GLOBAL GAPS IN CLEAN ENERGY RESEARCH, DEVELOPMENT, AND DEMONSTRATION

Prepared in support of the Major Economies Forum (MEF)
Global Partnership by the International Energy Agency

International
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INTRODUCTION

Current trends in energy supply and use are unsustainable—economically, environmentally, and socially. Without decisive action, energy-related emissions of CO_2 will more than double by 2050 and increased energy demand will heighten concerns over the security of supplies. We can change this path, but it will take an energy revolution. Every major country and sector of the economy must be involved, and we must ensure that investment decisions taken now do not saddle us with sub-optimal technologies in the long run.

Work on low-carbon energy technologies is ongoing in a number of international forums. In particular, development and deployment of low-carbon technologies is an important topic in the Major Economies Forum (MEF) and under the United Nations Framework Convention on Climate Change (UNFCCC). At the request of the G8, the International Energy Agency (IEA) is also developing roadmaps for some of the most important low-carbon energy technologies, including information on how enhanced international collaboration can help advance individual technologies toward commercialization. However, there is a growing awareness of the urgent need to turn such political statements and analytical work into concrete action.

In July 2009, the MEF countries established a collective goal to expand international technology collaboration, with a focus on multiple specific energy technology areas.[1] MEF countries called for increased global research, development and demonstration (RD&D) with a view towards doubling expenditures for low-carbon technologies by 2015.

This paper seeks to inform decision making and prioritisation of RD&D investments and other policies to accelerate low-carbon energy technologies in the MEF and IEA member countries and others by providing three primary sets of information: (1) estimated current levels of public[2] RD&D spending for the technology areas initially targeted by the MEF; (2) future RD&D priorities for these technologies, based on the IEA roadmaps and other efforts; and (3) an assessment of the gap between current levels of technology ambition and the levels that will be needed to achieve our shared climate change goals by 2050; concluding with suggestions for next steps that can be taken to advance the technologies.

This paper maps the following ten categories of low-carbon energy technologies/practices:[3]

- **Advanced vehicles** (including vehicle efficiency, electric/hybrid vehicles, and fuel cell vehicles)

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[1] For more information, see www.state.gov/g/oes/climate/mem/.

[2] Note: This analysis contemplates opportunities for public and private-led RD&D activities. Privately funded RD&D may exceed that from public sources in many areas. The reader is cautioned that data are incomplete and that general conclusions should be drawn carefully. Where weaknesses are known, they are noted. Where conclusions are drawn, they are ranged and caveated.

[3] A number of technologies (e.g., biofuels, smart grids) may be captured in other technology areas. This paper follows the IEA RD&D data categories and reporting for each technology area to minimize overlap or duplication. However, due to new cross-cutting categories (e.g., smart grids) and to differences in reporting, there is likely to be some overlap or duplication between categories.

- **Bioenergy** (including biofuels and biomass combustion for power and heat)
- **Carbon capture, use, and storage** (including storage and use of CO_2 from power plants, industrial processes, and fuel transformation)
- **Building energy efficiency** (commercial and residential)
- **Industrial energy efficiency**
- **High-efficiency and lower-emissions coal technologies** (for power and heat generation)
- **Marine energy (**including wave/tidal energy and ocean thermal energy conversion[4])
- **Smart grids** (including transmission and distribution systems, end-use systems, distributed generation, and information management)
- **Solar energy** (including solar photovoltaic power, concentrated solar power, and solar heating and cooling)
- **Wind power** (including onshore and offshore installations)

This exercise includes available data and results for all 17 members of the MEF, including European Union spending that was clearly additional to member state spending. The discussion below provides the following information for each of the focus technologies:

- Current RD&D spending levels (based on MEF country reporting of RD&D expenditures levels)
- Research and demonstration priorities (as identified in the IEA technology roadmaps and other efforts)
- An analysis of the gap between current funding levels and levels that will be needed to achieve international climate change goals (using the goals of the IEA *Energy Technology Perspectives* BLUE Map scenario, which aims to achieve a 50% reduction in energy-related CO_2 emissions from 2005 levels by 2050[5])

This paper adopts the IEA nomenclature and definitions for RD&D to include applied research and experimental development, but exclude basic research unless it is clearly oriented towards the development of energy technologies. Demonstration projects are included in the IEA statistics for RD&D and are defined as projects intended to help prove emerging technologies that are not yet ready to operate on a commercial basis. IEA definitions also exclude technology deployment-related activities.

Though 2008-2009 saw a number of governments provide significant new funding in the way of economic recovery or stimulus funds for low-carbon, clean energy technology research, development, demonstration, and deployment. This was a clear demonstration of renewed government support for clean energy. However, these announcements are not included in the technology sections since they are one-time

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[4] Marine energy will be addressed in subsequent updates.

[5] The IEA *Energy Technology Perspectives* BLUE Map scenario was chosen because it provides a comprehensive global look at the technology RD&D needs and investment requirements to reduce energy-related CO_2 emissions by 50% between 2005 and 2050. This abatement trajectory is broadly consistent with stabilisation of global temperatures at 2 C°. Information and assumptions of the BLUE Map scenario are available at http://www.iea.org/w/bookshop/add.aspx?id=330.

announcements; further, in many cases, funding has not yet been allocated. These announcements are included in the final section: *Findings and Conclusions: Assessing the GAP*.

This analysis may be characterised as an international discussion paper, where options are identified for consideration by interested governments. It is recognised that all research, development and demonstrations decisions will be made individual countries, based on their own policy contexts, priorities, and needs. .

1. ADVANCED VEHICLE TECHNOLOGIES

Advanced vehicle technologies include the technology solutions needed to significantly reduce CO_2 emissions in the transportation sector.[6] The primary technology areas[7] are:

- Energy efficiency in transportation
- Electric and plug-in vehicles
- Hydrogen fuel cell vehicles

The estimation of advanced vehicles RD&D effort levels should include:

- Current expenditures by governments and industry on RD&D for the development and market introduction of technologies
- Expenditures by governments and fuel and energy providers on RD&D related to advanced fuels production and distribution[8]
- Contribution of governments, electric utilities, energy storage companies, and research agencies to RD&D activities related to the introduction of advanced energy storage technologies and the development of the adequate electric recharging infrastructure

However, given the overlap in programs, differences in definitions and a tendency to combine results derived from different methodologies, these three elements are difficult to capture independently. Additionally, it is methodologically complex to isolate low-carbon RD&D expenditures on advanced vehicles from RD&D on other vehicle improvements, such as safety.

Current RD&D Expenditures

Current public RD&D expenditures on advanced vehicles were obtained from the IEA statistics under the categories of Transportation, Hydrogen and Fuel Cells, and Energy Storage; and through questionnaires submitted by MEF countries.

TABLE 1. ESTIMATED PUBLIC RD&D EXPENDITURE ON ADVANCED VEHICLES (IN MILLIONS OF U.S. DOLLARS)

United States	539.4
Japan	319.6
Australia	189.9

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[6] Note that biofuels are covered in the bioenergy section below.

[7] This mapping exercise focused primarily on light duty vehicles (LDVs), given the difficulties in collecting data and information for other low-carbon transport options (e.g., shipping; air, rail, or sea transport; and mass transit/transport modal shifts). Further study to assess these other important solutions is recommended.

[8] This is one area where data may overlap with the bioenergy category; as countries may be reporting biofuels infrastructure investments in this category.

France	135.8
European Commission	94.0
Korea	73.4
Italy	62.9
Germany	57.4
Canada	36.1
United Kingdom	19.0
Russia	15.2
Total Public Sector Spending	**1 542.7**

Data reported in the table are based on 2009 estimates, except for France (2007), and Italy, Japan, Korea, and United Kingdom (2008). Data reported in currencies other than U.S. dollars were converted at the prevailing exchange rate of the last eleven months. MEF countries not represented in the table are those for whom data are missing or unknown.

RD&D Priorities

Decarbonisation of the transport sector will require a significant move towards more efficient vehicles, advanced propulsion systems, improved vehicle energy storage, and low-carbon alternative fuel production and compatibility with vehicles. The highest priority advanced vehicle RD&D investments could include:

- **Energy storage:** For electricity and hydrogen to realise their full potential as transportation fuels, improved on-board storage devices will be needed, with energy densities two to three times those for current best performance levels. Target systems include plug-in electric vehicles (PHEVs) in the short term, followed by electric vehicles (EVs) in the medium term, and fuel cell vehicles (FCVs) in the long term. These vehicles will be more expensive than conventional vehicles; minimising any cost increase via reduced battery and other energy storage costs will be critical to their success.
- **Lightweight materials:** Significantly lighter vehicles are needed to increase vehicle efficiency, such as very high strength steel, aluminium, and composite materials.
- **Fuel efficient technologies**: Options include advanced internal combustion engine (ICE)-based power trains capable of recovering some of the energy lost as heat. Hybrid-electric vehicles (HEVs) represent a suite of technologies that continue to be improved and optimised. More efficient power trains are accompanied by energy efficiency improvements addressing all vehicle components, like low rolling resistance tires and more efficient on-board electric and electronic devices. Breakthroughs in thermoelectric materials for waste heat recuperation are also possible, both in bulk materials and those associated with nanotechnology.
- **Low-carbon fuels and fuel delivery infrastructure:** Advances in production of low-CO_2 hydrogen and pathways toward an affordable hydrogen distribution infrastructure are needed if fuel cell vehicles are to become a commercial reality. Similarly, recharging infrastructure for EVs will be required to scale up vehicle electrification, beginning in targeted cities and regions.

- **Fuel cell propulsion systems:** Continuous improvements in fuel cell systems are needed, including improved durability and performance under real-world conditions as well as system cost reduction. Much progress has been made in recent years but it must continue in order for fuel cell vehicles to become competitive with ICE vehicles.

Gaps between Current RD&D Spending and 2050 Climate Goals

The *Energy Technology Perspectives* BLUE Map scenario includes a 30% reduction in CO_2 emissions levels by the transport sector sees from 2005 to 2050. This reduction is achieved in part by the annual sale of approximately 50 million EVs and 50 million PHEVs per year by 2050, which would represent at least half of all LDV sales in that year.[9] An important assumption in these projections involves battery range and cost. The cost of batteries for EVs is assumed to start at about USD 500 to USD 600/kilowatt-hour (kWh) at high volume production (on the order of 100 000 units), and drops to under USD 400/kWh by 2020. PHEV batteries are assumed to start around USD 750/kWh for high-volume production and then drop to under USD 450 by 2020. The actual cost reductions would depend on cumulative production and learning process.

RD&D Investment Needs

The table below presents a summary of the investment needs for advanced vehicles. The first column shows the range of total public and private investment needs for research, development, demonstration and deployment (RDD&D). The second column is an estimate of the range of MEF countries' total RD&D needs (RDD&D less investment in deployment), assuming that RD&D needs are 10-20% of the average of low/high RDD&D needs, that total RD&D investment needs can be annualised over 40 years, and that the MEF countries' portion should be based on 80% of the annualised value, since the MEF countries make up approximately 80% of global energy sector emissions. These figures are then compared to the current annual investment in public RD&D, in column three, as derived from the best available data reported in the technology discussion above. The RD&D gap is then derived, shown as a range in the last column, by subtracting the reported current annual investment from the range of required annualised RD&D investments.

TABLE 2. ADVANCED VEHICLES RD&D SPENDING GAP (IN U.S. DOLLARS)

RDD&D needs to achieve BLUE Map 2050 Goals (billion)	Annual RD&D needs for MED countries to achieve BLUE Map 2050 Goals (million)	Current annual MEF countries' public spending (million)	Annual spending gap for MEF countries, (million)
7 500-9 100	16 600–33 200	1 543	15 057–31 657

This analysis reveals a gap in funding of USD 15.0–31.7 billion. However, it does not account for the private sector, which is believed to be the largest source of funds

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[9] A slightly revised BLUE Map scenario for transport has been developed for *Transport, Energy and CO_2: Moving Toward Sustainability* (IEA, 2009). This scenario retains the important role for EVs and PHEVs in meeting 2050 targets that is depicted in ETP 2008, but in addition to focusing on LDVs, also acknowledges that some electrification will likely occur in the bus and medium-duty truck sectors.

for advanced vehicles RD&D. Further, it does not capture advanced vehicles research investment in China, which is clearly expanding its capacities rapidly in this technology area (see box).

BOX 1. CHINA'S VEHICLE ELECTRIFICATION EFFORTS ARE EXPANDING

It is estimated that in 2004, 1.4% of revenues in the Chinese automotive industry were used for R&D. Local manufacturer Geely even claimed to invest 10% of revenues in R&D (Noble, 2006). By 2005, 130 auto and parts companies, including industry leaders like General Motors and Volkswagen, had invested in R&D facilities in China. To receive government approval, foreign investors need to undergo a screening process and have to make concessions, for example, committing themselves to invest in R&D and to share technologies. Similarly, foreign manufacturers have a greater chance to be considered in public tenders if they set up R&D centers in China—Chinese authorities ''swap market for technology'' (Long, 2005, p. 334).

Twenty million electric vehicles are already on the road in China in the form of two-wheeled electric bikes (e-bikes) and scooters. The number of e-bikes has grown from near-zero levels ten years ago, due to technological improvements and favorable policy. Improvements in e-bike designs and battery technology made them desirable, and the highly modular product architecture of electric two-wheelers (E2Ws) resulted in standardisation, competition, and acceptable pricing. Policies favor e-bikes by eliminating the competition; gasoline-powered two-wheeled vehicles are banned in several provinces. Shanghai, for example, has banned gasoline-powered two-wheeled vehicles from 1996 (Weinert 2007).

Although sales volumes for four-wheeled vehicles are much smaller, according to government officials and Chinese auto executives, China is expected to raise its annual production capacity to 500 000 plug-in hybrid or all-electric cars and buses by the end of 2011 (*Bradsher* 2009), with plans to eventually export EVs. The Chinese government has enacted programs to promote vehicle electrification on a national scale. In late 2008, Science and Technology Minister Wan Gang initiated an alternative-energy vehicles demonstration project in eleven cities. 500 EVs are expected to be deployed by late 2009, and total deployment should reach 10,000 units by 2010 (Gao, 2008). The national government also provides an electric-drive vehicle subsidy of RMB 50 000 (US$7,316) that was launched in December 2008, but the BYD F3DM is the only vehicle that currently qualifies (Fangfang, 2009).

2. BIOENERGY

Generating bioenergy involves complex conversion processes that can follow many possible pathways from raw material to finished product. Biomass fuels and residues can be converted to energy via thermal, biological, mechanical, or physical processes for generating power, heat, or liquid biofuels for transport. Biomass is defined as plant matter used directly as fuel or converted into other forms before combustion, and covers a wide range of products, by-products, and waste streams derived from forestry and agriculture, as well as municipal and industrial waste streams. Producing bioenergy requires the coordination of a long chain of activities, including planting, growing, harvesting, pre-treatment (storage and drying), fuel upgrading, and conversion to an energy carrier.

This report focuses on liquid biofuels and biomass for power and heat generation. Biofuels can be divided into a number of categories, including type (liquid and gaseous), feedstock, and conversion process. The conversion processes may vary based on the nature of the feedstock, with commercial production underway based on food-crop feed stocks, and the potential for advanced-technology biofuels from the use of non-food biomass feed stocks, such as woody and cellulosic plants and waste material.

Current RD&D Expenditures

Government budgets for bioenergy RD&D in IEA member countries include data on production of transportation biofuels,[10] production of other biomass-derived fuels,[11] application for heat and electricity,[12] and other bioenergy expenses.[13] The total investment reported below is provided by the IEA Statistics, supplemented by MEF countries' data submissions for the purpose of this exercise.

TABLE 3. ESTIMATED PUBLIC RD&D EXPENDITURES ON BIOENERGY (IN MILLIONS OF U.S. DOLLARS)

United States	287.6
Brazil	62.8
Canada	43.2
France	40.2
Germany	34.7
United Kingdom	24.8
European Commission	19.2
Japan	18.7

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[10] Includes conventional biofuels; cellulosic conversion to alcohol; biomass gas-to-liquids; and other.

