granular bed filters and high-temperature ESPs have been under development for many years. Some of these are in the demonstration stage but further development is needed to enable commercial exploitation [5]

2.1.2.6. Selective Catalytic Reduction (SCR) & Selective Non-Catalytic Reduction (SNCR)

In selective catalytic reduction systems, ammonia vapor is used as the reducing agent and is injected into the flue gas stream, passing over a catalyst. The optimum temperature is usually between 300°C and 400°C. The key difference between SCR and SNCR is the presence in SCR systems of a catalyst, which accelerates the chemical reactions. The catalyst is needed because SCR systems operate at much lower temperatures than SNCR; typical temperatures for SNCR are 870-1200°C. [5]

2.1.2.7. Wet Particle Scrubbers

Wet particle scrubbers for particulate control are used in a limited number of coal-fired plants, with most of these installations located in the USA, to capture fly ash in addition to sulphur dioxide (SO_2). Water is injected into the flue gas stream to form droplets. The fly ash particles impact with the droplets forming a wet by-product, which then requires being disposed. Wet particle scrubbers have a removal efficiency of 90-99.9%. [5]

2.1.2.8. Ultra-Clean Coal

Ultra Clean Coal - UCC means coal containing less than 0.1% by weight mineral matter. UCC has the potential to be fired directly in a gas turbine, generating electricity far more efficiently than conventional means, and reducing CO emissions. Generally, the level of mineral matter in coal for use in a direct coal fired turbine must be below 0.1% by weight. UCC could be used as a substitute for many carbon-based materials which are currently derived from oil, such as petroleum coke used to produce electrodes for the aluminum smelting process. It has been found that the direct hydrogenation of coal to produce liquid fuels or organic chemicals is adversely affected by the mineral matter in the coal. UCC is likely to be a better feedstock than coal for the production of carbon-based fuels, chemicals and materials, which are currently produced from oil. In addition, the carbon content of coal is much higher than that of oil, and is largely present as aromatic structures. The current influences on the future use of coal predict a demand for UCC. However, a technically and commercially viable technology or process for its production has not been established. Generally, the only way to reduce the level of mineral matter below approximately 1% by weight without losing a significant portion of the coal is by chemical coal cleaning techniques. Theoretically, chemical techniques have the potential to reduce the level of mineral matter in coal to less than 0.1% by weight. [7]

2.1.3. Efficient Combustion Technologies

2.1.3.1. Pulverized Coal Combustion

Conventional coal-fired generation today is normally via the route of pulverized coal combustion (PCC). (Figure: 2) PCC can be used to fire a wide variety of coals, although it is not always appropriate for those with high ash content. In PCC power stations, coal is first pulverized then blown into a furnace where it is combusted at high temperature. The resulting heat is used to raise steam, which drives a steam turbine and generator. Efficiencies have been steadily rising – and hence emissions reducing – for many years and the trend continues. [5]

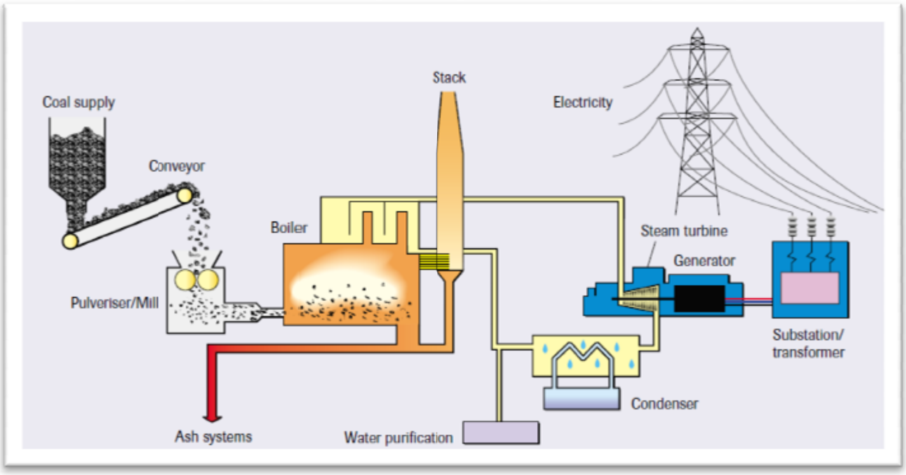

Figure 2: Generating Electricity from Coal **(5)**

2.1.3.2. Fluidized Bed Combustion

In fluidized bed combustion (FBC), coal is burned in a reactor comprised of a bed through which gas is fed to keep the fuel in a turbulent state. This improves combustion, heat transfer and recovery of waste products. The higher heat exchanger efficiencies and better mixing of FBC systems allows them to operate at lower temperatures than conventional (pulverized) coal-burning systems. By elevating pressures within a bed, a high-pressure gas stream can be used to drive a gas turbine, generating electricity. Fluidized bed combustion technologies include atmospheric pressure fluidized bed combustion in both bubbling (BFBC) and circulating (CFBC) beds, pressurized fluidized bed combustion (PFBC), whilst pressurized circulating fluidized bed combustion (PCFBC) is being demonstrated. [5]

- **Circulating Fluidized Bed Combustion** (CFBC) is the version of the technology that has been most widely applied and for which there is the most extensive operating history. CFBC uses the same thermodynamic cycle as PCC and therefore its power generation efficiency is in the same range, which is normally between 38% and 40%.
- **Pressurized Fluidized Bed Combustion** (PFBC) is based on the combustion of coal under pressure in a deep bubbling fluidized bed at 850°C. Depending on the velocity of the air through the fluidized bed, two PFBC variants exist – bubbling bed PFBC (lower velocities) and circulating bed PFBC (higher velocities).

2.1.3.3. Pressurized Pulverized Coal Combustion

Pressurized pulverized combustion of coal (PPCC) is a technology currently under development, mainly in Germany. Similar to conventional pulverized coal combustion, in that it is based on the combustion of a finely ground cloud of coal particles, the heat released from combustion generates high pressure, high temperature steam, which is used in steam turbine-generators to produce electricity. The pressurized flue gases exit the boiler and are expanded through a gas turbine to generate further electricity and to drive the gas turbine's compressor; hence this is a form of combined cycle power generation. [5]

2.1.3.4. Supercritical & Ultra supercritical Technology

Supercritical is a thermodynamic expression describing the state of a substance where there is no clear distinction between the liquid and the gaseous phase. The cycle medium is a single phase fluid with homogeneous properties and there is no need to separate steam from water. Once-through boilers are therefore used in supercritical cycles. Supercritical plant offer higher efficiencies than conventional, sub-critical plant. Ultra supercritical plants operate at very high temperatures and pressures and have the potential to offer efficiencies of over 50%. [5]

2.1.4. Gasification Technologies

2.1.4.1. Integrated Gasification Combined Cycle

In IGCC systems, coal is not combusted directly, but reacted with oxygen and steam to produce a 'syngas' composed mainly of hydrogen and carbon monoxide. The syngas is cleaned of impurities and then burned in a gas turbine to generate electricity and to produce steam for a steam power cycle. IGCC technology offers high efficiency levels, typically in the mid-40s – although plant designs offering close to 50% efficiencies are available – and as much as 95-99% of NO_x and SO_x emissions are removed. [5]

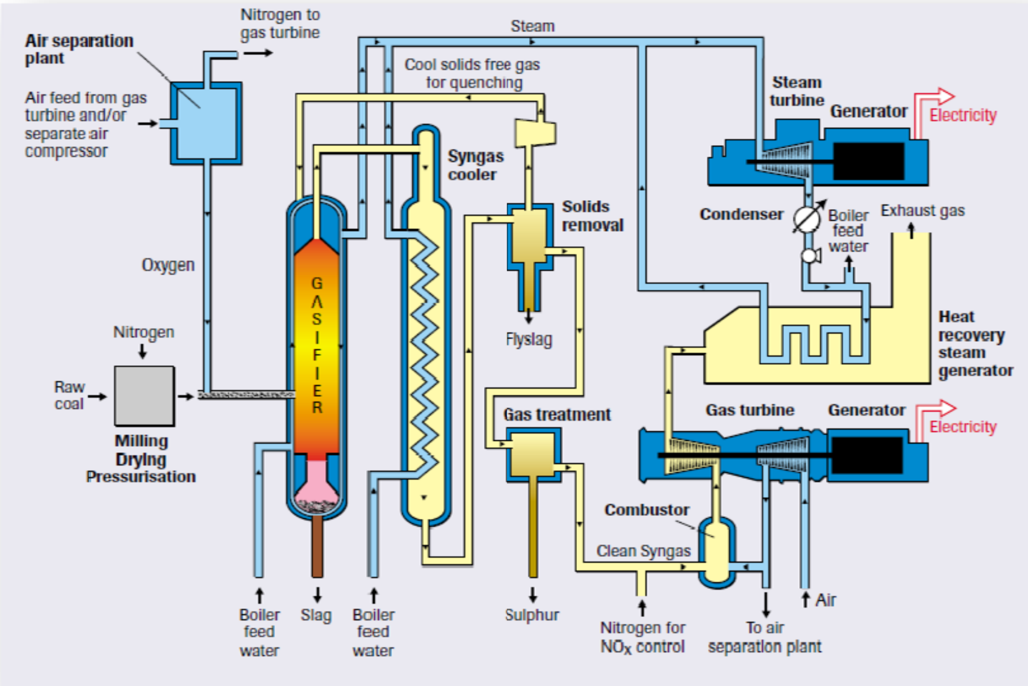

Figure 3: Integrated Coal Gasification Combined Cycle Unit[5]

The appeal of IGCC technology extends beyond the potential for increased efficiencies and further reductions in pollutants. IGCC technology may also be the chosen pathway for the ultra low emissions system of the future, using carbon capture and storage, and as part of a future hydrogen economy. In IGCC, the syngas can be 'shifted' to produce CO_2 and H_2, which can then be separated so that the hydrogen is available as a clean fuel product for use in power generation via gas turbines and fuel cells. The CO_2 is then available in a concentrated form for capture and storage. (Figure 3)

Fuel Cells

Today, hydrogen is produced from coal by gasification followed by processing the resulting synthesis gas, and is used primarily to produce hydrogen for the production of ammonia for fertilizer. Coal derived synthesis gas also is being converted to methanol for use as an intermediate product in the chemical industry. Methanol can be used as a hydrogen carrier for subsequent reforming applications or use in fuel cells, such as those being considered for small portable devices including laptop computers.

The coal first is gasified with oxygen and steam to produce a synthesis gas consisting mainly of carbon monoxide (CO) and hydrogen (H_2), with some CO_2, sulfur, particulates, and trace elements. Oxygen (O_2) is added in less than stoichiometric quantities so that complete combustion does not occur. This process is highly exothermic, with temperatures controlled by the addition of steam. Increasing the temperature in the gasifier initiates devolatilization and breaking of weaker chemical bonds to yield tars, oils, phenols, and hydrocarbon gases. These products generally further react to form H_2, CO, and CO_2. The fixed carbon that remains after devolatilization is gasified through reactions with O_2, steam, and CO_2 to form additional amounts of H_2 and CO.

2.1.5. Carbon Capture and Storage

Carbon dioxide (CO_2) capture and storage (CCS) is a process consisting of the separation of CO_2 from industrial and energy-related sources, transport to a storage location and long-term isolation from the atmosphere. CCS is considered as an important option in the portfolio of mitigation actions for stabilization of atmospheric greenhouse gas concentrations. [8] Other mitigation options include energy efficiency improvements, the switch to less carbon-intensive fuels, nuclear power, renewable energy sources, enhancement of biological sinks, and reduction of non-CO_2 greenhouse gas emissions.

CCS begins with the separation and capture of CO_2 from power plant flue gas and other stationary sources. CO_2 capture applies mainly to large power plants fired with hard coal, lignite and natural gas. It also applies to large, single point emission processes such as refineries, cement plants, chemical plants and steel mills that can use the same or similar technology - as well as transport infrastructure – thus increasing the efficiency of the entire CCS system. It can even apply to biomass fired power plants, paving the way for net *negative* emissions, because biomass also draws CO_2 down from the atmosphere whilst it is growing.

Ideal locations for large-scale CO_2 capture include gas processing plants, fertilizer manufacturing facilities, thermal power plants and other sites that produce large amounts of CO_2, often in excess of one million tonnes of CO_2 equivalent [1](MtCO_2e) annually. [9] These industrial facilities are often located near others, thus increasing the amount of available CO_2 for capture within the general vicinity.

There are three main technology options under development:

- ***Post-combustion*** systems separate CO_2 from the flue gases produced by combustion of a primary fuel (coal, natural gas, oil or biomass) in air. Post-combustion systems can be retrofitted to existing power plants, as well as new builds.
- ***Pre-combustion*** systems process the primary fuel (natural gas or synthetic gas from coal) in a shift reaction to produce streams of CO_2 and hydrogen which can be separated. The hydrogen can then be used for either electricity or as a fuel.
- ***Oxy-fuel combustion*** systems use oxygen instead of air for combustion, producing a flue gas that is mainly H_2O and CO_2, which can be easily captured after the water vapor is condensed.

[1] CO_2 Equivalent (CO_2e) is the weight of CO2 released into atmosphere having the same estimated global warming potential as a given weight of another greenhouse gas. It is computed by multiplying the weight of gas (methane, for example) by its global warming potential (1 for CO_2, 21 for methane)

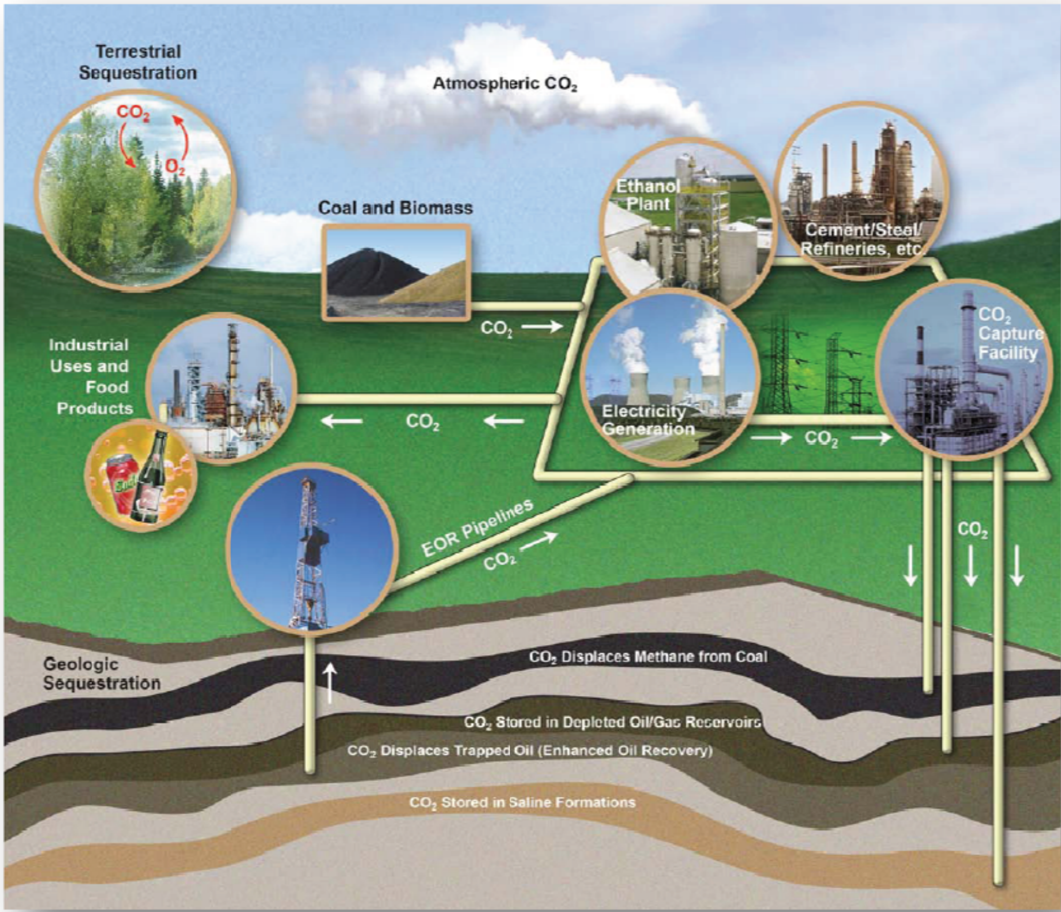

Figure 4: Schematic diagram of possible CCS systems [10]

Carbon storage is defined as the placement of CO_2 into a repository in such a way that it will remain stored or sequestrated permanently. It includes geological sequestration and terrestrial sequestration. Geological sequestration involves the injection of CO_2 into underground reservoirs that have the ability of securely contain it over long periods of time. The formations that can store CO_2 include running oil and gas reservoirs (with the purpose of recovery increase EOR, ENGR), depleted oil and gas reservoirs, deep saline aquifers, unminable coal seams oil and gas rich organic shales and basalts.

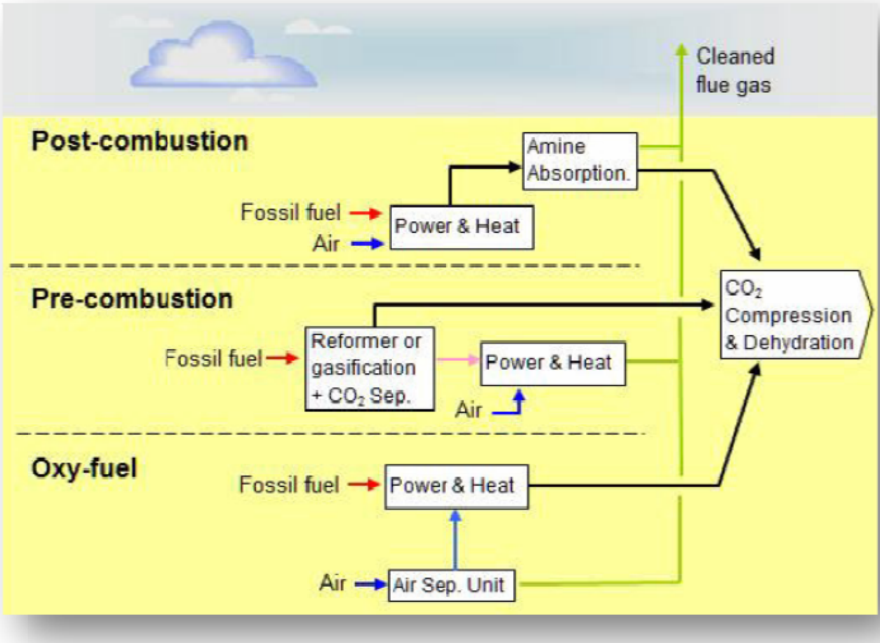

Figure 5: Main CO_2 Capture technology Options [11]

Once captured and compressed, CO_2 must be transported to a long-term storage site. In principle, transmission may be accomplished by pipeline, marine tankers, trains, trucks, compressed gas cylinders, as a CO_2 hydrate, or as solid dry ice. However, only pipeline and tanker transmission are commercially reasonable options for the large quantities of CO_2 associated with centralized collection hubs or point source emitters such as power stations of 500MWe capacity or greater. Trains and trucks are used in some present pilot studies (Schwarze Pumpe project, Vattenfall 2009) and may be appropriate for small volumes of CO_2 over short distances. [12]

2.1.6. Cross Cutting Technologies

There can some synergistic opportunities with all the above mentioned technologies which have a horizontal nature.

2.1.6.1. Biomass Co-Firing

Biomass can be directly fired in dedicated boilers. However, co-firing biomass and coal has technical, economical and environmental advantages over the other options. By co-firing biomass with coal, a continuous supply of biomass would not be an issue, since the boiler plant would always have the primary fuel, coal, for 100% utilization. Co-firing biomass with coal, in comparison with single coal firing, helps reduce the total emissions per unit energy produced. Coal and biomass fuels are quite different in composition. Co-firing biomass with coal has the capability to reduce both NO_x and SO_x levels from existing pulverized coal fired power plants. Co-firing may also reduce fuel costs, minimize waste and reduce soil and water pollution, depending upon the chemical composition of the biomass used. The oldest of all fuels, wood (or biomass), and the old original fuel of the industrial revolution, coal, are key to this move to a new mission. [13]

2.1.6.2. Combined Heat and Power (CHP) or Co-generation

CHP or Co-generation is an energy conversion process, where electricity and useful heat are produced simultaneously in one process. Both combustion and gasification facilities can be adapted to recover low-grade heat for use in process steam applications (such as pulp and paper industries or district heating) by using commercially available technology and by doing so will achieve efficiencies above 80%. Overall efficiencies may be greater than 90% by utilizing condensing heat exchanger to recover latent heat caused by evaporation form the flue gas, and using it for low-temperature need.