[11] Includes biosolids; bioliquids; biogas thermal; biogas biological; and other.

[12] Includes bioheat excluding multifiring with fossil fuels; bioelectricity excluding multifiring with fossil fuels; CHP (combined heat and power) excluding multifiring with fossil fuels; recycling and uses of urban, industrial and agricultural wastes not covered elsewhere.

[13] Includes improvement of energy crops; assessments of bioenergy production potential and associated land-use effects.

Italy	17.5
Russia	14.5
India	10.5
Australia	6.9
China	5.1
Korea	4.7
Total Public Sector Spending	**590.4**

Data reported in the table are based on 2009 estimates, except for Brazil which was based on 2008 expenditures on the Biodiesel Technological Development Program and Ethanol Science, Technology and Innovation Program (Ministry of Science and Technology); and investments under the National Agroenergy Development Program (Ministry of Agriculture, Livestock and Food Supply); China (Government expenditure of 35 million Yuan [USD 5.1 million] on biomass for energy R&D in 2006); European Commission (based on EC funds under the Sixth Framework Programme for Research and Technology Development - FP6); France (2007); India (reported budget of Rs.510 million [USD 10.5 million] for the period 2007-2008 for biomass program of the Ministry of New and Renewable Energy - MNRE); Italy, Japan, Korea and United Kingdom (2008). Data reported in currencies other than U.S. dollars were converted at the prevailing exchange rate of the last eleven months. MEF countries not represented in the table are those for whom data are missing or unknown.

The estimated total public RD&D expenditures reported above are also comparable with the result of a recent European Commission study that estimates the total EU investment in bioenergy R&D in 2007 at EUR 245 million (USD 366 million), of which EUR 65 million (USD 97 million) were allocated to transport biofuels.[14] Based on a European Commission assessment of the expenditures of 23 EU-based companies, private sector RD&D investment on biofuels amounted to USD 0.4 billion in 2007.[15]

RD&D Priorities

Based on several national bioenergy roadmaps and the work of the IEA Bioenergy Implementing Agreement,[16] the main areas of focus for biomass R&D could include the following:

- Improving basic plant science to increase sustainable biomass production rates
- Identifying the environmental factors associated with expanded production of biofuels and bio-based products (e.g., applying more efficient and sustainable agricultural, forestry, and land management practices and certification schemes to supply higher yields per unit of input without degrading the environment)

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[14] Accompanying document to the European Commission's Communication on Investing in the Development of Low Carbon Technologies (SET-Plan) (SEC(2009) 1296).

[15] The companies included in the *European Union's Industrial R&D Investment Scorecard 2008* study consisted of specialised biofuel companies, large car manufacturers and oil companies, with the latter two accounting for the larger part of corporate R&D investments. However, no figures could be obtained for a number of important biodiesel and ethanol producers.

[16] See www.ieabioenergy.com/.

- Developing new and improved feed stocks
- Promoting new, lower-cost conversion technologies at production scale, including thermo-chemical and biochemical processes and development of more robust enzymes and catalysts

The biggest breakthrough for bioenergy is expected to come from further developments in the cost-effective conversion of cellulose-rich biomass (such as that found in wood, perennial grasses, and agricultural residues like corn stalks, wheat straw, and bagasse) to usable energy forms. RD&D on cellulosic biomass conversion is a major priority in some MEF countries. However, there are no commercially operating facilities to date, only small-scale demonstrations. Considerable RD&D is needed to make cellulosic biofuels technologies viable, but at this stage these alternatives do not represent the main thrust of RD&D investment. Major barriers are the high cost of pre-treatment, effective large scale harvesting and storage of multiple feed stocks, and relatively low efficiencies in bioprocessing and thermo-chemical conversion.

Gaps between Current RD&D Spending and 2050 Climate Goals

The IEA *Energy Technology* Perspectives BLUE Map scenario sees global bioenergy usage increasing nearly four-fold by 2050, accounting for 23% of total world primary energy—150 Exajoules (EJ)/yr; 3,600 Million tonnes of oil equivalent (Mtoe)/yr. Around 700 Mtoe/yr of this is consumed to produce transport biofuels, and a similar amount to generate 2,450 Terawatt-hour (TWh)/yr of power. The remaining 2 200 Mtoe is used for biochemicals, heating and cooking, and in industry. Furthermore, in the BLUE Map scenario, 26% of total transport fuel demand is met by biofuels by 2050.

RD&D Investment Needs

The table below presents a summary of estimated investment needs for bioenergy in the *Energy Technology Perspectives* BLUE Map scenario. The first column shows a low and a high end range of total public and private investment needs for research, development, demonstration, and deployment (RDD&D). The second column is an estimate of the range of MEF countries' total RD&D needs (RDD&D less investment in deployment), making the assumptions that RD&D needs are 10-20% of the average of low/high RDD&D needs, that total RD&D investment needs can be annualised over 40 years, and that the MEF countries' portion should be based on 80% of the annualised value, since the MEF countries make up approximately 80% of global energy sector emissions. These figures are then compared to the current annual investment in public RD&D in column three, as derived from the best available data reported in the technology discussion above. The RD&D gap is then derived, and shown as a range in the last column, by subtracting the reported current annual investment from the range of required annualised RD&D investments.

TABLE 5. BIOENERGY RD&D SPENDING GAP (IN U.S. DOLLARS)

RDD&D needs to achieve BLUE Map 2050 goals (billion)	MEF countries' annual RD&D needs to achieve BLUE Map 2050 goals (million)	Current annual MEF countries' public spending (million)	Annual spending gap for MEF countries (million)
210–250	460–920	590	-130–330

Public sector RD&D investment on bioenergy in MEF countries falls short of the upper range estimate for annual RD&D needs for the BLUE Map target. Research in bioenergy has increased over the past decade, and a few countries are responsible for most of the spending. This means that international collaboration and collaborative efforts will be important to promoting further technology development. Further, much of the biofuels RD&D underway globally supports improving technologies to increase efficiency of the production process. There is a strong need to increase public and private funding for new, innovative and sustainable end-uses of biofuels which can be a driving force for sustainable development in countries that must address the challenge of increasing energy access and reducing the growth of CO_2 emissions.

Several studies suggest that RD&D funding needs over the longer term are larger than projected in this analysis. An assessment recently released by the European Commission estimates that the total public and private investment needed in Europe over the next 10 years is approximately EUR 9 billion (USD 13.5 billion), of which EUR 4.5 billion for optimising thermo-chemical pathways from lignocellulosic feedstock, and EUR 3.4 billion for biochemical pathways.[17] The remaining EUR 1 billion (USD 1.5 billion) is divided between support activities on biomass feedstock assessment, production, management, and harvesting for energy purposes (USD 600 million; USD 900 million) and the identification of new value chains (EUR 400 million; USD 600 million). This study includes the costs of research, technological development, demonstration, and early market up-take, but excludes the cost of deployment and market-based incentives.[18] Loan guarantee supports would most likely be an important aspect of ramping up production to these levels, particularly for new technology deployment.

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[17] European Commission's Communication "Investing in the Development of Low Carbon Technologies" (COM(2009) 519/4).

[18] Another recent study indicates that USD 250 billion capital investments would be required to build a 60 billion gallon per year biofuels capacity; *see* Sandia National Laboratories, *The Ninety Billion Gallon Biofuels Deployment Study* executive summary at http://hitectransportation.org/news/2009/Exec_Summary02-2009.pdf.

3. CARBON CAPTURE, USE, AND STORAGE

Carbon dioxide capture and storage (CCS) is defined as a system of technologies that integrates three stages: CO_2 capture, transport, and geologic storage.[19] The area with the most robust RD&D investments is currently CO_2 capture; this is because the capture process is approximately 70% of the capital cost investment of a CCS project. However, as countries expand spending efforts, they are focusing on advanced materials and tools for low-cost pipeline infrastructure expansion and modeling tools and solutions for improved CO_2 storage, as well as integration across the three areas. Various technologies with different degrees of maturity are currently competing to be the low-cost solution for each stage of the CCS value chain.

Current RD&D expenditures

Public RD&D CCS budgets for IEA countries support CO_2 capture/separation,[20] CO_2 transport and CO_2 storage.[21] The table below is based on data from the IEA statistics and from questionnaires submitted by some MEF countries for this exercise. Data on private sector CCS-related RD&D investments are available for Europe, based on a letter dated February 2008 from the EU Technology Platform for Zero Emission Fossil Fuel Power Plants to Commissioner Piebalgs, according to which the "corporate commitments" of the companies signed "already amount to a total of more than EUR 635 million (USD 948 million) over the past five years in aggregate." This figure corresponds to the EC's 2007 estimate of corporate CCS RD&D investments at EUR 240 million (USD 358 million). [22] Data for non-EU private sector spending were not available.

TABLE 6. ESTIMATED PUBLIC RD&D EXPENDITURES ON CCS (IN MILLIONS OF U.S. DOLLARS)

United States	594.0
Australia	123.5
France	38.8
Japan	36.8
European Commission	31.9
Canada	19.0
Korea	12.2
Italy	11.7

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[19] The only currently active area of CO_2 use is for enhanced oil recovery (EOR); with some public RD&D investments. However, there is a growing interest in other advanced uses of CO_2 (e.g., cement manufacture or algae for biofuels), and they may begin to attract new RD&D spending.

[20] CO_2 capture/separation covers: absorption; adsorption; cryogenic separation; membranes; oxygen combustion; hydrogen/syngas production; chemical looping; direct capture of CO_2 from air.

[21] CO_2 storage covers: deep saline aquifers; deep unminable coalbeds; mineralization; oil and gas reservoirs; monitoring and verification of stored CO_2; direct ocean injection.

[22] European Commission's Communication "Investing in the Development of Low Carbon Technologies" (COM(2009) 519/4).

Germany	8.3
United Kingdom	6.5
Russia	0.9
Total Public Sector Spending	**883.5**

Data reported in the table are based on 2009 estimates, except for European Commission (based on EC funds under the Sixth Framework Programme for Research and Technology Development - FP6); France (2007); Italy, Japan, Korea and United Kingdom (2008). Data reported in currencies other than U.S. dollars were converted at the prevailing exchange rate of the last eleven months. MEF countries not represented in the table are those for whom data are missing or unknown.

RD&D Priorities

For all CCS technologies, costs need to be lowered and commercial-scale demonstration is needed. Additional R&D is also needed to address different CO_2 streams from industrial sources. Further work is needed to test biomass gasification or combustion with CCS, which offers a pathway toward carbon-negative uses of CCS. The RD&D priorities reported below are based on the IEA *CCS Roadmap* released in October 2009.

R&D priorities for CO_2 capture technology are divided into the three main technology options commercially available today: post-combustion capture, pre-combustion capture, and oxyfuel combustion. Post-combustion systems separate CO_2 from the flue gases produced by the combustion of the primary fuel in air. R&D priorities for post-combustion systems include:

- Scale: Application at the scale required for flue gas streams for coal and gas fired plants. Capital costs are also high, >USD 50 million for a 5 million metric standard cubic meters (MMscm)/day (d) train.
- Combustion stream composition: Nitrogen oxide (NO_X), sulfur dioxide (SO_2), and oxygen in the flue gas all react with solvents to form stable salts, leading to rapid solvent degradation and unacceptably high costs. This can be addressed by upstream reduction of the concentration of these impurities.
- Energy penalty: The capture system requires a large amount of heat for current technologies such as amine solvent regeneration, as well as auxiliary power requirements for flue gas pre-treatments, blowers, pumps and compressors. This reduces overall operating efficiencies of the plant by 8-10% compared to standard plants. Overall boiler efficiency improvements are needed to reduce the gross energy penalty to <8% points by 2020-2025, with an associated reduction in capital and operating costs. A variety of novel post-combustion capture approaches are being investigated to reduce the energy penalty, including: advanced amine solvents and solvent systems; amines immobilised within solid sorbents; polymeric membrane absorbents; metal organic frameworks; structured fluid absorbents (CO_2 hydrates, liquid crystals, and ionic liquids); and non-thermal solvent regeneration methods, including electrical and electrochemical approaches.
- Integration: There is a need to optimise integration, particularly for retrofit applications, to achieve plant availabilities and capture rates above 85% by 2020.

Pre-combustion systems process the primary fuel in a reactor with steam and air or oxygen to produce a mixture consisting mainly of carbon monoxide and hydrogen ("synthesis gas"). Priorities for pre-combustion systems include:

- Scale: Demonstrate integrated gasified combined cycle (IGCC) technology for widespread use in baseload power generation with all types of fuels, especially equipped with CO_2 separation. Improve the overall efficiency and reliability of the IGCC process. Reduce the amount of steam required for the shift conversion. Increase the efficiency of the gas turbine used to combust the hydrogen. Make improvements in availability to 85%.
- Integration: Achieve process control with the parallel processes in IGCC plants with CO_2 capture
- Energy penalty: Reduce steam requirements in the shift converter on IGCC using gas separation membranes after 2030. Develop novel methods for pre-combustion CO_2 capture, including pressure swing adsorption, electrical swing adsorption, gas separation membranes and cryogenics
- H_2 combustion: Develop high efficiency and low-NO_x H_2 gas turbines able to withstand the high combustion temperature of H_2 without damage to turbine blades

Oxyfuel combustion systems use oxygen instead of air for combustion of the primary fuel to produce a flue gas that is mainly water vapour and CO_2. Priorities for oxyfuel combustion systems include:

- Energy penalty: Energy requirements for pure oxygen production are high, especially in large-scale applications. A key near-term milestone is to reduce the energy required for large-scale air separation. Further investigate how to optimise O_2 purity and post-combustion treatment needs
- Combustion stream composition: There is currently air leakage into the firing chamber, leading to contamination of the exit gases with nitrogen. There is a need to develop advanced materials that can withstand the high temperatures associated with oxyfuel capture
- Integration: Emissions of NO_X and SO_2 need to be better managed through staged combustion design
- Cement sector application: Due to the cement sector's anticipated need for CCS, it should be investigated whether the flame temperature in oxyfired cement kilns is suitable for clinker production

R&D priorities for CO_2 transport include a significant amount of additional work to map out the way in which pipeline networks and common carriage systems will evolve over time, with a long-term view that takes into account expansion from demonstration to commercialisation. This will require advanced modeling technologies and methods to integrate pipeline networks with existing rights-of-way, as well as use of advanced, lower-cost materials. Priorities include:

- Develop models and tools to perform regional analyses of source/sink distribution and optimise pipeline networks
- Improve understanding of CO_2 transport leakage scenarios and the effects of impurities on CO_2 pipeline transport
- Explore of options to modify existing natural gas pipelines for CO_2 transport

- Develop lighter, flexible, safer and lower-cost pipeline materials

R&D priorities for CO_2 storage include improving understanding of the capacity and injectivity of deep saline formations and the level of uptake for enhanced hydrocarbon recovery projects using CO_2, along with the efficacy of different geological media to achieve long-term secure storage. This will require development of advanced geologic modeling techniques for site selection and risk assessment, as well as monitoring and verification. Priorities include:[23]

- Develop computer models that have the capability to map saline formations for CO_2 storage suitability, including tools for predicting spatial reservoir and cap rock characteristics between 2010 and 2020
- Improve understanding of CO_2 and co-contaminant degradation of well-bores

Gaps between Current RD&D Spending and 2050 Climate Goals

The *Energy Technology Perspectives* BLUE Map scenario concludes that CCS contributes 19% of the necessary emissions reductions in 2050. According to the IEA *CCS Roadmap*, global deployment of CCS achieves over 10 gigatonnes (Gt) of CO_2 emissions captured in 2050. This represents a cumulative storage of around 145 $GtCO_2$ over the period 2010-2050. Capture from power generation represents 5.5 $GtCO_2$/yr (or 55% of the total captured) in 2050. Capture from industry accounts for 1.7 $GtCO_2$/yr (16%) and upstream (*e.g.*, gas processing and fuels transformation) accounts for 2.9 $GtCO_2$/yr (29%) of the total.

RD&D Investment Needs

The IEA *CCS Roadmap* indicates that this level of project development requires a total investment in CCS between now and 2050 of around USD 2.5-3 trillion (for deployment of some 3 400 projects, nearly half by the power sector, needing an average rate of 10 projects being built each year over the next 10 years). The additional investment in capture technology needed will amount to almost USD 1.3 trillion through 2050; investment in CO_2 transportation infrastructure will represent an additional USD 0.5-1 trillion, depending upon the extent to which pipeline networks are optimised over time and storage site investment a further USD 88-650 billion.

The table below presents a summary of the ETP investment needs for CCS. The first column shows a low and a high end range of total public and private investment needs for research, development, demonstration, and deployment (RDD&D). The second column is an estimate of the range of total RD&D needs (RDD&D less investment in deployment) for MEF countries, assuming that RD&D needs are 10-20% of the average of low/high RDD&D needs, that total RD&D investment needs can be annualised over 40 years, and that the MEF countries' portion should be based on 80% of the annualised value, since the MEF countries make up approximately 80% of global energy sector emissions. These figures are then compared to the current annual investment in public RD&D, in column three, as derived from the best available data reported in the technology discussion above. The RD&D gap is then derived, and shown as a range in the last column, by subtracting the reported current annual investment from the range of required annualised RD&D investments.

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[23] The IEA GHG Implementing Agreement is the leading global technology cooperation network on CO_2 storage and has more detailed assessments of needs and current status. See www.ieagreen.org.uk/.

TABLE 7. CCS RD&D SPENDING GAP (IN U.S. DOLLARS)

RDD&D needs to achieve BLUE Map 2050 goals (billion)	MEF countries' annual RD&D needs to achieve BLUE Map 2050 goals (million)	Current annual MEF countries' public spending (million)	Annual spending gap for MEF countries (million)
2 500–3 000	5 500–11 000	884	4 617–10 117

This analysis reveals a gap in funding of USD 4.6-10.1 billion. Governments are beginning to address this gap, as indicated by an increase in announcements of funding for such projects in the past year (see box).[24] While these announcements are a positive start, current 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. Further, non-OECD countries are expected to host the majority of CCS plants after 2025, and there has been very little investment in CCS demonstration in fossil-based non-OECD countries to date.

BOX 2. MAJOR ANNOUNCEMENTS OF CCS FUNDING

- Australia: The Australian government has committed AUD 2 billion (USD 1.65 billion) in funding for large-scale CCS demonstrations in Australia. In addition, Australia has committed AUD 100 million (USD 78 million) a year over four years for the formation of the Global CCS Institute.
- Canada*:* The Canadian federal government has announced financial support of CAD 1.3 billion (USD 1.2 billion) for research and development (R&D), mapping and demonstration project support. In addition, the Province of Alberta has assigned CAD $2 billion (USD 1.8 billion) in funding to support CCS deployment.
- European Union*:* The European Union (EU) has set aside the revenue from the auctioning of 300 m credits within their Emissions Trading Scheme for the support of CCS and renewable energy. The EU has also allocated EUR 1.05 billion (USD 1.5 billion) from their economic recovery energy program for the support of seven CCS projects.
- Japan*:* The Japanese government has budgeted JPY 10.8 billion (USD 116 million) for study on large-scale CCS demonstration since fiscal year 2008 (FY 2008).
- United Kingdom*:* In addition to the broader EU funding, the United Kingdom (UK) has announced funding for up to four CCS projects. The first of these projects will be selected from projects via the CCS competition. The winner will have the additional costs of CCS covered by a government capital grant. The UK has recently announced that the remaining projects will be funded through a levy on electricity suppliers, to take effect in 2011. This is expected to raise GBP 7.2-9.5 billion (USD 11.2-14.8 billion) over a 15-20 year period.[25]
- United States*:* The recent Economic Recovery Act includes USD 3.4 billion in funding for clean coal and CCS technology development. USD 1.0 billion has been allocated for developing and testing new ways to produce energy from coal. USD 800 million will augment funds for the Clean Coal Power Initiative with a focus on carbon capture, and USD 1.52 billion will fund industrial CO_2 capture projects, including a small allocation for the beneficial reuse of CO_2.

Source : IEA, CCS Roadmap (2009)

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[24] These spending amounts were not included in the gap analysis, due to the difficulties in verifying the status of the funding; some announcements are still subject to political approval.

[25] *See* http://www.decc.gov.uk/en/content/cms/consultations/clean_coal/clean_coal.aspx for additional information.

4. ENERGY EFFICIENCY IN BUILDINGS

Approximately one-third of end-use energy consumption in developed countries occurs in residential, commercial and public buildings.[26] Uses include heating, cooling, lighting, appliances, and general services. A wide range of technologies are available in the building envelope and its insulation, space heating and cooling systems, water heating systems, lighting, appliances, consumer products, and business equipment. Many of these technologies are already economic, but non-economic barriers can significantly slow their penetration.

Several recently developed technologies (e.g., high-performance windows, vacuum-insulated panels, high-performance reversible heat pumps), when combined with integrated passive solar design, can reduce building energy consumption and GHG emissions by 80%. A number of other technologies are under development (e.g. integrated intelligent building control systems) which, with further research, development, and demonstration, could have an increasingly large impact over the next two decades. In addition, more work is needed to better characterise the building stock in developing countries and provide tailored solutions in these regions.

Current RD&D Expenditures

Data on RD&D expenditures for IEA member countries are captured in the residential and commercial subcategories[27] and other conservation expenses.[28] The table below identifies current spending on energy efficiency in buildings, based on IEA statistics and on data submitted by some MEF countries for this exercise.

TABLE 8. ESTIMATED PUBLIC RD&D EXPENDITURES ON ENERGY EFFICIENCY IN BUILDINGS (IN MILLIONS OF U.S. DOLLARS)

Japan	139.0
United States	85.4
Italy	83.3
France	32.8
Germany	31.6
Australia	22.7

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[26] The range of buildings includes a number of commercial building types, each with its own energy efficiency technology solutions. Building types include commercial high-rise office buildings, schools, large retail complexes, hospitals, and university campuses, among others. Similarly, residential buildings also include a number of different types with varying energy requirements, from large multi-family apartment complexes to single family residences.

[27] Includes data on: space heating and cooling, ventilation and lighting control systems other than solar technologies; low energy housing design and performance other than solar technologies; new insulation and building materials; thermal performance of buildings; domestic appliances; and other expenses.

[28] Includes data on: waste heat utilization (heat maps, process integration, total energy systems, low temperature thermo-dynamic cycles); district heating; heat pump development; and reduction of energy consumption in the agricultural sector.

Russia	22.6
Canada	19.2
United Kingdom	8.2
Korea	8.0
Total Public Sector Spending	**452.8**

Data reported in both tables are based on 2009 estimates, except for France (2007); and Italy, Japan, Korea and United Kingdom (2008). Data reported in currencies other than U.S. dollars were converted at the prevailing exchange rate of the last eleven months. MEF countries not represented in the table are those for whom data are missing or unknown.

Energy RD&D priorities

There are a number of technology-specific and cross-cutting/optimisation RD&D priorities for energy efficiency in residential and commercial buildings.

- **New construction**: Building design that considers the building as a system and minimises energy consumption of the whole system should become more widespread, and tools to facilitate that approach should be refined to promote integrating the process of building design, build and delivery. Priorities include:
  - Coupling building science (thermodynamics, heat transfer, fluid mechanics, sensors, materials, components) with architecture (structure, façade, comfort, aesthetics) and information science (communication, computations, control) that lead to deeper understanding and pathways of how to integrate subsystems that will cooperate and collectively reduce energy consumption as a system
  - Tools for simulation, analysis, optimisation and data mining that can be used for both building design and operation
  - Self-tuning buildings: Continuous visualisation, monitoring, reporting, diagnostics, and demand-response of buildings
  - Expanding technical support for developers, builders, state and local government, utilities, and manufacturers as well as realtors, bankers, and insurance companies who are committed to building zero-energy homes and communities, to ensure the development of a stable anchor market for sustainable building products
  - Developing technology packages for various types of commercial buildings in different climate zones
  - Effective integration with on-site renewable technology for different building types, geometries, and for different climate zone
- **Retrofitting existing buildings**: Energy efficiency savings in existing buildings are possible by applying energy retrofits, sound operations and maintenance practices, re-tuning of energy management systems, and retro-commissioning. RD&D is needed to develop better methods to:
  - Optimise package(s) of energy efficiency measures for buildings
  - Apply quality control to retrofit installations
  - Track pre- and post-retrofit performance of buildings and use that information to continuously improve the retrofit process

  - Identify and prioritise sets of buildings of similar energy use intensity, type, vintage and location that are likely candidates for retrofit
  - Audit buildings quickly and effectively, using advanced data mining capabilities
  - Adapt new home technologies into existing infrastructure, including software tools and processes, and develop *minimum cost* technologies for different vintages, including:
    - Heating, ventilation, and air conditioning (HVAC)—enabling technologies for installation and diagnostics
    - Building envelope—installation of insulation in hard to access locations
    - Windows—various window sizes/adjustable frames for retrofits

- **Advanced components and equipment:** Needed to realise high energy performance levels. RD&D priorities include:
  - Envelope and window technology
  - Mechanical equipment, controls, and thermal storage technologies
  - Electrical and lighting equipment technology and controls

- **Building interaction and integration with the power grid**, including enabling storage technology.[29] The interaction of a building with the electricity distribution system and energy storage systems is an important area for realising building performance improvements. Priorities include:
  - Active integration of energy storage in buildings, including via plug-in hybrid electric vehicles
  - Smart interaction of building systems (optimisation of peak energy reduction with grid stabilisation)
  - Integration of renewable energy and energy storage systems with energy efficiency approaches

Finally, overarching goals include realising net-zero[30] energy performance in new homes and buildings and realising very significant improvements in the energy performance of existing buildings (see box).

BOX 3. NET-ZERO PERFORMANCE GOAL FOR BUILDINGS IN THE UNITED STATES

The importance of a "net-zero performance" goal for buildings is indicated in recent legislation in the United States. The Energy Independence and Security Act (EISA), passed in 2007, established net-zero energy (NZE) performance as the essential goal of the commercial buildings sector. Specifically, EISA states that NZE performance will be achieved in all new construction by 2030, in half the stock by 2040, and in all buildings by 2050. Realisation of such goals, at this scale, requires RD&D innovation across the built environment complex.

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[29] Note that this is an area of potential overlap in RD&D reporting with the new smart grids technology area (discussed below).

[30] A net-zero energy building is a residential or commercial building with greatly reduced needs for energy through efficiency gains (60 to 70% less than conventional practice), with the balance of energy needs supplied by renewable technologies.

Gaps between Current RD&D Spending and 2050 Goals

While there are clearly gaps between current levels of technology research, development and demonstration by governments and the stated 2050 goals, the IEA *Energy Technology Perspectives* BLUE Map scenario did not quantify the level of technology, research and development needed to reach the 2050 goals. Therefore, this analysis was not able to estimate a gap analysis for energy efficiency in buildings. There is a need to perform this analysis as a priority action.

5. ENERGY EFFICIENCY IN INDUSTRY

Industry accounts for approximately one-third of global final energy use and almost 40% of total energy-related CO_2 emissions, with the five most energy-intensive sectors being iron and steel, cement, chemicals and petrochemicals, pulp and paper, and aluminium. Together these sectors currently account for 75% of total direct CO_2 emissions from industry. Progress in industrial energy efficiency and CO_2 intensity achieved over recent decades has been more than offset by growing industrial production. As a result, total industrial energy consumption and CO_2 emissions have continued to rise. Of serious concern is the rapid deceleration of energy efficiency improvements since 1990.[31] Recent rates have been about half of those experienced in the previous two decades, although recent data show some signs that the rate of improvement may be increasing slightly. While significant energy efficiency potentials remain, they are smaller than in the building sector. There is therefore a need for a major acceleration of RD&D in breakthrough technologies that have the potential to significantly change industrial energy use or lower GHG emissions.

Current RD&D Expenditures

Data on energy efficiency RD&D expenditures for IEA member countries are captured in the following subcategory of industry.[32] The table below identifies current spending in this category, based on the IEA statistics and on data submitted by some MEF countries for this exercise.

TABLE 9. ESTIMATED PUBLIC RD&D EXPENDITURES ON ENERGY EFFICIENCY IN INDUSTRY (IN MILLIONS OF U.S. DOLLARS)

Japan	143.9
Korea	81.9
United States	79.9
Australia	26.4
Russia	23.4
France	16.7
Italy	13.2
Canada	12.6
Germany	11.0

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[31] IEA (2009), *Towards a More Energy Efficient Future: Applying Indicators to Enhance Energy Policy*, OECD/IEA, Paris.

[32] Includes data on: reduction of energy consumption in industrial processes including combustion (excluding bioenergy); development of new techniques, new processes and new equipment for industrial applications; and other expenses.

United Kingdom	1.8
Total Public Sector Spending	**410.8**

Data reported in both tables are based on 2009 estimates, except for France (2007); and Italy, Japan, Korea and United Kingdom (2008). Data reported in currencies other than U.S. dollars were converted at the prevailing exchange rate of the last eleven months. MEF countries not represented in the table are those for whom data are missing or unknown.

Energy RD&D Priorities

The industrial sector presents numerous opportunities for advanced technologies to make significant contributions to the reductions of CO_2 emissions. In the near term, advanced technologies can increase the efficiency with which process heat is generated, contained, transferred, and recovered. Process and design enhancements can improve quality, reduce waste, minimise reprocessing, reduce the intensity of material use (with no adverse impact on product or performance), and increase in-process material recycling.

Cutting-edge technologies can significantly reduce the intensity with which energy and materials are used. Industrial facilities can implement direct manufacturing processes, which can eliminate some energy-intensive steps, thus both avoiding emissions and enhancing productivity. On the supply side, industry can self-generate clean, high-efficiency power and steam and create products and by-products that can serve as clean-burning fuels. The sector can also make greater use of coordinated systems that more efficiently use distributed energy generation, combined heat and power, and cascaded heat.

In the long term, there is potential for saving energy by re-creating the production process in specific industrial sectors, such as steel making. There are also cross-cutting processes that reduce energy consumption in a particular application, such as catalyst or separation technologies. In addition, cross-cutting options valuable in many sectors include efficient motor and steam systems, combined heat and power, and increased use of recycled materials. Fundamental changes in energy infrastructure could also result in significant CO_2 emissions reductions. Revolutionary changes may include novel heat and power sources and systems, including renewable energy resources, hydrogen, and fuel cells. Innovative concepts for new products and high efficiency processes may be introduced that can take full advantage of recent and promising developments in nanotechnology, micro-manufacturing, sustainable biomass production, biofeedstocks, and bioprocessing. Advanced technologies will likely involve a mix of pathways, such as on-site energy generation, conversion, and utilisation; process efficiency improvements; innovative or enabling concepts, such as advanced sensors and controls, materials, and catalysts; and recovery and reuse of materials and by-products.

Industrial energy efficiency technology development priorities include the following mix of near- and long-term opportunities:[33]

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[33] Note that there are also a number of industrial low-carbon strategies that are being pursued via RD&D, but that do not fall under energy efficiency measures. These include: bioproducts that replace fossil feedstocks for manufacturing fuels, chemicals, and materials; biorefineries that utilise fuels from non-conventional feedstocks to jointly produce materials and value-added chemicals; and for non-combustion sources of CO_2, gas capture, separation and sequestration, or alternative processes or materials. Further,

- Advanced chemical and mechanical heat pumps
- Process heat exchangers and ceramic recuperators
- Advanced materials such as continuous fiber ceramic composites
- Advanced combustions systems for industry
- Cogeneration technology—combined heat and power (CHP)
- Sensors and controls
- Improved membranes for separation systems
- Process electrolysis

In addition, in the long-term, highly efficient coal gasifiers coupled with CO_2 sequestration technology could provide an alternative to natural gas, and even enable the export of electricity and hydrogen to the utility grid and supply pipelines.