2.1.6.3. Tri-generation

Tri-generation is a system of generating electricity, heating and refrigeration/cooling simultaneously with only one fuel input. In order to raise the total efficiency of the generation, the waste heat from the engine is collected, stored and used for heating, and also used to generate refrigeration/cooling through a heat-driven absorption refrigeration system. This technology has been proved to be of high efficiency and low emission energy system to supply power, heat and refrigeration simultaneously. [14]

2.1.6.4. Polygeneration

Polygeneration is considered a potentially attractive technology for energy utilization, as it could provide feasible solutions to the worldwide problems of excessive GHG emissions and ever-increasing depletion of fossil fuels. A typical polygeneration plant produces electricity and chemical synthesis products, in particular alternative fuels, such as methanol, dimethylether (DME) and hydrogen. Polygeneration energy systems are considered to be superior to conventional stand-alone plants. Their advantages lie in three main aspects:

Energy efficiency: due to the tight integration of the power generation and the chemical synthesis sections, the overall energy utilization of a polygeneration plant is expected to be higher than the overall efficiency of stand-alone plants, producing the same products.

Alternative fuels and energy carriers: chemical products produced by a typical polygeneration plant can be used as substitutions for traditional liquid fuels; for example, methanol for gasoline, DME for diesel oil. Hydrogen can also be a product.

Cost-effective emissions reduction: the large-scale of polygeneration energy systems is expected to result in cost-effective solutions for the implementation of CCS units. [15]

2.1.6.5. Chemical Looping

Chemical Looping Combustion (CLC) is one of important techniques used to combine fuel combustion and pure CO_2 production in situ allowing for CO_2 capture. This occurs via indirect combustion whereby oxygen (from air) is transferred by a solid oxygen carrier to fuel combustion. In a CLC process, fuel gas (natural gas, syngas, etc.) is burnt in two reactors designated as fuel and air reactors. Metal oxide, which circulates between the air reactor and fuel reactor, acts as oxygen carrier, and transfers oxygen from air to fuel. In this way, the nitrogen from the air leaves the system from the air reactor, whereas the flue gas from the fuel reactor consists of only CO_2 and water. After water condensation, almost pure CO_2 can be obtained. [16]

2.2. Emerging Energy Scene

Energy is at the heart of the climate change problem; it accounts for 65% of the world's greenhouse-gas emissions, and so must be at the heart of the solution.

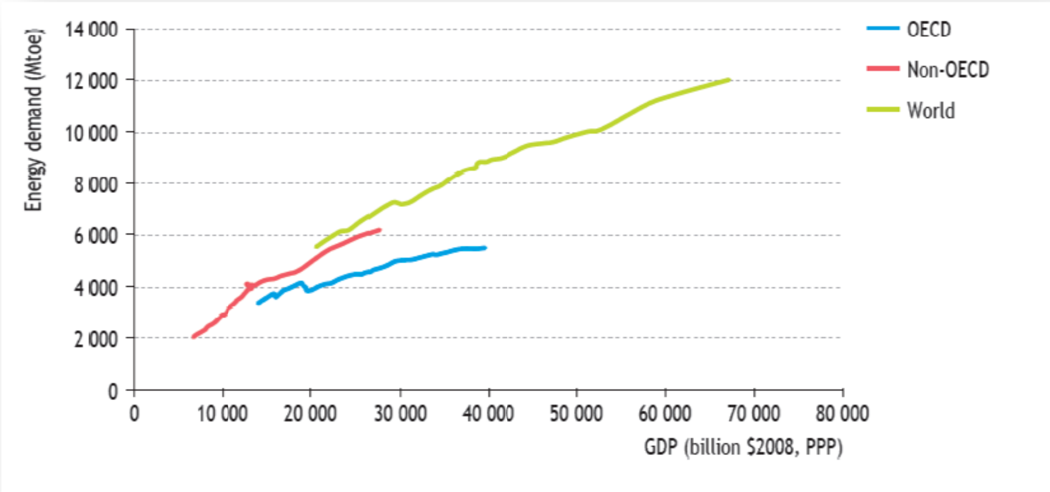

Figure 6: Primary energy demand and GDP, 1971-2007[3]

According to IEA analysis since the 1970s, primary energy demand has risen in a broadly linear fashion along with GDP (Gross Domestic Product): between 1971 and 2007, each 1% increase in global GDP (expressed in real purchasing power parity, or PPP, terms) was accompanied by a 0.7% increase in primary energy consumption (Figure 6). Demand for electricity and transport fuels has been particularly closely aligned with GDP. However, the so-called income elasticity of primary energy demand — the increase in demand relative to GDP — has changed over time. It fell sharply from 0.8 in the 1970s to 0.5 in the 1990s, but then rebounded to 0.7 in 2000-2007, mainly because of a surge in energy-intensive manufacturing in China.

2.2.1. Global Energy Trends – Reference scenario

IEA's Reference Scenario that was described in World Energy Outlook 2009 is not designed to be a forecast of what will happen but to be a baseline picture of how global energy markets would evolve if governments make no changes to their existing policies and measures. The assumptions made are summarized below:

Global primary energy demand is projected to rise by 1.5% per year on average between 2007 and 2030 — an overall increase of 40%. China and India are the main drivers of growth, followed closely by the Middle East.

Oil demand is projected to grow by 1% per year on average over the projection period, from 85 million barrels per day in 2008 to 105 mb/d in 2030. All the growth comes from non-OECD countries; OECD demand falls. The transport sector accounts for 97% of the increase. As non-OPEC conventional oil production peaks around 2010, most of the increase in output comes from OPEC countries, which hold the bulk of remaining recoverable resources

World primary demand for natural gas expands on average by 1.5% per year in 2007-2030, reaching 4.3 trillion cubic meters. The biggest increases occur in the Middle East, China and India, but North America, Russia and Europe remain the leading consumers in 2030. New power stations absorb 45% of the increase. The Middle East sees the biggest increase in production while output also increases markedly in Russia, the Caspian and Africa.

Demand for coal grows more strongly than demand for any other energy sources except non-hydro modern renewables — at an average annual rate of 1.9% — reaching almost 7000 MtCO_2e in 2030. Growth in production in all other regions is dwarfed by China's 61% share of incremental global production, as it strives to satisfy a near-doubling of domestic demand.

World electricity demand is projected to grow at an annual rate of 2.5% to 2030. Over 80% of the growth takes place in non-OECD countries. Globally, additions to power-generation capacity total 4 800 GW by 2030. The largest additions occur in China. Coal remains the backbone fuel of the power sector worldwide, its share of the generation mix rising by three percentage points to 44% in 2030. The share of renewables rises from 18% in 2007 to 22% in 2030, with most of the growth coming from non-hydro sources. Nuclear power grows in all major regions bar Europe, but its share in total generation falls.

Cumulative energy investment needs amount to $26 trillion (in year-2008 dollars) in 2008-2030, equal to $1.1 trillion (or 1.4% of global GDP) per year on average. The power sector requires 53% of total investment, followed by oil (23%), gas (20%) and coal (3%). Over half of all investment worldwide is needed in non-OECD countries, where demand and production are projected to increase fastest.

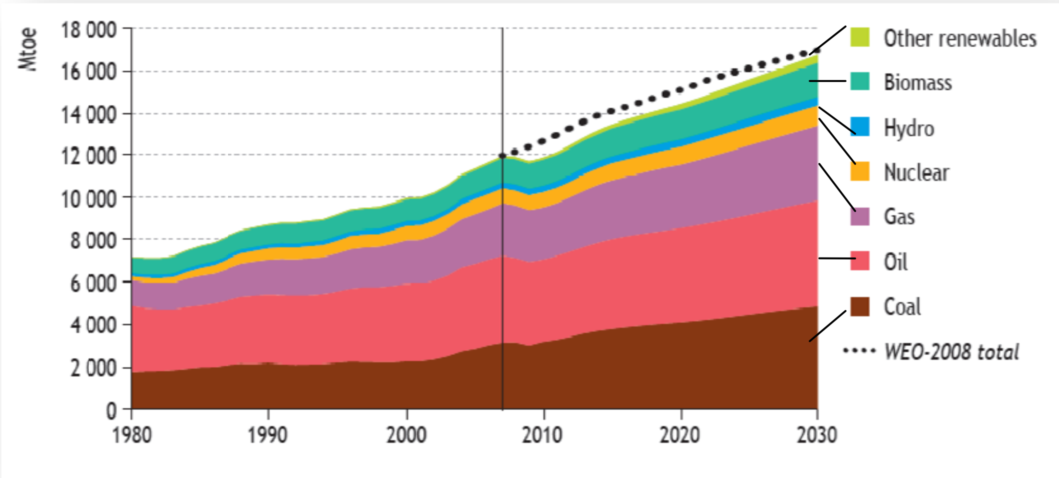

Figure 7: World primary energy demand by fuel in the Reference Scenario [3]

2.2.2. Sectoral Trends

When sectoral trends are considered, the power and heat generation, and transport sectors will account for nearly three-fourths of the global increase in primary energy use in absolute terms over the projection period, in line with past trends. Their combined share of global demand rises from 57% in 2007 to 62% in 2030. Inputs to power stations and heat plants worldwide grow by 1.9% per year between 2007 and 2030, while energy use in transport rises at an annual rate of 1.6%. Demand for mobility and electricity-related services will continue to grow broadly in line with GDP, but at a slower rate than in the past, thanks to a policy- and price-driven acceleration in efficiency gains.

Energy use in final sectors — transport, industry, households, services, agriculture and non-energy uses — in aggregate is projected to grow by 1.4% per year through to 2030, approximately the same rate as for primary energy demand. Industry demand grows most rapidly, at 1.7% per annum. Industry demand climbs in most regions, with the fastest growth occurring in the Middle East. Transport nonetheless remains the single largest final sector, just ahead of industry (Figure 8). Demand in the residential sector grows by only 1% per year on average, as efficiency gains largely offset the effects of rising population, urbanization and growing wealth.

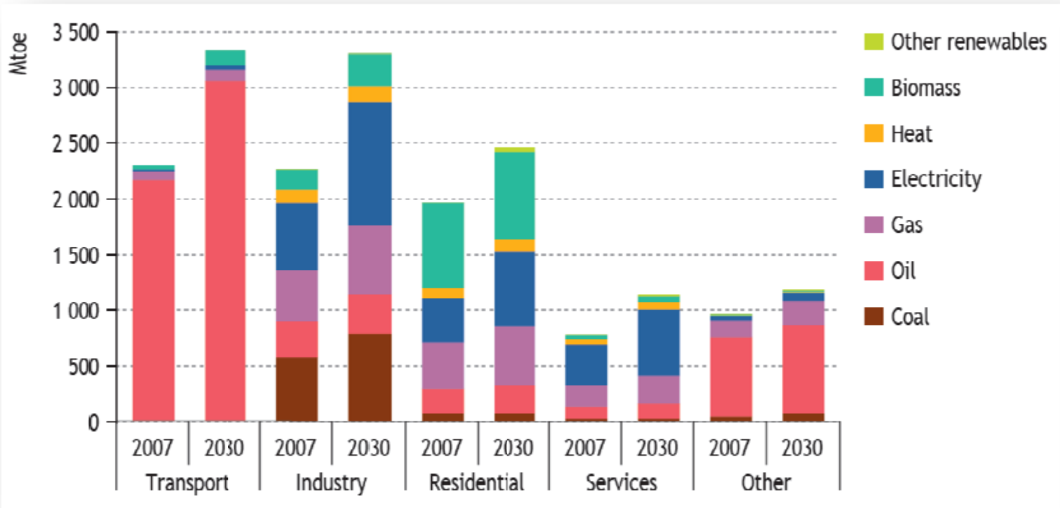

Figure 8: World final energy consumption by fuel and sector in the Reference Scenario [3]

Among final forms of energy, after other renewables, electricity consumption continues to expand most rapidly over the projection period as a result of increased demand for household appliances, and industrial and commercial electrical equipment, in line with rising prosperity. Worldwide, electricity use grows by 2.5% per year on average, and its share in final energy consumption rises from 17% in 2007 to 22% in 2030. The shares of all the other fuels either remain flat or fall. The share of oil drops most, from 43% in 2007 to 40% in 2030, as demand grows only very slowly in non-transport sectors.

2.2.1.2. Global trends in energy-related CO_2 emissions

The Reference Scenario sees a continued rapid rise in energy-related CO_2 emissions through to 2030, resulting from increased global demand for fossil energy. Having already increased from 20.9 Gt in 1990 to 28.8 Gt in 2007, energy-related CO_2 emissions are projected to reach 34.5 Gt in 2020 and 40.2 Gt in 2030 — an average rate of growth of 1.5% per year over the full projection period (Figure 9). Non-OECD countries account for all of this emissions growth: OECD emissions are projected to dip slightly over the period, due to a slowdown in energy demand (resulting mainly from big improvements in energy efficiency) and the increased use of nuclear and renewables, in large part due to the policies already adopted to mitigate climate change and boost energy security.

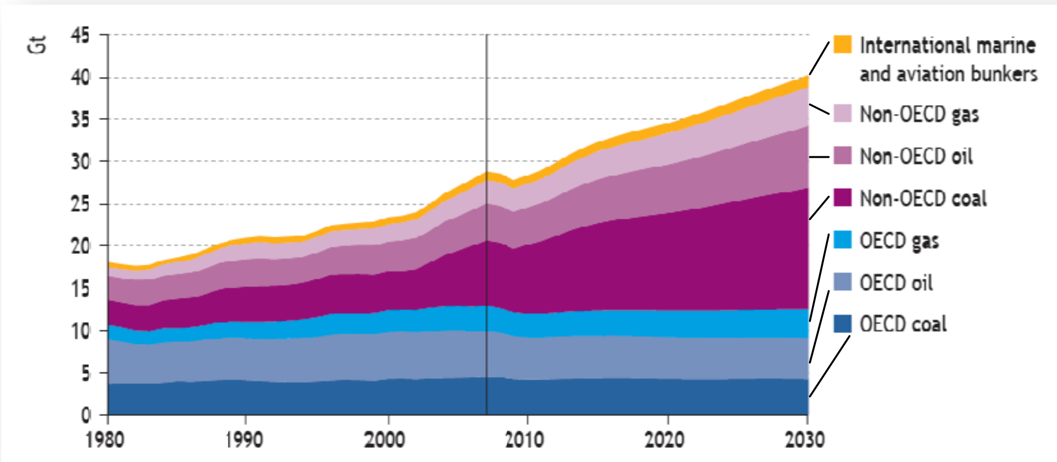

Figure 9: Energy-related CO_2 emissions by fuel and region in the Reference Scenario [3]

Total emissions of greenhouse gases, across all sectors, were 42.4 gigatonnes (Gt) of CO_2e in 2005 (Figure 10). In the Reference Scenario, they reach 50.7 Gt in 2020 and 56.5 Gt in 2030 (Figure 11).

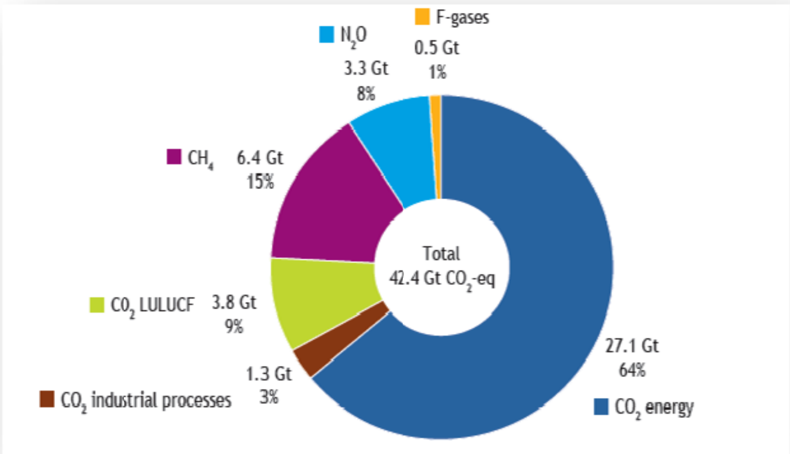

Figure 10: World anthropogenic greenhouse-gas emissions by source, 2005[3]

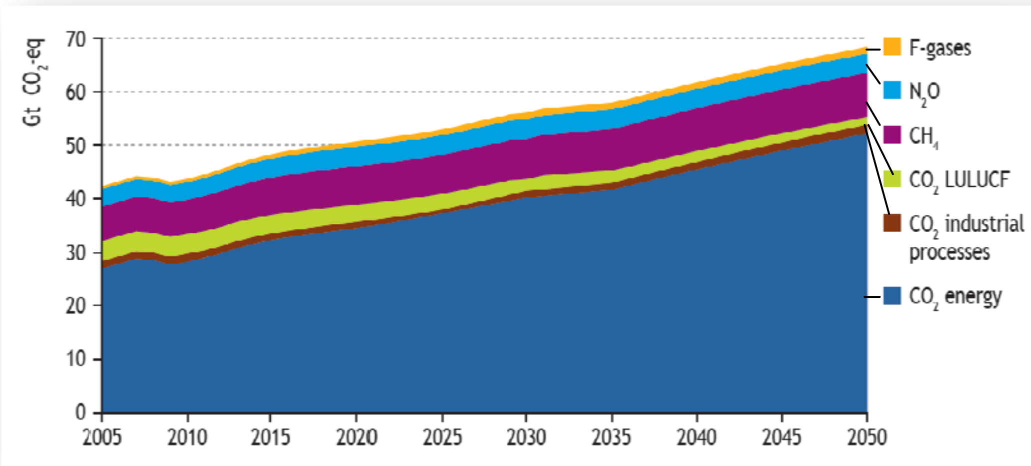

Figure 11: World anthropogenic greenhouse-gas emissions by source in the Reference Scenario [3]

Within this total, energy-related CO_2 is the major component. CO_2 and other greenhouse gases have their source in both energy-related and non energy-related activities. Emissions of greenhouse gases other than energy-related CO_2 are projected to increase by around 6% between 2005 and 2020, and to stabilise between 2020 and 2030. Within this category, methane emissions increase the most by volume — from 6.4 Gt CO_2e in 2005 to 7.2 Gt in 2020 and 7.6 Gt in 2030. Most of this increase comes from to wastewater, coal mining and the increased pipeline leakage associated with higher global gas demand, although there has recently been a reduction in gas leakages in OECD countries and several producing countries are taking measures to reduce flaring and venting. Nitrous oxide emissions grow by around 10% between 2005 and 2030, while F-gases[2] more than double. CO_2 emissions from land use, around 3.8 Gt in 2005, fall by around one-third in the Reference Scenario, to 3.2 Gt in 2020 and 2.6 Gt in 2030, due to a deceleration in the rate of land-use change — in part a result of international policy action. Between 2030 and 2050, total greenhouse-gas emissions continue to rise in the Reference Scenario (despite a slight reduction in N_2O and in land-use CO_2), reaching 68.4 Gt in 2050.

Power generation

In the power-generation sector, CO_2 emissions increase by 26% between 2007 and 2020, while in 2030 they reach 50% above today's level. These higher emissions are driven by the rapid growth in demand for electricity and the consequent increased use of fossil fuels, particularly coal. Emissions from coal-fired plants are projected to grow by 60% between 2007 and 2030, by which time they comprise over three-quarters of power-sector emissions (Figure 12).

Industry

The industrial sector, comprising manufacturing such as iron and steel, chemicals, non-metallic minerals and paper, as well as related products and processes, accounts for 17% of today's world energy-related CO_2 emissions. In 2007, CO_2 emissions from fossil fuel combustion in industry totaled 4.8 Gt, an increase of 21% since 1990. In the Reference Scenario, these emissions reach 5.6 Gt in 2020 and 6.2 Gt in 2030 (Figure 13), with this growth driven entirely by non-OECD countries.

[2] F-gases include hydrofluorocarbons (HFCs), perfluorocarbons (PFCs) and sulfur hexafluoride (SF_6) from several sectors, mainly industry.