Gaps between Current RD&D Spending and 2050 Climate Goals

Energy efficiency is the largest contributor to the *Energy Technology Perspectives* BLUE Map scenario, with over 50% of the expected CO_2 reductions in 2050. The building sector plays a vital role in achieving low-cost CO_2 reductions. In the BLUE Map scenario CO_2 emissions are reduced by 43% below the baseline scenario level in 2050. In addition, direct CO_2 emissions in industry fall by 21% compared with today. In 2050, this represents a CO_2 reduction from baseline scenario emissions of 7.5 Gt to 8.5 Gt.

RD&D Investment Needs

The table below presents a summary of the BLUE Map scenario investment needs for energy efficiency in industry only, because of the difficulties in identifying global RD&D needs for energy efficiency in buildings. The first column shows a low and a high end range of total public and private investment needs for research, development, demonstration and deployment (RDD&D). The second column is an estimate of the range of MEF countries' total RD&D needs (RDD&D less investment in deployment) making an assumption that RD&D needs are 10-20% of the average of low/high RDD&D needs, that total RD&D investment needs can be annualised over 40 years and that the MEF countries' portion should be based on 80% of the annualised value, since the MEF countries make up approximately 80% of global energy sector emissions. These figures are then compared to the current annual investment in public RD&D, in column three, as derived from the best available data reported in the technology discussion above. The RD&D gap is then derived, and shown as a range in the last column, by subtracting the reported current annual investment from the range of required annualised RD&D investments.

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integrated modelling of fundamental physical and chemical properties, along with advanced methods to simulate processes, will stem from advances in computational technology. There are a number of industry-specific sector analyses and roadmaps that provide additional sector-specific details; see http://www.climatetechnology.gov/stratplan/final/CCTP-StratPlan-Ch04-Sep-2006.pdf.

TABLE 10. INDUSTRIAL ENERGY EFFICIENCY SPENDING GAP (IN U.S. DOLLARS)

RDD&D needs to achieve BLUE Map 2050 goals (billion)	MEF countries' annual RD&D needs to achieve BLUE Map 2050 goals (million)	Current annual MEF countries public spending (million)	Annual spending gap for MEF countries (million)
2 000–2 500[34]	4 500–9 000	411	4 089–8 589

This analysis reveals a gap in funding of USD 4.1–8.6 billion for industrial energy efficiency. However, this estimate does not take into account the private sector investment in industrial energy efficiency, and this is likely to be much larger than the public investment. Collecting valid private sector data on industrial energy efficiency RD&D investment is a priority for the future.

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[34] This figure was taken from IEA (2009), *Towards a More Energy Efficient Future: Applying Indicators to Enhance Energy Policy*, OECD/IEA, Paris. Note that this figure overstates the gap in industrial energy efficiency, as it includes low-carbon (and more energy intensive) options such as fuel switching, carbon capture and storage and other options. Further work is needed to isolate the gap for energy efficiency in industry.

6. HIGHER EFFICIENCY AND LOWER-EMISSIONS COAL TECHNOLOGIES

There are three main components of advanced systems for achieving higher efficiency and lower emissions from coal: (1) efficiency improvements in conversion processes; (2) substituting coal with less carbon-intensive fuels; and (3) carbon capture and storage.[35] Advanced coal technologies are being developed to reduce pollutants such as SO_2, NOx, heavy metals (e.g., mercury), and particulates. However, this section of the report will focus primarily on the reduction of CO_2 through efficiency improvements.

Current RD&D Expenditures

The table below identifies current RD&D expenditures on clean coal, including coal production, preparation, and transport;[36] coal combustion;[37] coal conversion (excluding IGCC);[38] and other coal expenses[39] based on the IEA statistics and on data submitted by some MEF countries for this exercise. There is currently no data available on private sector clean coal RD&D expenditures; however, this amount is likely to be significant.

TABLE 11. ESTIMATED PUBLIC RD&D EXPENDITURES ON CLEANER, MORE EFFICIENT COAL TECHNOLOGIES (IN MILLIONS OF U.S. DOLLARS)

United States	217.2
Australia	100.2
Japan	78.9
Germany	47.2
European Commission	43.0
Canada	17.1
Korea	16.9
Italy	16.1

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[35] CCS is covered in the carbon capture, storage and use MEF technology area. However, it is important to note that some countries may be duplicating their reporting between this technology area and the CCS area.

[36] These data include: mining techniques (operations underground and control of operations, mine safety); mechanical preparation of coal; coal degasification and desulphurization; coking, blending and briquetting of coal; and coal transport techniques, including coal slurries.

[37] These data include: conventional utility boilers; fluidized bed combustion; industrial applications; integrated coal gasification combined cycle (IGCC); re-powering, retrofitting, life extension and upgrading of coal power plants; readying of combustion technologies to incorporate CO_2 capture and storage (excluding CO_2 capture and storage); co-firing with biomass; and flue gas cleanup (excluding CO_2 removal).

[38] These data include: coal gasification (except for IGCC), including underground (in-situ) gasification; and coal liquefaction, including hydro generation, Fischer-Tropsch synthesis.

[39] These data include: coal, lignite and peat geological survey techniques, deposit evaluation techniques; peat production and conversion; and R&D on environmental, safety and health aspects of coal.

Russia	5.0
United Kingdom	2.0
Total Public Sector Spending	**543.6**

Data reported in the table are based on 2009 estimates, except for Italy, Japan, Korea and United Kingdom (2008). Data reported in currencies other than U.S. dollars were converted at the prevailing exchange rate of the last eleven months. MEF countries not represented in the table are those for whom data are missing or unknown.

RD&D Priorities

The efficiency of hard coal-fired power plants globally averaged about 35% (LHV[40]) from 1992 to 2005. The best available coal-fired plants can achieve around 47%. The average efficiency of hard coal-fired plants in the United States has not changed significantly over the last 30 years, while the efficiency of plants in Western Europe and China has increased about 6%. The efficiency of most coal-fired power plants operating today is well below current best practice; as a consequence, there is much potential for efficiency improvement. Raising efficiency levels increases the energy output per unit of coal and correspondingly reduces a plant's carbon footprint.

The primary coal-fired power generation technologies are pulverised coal combustion plant (supercritical—SC—and ultra-supercritical—USC), fluidised bed combustion (FBC) plant, and integrated gasification combined cycle (IGCC) plant.

Pulverised Coal Combustion Plant

PCC systems utilising SC and USC steam conditions operate at higher steam temperatures and pressures than conventional PCC units, achieving higher efficiencies and, consequently, significant CO_2 reductions. SC and USC plants are defined by the steam pressures and temperatures they generate. As steam pressure and superheat temperature are increased above 221 bar and 374.5°C, the steam becomes supercritical. Though USC steam often refers to supercritical steam above 590°C, there is no globally agreed definition. Similarly, terms such as advanced supercritical and advanced ultra-supercritical may also be used. Best practice today can achieve efficiencies of 46% or higher. These plants are more than 35% more efficient than today's U.S. fleet of plants, i.e. they would use 35% less coal for the same power output and emit 35% less CO_2. SC steam cycle technology has been used in OECD countries for several decades. Typically, a switch from SC to state-of-the-art USC steam conditions would raise efficiency by more than 6%. Overall, the efficiency of USC coal-fired power plant could be in the range 50% to 55% by 2020.

SC technology is already used in a number of countries. In China, more than 18 GW of SC units were installed in 2006 and, since then, USC technology has also been introduced. There are USC plants in operation in a number of other countries, notably Japan, Denmark, and Germany. USC units operating at temperatures of 700°C and higher are still in the RD&D phase, with nickel-based super-alloys being developed for the steam boilers and turbines. Although USC technologies can cost 12% to 15% more than subcritical steam-cycle technologies, because of their efficiencies, they are competitive. The balance-of-plant cost is 13% to 16% lower in

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[40] LHV = Based on the lower heating value of the coal.

an USC plant, because of reduced coal handling and reduced flue gas handling. The boiler and steam turbine costs can be as much as 40% to 50% higher for an USC plant.

The major barriers to advances in USC steam cycles concern metallurgical and control problems. Developments of the new super-alloys for water and steam boiler tubes and of high-alloy steels that minimise corrosion are expected to result in a dramatic increase in the number of USC plants installed over the next few years. New control equipment and operating strategies will also allow these plants to be more flexible than in the past.

The table below, from the IEA Clean Coal Centre Implementing Agreement's *Clean Coal Roadmap to 2030*,[41] provides a set of milestones and R&D focus areas for SC and USC to 2030.

TABLE 12. MILESTONES AND RD&D PRIORITIES FOR SC AND USC

	Technology Milestone	R&D Required
Current position, 2009	Commercial USC to 25-30 MPa/600°C/620°C, 46% net, LHV, bituminous coals, inland, EU, evaporative tower cooling (44% HHV)	
2009–15	Commercial USC to 25-30 MPa/600°C/620°C	R&D pilot tests for higher temperatures First 700°C demonstration begins operations 2014
2015–17	Commercial USC to 25-30 MPa/600°C/620°C	700°C demonstrations, R&D materials, Side-stream CCS
2017–20	Commercial CCS USC to 35 MPa/700°C/720°C (scrubbing only for 700°C; oxycoal to 600°C)	R&D materials, novel steam cycles, novel post-combustion, oxycoal materials 650°C-700°C
2020–25	Commercial CCS USC to 35 MPa/700°C/720°C (scrubbing only for 700°C; oxycoal to 600°C)	R&D studies supporting commercial plants oxycoal pilot 650°C-700°C
2025–30	Commercial CCS USC to 35 MPa/700°C/720°C; range of capture systems (oxycoal to 650°C only)	>700°C/720°C demonstrations, all with CCS, various types, R&D materials
post–2030	Commercial CCS USC routinely beyond 35 MPa/700°C/720°C all capture systems, all coals, all firing configurations Efficiencies 40-45%, net, LHV, including CO_2 capture, depending on conditions and systems used	

Integrated gasification combined cycle

Integrated gasification combined-cycle technology comprises four basic steps:

- Fuel gas is generated from the partial combustion of solid fuels such as coal at pressure in a limited supply of air or oxygen
- Particulates, sulfur, and nitrogen compounds are removed

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[41] Henderson (2009), available from www.iea-coal.org.uk/site/ieacoal/home.

- The clean fuel gas is combusted in a gas turbine generator to produce electricity;
- The residual heat in the hot exhaust gas from the gas turbine is recovered in a heat recovery steam generator—the steam is used to produce additional electricity in a steam turbine generator

There are 17 IGCC electric generating plants (totalling 4000 MW) operating in the world today; five are using coal or a coal/petcoke combination. The net efficiency of existing coal-fired IGCC plants is around 40% to 43% (LHV). The application of more recent gas turbines would enable this to be improved and, as for PCC plant, future developments should take efficiencies beyond 50%. The investment cost of IGCC is about 20% higher than that of PCC. There is, however, more uncertainty in IGCC costs, as there are no recently built coal-fuelled IGCC plants and the existing ones were originally constructed as demonstrations. Availabilities of IGCC plants have also not yet demonstrated the levels achieved by operating PCC units. Suppliers have plans to bring capital costs within 10% of that of PCC. IGCC reference plant designs of 600 MW have been developed by supplier groupings to encourage market uptake by driving down costs and providing turnkey IGCC plants. This is aimed at facilitating planning and decision-making for power producers. Examples are those from GE-Bechtel and Siemens-ConocoPhillips. With IGCC now available with commercial guarantees, more orders could follow as utilities see costs decreasing and availabilities improving.

Major R&D efforts are ongoing in the field of gasification systems, gas turbines and oxygen production. Research is being carried out to improve efficiency and availability and to reduce capital and operating costs. R&D is focusing on hot gas clean-up, development of large-scale gasifiers with 1200 MW_{th} to 1500 MW_{th} for a single train configuration, novel air separation technologies, improved coal feeding systems, improved slag and fly-ash removal systems, system optimisation, and the integration of fuel cells. Cogeneration of electricity and other products, such as hydrogen or other transportation fuels, is also being considered. Studies have shown that second-generation IGCC plants will need to have an investment cost around that of supercritical plants. Their competitiveness relative to NGCC plants depends on the evolution in natural gas prices.

While IGCC is inherently more expensive than PCC, IGCC with carbon capture appears likely to be less expensive than PCC and carbon capture. IGCC, which operates at pressure, lends itself favourably to efficient capture of CO_2 as the partial pressure of CO_2 in the pre-combustion fuel gas is much higher. The table below, from the IEA Clean Coal Centre's *Clean Coal Roadmap to 2030*, provides a set of milestones and RD&D focus areas for IGCC.

TABLE 13. MILESTONES AND RD&D PRIORITIES FOR IGCC

	Technology Milestone	**R&D Required**
Current position, 2009	Five demonstrations /ex-demonstrations operate, 250-300 MWe, various entrained gasifiers on various coals 600 MWe commercial plants under construction 40-43% net, LHV, 46% new plants (latest F-turbines) on bituminous coals Availability ~80%	

	Technology Milestone	R&D Required
2009–15	Construct, operate commercial plants with latest turbines	Reduce capital cost, increase availability, extend range of coals, gas turbine developments, dry syngas cleaning, non-cryogenic air separation
2015–17	Commercial plants with latest gas turbines some with capture Commercial operation of new water quench gasifiers	Reduce cost, extend range of coals, increase availability
2017–20	Commercial plants operating with latest gas turbines Various gasifier types	Develop H-class IGCC gas turbine
2020–25	Commercial plants operating with H- or J-class gas turbines able to burn high hydrogen Full CO_2 capture available capital cost comparable with PCC for non-capture systems	Studies supporting commercial plants
2025–30	Commercial IGCC with H- or J-class gas turbines with ultra-low NO_x on hydrogen fuel Full CO_2 capture	Studies supporting commercial plants Develop CO_2 gas turbines
post–2030	Advanced IGCC with CO_2 capture as standard using gas separation membranes and shift membrane reactors Capital cost lower than PCC with CCS Efficiency 40-45% LHV, including CO_2 capture, depending on technology, coal type, conditions Eventually other systems with CO_2 gas turbines, CO_2/H_2O gas turbines	

Circulating Fluidised Bed Combustion

Circulating Fluidised Bed Combustion (FBC) is a very flexible method of electricity production—most combustible material can be burned, including coal, biomass and general waste. FBC systems improve the environmental impact of coal-based electricity, reducing SO_2 and NO_x emissions by 90%.

There are hundreds of atmospheric Circulating FBC (CFBC) units operating worldwide, including a number of plants in the 250-300 MW range. Fluidised beds are particularly suited to the combustion of low-quality coals and most of the existing CFBC plants burn such materials. Moving to supercritical cycles is a logical step for very large CFBC units. The world's largest CFBC plant, the supercritical 460 MW, recently constructed at Lagisza, Poland, began operation in 2009, and designs for even larger 600 MW supercritical CFBC units have been developed. Other advantages of CFBC systems include fuel flexibility, good emissions performance and the ability to scale up from a few megawatts to over 500 MW.

FBC units can be employed at high pressure, in which case the boiler exhaust gases can be used to generate additional power. Heat is also recovered from the exhaust of the turbine. This approach has been applied in demonstrations at a small number of locations. The result is a combined gas and steam cycle that gives efficiencies of up to 44%. The first of such units had a capacity of about 80 MW, but two larger units are operating in Japan, at Karita (360MW) and Osaki (250MW), the former using supercritical steam. Second generation pressurised FBC cycles (such as hybrid systems incorporating higher-temperature turbines with supplementary firing of coal-derived gas after the combustor) have been considered in some locations, including Japan.

The table below, from the IEA Clean Coal Centre Implementing Agreement's *Clean Coal Roadmap to 2030*, provides a set of milestones and R&D focus areas for FBC to 2030.

TABLE 14. MILESTONES AND R&D PRIORITIES FOR FBC

	Technology Milestone	R&D Required
Current position, 2009	Commercial subcritical at 200-400 MWe, supercritical offered at 400-600 MWe	
2009–15	First commercial SC CFBC at 25-30 MPa/565°C/580°C	R&D, pilot tests revised boiler designs, materials, refractories, cycles
2015–17	Commercial SC CFBC routinely at 25-30 MPa/565°C/580°C	Demonstration USC CFBC 25-30 MPa/ 600°C/620°C Sidestream CO_2 capture
2017–20	Commercial USC CFBC to 25-30 MPa/600°C/620°C	R&D boiler designs, materials for >620°C CO_2 capture
2020–25	Commercial CCS USC to 30 MPa/650°C/650°C (scrubbing only for 650°C technology)	R&D boiler designs, materials, to 650°C
2025–30	Commercial CCS USC to 30 MPa/650°C/650°C in various technologies	R&D boiler designs, materials for >650°C
post–2030	Commercial CCS USC at up to 35 MPa/700°C/720°C all CO_2 capture systems, all solid fuel types. Efficiencies 40-45%, net, LHV, including CO_2 capture, depending on conditions and systems used	

There are also RD&D investment priorities for coal production, transport, conversion, and biomass co-firing; but there was insufficient time to capture these priorities in this exercise.

Gaps between Current RD&D Spending and 2050 Climate Goals

The contribution of cleaner, more efficient coal combustion to global emissions reductions will be significant. The BLUE Map scenario from the IEA *Energy Technology Perspectives* report sees 18 Gt of CO_2 reductions within the electricity sector in 2050. Of this amount, 8% comes through the deployment of additional SC, USC and IGCC technologies. This is in addition to the plants in the baseline scenario.

RD&D Investment Needs

The table below presents a summary of investment needs for cleaner, more efficient coal technologies. The first column shows a low and a high end range of total public and private investment needs for research, development, demonstration and deployment (RDD&D). The second column is an estimate of the range of MEF countries' total RD&D needs (RDD&D less investment in deployment) making an assumption that RD&D needs are 10-20% of the average of low/high RDD&D needs, that total RD&D investment needs can be annualised over 40 years and that the MEF countries' portion should be based on 80% of the annualised value, since the MEF countries make up approximately 80% of global energy sector emissions. These figures are then compared to the current annual investment in public RD&D, in column three, as derived from the best available data reported in the technology discussion above. The RD&D gap is then derived, and shown as a range in the last column, by subtracting the reported current annual investment from the range of required annualised RD&D investments.

TABLE 15. CLEANER, MORE EFFICIENT COAL TECHNOLOGY (IGCC AND USCSC) RD&D GAPS (IN U.S. DOLLARS)

RDD&D needs to achieve BLUE Map 2050 goals (billion)	MEF countries' annual RD&D needs to achieve BLUE Map 2050 goals (million)	Current annual MEF countries' public spending (million)	Annual spending gap for MEF countries (million)
700–800	1 500–3 000	544	956–2 456

This analysis arrives at a spending gap of USD 1.0–2.5 billion for higher-efficiency coal technologies. There are, however, some important countries with strong cleaner coal RD&D programs that are not captured here due to a lack of verifiable data, including China, India, Indonesia, and South Africa. These countries have sizeable clean coal research projects underway to address power plant efficiency; future estimates should aim to verify spending amounts to provide for a more accurate gap analysis.

7. SMART GRIDS

Smart grids are a new, cross-cutting element of a low-carbon energy future, which integrates transport and electricity and heat/energy storage solutions to deliver energy more efficiently and reliably. They also provide the capacity to integrate low-carbon renewable energy into existing networks to a much greater extent, as well as electric vehicles. Further, smart grid technologies enable consumer interaction with the grid, both through incorporation of small-scale distributed generation technologies and through demand response coupled with greater energy efficiency based on data and information received on real-time prices and conditions. Due to the newness of smart grids as a RD&D priority, there is no internationally accepted definition of the suite of technologies included in the category of smart grids. One definition is:

> *the modernization of the electricity delivery system so it monitors, protects, and automatically optimizes the operation of its interconnected elements—from the central and distributed generator through the high-voltage network and distribution system, to industrial users and building automation systems, to energy storage installation and to end-use consumers and their thermostats, electric vehicles, appliances, and other household devices.*[42]

It is generally accepted that smart grids include the following technology areas:

- Electricity delivery infrastructure (transmission and distribution)
- End-use systems
- Distributed generation and storage (including electric vehicles)[43]
- Information management (such as advanced meter infrastructure, data security and other technologies/practices)

Current Energy RD&D Expenditures

Data on current RD&D expenditures in smart grids is provided by existing IEA statistical data supplemented by some MEF countries' data submissions for this exercise, and is captured under the category of Other Power and Storage Technologies. This category includes the following subcategories:

- Electric power conversion
- Electricity transmission and distribution
- Energy storage (not associated with mobile applications)

An internationally agreed upon definition of smart grid technology areas would allow for a more detailed breakdown of funding expenditures within the technology.

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[42] Report to US National Institute on Standards and Technology (NIST) on Smart Grid Interoperability Standards Roadmap June 17, 2009, p. 6.

[43] There may be some overlap in country reporting between electric vehicles RD&D and smart grids energy storage RD&D.

TABLE 16. ESTIMATED PUBLIC RD&D EXPENDITURES ON SMART GRIDS (IN MILLIONS OF U.S. DOLLARS)

Japan	94.4
Italy	90.6
United States	60.2
Germany	57.4
Korea	27.7
Australia	20.8
European Commission	18.9
United Kingdom	15.6
Canada	12.2
France	12.2
Russia	9.6
Total Public Sector Spending	**419.8**

Data reported in the table are based on 2009 estimates, except for the European Commission (based on EC funds under the Sixth Framework Programme for Research and Technology Development - FP6); France (2007); and Italy, Japan, Korea and United Kingdom (2008). Data reported in currencies other than U.S. dollars were converted at the prevailing exchange rate of the last eleven months. MEF countries not represented in the table are those for whom data are missing or unknown.

The private sector is also an important source of RD&D spending on smart grid technologies. There are many stakeholders, including utilities, service providers, information technology companies, and electricity sector equipment suppliers. Many of these stakeholders serve multiple markets and therefore RD&D data specific to smart grids are difficult to aggregate. As a result, indicative estimates are presented below.

TABLE 17: INDICATIVE ESTIMATES OF PRIVATE SECTOR SPENDING ON SMART GRIDS (IN MILLIONS OF U.S. DOLLARS)

U.S. venture capital investment in smart grid firms from 2004–2008*	820
European Union 2004 transmission and distribution R&D by electricity component manufacturers**	2 000
European Union 2004 transmission and distribution R&D by the electricity supply industry**	140

**Source*: Cleantech Group as reported by The Economist October 10th -16th 2009.
**European Research spending for Electricity Supply, 2008, http://www.ermine.cesiricerca.it/content/files/MAP%20REPORT/map%20report%20final.pdf.

RD&D Priorities

Many of the technologies required for smart grid deployment are reasonably mature, but need to be integrated and applied in the context of an electrical grid. In addition, there are many standards and regulatory and customer/end user aspects that must also be considered along with any technology development. The following is a brief list of smart grid RD&D priorities:[44]

- Component and system integration methodologies to aid in the decrease of time for system design
- Development of system operation and management and control methodologies
- Development of enabling technologies (e.g., super conducting devices, storage technology, power conversion technology, communication technology)
- End use interaction and communication
- System security
- System demonstration projects

Gaps between Current RD&D Spending and 2050 Climate Goals

Smart grid RD&D needs were not directly evaluated in the 2008 IEA *Energy Technology Perspectives (ETP 2008)* study and therefore were developed using an alternative approach. Investments in the electricity sector for new equipment, maintenance and expansion were estimated in ETP 2008, both for the baseline scenario as well as investments required for the Blue Map scenario, aggregated under the categories of generation, transmission and distribution. RD&D for smart grids was developed by considering the overall investments required to meet the Blue Map scenario and estimating a percentage of transmission and distribution investments needed. The percentage allocated was benchmarked against the generation portion of the electricity sector investment for which RD&D was directly estimated in ETP 2008.

RD&D Investment Needs

The table below presents a summary of the investment needs for smart grids. The first column shows a low and a high end range of total public and private investment needs for research, development, demonstration and deployment (RDD&D). The second column is an estimate of the range of MEF countries' total RD&D needs (RDD&D less investment in deployment) making an assumption that RD&D needs are 10-20% of the average of low/high RDD&D needs, that total RD&D investment needs can be annualised over 40 years and that the MEF countries' portion should be based on 80% of the annualised value, since the MEF countries make up approximately 80% of global energy sector emissions. These figures are then compared to the current annual investment in public RD&D, in column three, as derived from the best available data reported in the technology discussion above. The RD&D gap is then derived, and shown as a range in the last column, by subtracting the reported current annual investment from the range of required annualised RD&D investments.

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[44] Global understanding on these priorities will increase with the publication of the planned IEA Smart Grid Roadmap in 2010.

TABLE 18. SMART GRID ENERGY RD&D GAPS (IN U.S. DOLLARS)

RDD&D needs to achieve BLUE Map 2050 goals (billion)	Annual RD&D needs to achieve BLUE Map 2050 goals (million)	Current annual MEF country public spending (million)	Annual spending gap for MEF countries (million)
2 550–3 000	5 560–11 100	420	5 140–10 680

This puts the smart grids spending gap at USD 5.1–10.7 billion. However, this is a first attempt to estimate global RD&D smart grid investment needs, and it is likely low due to the fact that it does not consider a number of smart grid technology areas such as energy storage, demand-side management, and others. On the other hand, there are significant anecdotal reports of private sector spending on smart grid technologies which are not included in the gap estimate. Further analysis is needed to better understand the RD&D needs for this important clean energy technology area.

8. SOLAR ENERGY

Solar energy is used in three different ways: It can be used to produce electricity through either photovoltaic (PV) or concentrated solar power (CSP), and it can also be used to supply heat to the residential sector and industrial processes—solar heating and cooling (SHC). PV power generation involves direct conversion of sunlight into electricity using a solid-state device, the photovoltaic cell. CSP concentrates sunlight several fold to reach higher energy densities and thus higher temperatures. The heat is used to operate a conventional power cycle which drives a generator. In addition to producing electricity, CSP has a wide range of other current or potential uses, including providing direct heating/cooling for buildings or industrial processes, use in water desalination, or to produce fuels such as hydrogen. SHC covers a broad spectrum of technologies, including solar water heating; solar space heating and cooling; using active technologies and passive system designs; day lighting; and agricultural and industrial process heating.

Current Solar Energy RD&D Expenditures

Data on RD&D expenditures was captured in IEA statistical data under the following subcategories: total solar energy;[45] solar heating and cooling (including day lighting);[46] photovoltaic;[47] and solar thermal power and high-temperature applications.[48] The following table presents current public sector RD&D expenditures in solar energy based on IEA statistics and questionnaires submitted by some MEF countries for this mapping exercise.

TABLE 19. ESTIMATED PUBLIC RD&D EXPENDITURES ON SOLAR ENERGY (IN MILLIONS OF U.S. DOLLARS)

United States	190.3
Italy	93.6
Germany	79.0
Korea	58.3
France	47.9
European Commission	44.4
United Kingdom	40.0
Australia	39.0

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[45] Includes data on solar heating and cooling (including day lighting), photovoltaics, and solar thermal power and high temperature applications.

[46] Includes data on collector development; hot water preparation; combined-space heating; active solar heating and cooling; passive solar heating and cooling; day lighting; solar architecture; solar drying; solar-assisted ventilation; swimming pool heating; low-temperature process heating; and other expenses.

[47] Includes data on solar cell development; PV module development; PV-inverter development; building-integrated PV-modules; PV-system development; and other expenses.

[48] Includes data on concentrating collector development; solar-thermal power plants (design, construction and testing); solar-high temperature applications for process heat; solar-chemistry; and other expenses.

China	29.3
India	20.6
Canada	13.6
Russia	6.9
Japan	1.0
Total Public Sector Spending	**663.8**

Data reported in the table are based on 2009 estimates, except for China (government expenditure of CNY 200 million [USD 29.3 million] on solar energy R&D in 2006); the European Commission (based on EC funds under the Sixth Framework Programme for Research and Technology Development - FP6); France (2007); India (budget of INR 1.31 billion [USD 20.6 million] for the period 2007-2008 for solar program of the Ministry of New and Renewable Energy [MNRE]); and Italy, Japan, Korea and United Kingdom (2008). Data reported in currencies other than U.S. dollars were converted at the prevailing exchange rate of the last eleven months. MEF countries not represented in the table are those for whom data are missing or unknown.

According to an assessment recently published by the European Commission,[49] aggregated 2007 research investments in PV technologies are EUR 384 million (USD 571 million) in Europe, with public funds accounting for a substantial share (42%, or about USD 240 million). In parallel, public R&D funding for CSP in 2007 in Europe amounted to EUR 36 million (USD 53 million).

Data on corporate R&D investments in solar energy are available for Europe, based on the same European Commission study, which concludes that corporate R&D investment in PV accounted for EUR 221 million (USD 329 million) in 2007 in the EU, based on the assessment of 30 key companies in this sector, for which data could be obtained. Only four of the top 15 manufacturers of PV modules are located in the EU though, and the EU correspondingly produced 28.5% of global PV cells (EUROBSERVER, 2008).[50] This means that the amounts of private sector spending in the table above are most likely underestimated. Corporate R&D investments in CSP in Europe in the same year were significantly lower than in PV, amounting to EUR 50 million (USD 74 million).

RD&D Priorities

The highest RD&D priorities for PV, CSP and SHC are taken largely from the draft IEA Solar PV and Solar CSP *Roadmaps*, and are listed below.

Photovoltaic Systems

Commercially available modules are generally divided in two broad categories:

- Wafer-silicon systems

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[49] Accompanying document to the European Commission's Communication on Investing in the Development of Low Carbon Technologies (SET-Plan) (SEC(2009) 1296)

[50] EUROBSERV'ER (2008): Photovoltaic Energy Barometer. Total EU installed capacity in 2007 4689.5 MWp.

- Thin films, which include thin-film silicon, copper-indium/gallium-selenide/sulfide (CIGS), amorphous silicon (a-Si) and cadmium telluride (CdTe)

Today, the vast majority of PV modules (> 85% of the market) are based on wafer silicon technology. The main challenge for c-Si modules is to improve resource effectiveness through materials reduction, improved cell concepts and automation of manufacturing.

TABLE 20. PROSPECTS AND KEY R&D ISSUES FOR CRYSTALLINE SILICON TECHNOLOGIES

Crystalline Silicon Technologies	2010–2015	2015–2020	2020-2030/2050
Efficiency targets in %	• Single-crystalline: 21% • Multi-crystalline: 16%	• Single-crystalline: 23% • Multi-crystalline: 18%	• Single-crystalline: 27% • Multi-crystalline: 21%
Industry manufacturing aspects	• Si consumption <5g/Wp	• Si consumption <3g/Wp	• Si consumption <2g/Wp
R&D aspects	• New silicon materials and processing • Cell contacts, emitters and passivation	• Low defect silicon wafers • Improved device structures	• Wafer equivalent technologies • New device structures with novel concepts

Source: *IEA PV roadmap (forthcoming).*

Increased R&D is needed to bring thin film technologies to market and to create the necessary experience in industrial manufacturing and long-term reliability. The most promising manufacturing R&D areas include improved device structures and substrates, large area deposition techniques, interconnection, roll-to-roll manufacturing, and packaging. The following table summarises the prospects and key R&D issues for thin film technologies until 2030:

TABLE 21. PROSPECTS AND KEY R&D ISSUES FOR THIN FILM TECHNOLOGIES

Thin-Film Technologies	2010–2015	2015–2020	2020–2030
Efficiency targets in %	• Thin film Si: 10% • CIGS: 14% • CdTe: 12%	• Thin film Si: 12% • CIGS: 15% • CdTe: 15%	• Thin film Si: 15% • CIGS: 18% • CdTe: 18%
Industry manufacturing aspects	• High rate deposition • Roll-to-roll manufacturing • Packaging	• Simplified production processes • Low cost packaging	• Large high-efficiency production units
R&D aspects	• Large area deposition processes • Improved substrates and transparent conductive oxides	• Improved cell structures • Improved deposition techniques	• Advances materials and concepts

Source: IEA PV roadmap (forthcoming).