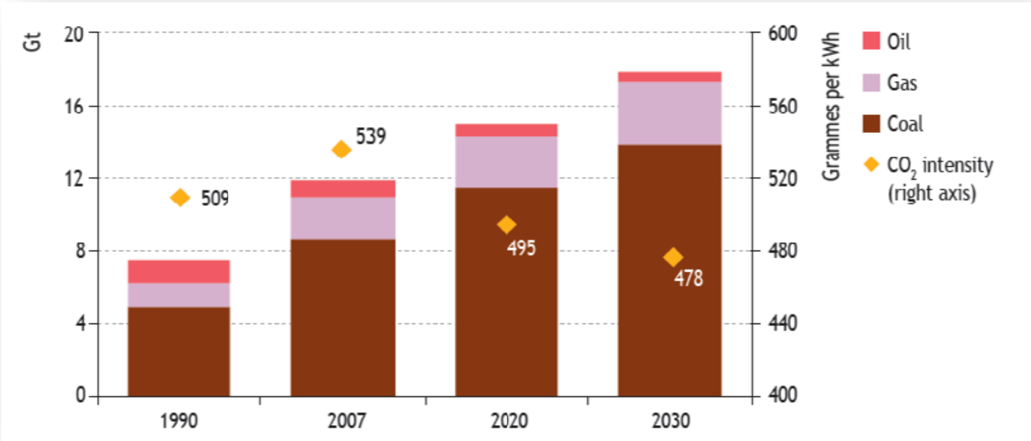

Figure 12: World energy-related CO_2 emissions from the power sector and CO_2 intensity of power plants in the Reference Scenario [3]

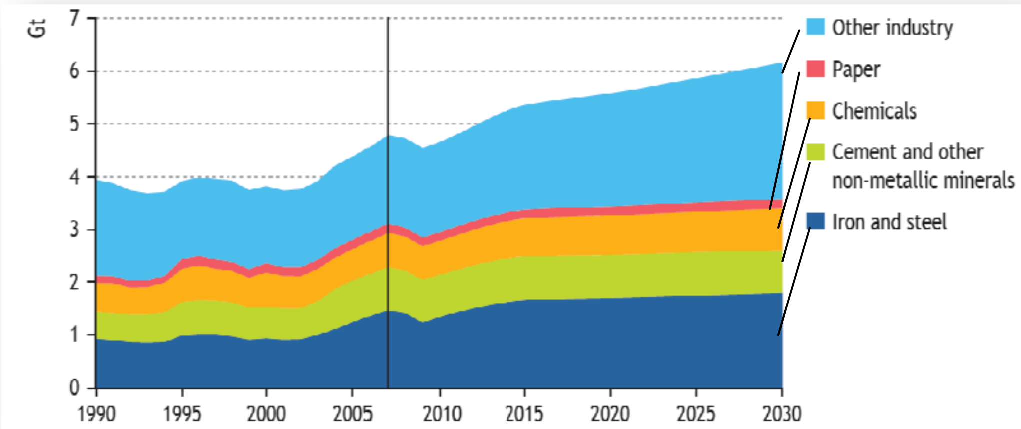

Figure 13: Industry energy-related CO_2 emissions by sub-sector in the Reference Scenario [3]

2.2.2. Low Carbon Scenario

IEA's 450 Scenario, that was described in World Energy Outlook 2009, depicts a world in which collective policy action is taken to limit the long-term concentration of greenhouse gases in the atmosphere to 450 parts per million of CO_2e (ppm), an objective that is gaining widespread support around the world. Following the introduction of economy-wide emission targets in OECD+ countries, the 450 Scenario assumes the implementation of a cap-and-trade system for the power and industry sectors from 2013. In addition, this scenario also includes strong government intervention in support of renewables, nuclear and CCS technologies.

The Reference Scenario still leaves the world on course for a concentration of greenhouse gases in the atmosphere of around 1000 parts per million, implying a global temperature rise of around 6°C. If the world wishes to limit to 25% the probability that a temperature rise in excess of 2°C will occur, CO_2 emissions over the period 2000-2049 must not exceed 1 trillion tones. Between 2000 and 2009, the world emitted 313 billion tones of CO_2.

If all the most ambitious 2020 emissions aspirations of OECD countries were met (including Japan's new 25% target, a 20% cut for the European Union and a 25% reduction in Australia), their total reduction, compared with 2007, would be 2.7 Gt. Governments have announced nearly $250 billion of stimulus funding for green energy projects. But further efforts will be needed to ensure that, when economies rebound, the historical link between CO_2 emissions and economic output (Figure 14) can finally be broken. A recent IEA paper analyzing the response to the financial crisis indicates that existing government commitments would need to be increased four-fold to meet a 450 Scenario. [3] Therefore an energy and environmental revolution is needed, and action to address the financial and economic crisis.

The projected trend approximates that required to achieve long-term stabilization of the total greenhouse-gas concentration in the atmosphere at 450 ppm CO_2e, corresponding to a global average temperature increase of around 2°C. World GDP is assumed to grow at a rate of 2.7% per year after 2030.

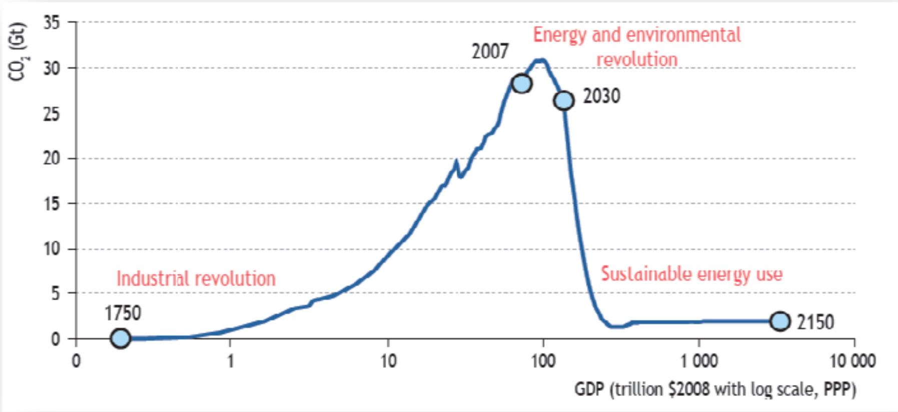

Figure 14: Historical link between energy-related CO_2 emissions and economic output, and the pathway to achieving a 450 Scenario [3]

Each year of delay before moving to a more sustainable emissions path would add around $500 billion to the global investment cost of delivering the required energy revolution (some $10.5 trillion for the period 2010-2030 in the 450 Scenario). A delay of just a few years would render a 450 Scenario completely out of reach.

In the 450 Scenario, global greenhouse-gas emissions peak in 2020 at 44 Gt of CO_2e and decline to 21 Gt in 2050, around half 2005 levels. Emissions from land use, land use change and forestry (LULUCF), exogenous to ENV-Linkages[3], are assumed to decline from 3.8 Gt in 2005 to 3.2 Gt in 2020 and 1.4 Gt in 2050, the same trajectory as in the Reference Scenario. This assumption reflects the large uncertainty surrounding estimates of these emissions, their reduction potential and the costs of action in this sector. Combined emissions from methane (CH_4), nitrous oxide (N_2O), F-gases and CO_2 from industrial processes peak soon after 2010 at 11.7 Gt and decline to 5.1 Gt in 2050. Steps to reduce methane leakage, lower levels of gas flaring, improve process efficiencies and better agricultural management is the key measures that are assumed to bring about those savings.

[3] OECD ENV-Linkages General Equilibrium model has been developed by the Environment Directorate of the OECD Secretariat in order to assess the economic impact of abating Greenhouse Gases using several different economic instruments

Because of the lower abatement cost of these measures, relative to those aimed at reducing energy-related CO_2 emissions, abatement from these gases accounts for more than 40% of global greenhouse-gas abatement by 2020, compared with the Reference Scenario. In 2050, these gases account for just 20% of total abatement, as their abatement potential is almost fully utilized.

Energy-related CO_2 emissions peak just before 2020 at 30.9 Gt and decline steadily thereafter, reaching 26.4 Gt in 2030 and 15 Gt in 2050. The pace of the decline in energy-related CO_2 emissions is about 1.5% per year in the period 2020-2030. Reductions are faster in the period 2030-2050 (around 3% per year). In 2020, emissions are more than 6% higher than today's levels, while in 2030 they are 8% lower. Compared with the Reference Scenario, these figures represent a reduction of almost 4 Gt in 2020 and about 14 Gt in 2030. (Figure 15)

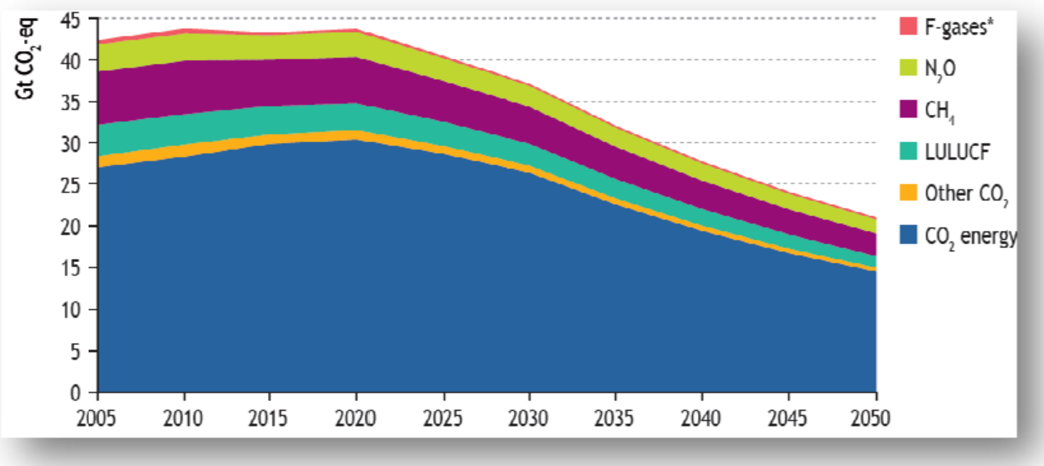

Figure 15: World greenhouse-gas emissions by type in the 450 Scenario [3]

2.2.2.1. Contribution of different abatement measures to the 450 Scenario

End-use efficiency is the largest contributor to CO_2 emissions abatement in 2030 compared with the Reference Scenario, accounting for more than half of total savings (Figure 16). Energy-efficiency measures in buildings, industry and transport usually have short pay-back periods and negative net abatement costs, as the fuel-cost savings over the lifetime of the capital stock often outweigh the additional capital cost of the efficiency measure, even when future savings are discounted. Early retirement of old, inefficient coal plants and their replacement by more efficient coalfired power plants, mainly in China, accounts for an additional 5% of the global emissions reduction. The increased use of biofuels in the transport sector accounts for 3% of CO_2 savings, while increased deployment of renewables in power generation and heat production accounts for 20%. Finally, additional CCS in power and industry and efficiency increase in power plants (including clean coal technologies) will represent 15% of the savings in 2030, relative to the Reference Scenario.

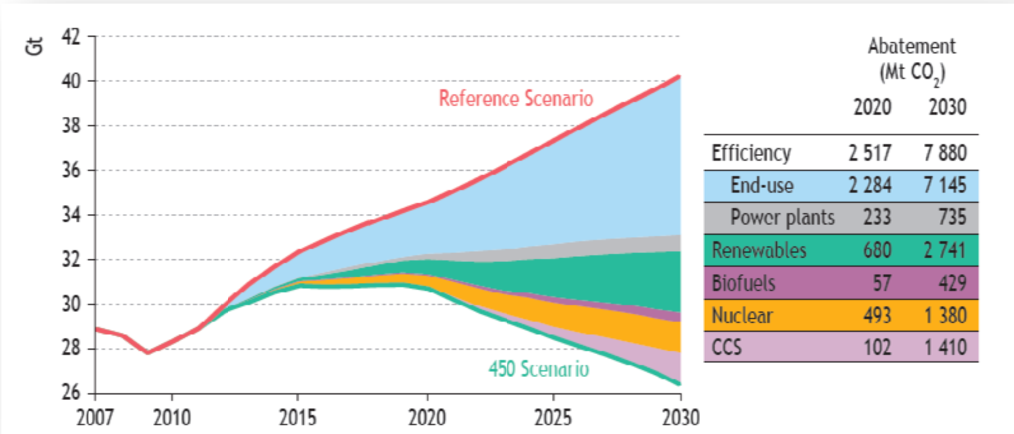

Figure 16: World energy-related CO_2 emission savings by policy measure in the 450 Scenario [3]

As a conclusion IEA analysis projects that energy sector CO_2 emissions will increase by %142 above 2009 levels in the absence of new policies or from supply constraints resulting from increased fossil fuel usage. Addressing this increase will require an energy technology revolution involving a portfolio of solutions: greater energy efficiency, increased renewable energies and nuclear power, and near-decarbonisation of fossil fuel-based power generation. [3] Clean coal and CCS technologies are the only technology available to mitigate GHG emissions from large-scale fossil fuel usage in fuel transformation, industry and power generation.

2.2.3. Energy Scene in Turkey

During the period 1990-2008, Turkey has tripled her energy demand with regards to world average and it corresponds to %4.3 of world total demand. Among OECD countries, Turkey has the fastest growing energy demand in past 10 years due to her increasing population and economic development. Since 2000, Turkey has the second largest increase after China in electricity and natural gas demand. Projections performed by Energy and Natural Resources Ministry of Turkey (ENRM) showed that this trend will continue in the medium term. Primary energy consumption has reached 108 million TPE at the end of 2008 and it is estimated to increase by an average of 4% annual rate until 2020. Net import dependence is 74% and nearly all of the oil and natural gas and 20% of coal are being imported. Therefore energy independency, diversity in supply side and technology is the basic energy policy in Turkey. Recently oil and natural gas exploration has been increased both inland and abroad.

The large increase in energy consumption in Turkey in the last decade is due to the increasing population and economic development. Turkey's primary energy sources are hard coal, lignite, hydropower, oil, natural gas, geothermal, solar and biomass. But, the level of primary energy production is very limited. Turkey has to import nearly 70% of the energy from abroad in that she has very limited indigenous energy sources. Thus, Turkey should revise its energy production plan so as to meet the increased energy demand. For a proper energy planning, at least 10 subsequent years should be predicted since the time period between setting up energy production systems and starting the production is considerably high for the countries like Turkey that could never ignore the economic stability throughout the country. [17]

Turkey has dynamic economic development and rapid population growth. It also has macro-economic, and especially monetary, instability. The net effect of these factors is that Turkey’s energy demand has grown rapidly almost every year and is expected to continue growing, but the investment necessary to cover the growing demand has not been forthcoming at the desired pace. On the other hand, Turkey's primary energy reserves are not enough to meet energy demand. Turkey is an energy importing nation with more than 70% of total energy consumption met by imported fuels such as oil, natural gas and hard coal. [18]

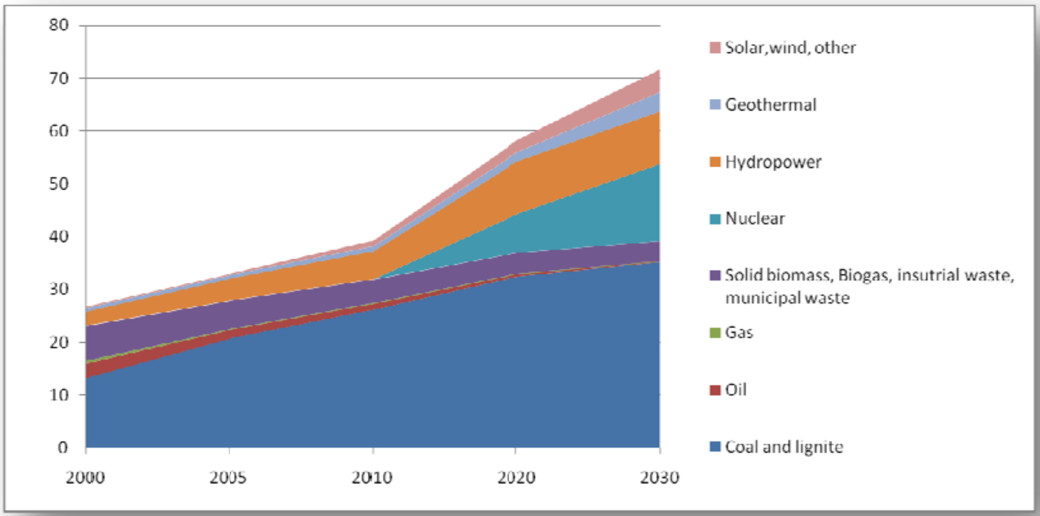

Figure 17: Present and future total final energy production in Turkey, Mtoe [18]

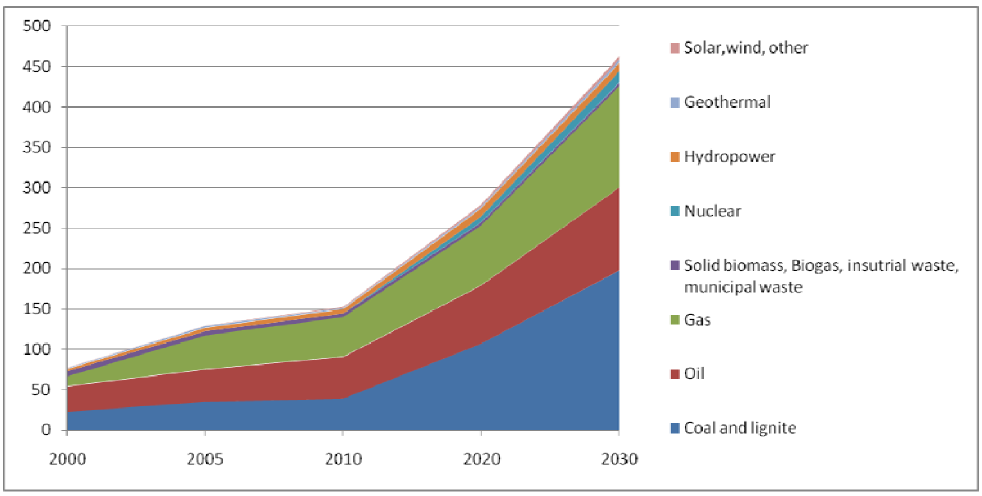

Figure 18: Present and future total final energy consumption in Turkey, Mtoe [18]

According to recent projections conducted by Ministry of Energy and Natural Resources of Turkey, Total Primary Energy Supply will almost double between 2004 and 2020, with coal accounting for an increasingly important share, rising from 24% in 2004 to 36% in 2020, principally replacing oil, which is expected to drop from 40% to 27%. [19] (Figure 17 and Figure 18)

Turkey's installed power capacity in 1988 was 14520.6 MW, which increased around three times in 20 years, and was 41817.2 MW in 2008. On average, Turkey has added every year about 1400 MW of net installed capacity. Turkey generated about 198418.0 GWh of electricity in 2008. [20] The majority of the installed power capacity in Turkey is based on fossil fuel like the other developing countries in the

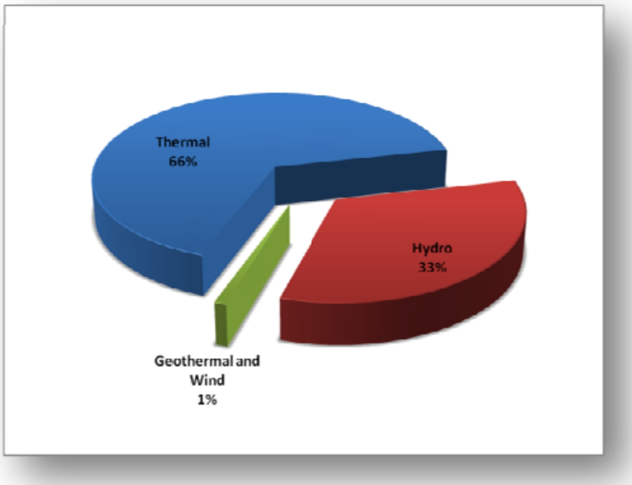

Figure 19: Share of resources in Turkey's installed capacity in 2008

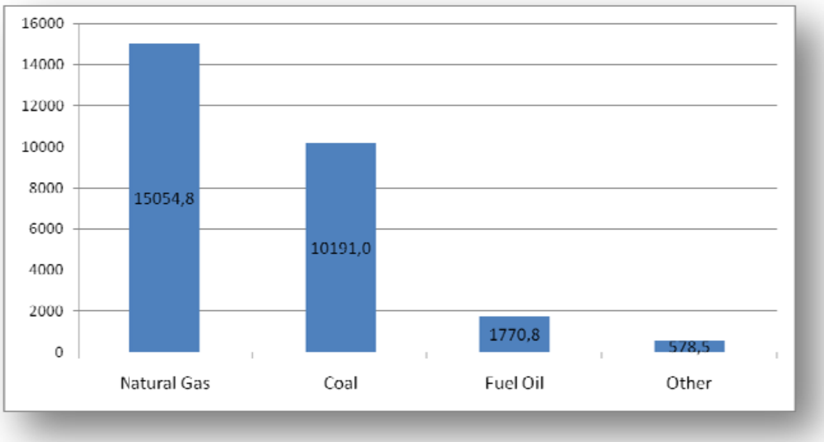

Figure 20: Share of resources in thermal power generated in 2008

world Of the total installed generation capacity, about 66 % is fossil-fuel-based thermal power generation. Figure 19 shows the share of resources in Turkey's installed capacity. As can be seen from Figure 20 currently natural gas is the largest source of fuel for electricity generation followed by coal and fuel oils.