The main short-term (S), medium-term (M) and long-term (L) R&D priorities for PV are:

- Improve the technical performance and cost-efficiency of solar cells, modules, and system components, both for existing as well as for new solar cell technologies (S-L)
- Improve manufacturability of components and systems for industry-scale production with substantial mass production and cost reduction potential (including manufacturing plant demonstration) by utilising economies of scale and scope (S)
- Develop technical solutions for high penetration and integration of PV systems in electricity grids, (e.g., smart grids, storage [S-M])
- Design PV as a building material and architectural element answering technical, functional, and aesthetical requirements and cost targets (S)
- Develop emerging technologies and novel concepts with potentially significant performance and/or cost advantages (M-L)
- Apply life-cycle assessments and reduce environmental impact of PV systems (M-L)
- Develop and implement recycling solutions for the various PV technologies (S-M)
- Continue to investigate alternative semi-conductors for PV use to alleviate the risk of markets preventing developing nations adopting mass roll out of PV (S)

Concentrated Solar Power and Fuels (CSP)

Commercially available and emerging technologies are generally divided in four categories:

- Parabolic trough plants, the most commercially mature technology
- Linear Fresnel Reflectors (LFR)
- Central receiver systems (CRS or “towers”)
- Parabolic dishes

Except for dishes, CSP technologies can provide firm, dispatchable electricity thanks to heat storage and back-up/hybridisation with fuels. Solar-to-electricity efficiencies are about 10% (LFR), 15% (troughs), and 30% (dishes). Tower efficiencies range from 15 to 20% today but could reach 25% to 30% with Rankine cycles and 35% with Brayton and combined cycles.

Always involving hydrogen production, solar fuels using fossil fuels and/or water as feedstock and high temperature concentrated sunlight as primary energy source are currently under development. They will offer new opportunities to increase the solar fraction of the global energy mix beyond electricity generation, through hydrogen blending in gas networks and the manufacturing of liquid fuels and other energy carriers.

R&D priorities are focusing on increasing system efficiency (in particular through higher process temperatures), reducing material consumption, including advanced manufacturing, and automating operations, including advanced dispatch strategies. This involves the following research priorities:

- Materials research
  - Tailored optical properties, stable to ambient conditions or even higher temperatures, deposited on different surfaces
  - High-temperature construction material for receivers, reactors, and thermal storage systems which can withstand cyclic thermal loads
  - Methods for accelerated aging for these new materials to verify lifetime expectations
  - Reduced-cost materials for concentrator optics
- Heat and mass transfer
  - Numerical tools to analyse conjugated heat and mass transfer problems including chemical reaction in complex 3D geometries used in receivers, reactors, and storage systems
  - Optimised cooling systems with low water consumption
- System technology
  - High temperature receivers and power blocks
  - Heat storage systems adapted to higher temperatures[51]
  - Heliostat field and field management for solar towers
  - Large-scale demonstrations to verify and model system behaviour
- Manufacturing technology and logistics designed for assembly at remote construction sites and for large-scale power units
- Measurement technology to identify and monitor optical and mechanical quality for concentrator components in-situ in large solar fields
- Automated control and maintenance
  - Predictive control methods for solar thermal systems based on weather and revenue estimations
  - Self-calibrating tracking systems with high accuracy and reliability
  - Advanced maintenance and cleaning concepts

Solar Heating and Cooling

The main RD&D priorities for SHC are:

- Further innovation in the design of collectors; medium-temperature collectors for process heat (with no concentration) are necessary for new and challenging applications such as solar cooling and solar heat for industrial processes
- Compact heat storage systems that allow a reduction of storage volume
- Thermally-driven cooling devices for industrial applications
- Polymeric materials for solar thermal applications
- Combined solar and heat pump systems
- Solar thermal district heating systems

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[51] Includes the development of new heat transfer fluids that do not breakdown over 400 C° and do not freeze with low temperatures, as well as improvements to storage systems (working fluid used as well as configuration) to provide additional working hours for CSP systems.

- Building integration of solar thermal collectors

Gaps between Current RD&D Spending and 2050 Climate Goals

The future market deployment for solar PV is expected to stay strong. Assuming a conservative average growth rate of 17% in the decade from 2010 to 2020 would bring about a global cumulative installed PV power capacity of 210 GW by 2020. For the following decade, an average growth rate of 11% is assumed which will bring the global cumulative installed photovoltaic power capacity to around 900 GW by 2030. The annual market volume by that time could thus be just over 100 GW. Such a volume will allow PV to make substantial progress with relatively moderate growth rates in the decades from 2030 to 2050. Total cumulative installed PV power capacity could grow to 2 TW by 2040 and 3 TW by 2050, taking into account PV system replacement.[52] This capacity is expected to supply almost 5% of total global electricity generation in 2030 and almost 11% in 2050.

The IEA BLUE Map scenario puts global CSP capacity in 2050 at 630 GW (production 2,200 TWh), with significant storage capacity (load factor 40%, or 3500 hours/year).[53] The SHC abatement potential by 2050 was estimated at 0.5 Gt CO_2 in the BLUE Map scenario.

RD&D Investment Needs

The table below presents a summary of investment needs for solar energy. The first column shows a low and a high end range of total public and private investment needs for research, development, demonstration, and deployment (RDD&D). The second column is an estimate of the range of MEF countries' total RD&D needs (RDD&D less investment in deployment), making an assumption that RD&D needs are 10-20% of the average of low/high RDD&D needs, that total RD&D investment needs can be annualised over 40 years, and that the MEF countries' portion should be based on 80% of the annualised value, since the MEF countries make up approximately 80% of global energy sector emissions. These figures are then compared to the current annual investment in public RD&D, in column three, as derived from the best available data reported in the technology discussion above. The RD&D gap is then derived, and shown as a range in the last column, by subtracting the reported current annual investment from the range of required annualised RD&D investments.

TABLE 22. SOLAR ENERGY RD&D GAPS (IN U.S. DOLLARS)

RDD&D needs to achieve BLUE Map 2050 goals (billion)	MEF countries' annual RD&D needs to achieve BLUE Map 2050 goals (million)	Current annual MEF countries public spending (million)	Annual spending gap for MEF countries (million)
750–890	1 640–3 280	664	976–2 616

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[52] A revised BLUE Map scenario for PV has been developed for the *IEA PV Roadmap (forthcoming)*. The main difference in this scenario compared to the ETP 2008 model is a substantially higher market volume over the next two decades, leading to a capacity of about 3 TWp by 2050.

[53] This analysis only evaluated resources close to consumption centres. The IEA CSP Roadmap (forthcoming in early 2010) will consider long-range DC lines for transportation of CSP electricity, including international exports, and will likely more than double the expected capacities.

This analysis reveals a gap in funding of USD 1-2.6 billion for solar energy. However, this estimate does not include private sector RD&D spending in solar energy, which has exploded over the past decade. Further, other studies have called for much larger spending then estimated in this exercise. For example, a study from the European Photovoltaic Technology Platform[54] estimates the necessary RD&D spending until 2013 for PV in the EU as EUR 6.6 billion, of which 55% private (EUR 3.6 billion), and 45% public (EUR 3 billion). Spread over four years, public investment would be EUR 0.75 billion (about US$1 billion). Therefore, the BLUE Map values might be low. More work is needed to refine the estimate of the true gap. Finally, simply counting public sector spending on RD&D does not capture the full public sector role in advancing technology innovation for solar or other technologies (see box).

BOX 4: STIMULATING INDUSTRY PV R&D IN JAPAN

Japan's Ministry of International Trade and Industry (MITI) initiated PV development under its Sunshine Project (R&D Program on New Energy) by (1) encouraging the broad involvement of cross-sectoral industry, (2) stimulating inter-technology stimulation and cross-sectoral technology spill over, and (3) inducing vigorous industry investment in PV R&D, leading to an increase in industry's PV technology knowledge stock. An increase in this technology knowledge stock contributed to a dramatic increase in solar cell production. These production increases led to a dramatic decrease in solar cell price and an increase in solar cell production. In turn, this increase in solar cell production induced further PV R&D, thus creating a "virtuous cycle" between R&D, market growth and price reduction.

Approximately 40% of MITI's PV R&D budget was appropriated to eight leading PV Firms. An analysis of the results of a correlation analysis of the PV R&D expenditures of these eight firms and MITI's financial support for PV R&D initiated by respective firms indicates that MITI's financial support significantly induced PV R&D expenditures based on a one-year time lag in all firms examined. This demonstrates that the Sunshine Project functioned well in stimulating industry PV R&D by inducing vigorous R&D expenditures. The solar cell production price in 1974, the year the Sunshine Project was started, was JPY 20,000/w; it decreased to JPY 5000/w in 1980, JPY 2000/w in 1983, JPY 1200/w in 1985, JPY 650/w in 1990, and JPY 600/w in 1994, respectively, at current prices.

Source: Watanabe et al. (2000), Industrial dynamism and the creation of a "virtuous cycle" between R&D, market growth and price reduction.

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[54] European Photovoltaic Technology Platform (2009).

9. WIND ENERGY

Wind turbines convert the kinetic energy in the wind into mechanical power; a generator then converts this power into electricity. Wind turbines are usually installed in groups of wind farms to generate large amounts of electricity. Wind farms can be located on land and offshore. Onshore wind has proven to be a commercially viable option with large installed capacities in MEF countries, while offshore wind is an emerging technology area. High-level technology aspects include further progress on cost reduction, better assessments of wind resources and external conditions on land and offshore, construction and operation of especially offshore projects and intelligent solutions for grid integration.

Current RD&D Expenditures

Current RD&D expenditures are captured in IEA statistical data in the following categories: converter development, system integration, on-shore applications, offshore applications and other expenses. Total spending reported below is based on IEA statistics and on data submitted by some MEF countries for the purpose of this mapping exercise.

TABLE 23. ESTIMATED PUBLIC RD&D EXPENDITURES ON WIND ENERGY (IN MILLIONS OF U.S. DOLLARS)

Germany	49.9
United States	31.7
United Kingdom	30.9
Korea	18.4
European Commission	15.9
China	11.7
Canada	8.3
Australia	5.7
Italy	4.4
India	4.3
France	2.5
Japan	1.9
Total Public Sector Spending	**185.6**

Data reported in the table are based on 2009 estimates, except for China (government expenditure of CNY 80 million [USD 11.7 million] on wind energy R&D in 2006); the European Commission (based on EC funds under the Sixth Framework Programme for Research and Technology Development - FP6); France (2007); India (Budget of INR 210 million [USD 4.3 million] for the period 2007-2008); and Italy, Japan, Korea and United Kingdom (2008). Data reported in currencies other than U.S. dollars were converted at the prevailing exchange rate of the last eleven months. MEF countries not represented in the table are those for whom data are missing or unknown.

Data on RD&D investment in wind energy by the private sector are available for Europe, based on an assessment of the Technology Platform Wind, which assumed corporate R&D investments in Europe to be in the order of EUR 175 million in 2006 (USD 260 million).[55] This study is the result of an assessment of some active companies in the sector (see Table 24).

TABLE 24. PRIVATE SECTOR ENERGY RD&D PUBLIC EXPENDITURES ON WIND ENERGY IN EUROPE (2006)

Company	Country	R&D Investment (in millions of U.S. dollars) 2006	Net Sales (in millions of U.S. dollars) 2006	Net Ratio 2006	Sales 2005
Acciona	Spain	33.9	9 408	0.4	0.1
Gamesa	Spain	49.7	3 587	1.4	1.6
Nordex	Germany	16.9	771	2.2	2.9
Repower Systems	Germany	21.0	689	3.1	3.1
Vestas Wind Systems	Denmark	132.9	5 781	2.3	2.4
Clipper Windpower	UK	8.0	9	88.8	193

Source: TPWind, 2008.

More recently, the European Commission conducted a similar study that covers a larger number of companies with a focus on component suppliers and specialised wind energy turbine producers. In this study, based on the assessment of 13 of the largest investors in this sector, the Commission estimated that the aggregated RD&D investment of EU-based companies in 2007 amounted to around EUR 292 million (USD 435).[56] If we consider that EU companies have about 60% of the market, global private RD&D expenditures can be estimated at USD 725 million.

RD&D Priorities

Wind energy technology is proven but continues to focus research and development on new developments in material sciences, power semiconductor technology and information technology. Priorities include:

- Improved assessment and forecast of the wind resource and conditions
- Improvements in efficiency and cost reductions for land-based wind plants
- Improvements in efficiency and cost reductions for offshore plants
- Transmission technology and design
- Operation of power systems with large shares of wind power
- Further weight reduction of rotor and drive train

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[55] TP Wind (2008): European Wind Energy Technology Platform – Strategic Research Agenda. Market Deployment Strategy. From 2008 to 2030.

[56] Accompanying document to the European Commission's Communication on Investing in the Development of Low Carbon Technologies (SET-Plan) (SEC(2009) 1296)

- New concepts for transportation and installation of wind turbines on land and (especially) offshore

In the future, public sector funding for wind RD&D should target early stage research, design and testing, and new offshore technology, rather than later stage development and deployment, where private finance is more likely to be available. The following priorities are based on the forthcoming IEA *Wind Energy Roadmap*.

TABLE 25. WIND ENERGY RD&D PRIORITIES

Wind Energy Technology Actions	Timeline
Improve wind output forecasting models; refine and set standards for wind resource modeling techniques and site-based data measurement with remote sensing technology; deepen understanding of complex terrain, offshore conditions, and icy climates	More accurate output forecast models for use in system operation by 2015
Accelerate development of stronger, lighter materials to enable larger rotors and lighter nacelles, and to reduce dependence on steel for towers; develop super-conductor technology for lighter, more electrically efficient generators; deepen understanding of behaviour of very large, more flexible rotors	Developments ongoing
Develop competitive, alternative foundation-types for use in water depths up to 40m; develop deep-water foundations/sub-surface structures for use in depths up to 200m; fundamentally design new generation of turbines for offshore application, with minimum operations and maintenance needs	Deployment of new foundation types <40 meters (m) depth from 2015; demonstration of <200m foundations from 2020 onwards; demonstration of dedicated offshore turbines from 2020 onwards
Power System and Transmission Technology Actions	
Develop methods to assess the need for additional power system flexibility to enable variable renewable energy deployment; carry out grid studies to examine the opportunities, costs and benefits of high shares of wind power integration	By 2015
Accelerate development of innovative demand-side response, and storage technologies	Developments ongoing
Design and deploy very large, onshore high voltage transmission overlays to link up continental grids (where feasible); design and deploy offshore grids linking existing transmission lines, offshore wind resources and bordering power markets (where appropriate)	By 2030

Source: IEA, *Wind Energy Roadmap* (forthcoming 2009).

Gaps between Current RD&D Spending and 2050 Climate Goals

The *Energy Technology Perspectives* BLUE Map scenario sees wind power providing 2,700 terawatt hours (TWh) annually in 2030, from 1,027 GW of capacity, corresponding to 9% of global electricity production. This rises to 5,200 TWh (12%, 2,016 GW) in 2050. The wind industry suggests that production could increase considerably higher; for example, the Global Wind Energy Council projects wind power to reach 5,400 TWh in 2030, and 9,100 TWh in 2050.