2.2.3.1. Special Focus on Coal

Turkey has significant coal reserves, especially lignite, but also some hard coal. At end of 2002, hard coal reserves were estimated at about 1.13 billion tons, 428 million tons of which were proven reserves. Hard coal is found and mined in only one location, the Zonguldak basin near the north-western Black Sea coast and mine is operated by the fully state-owned Turkish Hard Coal Enterprise (TTK). Hard coal production has declined since the mid-1980s, falling from 2.7 million tons in 1990 to 2.4 million tons in 2002. TTK is trying to reserve this trend and aims to increase production to 3 million tons [21]

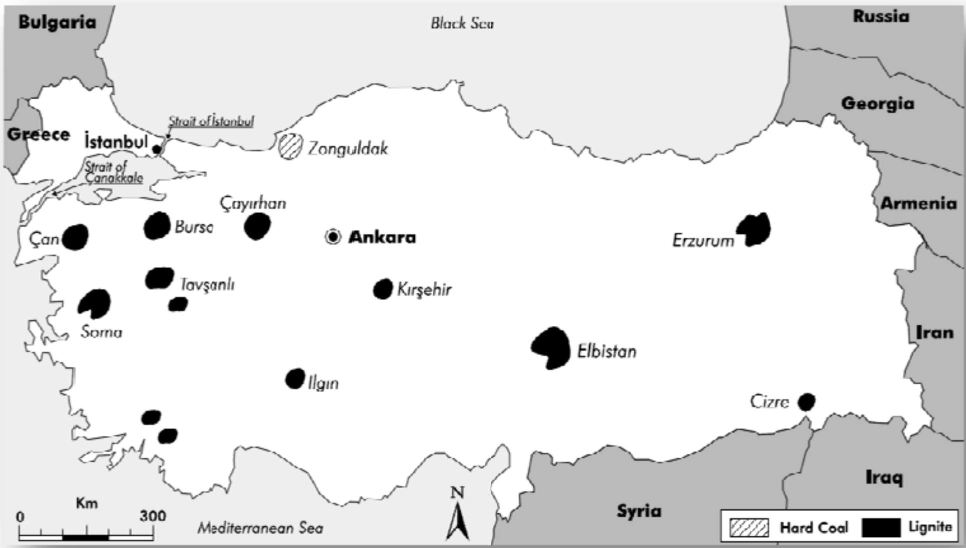

Figure 21: Coal Deposits in Turkey [22]

Total proven lignite reserves were estimated at about 8.1 billion tons. Turkish lignite has low calorific value and high sulphur, dust and ash content. Turkish hard coal is of low grade but of cokeable or semi-cokeable quality. The most important reserves are in the Afşin-Elbistan, Beypazarı, Muğla, Soma, Seyitömer, Tunçbilek, and Sivas regions. About 40% of the country's lignite resources (about 3.4 billion tons) are situated in the Afşin-Elbistan basin in the South-Eastern part of the country. Much of the remainder and over half of all lignite production are located in the western parts of the country. About 90% of lignite production is open-cast, but low-cost open-cast mines are nearing depletion. There are also asphaltite reserves of 82 million tons in the Şırnak and Silopi areas. [21]

The state-owned Turkish Hard Coal Enterprises (TTK) has a de facto monopoly in hard coal production, processing, and distribution, although there are no legal restrictions on private sector involvement. State-owned and private companies produce, process, and distribute lignite reserves, although state-owned Turkish Coal Enterprises (TKI) has a majority market share. Restructuring of Turkey's coal sector has been underway since the 1990s, with a final goal of eventually privatizing TTK and TKI as well as closing down smaller, less profitable mines.

2.3. Environmental Concerns and Climate Change

Today's fossil fuel industries already use many innovative technologies to reduce their environmental footprint on land, water and air resources. Examples include reduced land footprint from oil and gas activities and active land reclamation, reduced pipeline and offshore leaks and spills, tailings pond management for coal preparation plants and reduced gas flaring and venting from oil and gas production sites. Continual improvement in practices and procedures, and higher industry standards also contribute to reduced environmental impacts.

Significant air emissions reductions have already been achieved at existing power plants, oil refineries and natural gas processing facilities. However, further reductions are needed to continue to reduce environmental impacts such as acid rain, smog, particulates and air toxics build-up, and climate change. Solutions to all of these problems are needed. CCS together with CCT is one of many options suggested for dealing with climate change-causing GHG emissions, and therefore the issue of climate change is one of the primary drivers behind CCS development today.

The key environmental challenges facing coal, and the nature and status of the technological responses to those challenges, are summarized in the Table: 1.

Table 1: Environmental Challenges facing coal and current technological status [5]

Environmental Challenges	**Technological Responses**	**Status**
Particulate Emissions Such as ash from coal combustion. Particulates can affect people's respiratory systems, impact local visibility and cause dust problems.	Electrostatic precipitators and fabric filters control particulate emissions from coal-fired power stations. Both have removal efficiencies of over 99.5%.	Technology developed and widely applied both in developed and developing countries.
Trace Elements Trace element emissions from coal-fired power stations include mercury, selenium and arsenic. They can be harmful to the environment and to human health.	Particulate control devices, fluidized bed combustion, activated carbon injection and desulphurization equipment can all significantly reduce trace element emissions.	Technologies developed, commercialized and widely applied in developed countries. The application of NO_x control and desulphurization techniques is less prevalent in developing countries and, although increasing, could be more widely deployed.
NO_x Oxides of nitrogen, referred to collectively as NO_x, are formed from the combustion process where air is used and/or where nitrogen is present in the fuel. They can contribute to smog, ground level ozone, acid rain and greenhouse gas emissions.	NO_x emissions can be cut by the use of low NO_x burners, advanced combustion technologies and techniques such as selective catalytic reduction and selective non-catalytic reduction, which lower emissions by treating the NO_x in the flue gas. Over 90% of NO_x emissions can be removed using existing technologies	
SOx Oxides of sulphur (SO_x), mainly sulphur dioxide (SO_2), are produced from the combustion of the sulphur contained in many coals. SO_x emissions can lead to acid rain and acidic aerosols (extremely fine airborne particles).	Technologies are available to minimize SO_x emissions, such as flue gas desulphurization and the advanced combustion technologies. Emissions can be reduced by over 90% and in some instances by over 95%.	
Waste from Coal Combustion Waste consists primarily of uncombustible mineral matter (with a small amount of unreacted	Waste can be minimized both prior to and during coal combustion. Coal cleaning prior to combustion is a very cost-effective method of	Technologies developed and continually improving. Awareness of opportunities for the re-

carbon).	providing high quality coal; it reduces power station waste and emissions of SO_x, as well as increasing thermal efficiencies. Waste can also be minimized through the use of high efficiency coal combustion technologies – the residual waste can then be reprocessed into construction materials.	use of power station waste (e.g. fly ash in cement making) is steadily increasing.
CO_2 Reduction CO_2 is the main oxide of carbon produced when fuels containing carbon are burnt. CO_2 is a significant greenhouse gas; progressively reducing CO_2 from fossil fuel based power is an essential element of a global response to the risks of global warming and climate change.	In the short to medium term, substantial reductions in the greenhouse intensity of coal-fired generation (CO_2 per megawatt hour of electricity produced) can be achieved by increased combustion efficiency (megawatt hours per tonne of coal consumed).	The efficiency of pulverized coal generation increased substantially during the latter part of the 20th century and, with the development of supercritical and ultra supercritical processes, will continue its steady upward advance over the next two decades. Circulating fluidized bed combustion technology offers similar benefits to advanced pulverized coal combustion and is well suited to co-combustion of coal with biomass.
CO2 Elimination The virtual elimination of CO_2 emissions from fossil fuel based power – including coal-fired generation – offers the prospect of reconciling growing energy demand with the long term global goal of stabilizing the concentration of greenhouse gases in the atmosphere at an acceptable level.	'Zero-emissions technologies' to enable the separation and capture of CO_2 from coal-based generation and its permanent storage in the geological subsurface.	CO_2 separation, capture and geological storage technologies have been developed beyond the stage of technical feasibility. Researchers and technicians are planning to improve these component technologies and demonstrate them in integrated configurations. Deployment may start within a decade.

2.3.1. Climate Change

The world is entering a new era in addressing the challenge of climate change. The world's climate has always varied naturally but compelling evidence from around the world indicates that a new kind of climate change is now under way, foreshadowing drastic impacts on people, economies and ecosystems. Levels of carbon dioxide (CO_2) and other 'greenhouse gases' (GHG) in the atmosphere have risen steeply during the industrial era owing to human activities like fossil fuel use and deforestation, spurred on by economic and population growth. Like a blanket round the planet, greenhouse gases trap heat energy in the Earth's lower atmosphere Figure 22: If levels rise too high, the resulting overall rise in air temperatures, global warming, is liable to disrupt natural patterns of climate. [23]

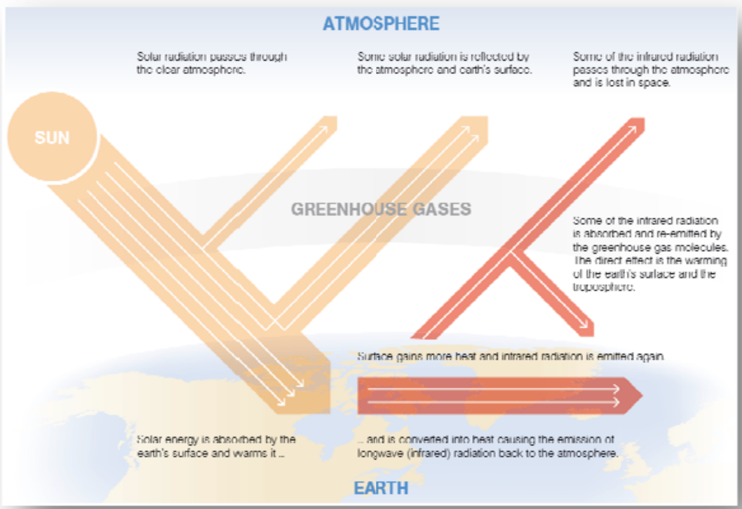

Figure 22: The green house effect [23]

The impacts of global warming on the world economy have been assessed intensively by researchers since the 1990s. World-wide organizations, such as the United Nations, have been attempting to reduce the adverse impacts of global warming through intergovernmental and binding agreements. The Kyoto Protocol is such an agreement that was signed in 1997 after immense discussions. It is a protocol to the United Nations Framework Convention on Climate Change (UNFCCC) with the objective of reducing greenhouse gases (GHG) that cause climate change. The Kyoto Protocol identifies constraints to environmental pollutants and requires a timetable for realizations of the emission reductions for the developed countries. It demands the reduction of GHG emissions to 5.2% lower than the 1990 level during the period 2008–2012. [19]

In consequence of widespread increase in the emission of greenhouse gases some international steps have been taken. As an important first step, the UN Conference on Environment and Development was held in Rio de Janeiro in 1992 and formed the UNFCCC to protect the Earth's climate system against the effects of greenhouse gases and global warming. Under the UNFCCC, the socalled Annex I countries committed, on a voluntary basis, to limit their gaseous emissions to 1990 levels. The OECD and EU countries further joined to form the Annex II bloc and agreed to provide technical and financial assistance to those countries that remained outside the Annex I to aid their environmental policies to reduce greenhouse gas emissions. Based on voluntary participation, the specific economic and political components of such commitments of the Convention remained ambiguous. This led to culmination of efforts towards binding commitments as signed in the Kyoto Protocol in December 1997. Accordingly, the Annex I countries agreed to reduce their gaseous emissions by 5.2% relative to 1990 levels over the period 2008–2012. The Kyoto Protocol, signed in 1997 and enacted on February 16, 2005 after being ratified by the Russian Parliament, is the first agreement trying to bring constraints to emissions and requiring a timetable for realization of the reductions. The Protocol does not bring any limitations for developing countries. At present, more than 170 countries have signed the protocol. [19]

The principal gases associated with climate change are carbon dioxide (CO_2), methane (CH_4), and nitrous oxide (N_2O), which together accounted for over 99% of GHG emissions in 2005. CO_2 is the dominant greenhouse gas, accounting for 64% of global emissions in 2005, excluding land use and forestry emissions and removals. Including land use change and forestry increases the share of CO_2 in 2005 to 76% globally. Hydrofluorocarbons (HFCs), perfluorocarbons (PFCs) and sulphur hexafluoride (SF6) account for less than 1% of total global GHG emissions, but they are growing quickly. All these greenhouse gases are subject to international obligations under UNFCCC, including national monitoring and reporting of emissions and removals of greenhouse gases. [19]

Fossil fuel combustion is by far the largest global source of CO_2 emissions, accounting for 66% of global GHG emissions in 2005. Of this, fossil fuel combustion in power generation is the most important source, and accounted for about one-quarter of all global GHG emissions in 2005. Electricity-related CO_2 emissions are also a rapidly growing source of GHGs, particularly in Asia, reflecting both increased electrification rates and the continued predominance of fossil-fired electricity. [19]

The Intergovernmental Panel on Climate Change (IPCC) was established to provide scientific, technical and socio-economic information relevant to the understanding of climate change, and provides much of the technical information used at UNFCCC meetings for discussion and decisions. In 2005, IPCC completed a report on CCS entitled IPCC Special Report on Carbon Dioxide Capture and Storage, which states the important role of CCS in a portfolio of global measures aimed at stabilizing GHG concentrations. The IPCC also identified the significant role that CCS will continue to play in developing transformational new energy systems and infrastructure based on hydrogen/electricity, and perhaps even bio-based energy carriers. [24]

2.3.2. Turkish Scene

According to UNFCCC GHG Database, Turkey's total GHG emissions amounted to 372.63 million tons (Mt) in 2007. Land Use, Land-Use Change and Forestry (LULUCF) activities account for -76.27 Mt. Therefore the total GHG emissions add up to 269.36 Mt. Emissions grew by 119% compared to 1990 levels. Figure 23 presents GHG emission distributions for different sectors and the increase rate corresponding to base year in Turkey from 1990 to 2007.

In 2007, energy production was the single most important source of GHGs in Turkey, representing 77.4% of the total. The waste disposal was the second largest, representing 8.5% of total emissions, followed by industry and agriculture, which represented 7% each. Since 1990, emissions from energy production have fluctuated between 72% and 77%. Simultaneously, the share of emissions from industry sector was between 7% and 10%. [19]

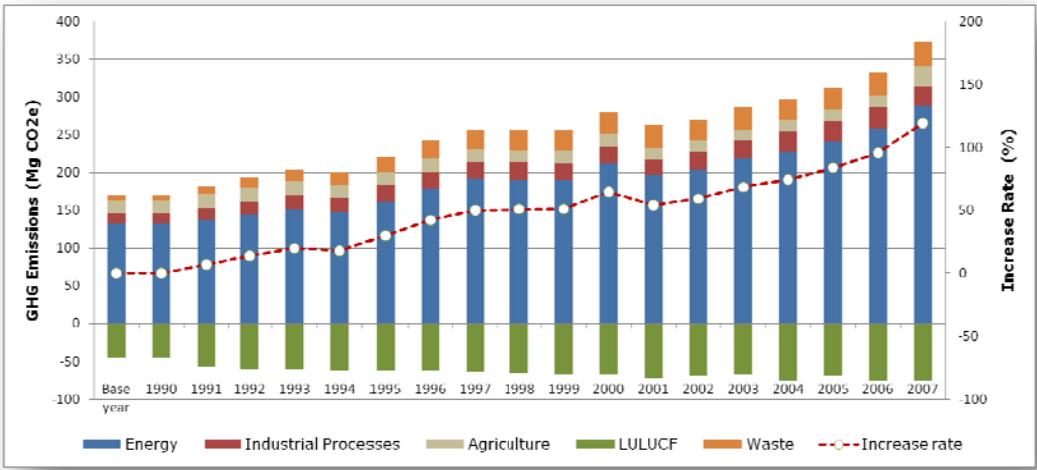

Figure 23: Annual Sectoral GHG Emission Distributions in Turkey [2]

Per capita CO_2 emissions were at 3.3 tons in 2003, much lower than the OECD average of 11.1 tons and EU-25 average of 9 tons. Between 1990 and 2004, per capita emissions in Turkey grew by 22% while on average they grew by only 4% at the OECD level and dropped by 3% in the IEA Europe region. In 2005, Turkey was the 90th country with 3.4 tons of CO_2 per capita emissions. Historically these emissions have been much lower than the OECD average. However, owing to the important growth in emissions that took place over the 1990s, by 2004 CO_2 emissions per unit of GDP were only marginally lower than the OECD average. (19) The growth of Turkey's GHG emissions, including and excluding LULUCF, is the highest among Annex I countries.(Figure 24 and Figure 25) [2]

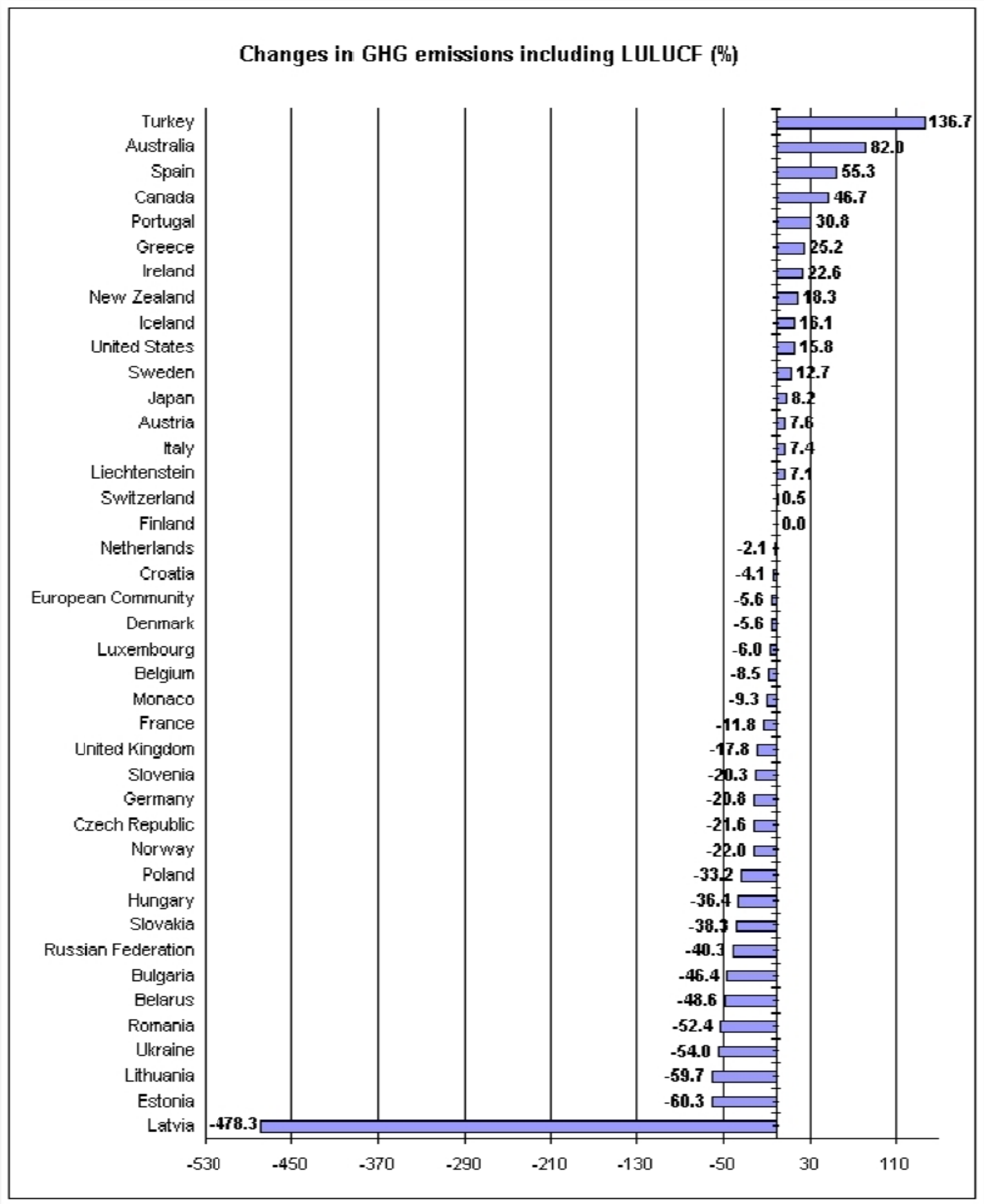

Figure 24: Changes in GHG emissions including LULUCF among Annex I countries 1990-2007[2]

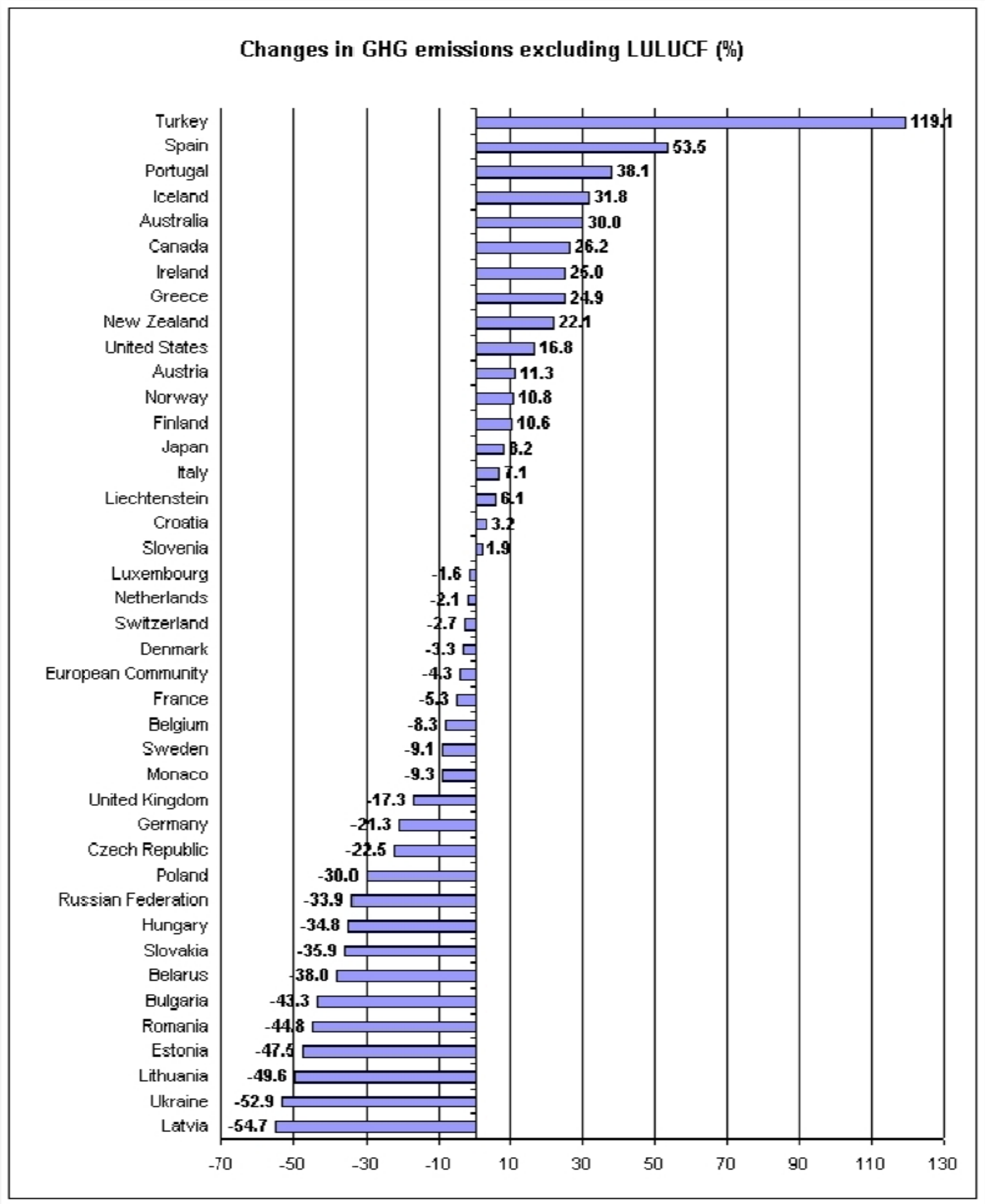

Figure 25: Changes in GHG emissions excluding LULUCF among Annex I countries 1990-2007 [2]

According to Ministry of Energy and Natural Resources of Turkey, such trends will lead to a significant rise in CO_2 emissions, which are projected to reach nearly 600 Mt in 2020, about two times of 2007 levels in Turkey. [19]

Turkey, being a member of the OECD, was initially listed in both Annexes I and II of the UNFCCC in 1992. Under the convention, Annex I countries have to take steps to reduce emissions and Annex II countries have to take steps to provide financial and technical assistance to developing countries. However, in comparison to other countries included in these annexes, Turkey was at a relatively early stage of industrialization and had a lower level of economic development as well as a lower means to assist developing countries. Therefore, claiming for its special circumstances, Turkey declined to be a participant to the Convention. During the 7th Conference of Parties held in Marrakech in 2001 Turkey was granted its omission from the Annex II, and its ''special circumstances'' was recognized as an Annex I country with an accompanying footnote specifying that Turkey should enjoy favorable conditions considering differentiated responsibilities. Turkey has signed the UNFCCC as the 189th participant on May 24, 2004. However, Turkey did not sign the Kyoto Protocol until 2009. Turkish refusals to sign the protocol were mainly related to its expected excess implementation costs and consequently the fear of degrading her competitiveness unfairly in international trade. As a candidate country to the European Union (EU), nevertheless Turkey has strict environmental obligations to fulfill in order to quality for full membership. According to the Commission of the European Communities, the EU aims at reducing environmental pollutants 30% below the 1990 levels by 2020. Thus, Turkey has been under strong pressure from the EU to comply with the Union's regulations on environmental policy, even though pollutant emission reduction is not currently a membership criterion. Finally, on February 5, 2009, Turkish Parliament ratified an agreement to sign the Kyoto Protocol after intense pressure from both the European Union and international environmental organizations. Three voted against as 243 lawmakers voted in favor of the protocol. [19]

Turkey was not a party to the convention adopted in 1992 when the Kyoto Protocol was negotiated, and it is not currently included in the agreement's Annex B, which includes 39 countries that are obliged to reduce their greenhouse emissions to 1990 levels between 2008 and 2012. However, after 2012, Turkey has to enact a series of measures in every sphere from transportation to agriculture and heating to industry to reduce carbon emissions. The government estimates the cost of making the necessary changes by that year at 58 billion Euros. Environment and Forestry Minister stated that 15 billion of the total investment of 58 billion Euros will be made by the private sector. [19]

2.4. The Rationale for CCS and CCT

As it has already been discussed, economic growth is closely tied to energy availability and consumption, particularly lower-cost fossil fuels. The use of these fossil fuels results in release of CO_2 and other GHG, which contribute to the climate change. Balancing the economic value of fossil fuels with the environmental concerns is a difficult challenge. According to IEA fossil fuels will be used extensively and CO_2 emissions will rise over the next half century, if no new policies are put in place. World energy demand is expected to expand by 45% between 2008 and 2030 by an average rate of increase of 1.6% per year, with coal accounting for more than a third of the overall rise. [25]

The analysis in IEA Energy Technology Perspectives 2008 (ETP) projects that energy sector CO_2 emissions will increase by 130% above 2005 levels by 2050 in the absence of new policies or from supply constraints resulting from increased fossil fuel usage. According to IEA addressing this increase will require an energy technology revolution involving a portfolio of solutions: greater energy efficiency, increased renewable energies and nuclear power, and the near-decarbonisation of fossil fuel-based power generation. CCS is the only technology available to mitigate GHG emissions from large-scale fossil fuel usage in fuel transformation, industry and power generation. The ETP BLUE Map scenario, which assessed strategies for reducing GHG emissions by 50% by 2050, concluded that CCS will need to contribute one-fifth of the necessary emissions reductions to achieve stabilization of GHG concentrations in the most cost-effective manner. [25]

According to IEA scenario results if CCS technologies are not available, the overall cost to achieve a 50% reduction in CO_2 emissions by 2050 will increase by 70% [26] Intergovernmental Panel on Climate Change's (IPCC) Third Assessment Report (TAR) in 2001, indicated that no single technology option will provide all of the emission reductions needed to achieve stabilization, but a portfolio of mitigation measures will be needed. In addition IPCC CCS Special Report found that CCS would provide 15% to 55% of the cumulative mitigation effort up to 2100 [27] The Stern Review found that omitting CCS would, on average, increase overall GHG abatement costs. [28] CCS, is therefore an essential part of the portfolio of technologies that is needed to achieve substantial global emissions reductions.

Developing and deploying CCT and CCS technologies on a global scale offers the opportunity to maintain a strong and vibrant global economy fuelled by affordable, convenient and available fossil fuels, while disconnecting the linkage between growth in economic activity and GHG emissions. The technology involved in CCT and CCS is both transitional and transformative in nature, as it allows for the continued movement along the current technological trajectory of developing and providing a means to low-emissions fossil fuels. Meanwhile, CCS is critical to future transformational change to a hydrogen/electricity-based energy economy. CCT and CCS will be a crucial technology in the first commercial operations that produce hydrogen on a large-scale for transportation and distributed generation. [24]

Developing CCT and CCS is strategically important to Turkey for several reasons. First, Turkey is an energy importing country and being an indigenous resource coal can play an important role in the current and future energy mix of Turkey. Developing CCT and CCS technology is a means to extract the economic benefits of these resources while maintaining strong environmental objectives.

In addition CCS is not simply about enabling the use of existing energy reserves; rather it is about increasing resource recovery factors and thereby increasing total Turkey energy reserves through efficiency gains in recovery operations. It is possible that CCS may be used to enhance the recovery of oil, natural gas and coal bed methane resources.

2.4.1. The Potential for CCT and CCS

The development and commercialization of CCT and CCS technology would have positive impacts in certain regions of Turkey. Many domestic industries utilize CO_2-intensive processes in their activities and many regions throughout the country have storage potential in close proximity to the sources.

Being independent from the location CCTs can be applicable to all the existing and new coal, natural gas, fuel oil and biomass fueled power plants in Turkey. However applicability of CCS technologies depends on the matching between CO_2 sources of point and CO_2 storage areas. Currently, a R&D project funded by TUBITAK on creating an emission database and evaluating the potential of CO_2 storage in geological structures in Turkey is ongoing. However in order to show some preliminary results on source-storage matching in Turkey below figures have been created.

Major CO_2 emitters are determined as fossil fuel based power plants, cement and iron-steel factories, petroleum refineries. (Figure 26) Major potential CO_2 storage areas are determined as oil and natural gas fields, lignite and hard coal reserves. (Figure 27 and 28) In addition further analysis is needed for basalt and deep saline aquifers in Turkey.

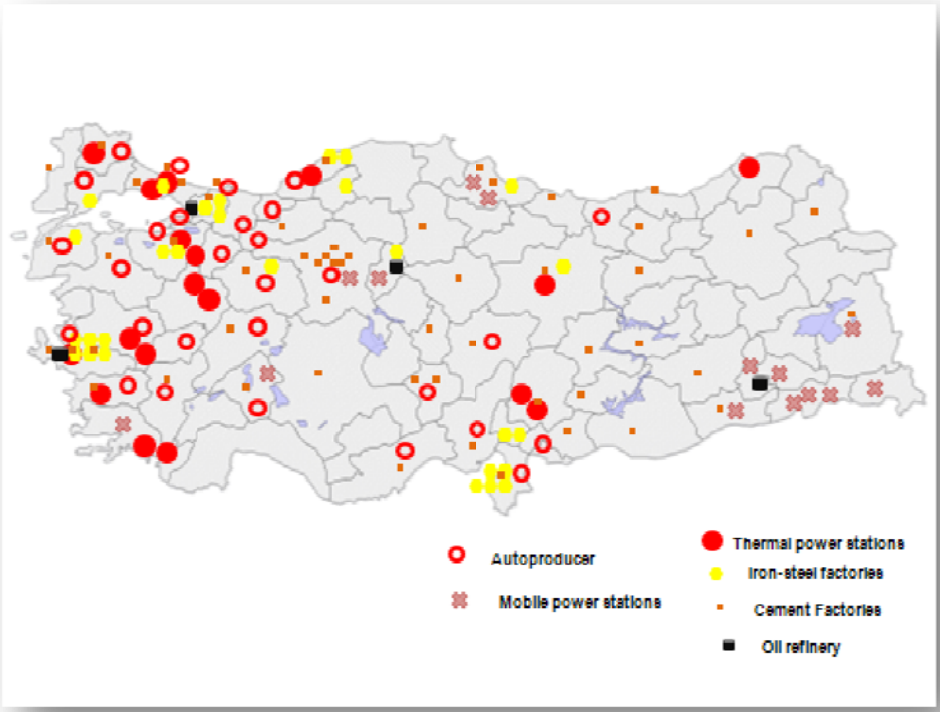

Figure 26: CO_2 Sources

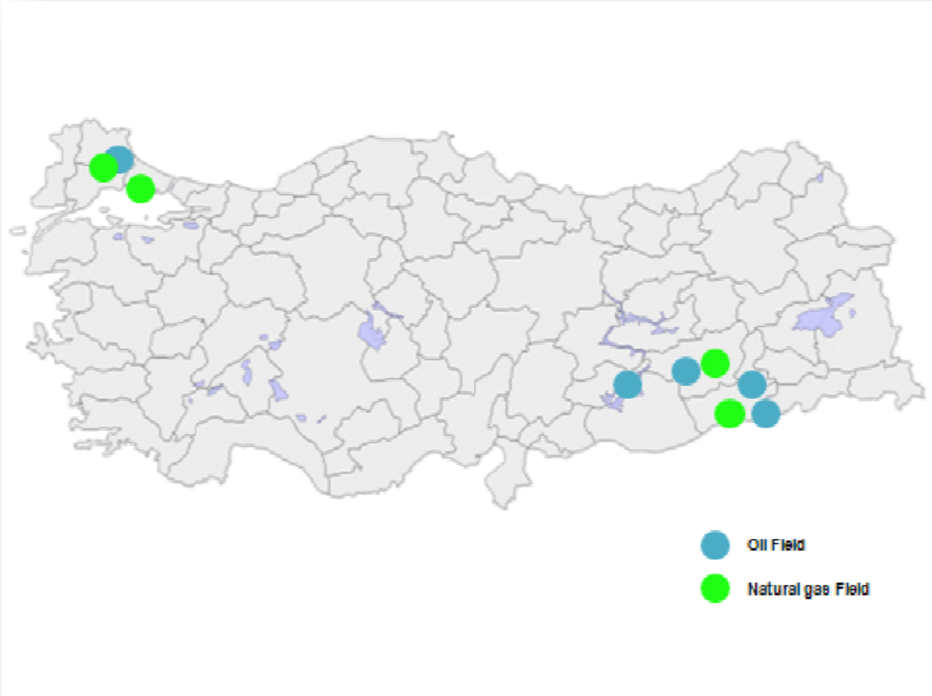

Figure 27: Oíl and Natural Gas Fields

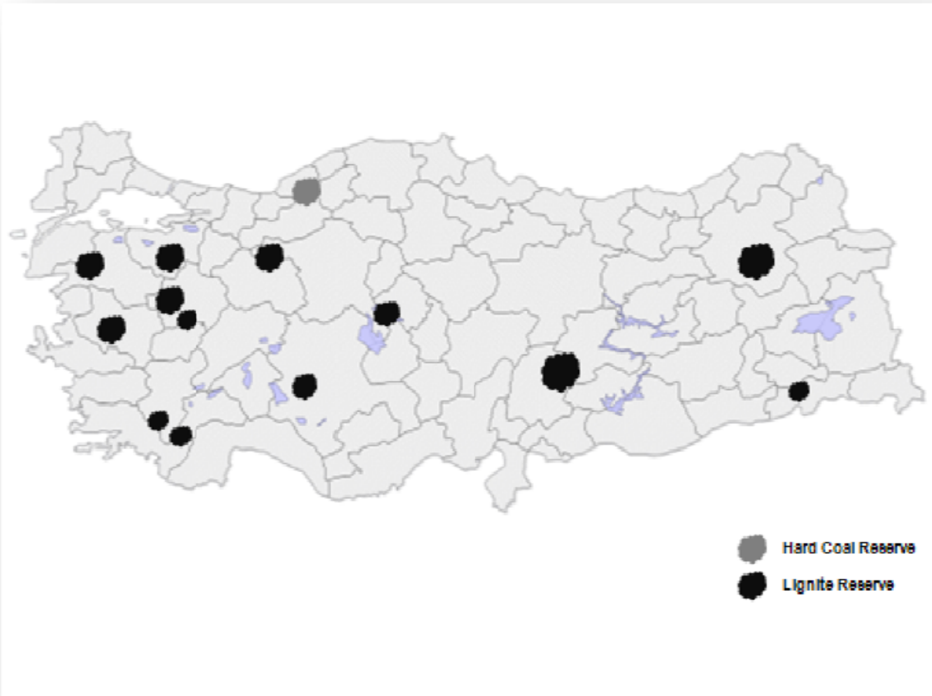

Figure 28: Coal Reserves

By matching local point sources with potential commercially CO_2-EOR, CO_2-ENGR or CO_2-ECBM activities, some opportunities on both the capture and storage sites of the equation, are summarized below (Figure 29):

- Manisa Soma Lignite reserve has a potential to store the CO_2 emissions coming from thermal power stations, iron-steel and cement factories and petroleum refinery in Izmir, Manisa and Aydin
- Kutahya Tavsanli lignite reserve has the potential to store CO_2 emissions coming from coal fired thermal power stations around Kutahya
- Bursa lignite reserve has the potential to store CO_2 emissions coming from coal fired thermal power stations, iron-steel factories in Bursa; iron-steel factories and the petroleum refinery in Kocaeli
- Cayirhan and Kirsehir lignite reserve may be used to store CO_2 emissions coming from coal fired thermal power stations in Ankara and refinery in Kirsehir
- Mugla Yatagan lignite reserve has the potential to store CO_2 emissions coming from coal fired thermal power stations around Mugla
- Zonguldak hard coal reserve has the potential to store CO_2 emissions coming from coal fired thermal power stations, iron-steel and cement factories and in Zonguldak.
- Natural gas and oil fields in Trace region may be used to store CO_2 emissions coming from coal fired thermal power stations around Kirklareli
- Kahramanmaras Elbistan lignite reserve may be used to store CO_2 emissions coming from power stations in Kahramanmaras and iron-steel factories in Osmaniye and Hatay.
- South East Anatolia oil and natural gas fields, especially Batı Raman field in Batman has ongoing EOR activities because of the high density oil production from these fields. Currently CO_2 is produced Dodan field however CO_2 emissions can be captured from petroleum refinery in Batman and coal fired mobile power stations around Batman. Commercial CO_2 injection activities are also ongoing in Bati Kozluca.