RD&D Investment Needs

The table below presents a summary of the investment needs for wind energy. The first column shows a low and a high end range of total public and private investment needs for research, development, demonstration and deployment (RDD&D). The second column is an estimate of the range of MEF countries' total RD&D needs (RDD&D less investment in deployment) making an assumption that RD&D needs are 10-20% of the average of low/high RDD&D needs, that total RD&D investment needs can be annualised over 40 years and that the MEF countries' portion should be based on 80% of the annualised value, since the MEF countries make up approximately 80% of global energy sector emissions. These figures are then compared to the current annual investment in public RD&D, in column three, as derived from the best available data reported in the technology discussion above. The RD&D gap is then derived, and shown as a range in the last column, by subtracting the reported current annual investment from the range of required annualised RD&D investments.

TABLE 26. WIND ENERGY RD&D GAPS (IN U.S. DOLLARS)

RDD&D needs to achieve BLUE Map 2050 goals (billion)	MEF countries' annual RD&D needs to achieve BLUE Map 2050 goals (million)	Current annual MEF countries' public spending (million)	Annual spending gap for MEF countries (million)
600–700	1 300–2 600	186	**1 114–2 414**

This analysis reveals a gap in funding of US$1.1-2.4 billion for wind energy. In comparison, in 2006, the Technology Platform for Wind Energy suggested a total RD&D budget shortfall of some USD 1.45 billion (EUR 1 billion). Additionally, as with solar and other technologies, RD&D spending alone does not capture the full public role in advancing energy technology innovation. A number of countries have seen success with mandates and/or incentives (see box).

BOX 5. FEED-IN TARIFFS DRIVING RENEWABLE ENERGY R&D IN GERMANY

Feed-in tariffs have been introduced in Germany to encourage the deployment of onshore and offshore wind power, biomass, hydropower, geothermal, and solar PV. Each generation technology is eligible for a different rate according to its size and type. Solar energy receives between EUR 0.457 to 0.624 per kWh, while wind receives EUR 0.055 to 0.091per kWh. Once the technology is built the rate is guaranteed for 20 years. The level of support for deployment in subsequent years declines over time by 1% to 6.5% each year with the rate of decline derived from estimated learning curves.

In 2005 10% of electricity came from renewables (70% supported with feed-in tariffs). The average level of feed-in tariff was EUR 0.0953 per kWh in 2005 (compared to an average cost of displaced energy of EUR 0.047 kWh). The total level of subsidy was EUR 2.4 billion Euro at a cost shared by all consumers of EUR 0.0056 per kWh (3% of household electricity costs).

The 44 TWh of electricity covered by the feed in tariffs was split mostly between wind (61%), biomass (19%) and hydropower (18%). It has succeeded in supporting several technologies. Solar accounted for 2% (0.2% of total electricity) with an average growth rate of over 90% over the last four years. Despite photovoltaic's low share Germany has a significant proportion of the global market with 58% of the capacity installed globally in 2005 (39% of the total installed capacity) and 23% of global production.

Source: STERN REVIEW: The Economics of Climate Change, Part IV: Policy Responses for Mitigation

10. FINDINGS AND CONCLUSIONS: ASSESSING THE GAP

This exercise has attempted to estimate current levels of low-carbon energy technology RD&D investment and identify future priorities. The remaining challenge is to assess the gap between current levels of activity and what may be needed to achieve the halving of global energy-related CO_2 emissions that is envisioned in the IEA *Energy Technology Perspectives* Blue Map analysis.

This estimate is by its nature a preliminary one, as there is a lack of comprehensive, high-quality RD&D data from all countries. The level of private sector technology investment is also not well-known. In addition, the diverse nature and unknown potential of the energy technologies available to mitigate greenhouse gas emissions pose a challenge to those trying to invest public funds in an optimal research, development, and demonstration portfolio. Some important considerations include:

- The pace at which technologies must progress in order to meet performance targets
- The difficulty of the technical challenges
- The uncertainty about the extent to which technical efforts will be successful
- The degree to which a portfolio of technologies should be hedged in order to guard against inadequate outcomes
- The division of innovation investment between the public and private sectors
- The role of supporting policy, including market-based pricing of GHG emissions, technology mandates, financial incentives, and risk mitigating measures, such as loan guarantees.

These and other potential variables may materially affect the pace of technology development and deployment, and indirectly influences the optimal level of public RD&D investment. As a result, developing a systematic assessment of the gap between current levels of government spending on RD&D and those out to 2050 is a challenging task.

For this exercise, the IEA *Energy Technology Perspectives* BLUE Map scenario was used, as it contains a global estimate for the amount of technology deployment that would be required to achieve a 50% reduction in energy-related CO_2 emissions between 2005 and 2050.[57] Figure 1 displays the various technology “wedges” under this scenario that contribute to meeting global climate goals in 2050.

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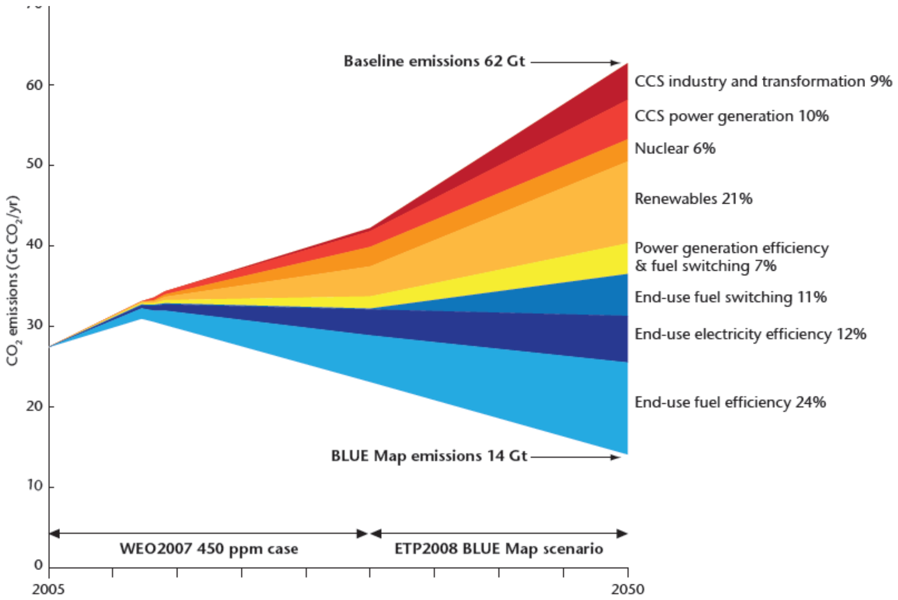
[57] IEA believes this to be broadly consistent with stabilising climate change at 2 C°.

FIGURE 1. ETP BLUE MAP SCENARIO TECHNOLOGY CONTRIBUTIONS



Source: IEA, *Energy Technology Perspectives* (2008)

In effect, the ETP 2008 study outlines potential paths for the deployment of each technology under idealised conditions. In reality, some technologies will not meet expectations and others will be called upon to fill the gap, if the overall goal is to be achieved. Not knowing *a priori* the actual performance of each technology, some over-investment may be needed to ensure sufficient overall success delivering a portfolio of technologies to market. On the other hand, many of these technologies are potential substitutes—for example if end-use efficiency falls short then various low-carbon energy sources may be able to meet the abatement challenge if they can be deployed quickly enough. Therefore, the RD&D gap analysis presented below should be regarded as an initial approximation.

Findings

The ETP 2008 study includes an estimate of RDD&D investment needs by technology for the BLUE Map scenario. Table 27 presents a summary of the ETP investment needs by MEF technology area. The first column is total public and private investment needs for RDD&D. The second column is an estimate of the range of total RD&D needs (RDD&D less investment in commercialisation and deployment), making an assumption that RD&D needs are 10% to 20% of the mean of the RDD&D needs. To arrive at an estimate of the MEF countries' annual RD&D needs, an assumption is then made that total RD&D investment needs can be annualised over 40 years and that the MEF countries' portion should be based on 80% of this annualised value, since the MEF countries make up approximately 80% of global energy sector emissions. Using this methodology, the recommended annualised MEF-wide RD&D investment needs for each technology appears in column three. These figures are then compared to the current annual investment in public RD&D, as derived from the best available data reported in the technology discussions above. The RD&D gap is then derived, and shown as a range, by subtracting the reported current annual investment from the range of required annualised RD&D investments.

It is important to note that the resulting RD&D gap is a total RD&D gap and does not distinguish explicitly between public and private RD&D spending needs, as this is a difficult distinction to make without a full assessment of the evolving policy context and resulting private investment levels. As discussed above in the solar and wind sections, different MEF countries have approached technology innovation in varying ways, with some favouring a strong public sector investment ("technology push"), and others favouring the use of policy ("technology pull"). Experience with the development of advanced energy technologies, particularly where environmental and other public benefits are primary motivations for their development, suggests that the public share is typically greater than 80%. Relying on this experience, it was concluded that at least half of the RD&D gap identified is public investment.

TABLE 27. RD&D GAP ANALYSIS OVERVIEW

	RDD&D Needs to Achieve BLUE Map 2050 Goals (Billion U.S. dollars)[1]	RD&D Needs to Achieve BLUE Map 2050 Goals Using 10% to 20% of RDD&D Mean (Billion U.S. dollars)[2]	MEF Countries' Annual RD&D Needs to Achieve BLUE Map 2050 Goals (Million U.S. dollars)[3]	MEF Countries' Current Annual Public RD&D Spending (Million U.S. dollars)[4]	MEF Countries' Estimated Annual RD&D Spending Gap (Million U.S. dollars)[5]
Advanced vehicles	7 500–9 100	830–1 660	16 600–33 200	1,543	15 057–31 657
Bioenergy	210–250	23–46	460–920	590	-130–330
CCS	2 500–3,000	275–550	5 500–11 000	884	4 617–10 117
Energy efficiency (industry)	2 000–2 500	225–450	4 500–9 000	411	4 089–8 589
Higher efficiency coal	700–800	75–150	1,500–3,000	544	956–2,456
Smart grids	2 550–3 000	278–555	5 560–11 100	420	5 140–10 680
Solar	750–890	82–164	1 640–3 280	664	976–2 616
Wind energy	600–700	65–130	1 300–2 600	186	1 114–2 414
Totals	**16 810–20 240**	**1 853–3 705**	**37 060–74 100**	**5 242**	**31 818–68 858**

Notes

1 RDD&D values taken from ETP 2008 BLUE Map scenario for 2050.

2. RD&D values derived using 10% and 20% of low/high average RDD&D value (Column 1) for Blue Map 2050 scenarios.

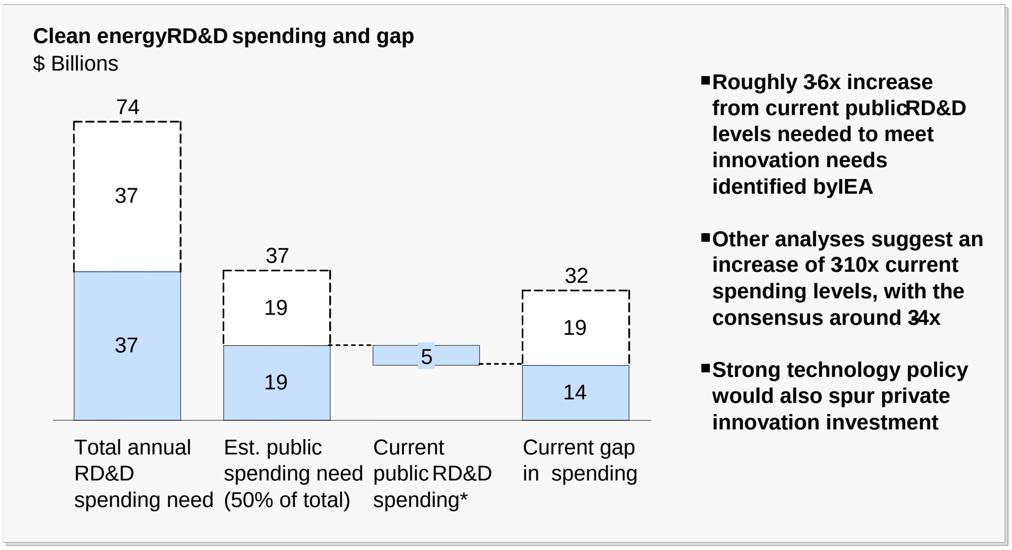
3 Derived from taking RD&D values (column 2) and assuming 80% attributed to MEF countries, and dividing by 40 years, and converting to U.S. dollars.

4 Derived from IEA data call for MEF countries.

5 The difference between columns 3 and 4.

Table 27 shows that MEF countries are spending an annual amount of USD 5,242 million on the selected MEF technology areas. Since the Blue Map 2050 scenario did not address building efficiency, Table 27 and the figure do not include projected annual needs or spending in this area. In addition, this figure does not include MEF country RD&D spending in other energy technology areas, nor does it include one-time investments related to economic recovery spending (discussed below). The required RD&D funding level, by contrast, has been estimated USD 32–69 billion, of which at least half is likely required from public sources. Figure 2 displays the public sector RD&D funding and the funding gap.

FIGURE 2. CLEAN ENERGY RD&D SPENDING AND GAP



* Excludes one-time recovery spending

The increase of steady-state RD&D spending by MEF countries suggested by this analysis is significant, but varies widely for each technology area. The gap appears to be much larger for some technologies, including advanced vehicles and smart grids, than for others (e.g., bioenergy, higher efficiency coal, solar and wind power). Across all technologies combined, the estimated gap in steady-state public sector RD&D spending (assuming public sector spending accounts for 50% of total RD&D spending as discussed above) is USD 14 billion, or about 3 times current levels, and may be as high as USD 32 billion, or 6 times current levels.

Other reports, using different methodologies and sources of information, have suggested similar increases in RD&D investment (Table 28). The most recent of these is that prepared by the Joint Research Council of the European Commission, known as the Strategic Energy Technologies Plan (SET-Plan 2009)[58], which calls for additional investment in EU countries of €50–70 billion over 10 years (an annualised range of USD 7–11 billion). Cost estimates in the proposed SET-Plan for the

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[58] Accompanying document to the European Commission’s Communication on Investing in the Development of Low Carbon Technologies (SET-Plan) (SEC(2009) 1295).

technologies assessed in this exercise suggest a need for an increase of funding on the order of at least 3 times the current average annual spending levels. Other studies have called for increases of two to ten times current levels.

TABLE 28. RD&D INVESTMENT NEEDS FROM OTHER STUDIES

Selected Studies	Estimated RD&D Investment Needs	Methodology
PCAST (1997)	Recommended doubling federal R&D spending	Recommended a bottom-up technology portfolio with an appropriate level of federal R&D investments. http://www.ne.doe.gov/pdfFiles/pcast.pdf
Shock, et al. (1999)	Concluded that energy RD&D needs to be increased by a factor of four	Values energy RD&D by estimating the cost of the insurance needed against four types of energy-related risks (oil price shocks, power supply disruptions, local air pollution and climate change). http://arjournals.annualreviews.org/doi/pdf/10.1146/annurev.energy.24.1.487
Davis and Owens (2003)	Found that the option value of energy R&D justifies increasing spending to 4 times the present level	Examined renewable technologies, and using real options analysis, determined that the optimal level of renewable R&D investment is USD 1.2 billion/yr, approximately four times the U.S. federal program's FY2000 funding level. http://www.nrel.gov/docs/fy03osti/31221.pdf
Stern et al. (2006); Anderson (2006)	Recommended a doubling of the public investment in energy RD&D	Estimates the necessary investment in innovation as the difference between the average incremental costs of investment in new technologies and that of mature technologies. http://www.hm-treasury.gov.uk/stern_review_report.htm
Nemet and Kammen (2007)	Concluded that three to ten times the current level of RD&D spending is needed	Adopts same methodology as Shock et al. (1999)* http://escholarship.org/uc/item/9gn1m38m
UNFCCC (2007)	Concluded that government budgets for energy R&D and support for technology deployment need to double, increased expenditures in 2030 are expected at USD 10 and USD 30 billion respectively	Based on a background paper prepared by the UNFCCC Secretariat, which covers an assessment of investment and financial flows needed in 2030 to meet worldwide mitigation and adaptation requirements under different scenarios of social and economic development. http://unfccc.int/cooperation_and_support/financial_mechanism/items/4053.php
EC (2009)	Concluded that public and private investment in R&D in the EU has to increase at least 3 times current levels.	Identifies the potential gap between present public and private sector R&D investments and the investments required for achieving the European Strategic Energy Technology Plan (SET-Plan) targets for a group of priority technologies. http://ec.europa.eu/energy/technology/set_plan/doc/2009_comm_investing_development_low_carbon_technologies_en.pdf

*Note: While Shock et al. treated stabilisation levels as an uncertain parameter between 650 ppm and 750 ppm with a known probability density function (35%), Nemet and Kammen used a lower CO_2 stabilisation target of 550 ppm.