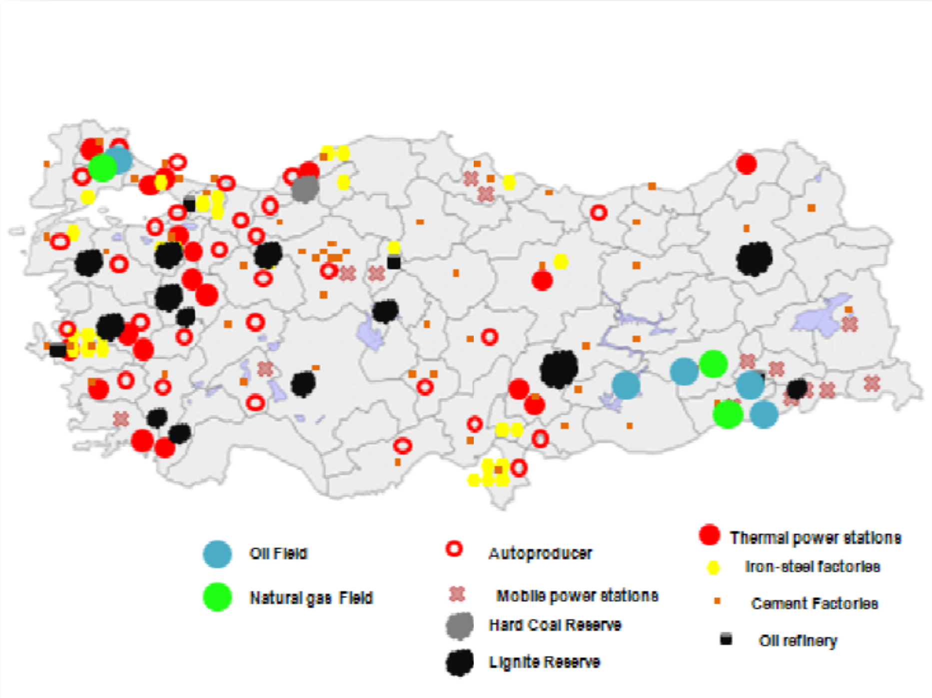

Figure 29: Source and Storage Matching

Turkey has the experience in research and field applications of CO_2 injection for Enhanced Oil Recovery purposes for the running oil wells. In Bati Raman CO_2 injection started in 1986 as the first of its kind outside North America. Turkey had the first CO_2-EOR project outside North America. The Bati-Raman limestone field in the Diyarbakir area was discovered in 1961. It contains low gravity (12-API) heavy oil and would have a recovery rate lower than 2% without a tertiary mechanism. CO_2 was obtained from a high purity reservoir (Dodan) located 90 km from the field and transported via a 1 Mtpa capacity pipeline. (Figure 30) The use of CO_2 as an immiscible flood has allowed an increase of recovery by 300% compared to initial estimates. [26]

In addition to Bati Raman, CO_2/WAG feasibility in Batı Kozluca Field was investigated through a reservoir study and promising results led to investments for the application. CO_2 injection from 6 injection wells started in May 2003. By the end of December 2008, cumulative gas injection reached 5.294 million scf (150 million sm^3). The injection process is still underway. In order to increase the effect of CO_2 injection, additional 11 wells were drilled at the Bati Kozluca Field. [29]

Figure 30: Dodan CO_2 Transportation Facilities [29]

Figure 31: Silivri Natural Gas Storage Facilities [29]

In principle, a CO_2 storage facility requires the same conditions as a natural gas storage facility. The first national natural gas storage project with 1,6 billion m^3 capacity, Silivri natural gas storage plants' provisional acceptance has made, and injection of approximately 10 million m natural gas provided from BOTAS to K.Marmara-Değirmenköy gas fields has initiated. It has been planned to increase a total of 3 billion m^3 storage capacity and studies are carried on accordingly. (Figure 31) [29]

Rehabilitation studies at some power plants are being carried out by EUAS (Electricity Generation Company) and some private organizations. However according to EUAS data the thermal efficiencies in coal-fired plants owned by EUAS are shown in Figure 32.**[30]**

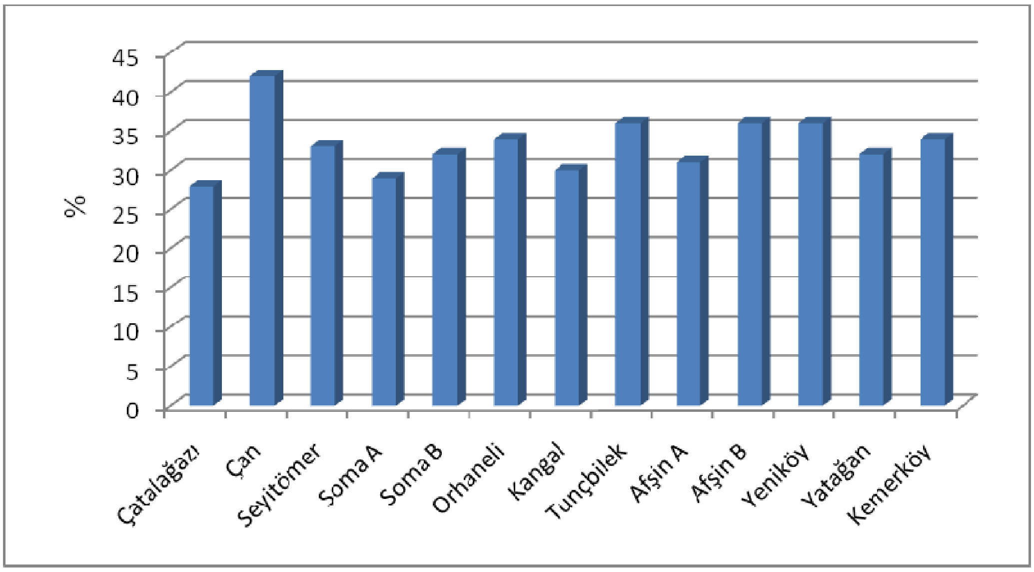

Figure 32: Thermal Efficiencies of Turkish Coal-Fired Power Stations in 2007 [30]

Flue gas desulphurization technologies are available in Çayırhan I-II-III-IV, Kemerköy, Orhaneli, Yatağan Yeniköy, Kangal III and Elbistan B. Electrostatic Precipitator technologies are available in all existing power plants. In terms of CO_2 reduction, atmospheric fluidized bed combustion technology is installed in Çan 18 Mart Power Plan with an efficiency of 42%.

There is only limited information about the activities of private sector fossil fuel power plants. The 2 x 605 MW Iskenderun coal-fired power stations, located in southeast Turkey and built by German company STEAG AG, went into commercial operation in November 2003. The plant meets both Turkish and World Bank environmental standards. Particulate emissions from the plant are 80% lower than Turkish limits, NO_x emissions are 25% lower, and SO_2 emissions are 65% below national standards. Iskenderun has an efficiency level of 41% and the plant is able to cover as much as 8% of Turkey’s current power demand. (Figure 33) [5]

Figure 33: Iskenderun Power Plant [5]

CHAPTER 3

STATEMENT OF THE PROBLEM

The level of primary energy production of Turkey is very limited. Turkey has to import nearly 70% of the energy from abroad in that she has very limited indigenous energy sources. [17] Currently coal is the second largest source of fuel for electricity generation after natural gas. Turkey has significant coal reserves, especially lignite, but also some hard coal. However the lignite reserves are of low quality.

In 2007, energy production was the single most important source of GHGs in Turkey, representing 77.4% of the total. The growth of Turkey's GHG emissions, including and excluding LULUCF, is the highest among Annex I countries. [2] During the period 1990-2008, Turkey has tripled her energy demand with regards to world average and it corresponds to %4.3 of world total demand. Among OECD countries, Turkey has the fastest growing energy demand in past 10 years due to her increasing population and economic development. Since 2000, Turkey has the second largest increase after China in electricity and natural gas demand. Projections performed by Energy and Natural Resources Ministry of Turkey (ENRM) showed that this trend will continue in the medium term.

Signing Kyoto protocol in 2009, Turkey has to enact a series of measures in every sphere from transportation to agriculture and heating to industry to reduce carbon emissions after 2012. The government estimates the cost of making the necessary changes by that year at 58 billion Euros. Environment and Forestry Minister stated that 15 billion of the total investment of 58 billion Euros will be made by the private sector. [19]

According to IEA, addressing the increase in energy demand will require an energy technology revolution involving a portfolio of solutions: greater energy efficiency, increased renewable energies and nuclear power, and near-decarbonisation of fossil fuel-based power generation. [3] Clean coal and CCS technologies are the only technology available to mitigate GHG emissions from large-scale fossil fuel usage in fuel transformation, industry and power generation.

Recently most of the industrialized countries USA, UK, Canada, Australia and Japan created their near-decarbonisation of fossil fuel-based power generation strategies and technology roadmaps. Turkey needs to act now in order not be behind this energy technology revolution. This study will act as a basis for a future draft roadmap for Turkey on CCS and CCT.

CHAPTER 4

ROADMAP

Common to any such technology road mapping effort is the recognition and identification of challenges that currently hinder commercialization. Various technical, economic, and social challenges currently prevent CCT and CCS from being a widely used commercial technology. In the second part of this section the challenges are addressed through applied research, proof-of-concept technology evaluation, pilot-scale testing, demonstration, large-scale deployment, stakeholder involvement, and public outreach actions. These R&D&D actions discussed in the existing roadmaps and/or new actions were carefully selected and suggested as a draft Turkish CCT and CCS Roadmap that needs further development and discussion by the input of interdisciplinary national stakeholders. Also a goal driven roadmap is envisaged.

4.1. Challenges

4.1.1. Cost Effective Capture

For geologic sequestration applications in which the CO_2 is stored underground, there are three main cost components: capture, transport, and storage (which encompass injection and monitoring). The cost of capture is typically several times greater than the cost of both transport and storage. In today’s economic and regulatory environment, carbon capture technologies could increase electricity production costs by 60-100 percent at existing power plants and by 25-50 percent at new advanced coal-fired power plants using integrated gasification combined cycle (IGCC) technology. While industrial CO_2 separation processes are commercially available, they have not been deployed at the scale required for large power plant applications and, consequently, their use could significantly increase electricity production costs. Improvements to existing CO_2 capture processes, therefore, as well as the development of alternative capture technologies, are important in reducing the costs incurred for carbon capture. [31]

4.1.2. Geographical Diversity

Carbon capture and storage efforts will be inherently regional in nature. Geographical differences in the number, type, size, and concentration of stationary GHG sources, coupled with geographical differences in the number, type, and potential capacity of sequestration sites, dictate a regional approach to carbon management. [31] For example, South East Anatolia and Trace regions which are the oil and gas provinces, may focus carbon management practices on capturing CO_2 and injecting it into producing oil and gas fields to enhance recovery. In Aegean Region captured CO_2 may be stored in depleted or unminable coal reserves.

CCS and CCT complement each other, in the regions where CO_2 storage proves impractical; the focus can be on improving output efficiency to reduce CO_2 emissions, in other words CCT.

4.1.3. Permanence

One challenge facing carbon capture and storage is the long-term fate or "permanence" of the stored CO_2. To ensure that carbon sequestration represents an effective pathway for CO_2 management, permanence must be confirmed at a high level of accuracy. The concept of permanence is applicable to both terrestrial and geologic sequestration. For terrestrial sequestration, permanence refers to the fate of CO_2 absorbed by plants and stored in soils. For geologic sequestration, permanence refers to the retention of CO_2 in underground geologic formations. Scientific analysis supports the long-term storage value attributed to carbon sequestration. As stated in the 2005 IPCC special report, Carbon Dioxide Capture and Storage, observations and analysis of current CO_2 storage sites, natural systems, engineering systems, and models indicate that the amount of CO_2 retained in appropriately selected and managed reservoirs is very likely (probability of 90-99 percent) to exceed 99 percent over 100 years and is likely (probability of 66-90 percent) to exceed 99 percent over 1,000 years. Moreover, the potential for leakage is expected to decrease over time as other mechanisms provide additional trapping. [31]

In addition Nagaoka Project for CO_2 Geological Storage in Japan, a series of field surveys and measurements consisting of cross well seismic tomography, well logging, the reservoir formation pressure and temperature measurements, and micro-seismicity monitoring has been conducted. They didn't observe any CO_2 leakage from the reservoir, even a huge earthquake (Magnitude 6.8) hit the Mid-Niigata area on October 23, 2004. Distance between the earthquake epicenter and the CO_2 injection site is about 20 km. [32]

4.1.4. Monitoring, Mitigation and Verification

Closely related to permanence is the issue of monitoring, mitigation, and verification. The ultimate success of carbon capture and storage projects will hinge on the ability to measure the amount of CO_2 stored at a particular site, the ability to confirm that the stored CO_2 is not harming the host ecosystem, and the ability to effectively mitigate any impacts associated with a CO_2 leakage. As with permanence, MM&V is applicable to both terrestrial and geologic sequestration. Terrestrial MM&V must overcome difficulties in assessing carbon storage in large ecosystems (such as forests) and in gauging carbon storage potential in various types of soils. Geologic MM&V must contend with challenges spanning the movement of CO_2 in geologic reservoirs, the effect of various physical and chemical forces on the CO_2 plume, leak detection, and the development of robust mitigation techniques that can respond to a variety of potential leakage events. [31]

4.1.5. Integration and Long Term Performance

A number of the technological elements associated with CCS are proven, but there has been no demonstrated long-term performance at large industrial sites integrating carbon capture, transportation, and final storage. Much of the knowledge base pertaining to carbon capture and storage has been derived from the oil and natural gas industries, where CO_2 has been injected for over 30 years for oil recovery and the incremental storage cost is small. Broader implementation is required, particularly in the power generation industry, but such commercialization is not likely absent emission regulations, incentives, or government funding. Long-term integrated testing and validation is necessary for technical, economic, and regulatory reasons. From a technical perspective, the ability to separate a CO_2 stream from the power plant flue gas stream, compress it for pipeline delivery, and sustain delivery at pressures adequate to ensure dependable injectivity and reservoir permeability must be confirmed. From an economic perspective, the costs associated with CCS must be quantified in greater detail to encourage investment and ensure cost recovery. From a regulatory perspective, long-term operating data must be collected to ensure that CO_2 transportation systems, injection wells, and storage reservoirs are properly regulated to safeguard the environment and public health. [31]

4.1.6. Infrastructure

If CCS is widely deployed to control CO_2 emissions, significant infrastructure investments will be required, particularly for geologic sequestration. Stationary source CO_2 emitters like coal-fired power plants may have to invest in a host of non-core assets, including carbon separation systems, CO_2 pipelines, drilling rigs, injection systems, and monitoring networks. Beyond the capital investment required, emitters may face resource competition for the equipment and personnel needed to install, operate, and maintain these systems. Access to drilling rigs, for example, could become an important key issue.

During the large-scale carbon sequestration test projects planned for the next 10 years, an additional infrastructure challenge involves the supply of sufficient CO_2 to enable long-term deployment and evaluation. While huge quantities of CO_2 are theoretically available from power plant sources, separation and supply of this CO_2 for the carbon storage deployments projects is unlikely because of the expense involved in separating the CO_2 in the absence of CO_2 emission regulations and/or because of the uncertain reliability associated with utility-scale CO_2 separation systems. In most cases, the CO_2 required for the deployment projects will be supplied from natural sources or from industrial processes that produce a relatively pure CO_2 stream as a by-product. Securing sufficient quantities of CO_2 from these sources is a key requirement. [31]

4.1.7. Alternative Energy Sources

A number of other options exist to try to reduce CO_2 emissions from energy systems. These alternatives compete as a fuel source for electricity generation and it is very clear that several of them will have a significant place in Turkey’s energy mix. While the fossil fuel sectors continue to be the most dominant providers of energy on the global scene, a number of alternative energy sources continue to compete, and over time, are making inroads into conventional markets. Therefore, these other sources (which have been briefly discussed) should be considered in the Turkish context to determine what impacts, if any, they might have on fossil fuel sectors, because any such impacts would also affect CCS and CCT.

4.1.7.1. Natural Gas

One option is to reduce emissions through fuel switching to less CO_2-intensive fuels like natural gas. However, using natural gas still results in significant GHG emissions, and therefore capturing these emissions for storage would still be necessary. Also switching to natural gas will decrease the energy security.

Among the fossil fuels, natural gas is the cleanest fuel with very low SO_x, NO_x, PM and toxic emissions, and relatively low GHG emissions. In fact GHGs from a gas-fired facility are half that of an equivalent conventional coal fired plant. Gas-fired plants are relatively easy to build and take less to commission than other large scale facilities (especially nuclear or hydro). Gas fired plants have other advantages over coal; they require less capital to build and involve short constructions lead-times. Delivery of the gas is simple, as it comes by pipeline and is relatively risk free. On-site fuel preparation, storage, and solid waste disposal are not required with natural gas, as the necessary processing has already occurred prior to the gas delivery. Coal processing and preparation occurs on site at the power generation facility, which accounts for part of the emission imbalance between two fuels. For coal, more than 97% of CO_2 emissions occur at the power plant, while for natural gas almost 25% occur upstream. However natural gas is less GHG intensive than coal. A reason for gas' low emissions profile is its fuel to electricity conversion efficiency. For a natural gas the number is 48-52%, compared to 35-43% for coal. [24]

As it can be seen in Figure 20 natural gas has the largest share in fossil fuel powered electricity generation. According to Ministry of Energy and Natural Resources scenario, the natural gas in energy consumption is expected to rise from 16.3% of the fuel mix in 2000 to 27.2 % in 2030.

4.1.7.2. Biomass

Turkey has a considerably high level of renewable energy resources that can be a part of the total energy network of the country. Turkey's renewable sources are the second largest source for energy production after coal. About two-thirds of the renewable energy produced is obtained from biomass. Various agricultural residues such as grain dust, wheat straw and hazelnut shell are available in Turkey as the sources of biomass energy. The annual biomass potential of Turkey is approximately 32 Mtoe. The total recoverable bioenergy potential is estimated to be about 17.2 Mtoe. The importance of agriculture is increasing due to biomass energy being one of the major resources in Turkey. [33]

Turkey's first solid waste power project is in Adana province at an installed capacity of 45 MW. Another waste-to-power plant is in Izmit with an installed capacity of 5.4 MW. Two others, at a total capacity of 30 MW are, are at the feasibility study stage in Mersin and Tarsus provinces. A US firm will establish a 10 MW capacity power plant in Ankara - Mamak, which will use landfill gas generated by garbage. Similar potential exists in large municipalities such as Istanbul, Izmir, Bursa, Adana and Antalya [34]

Biomass on its own is not an economically feasible option in most cases, but it can be co-fed into advanced fossil fuel-fired facilities to generate significant emissions reductions over a regular plant. Energy efficiency improvements and biomass co-feeding can dramatically improve the emissions intensity of either coal or natural gas-fired generating stations. [24] Co-firing is potentially a major option for the utilization of biomass if some of the technical, social and supply problems can be overcome. Co-firing of biomass with fossil fuels, primarily coal or lignite, has received much attention particularly in Denmark, the Netherlands and the United States. For example, in the United States tests have been carried out on over 40 commercial plants and it has been demonstrated that co-firing of biomass with coal has the technical and economic potential to replace at least 8 GW of coal-based generation capacity by 2010 and as much as 26 GW by 2020, which could reduce carbon emissions by 16–24 MtC (Millions tones Carbon). Since large-scale power boilers range from 100 MW to 1.3 GW, the biomass potential in a single boiler ranges from 15 to 150 MW. Biomass can be blended with coal in differing proportions, ranging from 2 to 25% or more. Extensive tests show that biomass energy could provide, on average, about 15% of the total energy input with modifications only to the feed in take systems and the burner. [35]

In addition, the same CCS processes being developed for fossil fuels may also be applied (with incremental changes) to co-fed facilities. By using CCS in conjunction with a biomass energy source, the result is not only the elimination of GHG emissions, but also the extraction of GHGs from the atmosphere and subsequent storage of them underground, thereby contributing net negative emissions. This process would begin by promoting the growth of biomass to increase the sequestration of CO_2, followed by the capture of that CO_2 when the biomass is either combusted, liquefied or gasified, and finally storing the CO_2 in geological formations. [24]

4.1.7.3. Hydrogen and Fuel Cell Technologies

A hope exists today for hydrogen to one day substitute for fossil-based energy. However, it should be noted that hydrogen is an extremely reactive substance not found in its pure form in the natural environment, and it must be derived from other substances such as water, hydrogen sulphide or hydrocarbons. This distinguishes hydrogen from the sources noted earlier in that it is a produced energy carrier much like electricity. Today, hydrogen production in commercial quantities comes from hydrocarbons. Using today's hydrogen production technology results in more CO_2 being generated (on a per-unit-of-heat basis) by producing hydrogen from fossil fuels and then converting it to energy (via a fuel cell or a turbine), than by generating an equivalent amount of energy through directly combusting the fossil fuel. Electrolyzing water using a renewable energy source such as hydro or nuclear, is a possibility for producing emissions-free hydrogen. However, this process is nowhere near cost-effective on a commercial scale, and until it is, the best use for these energy sources is to directly feed the electricity into the grid. [24]

Nevertheless, the notion of a 'hydrogen economy' receives a lot of attention and significant global efforts are underway to enable such a future. This includes the US-led International Partnership for the Hydrogen Economy and the European Hydrogen and Fuel Cell Technology Platform. The International Centre for Hydrogen Energy Technologies (UNIDO-ICHET) which was founded in 2003 in Istanbul under the authority of UNIDO (United Nations Industrial Development Organization) and the Turkish Ministry of Energy and Natural Resources has been working since with a mission to demonstrate viable technologies for the implementation of a hydrogen inclusive economy as well as to facilitate their widespread use, more particularly in developing countries.

All of these initiatives indicate that mass hydrogen will likely be produced from fossil fuels (for quite some time) in whatever hydrogen economy emerges. Therefore, like the fossil fuel based economy of today, a hydrogen economy of the future will likely rely on CCS technology to reduce CO_2 emissions arising from energy production. [24]

4.1.7.4. Geothermal

Turkey is located in the Mediterranean side of Alpine– Himalayan tectonic belt and, therefore, among the first seven countries of the world in terms of abundance of geothermal resources. Turkey has significant potential for geothermal energy production, possessing one-eighth of the world's total geothermal potential. Much of this potential is of relatively low enthalpy that is not suitable for electricity production but still useful for direct heating applications. Out of Turkey's total geothermal potential, around 94% is appropriate for thermal use (temperature less than 150 °C) and the remainder for electricity production (temperature more than 150 °C). The geothermal electricity generation capacity potential of Turkey is estimated at 2000 MW (16 TWh/year) and a generation capacity of 550 MW that utilizes geothermal sources is expected by the year 2013. The main utilization of geothermal energy in Turkey, however, is in domestic heating, greenhouses, spas and thermal resorts. The overall geothermal heat generation potential of Turkey is about 31,500 MW. It is projected that, by the years 2010 and 2020, the total installed capacity will increase to 3500 MW (500,000 residence equivalent, which is about 30% of the total residences in the country) and 8300 MW (1,250,000 residence equivalent) for space heating, respectively. [36]

Denizli Kızıldere field that was discovered by MTA geothermal electricity plan produces 20.4 MWe. Because of the waste CO_2 from the Kizildere field a factory utilizes 40000 tone/year CO_2 by producing liquid and dry ice CO_2. In addition to this, in Agri Diyadin there exists a potential of producing CO_2 together with geothermal liquid. [37] Therefore a strategy and new technologies is needed in order to assess and utilize CO_2 content of geothermal reserves in Turkey.

Recently breakthrough concepts like electricity generation through CO_2 Thermosiphon is gaining weight. Geothermal Power Generation Engineered/Enhanced Geothermal systems represent a significant unutilized energy source, with the potential to assist in meeting growing energy demands with clean, renewable energy. Traditional geothermal systems use water as the working fluid. An alternative working fluid is carbon dioxide which offers potential benefits including favorable thermodynamic and transport properties and the potential for sequestration. An important feature is that CO_2 does not dissolve mineral salts, and this will serve to reduce fouling and corrosion problems which afflict piping and surface equipment in conventional water cycles. The modeling shows that a CO_2-based power plant has net electricity production comparable to the traditional approach, but with a much simpler design, and demonstrates the comparative efficacy of CO_2 as a heat extraction and working fluid. While the economic viability of a CO_2-based system remains to be proven, this analysis provides a starting point for more detailed thermodynamic and economic models of engineered geothermal systems power conversion utilizing CO_2. [38]

4.1.8. Effective Policy

A non-technical challenge facing today’s energy industries is the lack of a clear and concise policy on the role of CCT and CCS, and the subsequent incentives and regulations that would result from such a policy agenda. Most of the work to date around the world has focused on technical issues, but social, political and administrative issues are very complex, and, unless properly addressed, could delay commercial deployment of the technology. There are some policy gaps exist today as this is a new technology area, and some of the uncertainties are still being worked through. However, policymakers must begin to tackle the issues facing CCT and CCS today and start to develop a framework under which a robust and vibrant industry can develop.

Work is being done to address many of the policy gaps and the recent IPCC Special Report on Carbon Dioxide Capture and Storage communicates an enormous amount of important technical information to help policymakers make their decisions. Another useful document for policymakers is the IEA's Prospects for CO_2 Capture and Storage. One of the aims of this roadmap is also to provide relevant information to the policymakers both in R&D and energy sector. With the correct technical information in mind, appropriate actions and strategies can be taken to develop policy and regulatory frameworks, capacity building and public awareness in Turkey.

4.1.9. Public Awareness and Acceptance

Public awareness and eventually acceptance of CCS and CCT is needed for such projects to be implemented widely. However, the notion of capturing and storing CO2 in geological structures is relatively new, and the general public is quite unaware of the topic in many countries. While surveys in Japan suggest that 31% of respondents know what CCS is, the US number is only 4%. Further, some responses indicate that CCS risks are being seen as an 'end-of-pipe' solution, a technology that simply treats the symptoms and not the root cause of climate change. Others may view CCS as a delay tactic that enables the continued use of fossil fuels instead of other renewable energy sources. Most surveys conducted to date suggest that even where there is support for CCS; it is described as 'reluctant' rather than 'enthusiastic' [27] Non governmental organizations like Greenpeace protest CCS and CCT and currently published a document called "False Hope: why carbon capture and storage won't save the climate"

Public support is critical to the success of research and commercialization efforts; more importantly, public disapproval is very difficult to overcome. It is imperative, therefore, that the relevant government and private entities engage the public to explain the technology and address environmental, health, and safety concerns as they arise. Public outreach activities conducted may include: development and utilization of a suite of educational and outreach tools to communicate with national and local audiences, policymakers, and stakeholders on the subject of carbon sequestration including a carbon sequestration video for general and non-technical audiences; focus groups to gauge public knowledge and perceptions of carbon sequestration; town hall-style meetings to inform and educate about sequestration; risk communication workshops; and carbon sequestration posters, presentations, and other outreach materials for public dissemination. A special case of awareness building is needed for financiers and insurers, because companies that develop and deploy CCS and CCT will depend on these stakeholders for investment and for risk management.

4.1.10. Funding and Support

The cost of developing and deploying new CCS and CCT technologies and approaches is high. Therefore, the industry needs to be focused and strategic in its activities and investments. An approach to investing in capacity building, both human and infrastructure, is an important step that needs to be guided by policy. Countries will benefit most by supporting an approach of cost-sharing, pooling of expertise, collaborating and disseminating knowledge to build global capacities. These technologies need to be piloted, field tested, adapted and commercially demonstrated, and far too many promising technologies exist for any one nation to undertake the necessary steps in solitude. In addition, large-scale projects are expensive. For example, the IEA Weyburn CO_2 Monitoring and Storage Project – a Canadian CO_2-EOR project in Saskatchewan – has cost (CDN) $28 million to date, but this is on top of an initial commercial project investment of (CDN) $1.5 billion. The Norwegian Saline Aquifer CO_2 Storage Project (or the Sleipner Project) cost a similar amount. It will take at least five or six more of these demonstration projects, followed by testing the most promising concepts in different locations, to ultimately determine best approaches. Because of the size of these investments and the long lead times in project development and proofing, international collaboration is important, and strategic policy aimed at building this global capacity is critical. [24]

The IEA CIAG (Coal Industry Advisory Group) supports the view that to introduce "near-zero" emission technologies will require massive R&D expenditure – primarily by governments in developed countries. A review of IEA data shows that while public budgets for R&D have increased in past decades, expenditure on energy R&D has declined, and the public sector decline has not been compensated for by an increase in private sector expenditure. Figure 34, derived from IEA data, suggests that energy R&D expenditures correlate with oil prices. The end of high oil prices in the second half of the 1980s and throughout the 1990s led to a significant decline in R&D expenditure on energy technologies. The period from 1980 to 2003 has seen funding decline in major R&D programme areas, including renewables, fossil fuels and nuclear (Table 2). Only energy conservation R&D funding has seen an increase.

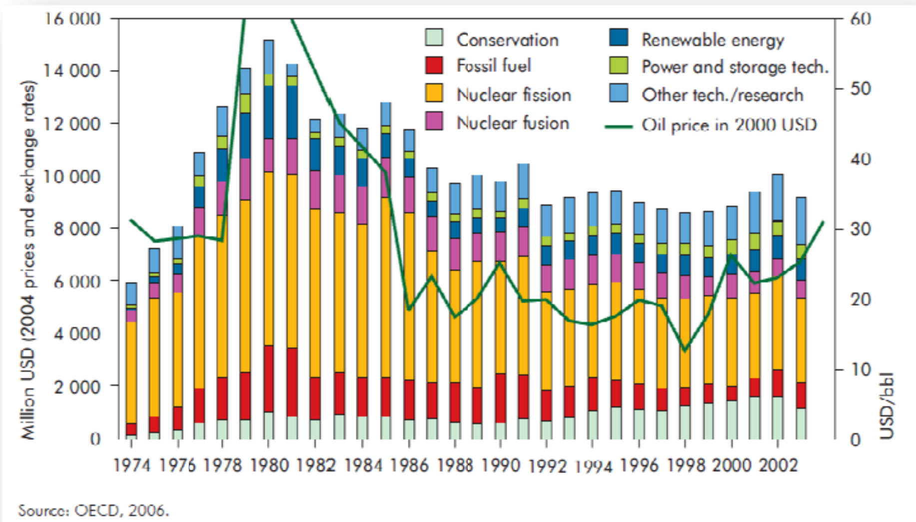

Figure 34: R&D expenditure in IEA countries (left axis) and oil price (right axis) 1974-2003 [6]

Table 2: Aggregate percentage change in major public sector energy R&D programme areas of eleven IEA member countries [6]

	1980-1990		1990-2003	
	All	w/o US, Japan	All	w/o US, Japan
Conservation	-20%	-42%	+78%	-36%
Fossil	-78%	-77%	-68%	-64%
Renewable	-75%	-56%	-5%	-14%
Nuclear	-91%	-83%	-88%	-63%
Aggregate	**-65%**	**-80%**	**-53%**	**-65%**

Source: Runci, 2005.

Total funding for fossil fuel R&D programmes declined to approximately USD 1 billion in 2004. CO_2 capture and storage technologies accounted for only 1.1% of the share of IEA member countries' total public R&D expenditure in 2004, with other aspects of fossil fuels, including generation efficiency, accounting for a further 10%. Furthermore, since there is a significant disincentive for private sector investment in basic R&D, because of the speed of leakage of new technological developments to competitors, many businesses are reluctant to invest in leading-edge energy technology R&D. A survey of energy R&D expenditure by industry in OECD countries reveals that this has been in steady decline since 1990. [6]

Governments will need to play a much greater role in funding R&D initiatives. In regard to CCS technologies, the role is not only to fill in knowledge gaps, but also to provide financing for early demonstration projects. Governments also play a crucial role in knowledge transfer, through conferences and encouraging government business collaboration. The CIAB finds it encouraging that governments are playing a role in funding and promoting public-private partnerships at the national and international level, in spite of the long-term decline of financial support for energy R&D. Though the effort is underfunded, the journey down the path towards reducing GHG emissions from coal use is underway. The European Union, individual EU member countries, the USA, Australia, Canada and Japan currently support research efforts for CO_2 capture, transport, storage, monitoring and verification. Governments have been joined in this effort by numerous large and small businesses from the coal supply and utilization chain which have provided funding and technical support. However, a significantly greater level of funding is needed to stimulate the many demonstration projects needed in the next decade. A 2007 study by the Australian Business and Climate Group strongly endorses emissions trading, but stresses the need for public-private partnerships and large-scale public support for R&D to accelerate deployment of CCS. Another study of CCS potential by the Massachusetts Institute of Technology recommended US government spending of USD 460 million per year for the next five years to cover necessary CCS analysis, research and development needs. [6]

Funding for near-term demonstration is required in order to continue to prove CCS at the commercial scale and to reduce costs. At current price levels, CO_2 markets and taxes will at most only provide up to half of the finances needed to cover the additional costs associated with CCS in OECD countries. Moreover, carbon markets do not provide a sufficiently stable mechanism to overcome the hurdles associated with large CCS investments. Governments will be required to address this gap, as without predictable market or regulatory drivers, it is unlikely the private sector will invest in CCS. Present CCS financing pledges from OECD governments are only about one quarter to one-third of the additional investment needs envisaged for those regions over the next decade. Given the magnitude of investment needed and the global growth path for CCS, the private sector should be willing to take on additional risk for CCS. Governments can help facilitate private sector investments via public-private partnerships in CCS demonstration. [8]

4.2. R&D&D Actions and Goals

4.2.1. Upstream Coal Cleaning

- Develop coal quality specifications that minimize maintenance costs and reduces environmental impact of existing power plants
- Develop appropriate coal beneficiation process (both conventional and non-conventional) to produce clean coal of a quality that is desirable to customers
- Develop technologies to transport high-density clean coal slurries(e.g. through pipelines)
- Explore and develop new mining methods to maximize resource extraction
- Explore low-cost techniques for making briquettes and pellets, and low-cost binders, especially for fine coal
- Develop solvent extraction and de-ashing technology to improve coal quality
- Optimize feed preparation for slurry feed systems

Goals

- Short Term: Installing upstream coal cleaning to all existing power plants

4.2.2. Combustion

- Develop improved coal feeding systems
- Indentify and optimize system integration to address site-specific CHP opportunities
- Integrate and optimize use of beneficiated coal and captured CO_2 in overall cycle
- Develop low-cost integrated emissions control technologies (including CO_2) and waste management control technologies
- Develop low-cost scrubbing solvents with better stability, improved corrosion and degradation resistance
- Develop improved contactors and mass transfer systems for CO_2 scrubbing solvents
- Develop low-temperature, low-pressure cryogenic/hybrid technologies for CO_2 separation
- Develop membrane of membrane/solvent technologies for CO_2 capture
- Develop "hybrid" power systems that would integrate a coal gasifier with an advanced coal combustor to achieve thermal efficiencies above 50% at a capital cost of $1000 per kilowatt or less

Goal:

- Short Term: Demonstrate advanced coal combustion
- Medium Term: At least two large scale industrial application of advanced coal combustion
- Medium Term: Demonstrate one hybrid power systems that would integrate a coal gasifier with an advanced coal combustor to achieve thermal efficiencies above 50% at a capital cost of $1000 per kilowatt or less
- Long Term: At least one hybrid power plant large scale application

4.2.3. Gasification

- Develop advanced feed preparation and feeding system

- Improve coal and slag characterization
- Provide modular gasification/ carbonator / calciner / hydrogen / separation tests
- Build pilot scale facilities so that advanced concepts for 2nd and 3rd generation gasifiers can be evaluated economically
- Develop plat optimization and integration tools involving the impact of coal beneficiation, impact of fuel cell development, and CO_2 capture systems
- Develop solid sorbent enhanced reaction systems for CO_2 separation and steam reforming or water gas shift
- Identify and evaluate polygeneration opportunities
- Keep technology watch and provide basic research to technology vendors on cryogenic / hybrid systems for CO_2 separation from hydrogen
- Maintain technology watch on less energy intensive, such as OTM (Oxygen Transport Membranes; integrate outcomes with advanced gasifier cycles
- Develop integrated hot gas clean-up systems for H_2S, COS, HCN, NH_3, CO_2, fine PM, and alkali removal

Goals:

- Short Term: Demonstrate at least one IGCC plant with H_2 production and equipped by CCS
- Long Term: At least two novel large scale industrial applications for IGCC

4.2.4. CO_2 Capture

4.2.4.1. Pre-Combustion

- Create test facilities for assessing advanced gasification, reformation, carbonation and hydrogen separation processes that will enable the conversion of Turkey's low rank coals
- Undertake research into full process integration and optimization of the components for power station applications
- Develop better systems for coal and residual liquid petroleum fuels gasification (e.g., higher efficiency shift processes), natural gas reformer, and syngas cooler
- Demonstrate IGCC for widespread use in base load power generation with all types of fuels, especially equipped with CO_2 separation (including biomass)
- Improve the overall efficiency and reliability of the IGCC process
- Reduce the amount of steam required for the shift conversion

- Achieve process control with the parallel processes in IGCC plants with CO_2 capture
- Reduce steam requirements in the shift converter on IGCC using gas separation membranes
- Develop novel methods for pre-combustion CO_2 capture, including pressure swing adsorption, electrical swing adsorption, gas separation membranes and cryogenics and chemical looping
- Develop high-efficiency and low-NO_x H_2 gas turbines (the combustion temperature of H_2 requires careful management to avoid damage to turbine blades, which can be achieved by recycling separated CO_2).

Goals:

- Short Term: Demonstrate at least one IGCC plant with H_2 production and equipped by CCS
- Long Term: At least two novel large scale industrial applications for IGCC

4.2.4.2. Post-Combustion

- Develop better solvents for CO_2 capture (Low-cost solvents with improved stability, and which are corrosion and degradation resistant
- Reduce the upstream concentration of NO_x , SO_2 and Oxygen in the flue gas, which all react with solvents to form stable salts, leading to rapid solvent degradation and higher costs
- Improved solid sorbent technologies
- Identify optimal capture process designs and ways of integrating the capture systems with power stations to reduce energy loss and environmental impact
- Improve boiler efficiency to reduce the gross energy penalty to, with an associated reduction in capital and operating costs (currently the capture system requires a large amount of heat for amine solvent regeneration, as well as auxiliary power requirements for flue gas pre-treatments, blowers, pumps and compressors, which reduces the overall operating efficiencies of the plant in the range of 8% to 10% points compared to standard plants)
- Optimize integration, particularly for retrofit applications, to achieve plant availabilities and capture rates

- Develop an application at the scale required for flue gas streams for coal – and gas fired plants, and reduce the capital costs (currently >USD 50 million for a 5 MMscm/d train or c.0.5 Mt CO_2/yr in the case of coal-fired plant)

Goals:

- Short Term: Demonstrate at least one post combustion plant equipped by CO_2 storage
- Long Term: At least two novel large scale industrial applications for post combustion plant

4.2.4.3. Oxyfuel

- Reduce the energy required for large-scale air separation (near-term) and further investigate how to optimize O_2 purity and post-combustion treatment (compression, and conditioning processes) needs to reduce the high energy requirements for pure oxygen production
- Develop advanced materials that can withstand the high temperatures associated with oxyfuel capture to help minimize air leakage into the firing chamber that can lead to nitrogen contamination of the exit gases
- Explore whether the flame temperature in oxy-fired cement kilns is suitable for clinker production (due to the cement sector's anticipated need for CCS)
- Research into the economics and technical issues for the adaptation of cryogenic air separation units (ASU) in oxy-fuel power stations
- Develop integrated systems for O_2/ CO_2 recycle, pure O_2, and hydroxyl-fuel combustion in direct, combined or hybrid cycles
- Improve understanding of the combustion, heat transfer, and pollution forming behavior of conventional and beneficiated coal for O_2/ CO_2 recycle, pure O_2, and hydroxyl-fuel combustion
- Improve understanding of optimization of recycle flows in combustors, process heaters and boilers
- Develop oxygen chemical looping combustion systems
- Design and develop high temperature tolerant combustors, process heaters, boilers, compressors, and turbo-machinery for O_2/ CO_2 recycle, pure O_2, and hydroxyl-fuel combustion
- Develop improved cycles and methods for CO_2 compression cooling, and separation in the presence of trace gaseous impurities

- Develop novel integrated multi-pollutant control technology for NO_x, SO_x, Hg, and fine PM, with heat recovery from oxy-fuel combustion flue gas streams
- Maintain technology watch on less energy intensive, such as OTM (Oxygen Transport Membranes; integrate outcomes with advanced oxyfuel cycles and support technology vendors with basic research
- Improve low-temperature cryogenic/distillation process for CO_2 purification

Goals:

- Short Term: Demonstrate at least one oxyfuel combustion system with CO_2 storage
- Long Term: At least two large scale industrial applications for oxyfuel combustion

4.2.5. CO_2 Storage

4.2.5.1. Geological Storage

Capacity Assessment

- Establishing standards for assessment of storage capacity and storage site selection based on safety, reliability, environmentally impact, cost effectiveness
- Analyzing and assessing CO_2 Storage Capacity in Turkey (deep saline aquifers, EOR, EGR and depleted reservoirs, soda caverns, basalt formations)
- Analyzing and assessing the potential CO_2 source sites in Turkey (including geothermal fileds)
- Create a comprehensive national CO_2 storage atlas (e.g., GIS-based) of suitable geological formations with information on emission sources and other relevant details

Reservoir characterization and Injection of CO_2

- Improve understanding of CO_2 flow and trapping mechanisms leading to an ability to harness them to improve storage permanence (simulation models and monitoring systems, best practice manuals)
- Improve predictive modeling capability for CO_2 injection in porous rock

- Develop technologies for assessing, modeling and predicting geomechanical effects during CO_2 injection; areas for research are pore pressure prediction, stress regime analysis and modeling, rock strength measurement and prediction, and especially fault reactivation modeling
- Develop technologies for assessing, modeling and predicting other near well bore formation damage during injection
- Develop technologies for assessing, modeling and predicting of near well bore chemical changes, especially conditions for hydrate formation
- Develop and adapt existing technologies for assessing and avoiding possible interaction of CO_2 storage projects with other resources such as coal, oil/gas, aquifers, surface amenities, soils, deep ecosystems etc. In particular interaction of CO_2 with subsurface organisms.