Analysis

There are a number of important limitations and considerations that need to be taken into account when interpreting these results. First, it is important to stress that international energy RD&D statistics—both public and private—urgently need to be improved through better data quality, transparency and completeness (see box). A number of countries have not reported a full set of RD&D spending data for the MEF technologies. For these reasons, this gap analysis should be considered a provisional first step. MEF countries are encouraged to continue providing updated data and other inputs to improve this analysis.

BOX 6. IMPROVED ENERGY RD&D DATA QUALITY AND AVAILABILITY IS A PRIORITY

Users of energy technology RD&D spending data and trends should be cautious about putting significant emphasis on any one data point. IEA and other energy RD&D data are, by their nature, imperfect reflections of actual activity. There are several challenges that arise when collecting high-quality energy RD&D data, including:

- **Different definitions/methods among countries on RD&D reporting**
    - Countries often report budget and expenditure data in the same year, making it unclear whether there is double-counting. It also makes it difficult to assign a single year to the spending activity, resulting in significant year-to-year changes for a particular energy technology area.
    - There is an insufficient level of disaggregation for some technology areas (notably smart grids and advanced vehicles).
    - There are discrepancies between how governments report multi-year projects; i.e., the budget amount is often defined for the whole project period rather than being reported on a yearly basis.
    - The degree (and transparency) to which regional and local expenditures are included varies considerably; some countries reliably report non-national RD&D expenditures, while others do not.
- **Gaps in IEA time series RD&D data for some countries due to a lack of reporting.**
- **An absence of a centralised, reliable source for RD&D spending data for non-OECD countries.**
- **A lack of reliable data on private spending and trends on RD&D.**
    - In some technology areas (e.g., energy efficiency) the private sector is believed to be the largest funder of RD&D. However, there is no internationally accepted source of private sector low-carbon energy RD&D data.

There is clearly a need to take comprehensive international measures to improve the relevance, quality and comparability of international energy RD&D statistics.

In addition, this assessment may understate public RD&D investment needs in some important ways. This estimate is based on one idealised ETP scenario where each technology delivers without significant failures or delays in development and deployment. To the extent that each technology in the portfolio is attended by risk, in terms of outcomes of its RD&D, additional investment (i.e., hedging against risk) may be required to ensure an adequate outcome for the overall portfolio. Further, forward-funding of the RD&D may be justified to bring advanced technologies to market more quickly, implying that near-term funding levels would be higher than the annualised (equal) investments over 40 years shown here. Perversely, if the correct amount of RD&D investment is not applied at the right time, delays in progress may magnify the need for enhanced RD&D funding later. Taking account these limitations, an argument can be made that a more realistic assessment for RD&D needs over the next 5-10 years, in order to meet the ETP BLUE Map expectations regarding technology readiness and timing, would far exceed the 3 times current levels noted as the low range cited above.

As noted above, however, there are also some important offsetting considerations. First, many of the targeted technologies are close substitutes, so it is not necessary for each to succeed in order to meet abatement goals, as long as successful substitute technologies can deploy sufficiently quickly. Moreover, this analysis focuses on public sector RD&D, which may constitute the smaller overall share of innovation investment for some low-carbon energy technologies. For example, one source estimates total global private sector RD&D investment for low carbon-clean energy technologies at USD 9.5 billion in 2008 (UNEP 2009).

The general pattern is for government-sponsored RD&D to focus on the high risk/return profile stages of technology development; whereas private sector investment more often covers later stages of the innovation pipeline. With supportive policies in place, it is expected that the private sector will increase investment in developing and demonstrating, new low-carbon energy technologies, particularly for those approaching commercialisation. In many sectors (particularly in those that rely on incremental innovations to improve performance rather than a step change in technology), the private sector can be expected to make research investments without public RD&D support, as has been the case recently in some countries for technologies targeted for strong deployment incentives such as advanced biofuels, wind, and solar photovoltaic.

Elaborating on this theme, an important limitation in assessing the role of public investment in RD&D, and hence the RD&D gap, is the differing use of public policy to advance technology in different countries. In addition to providing public RD&D investment (“technology push”), many countries use “technology-pull” policies and incentives to promote greater private sector investment in RD&D (and thereby reduce the role of the public sector). Some examples of existing policies driving energy technology innovation across the MEF countries include:

- Fiscal incentives (including reduced taxes on biofuels in the UK and United States)
- Mandated blending requirements of biofuels with petroleum based fuels in Brazil
- Capital grants for demonstration projects and programs (clean coal programs in the United States, PV programs in the United States, Germany and Japan)
- Feed-in tariffs (wind, PV, and other renewables in Germany; wind and solar schemes in Spain)
- Quota-based schemes (Renewable Portfolio Standards in several U.S. States, vehicle fleet efficiency standards in California)
- Tradable quotas (the Renewables Obligation and Renewable Transport Fuels Obligation in the UK)
- Tenders for tranches of output (the former UK Non Fossil Fuel Obligation), direct subsidies and procurement policies

It is likely that a combined strategy of linked RD&D and mass-market deployment could realise synergies to further accelerate technology progress. Such an approach sends a clear signal to the market and attracts additional investments and innovations. This foster technology efficiency and economies of scale and thereby reduces investment as well as electricity generation costs along the learning curve.

BOX 7. PUTTING GOVERNMENT INVESTMENT IN PERSPECTIVE AS A CONTRIBUTOR TO TECHNOLOGY INNOVATION

A study by Norberg-Bohm (2000) found that, of 20 key innovations in the past 30 years, only one technology was funded entirely by the private sector and nine were totally public. Nemet (2006) explored how the innovation process has occurred to spur rapid PV market growth in recent years. The study found that, of recent cost reductions, 43% were due to economies of scale, 30% to efficiency gains from R&D and learning-by-doing, and 12% were due to reduced silicon costs resulting from information technology (IT) industry demand.

Source: STERN REFVIEW: The Economics of Climate Change, Part IV: Policy Responses for Mitigation

Finally, at least USD 38 billion in public sector spending has been recently committed to support clean energy technologies, as a result of the stimulus packages and other future funding announced in 2008-2009 (Table 29). These data represent future increases in expenditure levels, while the available figures for 2009 represent current spending. Some of this funding is for one-off stimulus actions, but other commitments reflect the increasing importance of clean energy and emissions abatement for governments around the world. Some of this spending is also for deployment, not only RD&D. These commitments included many of the MEF technologies and can be viewed as the first instalment of enhanced efforts by governments to stimulate the development of low-carbon energy technologies.

TABLE 29. EXAMPLES OF STIMULUS FUNDS FOR CLEAN ENERGY TECHNOLOGIES[59]

Announcements of Future Funding			
Technology	**Funding Amount [Millions of U.S. dollars]**	**Status [announced, pending or passed]**	**Comments**
Australia			
Low-carbon power	3 594	Announced	Clean Energy Initiative including carbon capture and storage flagships, US$1.6 billion, and solar flagships, US$1.2 billion
Building energy efficiency	3 125	Announced	Energy Efficient Homes Package (3 years), and Green Building Fund (5 years)
Advanced vehicles	1 016	Announced	Green Car Innovation Fund (10 years)

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[59] This table includes only those countries which submitted data to the IEA for the purposes of this study; there are other countries that have funded clean energy technologies via stimulus packages that are not listed here.

Announcements of Future Funding			
Technology	**Funding Amount [Millions of U.S. dollars]**	**Status [announced, pending or passed]**	**Comments**
Smart grid	78	Announced	National Energy Efficiency Initiative; Smart Grids Initiative (4 years)
Canada			
Low-carbon power	3 445	Passed (except for US$1.05 billion announced)	Includes federal and provincial funding initiatives covering CCS, cellulosic ethanol, energy efficiency, clean energy research and development, and demonstrations.
Building energy efficiency	1 518	Passed	Renovation and retrofit initiatives (2009-2010)
Industrial energy efficiency	This program is funded through a Low-Carbon Power funding initiative from the Province of Quebec accounted for above.	Passed	A portion of funds from the Quebec Green Plan are allocated to energy audits and implementing energy efficient measures (2008-2014).
Advanced vehicles	375	Passed	Automotive Innovation Fund to support strategic, large-scale R&D projects (2009-2014) and Automotive Partnership to enhance automotive research capacity (2008-2014).
Smart grids	950	Announced	Green Infrastructure Fund, part of which is for sustainable energy generation and transmission (2009-2014).
European Commission			
Low-carbon power	1 560	Passed	EC co-funding of up to 12 CCS demonstration projects (2009-2013/2014).
Germany			
Building energy efficiency	8 625	Passed	December 2008- USD 4.5 Billion for energy efficiency for private households; February 2009- USD 1.125 billion for federal buildings, and USD 3 billion for educational institutions

Announcements of Future Funding			
Technology	**Funding Amount [Millions of U.S. dollars]**	**Status [announced, pending or passed]**	**Comments**
France			
Building energy efficiency	600		USD 300: 40% energy consumption reduction and 50% GHG emissions reduction in public buildings; USD 300: fund for improving residential building efficiency (2009-2010).
Advanced vehicles	995		USD 440: development, renovation and construction of high-speed train lines; USD 225: water/port efficiency projects; USD 330: early buy-back of low efficiency vehicles (2009-2010).
United States			
Low-carbon power	4 377	Passed	Includes CCS (USD 3401); wind (USD 118); Bioenergy (USD 817); and solar (USD 41) for the period 2009-2010.
Industrial energy efficiency	2 050	Passed	2009-2010
Advanced vehicles	994	Passed	2009-2010
Smart grids	4 131	Passed	2009-2010
Total	**37 513**		

Next Steps

Addressing climate change will clearly require a dramatic increase in government and private sector investment in low-carbon energy RD&D. This mapping exercise attempts to quantify the magnitude of this investment, based on current reported public sector spending levels, stated technology priorities, and assessments of technology needs out to 2050. A preliminary conclusion is that while recently announced packages are a first step, public funding will likely need to be increased between 3-10 times current amounts to achieve climate change goals. In addition, there is a need for increased effort to provide improved energy technology RD&D data for the public and private sector, along with policy analysis and transparency as we attempt to accelerate global low-carbon energy technology adoption as a key strategy to address the risks of climate change. This study recommends the following:

- **Increase public sector investments.** MEF countries should consider making a coordinated commitment to increase clean energy RD&D spending to strategically address the most serious investment gaps first. The recent financial stimulus package spending announcements for low-carbon energy technologies are a start in this direction. Long-term pledges would be valued in this regard.
- **Expand international technology collaboration.** One way to begin to address the RD&D gap is to increase and leverage public resources and improve efficiency of national energy RD&D investments by expanding international cooperation (e.g., exchange of low-carbon investment plans and collaborative R&D such as Implementing Agreements) and leveraging scarce RD&D funding via collaboration and division of labour (e.g., joint project planning and cost-sharing). The MEF Technology Action Plans and corresponding IEA technology roadmaps, as well as other energy technology assessment and capacity building efforts under the UNFCCC and other contexts, may help guide these efforts.
- **Improve upon this gap analysis for specific technologies.** Further investigation is warranted in both data collection and improving the scope/coverage of various technology elements. This is particularly important in emerging areas like smart grids and advanced vehicles, as well as for energy efficiency in buildings, an area where the main focus has been on implementation rather than RD&D. Future analysis should include a more thorough, technology-specific analysis of the role of policies and incentives, combined with direct government funding, in advancing energy technology innovation. The next step should be to engage public and private sector stakeholders on a technology-specific basis to review and refine the estimates and assumptions made in each of the technology discussions above.
- **Improve public and private RD&D data quality and transparency.** The MEF country governments should consider providing leadership for other countries by committing to provide more detailed, better-quality annual energy RD&D expenditure data for the clean energy technology areas, and consider actively engaging the private sector—via sector or other organisations—to provide more transparent data on low-carbon energy RD&D spending on a regular basis.

11. RELEVANT IEA IMPLEMENTING AGREEMENTS

The MEF countries aim to ensure energy security and address climate change in a cost-effective way via greater international technology cooperation. To encourage collaborative efforts to meet these energy challenges, the IEA created a number of technology Implementing Agreements that allow interested member and non-member governments or other organisations to pool resources to foster the research, development and deployment of particular technologies.

For more than 30 years, this network of international technology collaboration has been a fundamental building block in facilitating progress of new or improved energy technologies. More information for each of the relevant technology agreements can be found on the individual website listed below.

Advanced Vehicles

- IEA Advanced Fuel Cells Implementing Agreement, http://www.ieafuelcell.com/
- Implementing Agreement on Advanced Materials for Transportation Application, http://www.iea-ia-amt.org/
- Advanced Motor Fuels Implementing Agreement, http://www.iea-amf.vtt.fi/
- Hybrid and Electric Vehicle Implementing Agreement, http://www.ieahev.org/

Bioenergy

- IEA Bioenergy Implementing Agreement, http://www.ieabioenergy.com/
- Implementing Agreement on Renewable Energy Technology Deployment, http://www.iea-retd.org/

Carbon Capture, Use and Storage

- IEA Clean Coal Centre Implementing Agreement, http://www.iea-coal.org.uk/site/ieacoal/home
- IEA Greenhouse Gas R & D Programme, http://www.ieagreen.org.uk/

Energy Efficiency in Buildings

- IEA Energy Conservation in Buildings and Community Systems, http://www.ecbcs.org/
- Energy Conservation through Energy Storage Implementing Agreement, http://www.energy-storage.org/
- IEA Heat Pump Centre, http://www.heatpumpcentre.org/
- IEA Efficient Electrical End-Use Equipment Implementing Agreement, http://www.iea-4e.org/

Energy Efficiency in Industry

- Industrial End-Use Technologies and Systems, http://www.iea-iets.org/

Higher Efficiency Coal

- IEA Clean Coal Centre Implementing Agreement, http://www.iea-coal.org.uk/site/ieacoal/home
- IEA Implementing Agreement for Energy Conservation and Emissions Reduction in Combustion, http://ieacombustion.com/default.aspx

Marine Energy

- IEA Ocean Energy Systems, http://www.iea-oceans.org/

Smart Grids

- IEA Demand-side Management Programme, http://www.ieadsm.org/
- Electricity Networks Analysis, Research and Development, http://www.iea-enard.org/
- Energy Conservation through Energy Storage Implementing Agreement, http://www.energy-storage.org/
- High-temperature Superconductivity, http://www.superconductivityiea.org/

Solar Energy

- IEA Photovoltaic Power Systems Programme, http://www.iea-pvps.org/
- Implementing Agreement on Renewable Energy Technology Deployment, http://www.iea-retd.org/
- Solar Heating & Cooling Programme, http://www.iea-shc.org/
- IEA SolarPACES (concentrating solar power), http://www.solarpaces.org/

Wind Power

- Implementing Agreement for Co-operation in the Research, Development and Deployment of Wind Energy Systems, http://www.ieawind.org/
- Implementing Agreement on Renewable Energy Technology Deployment, http://www.iea-retd.org/

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