Mineralization

- Develop a technology for enhancing the rate of CO_2 mineralization in-situ
- Build on pioneer studies to further investigate the possibilities of enhancing mineral trapping of CO_2 and impurities in specific types of settings (basaltic and ultramafic aquifers, highly saline aquifers, geothermal reservoirs, etc.) and map these
- Study thermodynamics and kinetics of chemical and microbiological reactions, as well as impacts on fluid flow, injectivity, and geomechanics
- Carry out a techno-economical feasibility study relating to mineral storage of CO_2

Goals:

- Short Term: Initiate at least one large-scale demonstration of CO_2 storage in a geological formation
- Medium Term: Begin at least one demonstration in which CO_2 is sequestered in a saline formation and brine water from the saline formation is recovered for beneficial use
- Long Term: Initiate a field demonstration of at least one technology for enhancing the rate of CO_2 mineralization in-situ.

4.2.5.2. Terrestrial Storage

Terrestrial carbon sequestration is defined as the net removal of CO_2 from the atmosphere by the soil and plants and/or the prevention of CO_2 net emissions from terrestrial ecosystems into the atmosphere. The focus may be on increasing carbon uptake on mined lands, evaluate no-till agriculture, reforestation, rangeland improvement, wetlands recovery, and riparian restoration. Another important area of research in terrestrial sequestration is the development of technologies for quantifying carbon stored in a given ecosystem. If Turkey and all other countries one day adopt a carbon emissions trading program, measuring techniques with high precision and reliability will be necessary. Afforestation is a one of the high priorities of Turkey, recently it was announced that Turkey will afforest 2.2 million hectare field until 2020 which is the largest afforestation campaign in the world.

- Tree planting on inclined mined lands
- Rangeland improvement
- Wetland recovery
- Soil reclamation using coal combustion by-products (CCBs) of other solid residuals
- No-till farming, afforestation and other activities applied to a wide range of geographies to increase carbon uptake
- Enhance carbon transfer from plant to soil
- Develop technologies for quantifying carbon storage

Goal:

- Long term: Develop terrestrial sequestration technologies to the point of commercialization

4.2.6. CO_2 Transport

Practical experience shows that CO_2 transportation by pipeline is an established and commercial technology in most applications, and only incremental improvements are expected in most areas. In Turkey, CO_2 has been transported from Dodan natural CO_2 field to Bati Raman EOR project. (90 km)

- Conduct analysis of source/sink distribution to identify clusters regionally in Turkey

- Incentivize the linking of source and/or sinks through CO_2 transport hubs
- Perform a national analysis of the optimal layout of a pipeline network connecting major sources with storage sites
- Improve understanding and knowledge sharing of CO_2 transport leakage scenarios and the effects of impurities on CO_2 pipeline transport
- Create a database management system of CO_2 emissions streams in Turkey which includes CO_2 purity levels and other important information and end uses for each CO_2 source
- Comprehensive database of possible CO_2 emissions streams in Turkey, which includes CO_2 purity levels and other important information (e.g. trace gasses) And create a database end uses for each CO_2 source

Goal:

- Long Term: National CO_2 pipeline network

4.2.7. Monitoring, Mitigation and Verification

Monitoring, mitigation, and verification capabilities will be critical in ensuring the long-term viability of CCS systems – satisfying both technical and regulatory requirements. Monitoring and verification encompass the ability to measure the amount of CO_2 stored at a specific storage site, to monitor the site for leaks, to track the location of the underground CO_2 plume, and to verify that the CO_2 is stored in a way that is permanent and not harmful to the host ecosystem. Mitigation is the near-term ability to respond to risks such as CO_2 leakage or ecological damage in the unlikely event that it should occur. In general, MM&V research is aimed at providing an accurate accounting of stored CO_2 and a high level of confidence that the CO_2 will remain sequestered permanently. A successful effort will enable sequestration project developers to obtain permits for sequestration projects while ensuring human health and safety and preventing potential damage to the host ecosystem. MM&V also seeks to set the stage for emissions reduction credits, if a domestic program is established, that approach 100 percent of injected CO_2, contributing to the economic viability of sequestration projects. Finally, MM&V will provide improved information and feedback to sequestration practitioners, thus accelerating technology progress. [10]

Turkey has years of experience on modeling CO_2 injection to petroleum reservoirs.

- Develop robust, flexible accounting protocols
- Cost effective long term monitoring for CO_2 leaking
- Design monitoring network
- Modeling CO_2 storage reservoir
- Develop CO_2 leak detection technologies
- Underground plume tracking CO_2
- Develop plant matter measurement technologies for terrestrial CO_2 storage
- Develop soil carbon measurement technologies for terrestrial CO_2 storage

Goal:

- Short Term: Develop MM&V protocols
- Long Term: Develop a national monitoring network

4.2.8. Non-CO2 Greenhouse gas control

According to UNFCCC, non CO_2 greenhouse gas emissions contributed to 18% of the total GHG emissions in 2007. Landfill gas (mostly methane) significantly contributed to 47% of the Non- CO_2 emissions in Turkey. Methane emissions of fugitive gasses from coal mining represent only 3.5% of Turkish anthropogenic methane emissions. Since non- CO_2 GHG have significant economic value, emissions can be captured or avoided at low net cost. Turkey has landfill gas power generation experience in Ankara - Mamak, Istanbul, Izmir, Bursa, Adana and Antalya [34] In recent years, a private firm, Hattat Holding Energy Group (also known as HEMA Endustri) has obtained the license to produce coal bed methane gas near Amasra. It is estimated that gas potential of the field is 620 billion m^3.

- Explore methods to enhance the biological utilization of methane in landfill covers
- Study management practices at bioreactor landfills to control the conditions within the landfill to promote or suppress methane production
- Enhance methane capture in landfill and use for energy generation
- Control water and microbe management in landfill applications
- Cost effectively converting methane in coal mine ventilation air to CO_2 or upgrade the gas to pipeline quality specifications

Goals:

- Short Term: Transfer CBM to natural gas pipeline
- Long Term: Develop methane capture in landfill power generation facilities in all cities

4.2.9. Breakthrough Concepts

The objective of this section is to foster the innovative potential of academy and industry. The actions discussed below are the collections of ideas which are considered as breakthrough concepts all around the world.

- Hydrogen selective silica membrane
- Dual function membrane
- Molecular gate membrane
- Ionic liquids
- Microporous metal organic framework (MOFs)
- Carbonate sediment below the sea floor
- Mineral dissolution kinetics
- Mineral carbonation
- Microbial CO_2 conversion
- A hot dry rock geothermal energy concept utilizing captured supercritical CO_2 instead of water

CHAPTER 4

CONCLUSIONS AND FUTURE RECOMMENDATIONS

This work presents a draft national CCT and CCS technology roadmap to policy makers. Various technical and non-technical (economic and social) challenges that currently prevent CCT and CCS from being a widely used commercial technology are discussed and goals for each research pathway are defined. All this work needs further development and discussion by the input of interdisciplinary national stakeholders in order to improve this study.

Based on the results obtained the following technical and non-technical conclusion can be made:

- The cost of developing and deploying new CCS and CCT technologies and approaches is high. Therefore, the industry needs to be focused and strategic in its activities and investments. An approach to investing in capacity building, both human and infrastructure, is an important step that needs to be guided by policy.

- Turkish government will need to play a much greater role in funding R&D initiatives. In regard to CCS technologies, the role is not only to fill in knowledge gaps, but also to provide financing for early demonstration projects. Governments also play a crucial role in knowledge transfer, through conferences and encouraging government business collaboration.

- Turkish government can encourage industry by playing an important role in funding and promoting public-private partnerships in CCT and CCS demonstration at the national and international level, in spite of the long-term decline of financial support for energy R&D.

- Given the magnitude of investment needed and the global growth path for CCT and CCS, the private sector should be willing to take on additional risk for deployment of these technologies.

- Public support is critical to the success of research and commercialization efforts; more importantly, public disapproval is very difficult to overcome. It is imperative, therefore, that the relevant government and private entities engage the public to explain the technology and address environmental, health, and safety concerns as they arise. Public outreach activities need to be conducted. A special case of awareness building is needed for financiers and insurers, because companies that develop and deploy CCS and CCT will depend on these stakeholders for investment and for risk management.

- Another non-technical challenge facing today's energy industries is the lack of a clear and concise policy on the role of CCT and CCS, and the subsequent incentives and regulations that would result from such a policy agenda. There are some policy gaps exist today as this is a new technology area, and some of the uncertainties are still being worked through. However, policymakers must begin to tackle the issues facing CCT and CCS today and start to develop a framework under which a robust and vibrant industry can develop.

- The cost of CO_2 capture is typically several times greater than the cost of both transport and storage. In today's economic and regulatory environment, carbon capture technologies could increase electricity production costs by 60-100 percent at existing power plants and by 25-50 percent at new advanced coal-fired power plants using IGCC technology. Improvements to existing CO_2 capture processes, therefore, as well as the development of alternative capture technologies, are important in reducing the costs incurred for carbon capture. [31]

- Carbon capture and storage efforts will be inherently regional in nature. Geographical differences in the number, type, size, and concentration of stationary GHG sources, coupled with geographical differences in the number, type, and potential capacity of sequestration sites, dictate a regional approach to carbon management. For example, South East Anatolia and Trace regions which are the oil and gas provinces, may focus carbon management practices on capturing CO_2 and injecting it into producing oil and gas fields to enhance recovery. In Aegean Region captured CO_2 may be stored in depleted or unminable coal reserves. CCS and CCT complement each other, in the regions where CO_2 storage proves impractical; the focus can be on improving output efficiency to reduce CO_2 emissions, in other words CCT.

- One technical challenge facing carbon capture and storage is the long-term fate or "permanence" of the stored CO_2. Closely related to permanence is the issue of monitoring, mitigation, and verification. The ultimate success of carbon capture and storage projects will hinge on the ability to measure the amount of CO_2 stored at a particular site, the ability to confirm that the stored CO_2 is not harming the host ecosystem, and the ability to effectively mitigate any impacts associated with a CO_2 leakage. MM&V is applicable to both terrestrial and geologic sequestration. Terrestrial MM&V must overcome difficulties in assessing carbon storage in large ecosystems (such as forests) and in gauging carbon storage potential in various types of soils. Geologic MM&V must contend with challenges spanning the movement of CO_2 in geologic reservoirs, the effect of various physical and chemical forces on the CO_2 plume, leak detection, and the development of robust mitigation techniques that can respond to a variety of potential leakage events. [31]

- If CCT and CCS technologies are widely deployed to control CO_2 emissions, significant infrastructure investments will be required, particularly for CO_2 geologic sequestration and transport. Stationary source CO_2 emitters like coal-fired power plants may have to invest in a host of non-core assets, including carbon separation systems, CO_2 pipelines, drilling rigs, injection systems, and monitoring networks. Beyond the capital investment required, emitters may face resource competition for the equipment and personnel needed to install, operate, and maintain these systems. Access to drilling rigs, for example, could become a key issue.

- During the large-scale carbon sequestration demonstration projects an additional infrastructure challenge involves the supply of sufficient CO_2 to enable long-term deployment and evaluation. While huge quantities of CO_2 are theoretically available from power plant sources, separation and supply of this CO_2 for the carbon storage deployments projects is unlikely because of the expense involved in separating the CO_2 in the absence of CO_2 emission regulations and/or because of the uncertain reliability associated with utility-scale CO_2 separation systems. In most cases, the CO_2 required for the deployment projects will be supplied from natural sources or from industrial processes that produce a relatively pure CO_2 stream as a by-product. Securing sufficient quantities of CO_2 from these sources is a key requirement. [31]

- A number of other options exist to try to reduce CO_2 emissions from energy systems. These alternatives compete as a fuel source for electricity generation and it is very clear that several of them will have a significant place in Turkey's energy mix. While the fossil fuel sectors continue to be the most dominant providers of energy on the global scene, a number of alternative energy sources continue to compete, and over time, are making inroads into conventional markets. Therefore, policy makers need to consider these other sources Turkish context to determine what impacts, if any, they might have on fossil fuel sectors, because any such impacts would also affect CCS and CCT.

- Maintaining technology watch is very important in fast developing technology area. Establishment of a National CCT and CCS Technology Platform with the participation of all relevant sector and policy makers is suggested. Previously initiatives started by TKI under the support programme of TUBITAK ISBAP (Initiative to Build Scientific and Technological Cooperation Networks and Platforms) are needed to finalized. In addition participation in international organizations like CSLF, EU ZEP and World Coal Institute, relevant IEA Implementing Agreements (Clean Coal Sciences, Enhanced Oil Recovery, Fluidized Bed Conversion, IEA Clean Coal Centre, Greenhouse Gas RD Programme, Multiphase Flow Sciences), EU COST actions, Global CCS Institute.

- Because of the size of these investments and the long lead times in project development and proofing, international collaboration is important, and strategic policy aimed at building this global capacity is critical.

- In order to foster the innovative potential of academy and industrial, breakthrough concepts which has the potential to have a high impact like a hot dry rock geothermal energy concept utilizing captured supercritical CO_2 instead of water and mineral trapping in basalt formations in Turkey needs to be investigated.

REFERENCES

1. Kajikawa, Y., Usui, O., Hakata, K., Yasunaga, Y., Matsushima, K., (2008). Structure of knowledge in the science and technology roadmaps. *Technological Forecasting & Social Change*, *Vol. I*, *11*, 75

2. UNFCCC GHG Data. [Cited: January 7, 2010.] http://unfccc.int/ghg_data

3. International Energy Agency. (2009). *World Energy Outlook*. Paris, France

4. Changyoon, K., Hyoungkwan, K., Seung H., Kim, C., Kim, K.; Sang, H. P., (2009). Developing a technology roadmap for construction R&D through interdisciplinary. *Automation in Construction*, 330–337.

5. World Coal Institute. (2004) *Clean Coal Building a Future through Technology.* London, UK

6. International Energy Agency. (2008). *Clean Coal Technologies Accelerating Commerical and Policy Drivers for Deployment.* Paris, France

7. Steel, M., Besida, J., O'Donnell, T. A. (2002). Production of ultra clean coal: Part III. Effect of coal's carbonaceous matrix on the dissolution of mineral matter using hydrofluoric acid. *Fuel Processing Technology*. *Vol. 76*, *1*. 59.

8. International Energy Agency. (2009). *Technology Roadmap: Carbon Capture and Storage.* Paris, France

9. International Energy Agency. (2004). *Prospects For CO2 Capture And Storage*. Paris, France

10. US Department of Energy. (2004). *Carbon Sequestration Technology Roadmap and Program Plan*. Washington, US

11. EU Zero Emission Fossil Fuels Technology Platform. (2009). *The European Technology Platform for Zero Emission Fossil Fuel Power Plants Strategic Research Agenda.*

12. Carbon Sequestration Leadership Forum. (2009). *Carbon Capture and Storage Technology Roadmap.*

13. Demirbas, A. (2003). Sustainable co-firing of biomass with coal. *Energy Conversion and Management Vol. 44*, 1465–1479.

14. Yaodong W., Ye Huang B., Anthony P., Roskilly A., (2010). Trigeneration integrated with absorption enhanced reforming of lignite and biomass. *Fuel*, *Vol. 88*, 10.

15. Liua, P., Pistikopoulosa, E. N., Li, Z. B., (2008) A mixed-integer optimization approach for polygeneration energy systems design. *Computers & Chemical Engineering*,*Vol. 33*, 3.

16. Laihong, S., Jiahua, W., Jun, X., (2009) Experiments on chemical looping combustion of coal with a NiO based oxygen carrier. *Combustion and Flame. Vol. 156, 3*. 728.

17. Sozen, A., Alp, I., (2009) Comparison of Turkey's performance of green house gas emissions and local. *Energy Policy. Vol. 37,* 12.

18. Kaygusuz, K., (2009) Energy and environmental issues relating to greenhouse gas emissions for sustainable development in Turkey. *Renewable and Sustainable Energy Reviews. Vol. 13*, 1.270

19. Erdogdu, E., (2009) Turkish support to Kyoto Protocol: A reality or just an illusion. *Renewable and Sustainable Energy Reviews*.

20. TEIAS. [Cited: January 9, 2010.] http://www.teias.gov.tr/istatistik2008/index.htm.

21. World Energy Council-Turkish National Committee. (2002). *Energy report of Turkey.* Ankara

22. International Energy Agency. (2005) *Energy Policies of IEA countries Turkey 2005 Review*. Paris, France

23. United Nations Framework Convention on Climate Change. (2007). Uniting on Climate, A Guide to the Climate Change Convention and the Kyoto Protocol.

24. CANMET Energy Technology Centre. (2006). *Canada's CO2 Capture and Storage Technology Roadmap.*

25. International Energy Agency. (2008). *World Energy Outlook*. Paris, France

26. International Energy Agency. (2008). *CO2 Capture and Storage: A Key Carbon Abatement Option*. Paris, France

27. Intergovernmental Panel on Climate Change. (2005). *Special Report on Carbon Capture and Storage.*

28. Stern, N., (2007) *Stern Review: The Economics of Climate Change.* H.M.Treasury.

29. Turkish Petroleum Corporation. (2008). *Annual Report.*

30. Ersoy, M. The United Nations Economic Commission for Europe UNECE. [Cited: 1 14, 2010.] www.unece.org/energy/se/pp/clep/ahge2/18Nov08/13_Ersoy.pdf

31. U.S. Department of Energy. (2007). *Carbon Sequestration Technology Roadmap and Program Plan Ensuring the Future of Fossil Energy Systems through the Successful Deployment of Carbon Capture and Storage Technologies.*

32. Ministry of Economy, Trade and Industry (2006). Carbon Capture and Storage Activities in Japan

33. Erdogdu, E., (2008). An expose´ of bioenergy and its potential and utilization in Turkey. *Energy Policy. Vol. 36.*

34. Demirbas, A. (2008) Importance of biomass energy sources for Turkey. *Energy Policy.*

35. Gokcol, C., Dursun, B., Alboyaci, B., Sunan, E. (2008) Importance of biomass energy as alternative to other sources in Turkey. *Energy Policy.*

36. Erdogdu, E., (2009) A snapshot of geothermal energy potential and utilization in Turkey. *Renewable and Sustainable Energy Reviews*.

37. Elektrik Muhensileri Odası Türkiye'de jeotermal enerji aramalari ve potansiyeli. [Cited: 1 14, 2010.] www.emo.org.tr/ekler/e7b33fdea3adc80_ek.pdf.

38. Aleks D., Gurgenci H., Rudolph V. (2009) CO_2 Thermosiphon for Competitive Geothermal Power Generation. *Energy Fuels., Vol. 1*. 23

39. Kajikawa Y., Usui O., Hakata K., Yasunaga Y., Matsushima Y. (2008). Structure of knowledge in the sicence and technology roadmaps. *Technological Forecasting & Social Change. 1 11*, 75.

40. Cooperative Research Center for Greenhouse Gas Technologies. (2004), Carbon Capture and Storage Research Development & Demonstration in Australia, A Technology Roadmap

41. CANMET Energy Technology Center. (2007) Canada's Clean Coal Technology Roadmap.

42. UK Energy Research Center Consortium. (2007) Carbon Capture and Storage Roadmap.

43. Ministry of Energy and Natural Resources of Turkey. (2005) Energy Report of Turkey.