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The Next Frontier to Realize Industrial Energy Efficiency

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Abstract. Industry contributes directly and indirectly (through consumed electricity) about 37% of the global greenhouse gas emissions, of which over 80% is from energy use. Total energy-related emissions, which were 9.9 $GtCO_2$ in 2004, have grown by 65% since 1971. In the near future, energy efficiency is potentially the most important and cost-effective means for mitigating greenhouse gas emissions from industry. Despite the growth in energy use, industry has almost continuously improved its energy efficiency over the past decades. Yet, climate change and other future challenges will drive a quest for further energy-efficiency improvement. Both improvements with which industrial processes use energy and materials are key to realize strong reductions energy use. This paper discusses the potential contribution of industrial energy *and* material efficiency technologies to reduce energy use and greenhouse gas emissions to 2030 and beyond, and ways to realize them.

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1. Introduction

Industry uses almost 40% of worldwide energy. It contributes almost 37% of global greenhouse gas emissions (GHG). In most countries, CO_2 accounts for more than 90% of CO_2-eq GHG emissions from the industrial sector [1,2]. These CO_2 emissions arise from three sources: (1) the use of fossil fuels for energy, either directly by industry for heat and power generation or indirectly in the generation of purchased electricity and steam; (2) non-energy uses of fossil fuels in chemical processing and metal smelting; and (3) non-fossil fuel sources, for example cement and lime manufacture. Industrial processes, primarily chemicals manufacture and metal smelting also emit other GHGs, including methane (CH_4), nitrous oxide (N_2O), HFCs, CFCs, and PFCs,

The energy intensity of industry has steadily declined in most countries since the oil price shocks of the 1970s. Historically, industrial energy-efficiency improvement rates have typically been around 1%/year. However, various countries have demonstrated that it is possible to double these rates for extended periods of time (i.e. 10 years or more) through the use of policy mechanisms. Still, large potentials exist to further reduce energy use and GHG emissions in most sectors and economies. In this paper we discuss trends in industrial energy use and GHG emissions, and then focus on the opportunities to reduce the emissions, most notably by improved energy efficiency.

2. Historic Trends

Globally, energy-intensive industries still emit the largest share of industrial GHG emissions. Hence, this paper focuses on the key energy-intensive industries: iron and steel, chemicals (including fertilisers), petroleum refining, non-metallic minerals, and pulp and paper. The production of energy-intensive industrial goods has grown dramatically and is expected to continue growing as population and per capita income increase. Since 1970, global annual production of cement increased 336%; aluminium 252%; steel 95%, ammonia 353% and paper, 190%. Much of the world's energy-intensive industry is now located in developing nations. In 2006, developing countries accounted for 74% of global cement manufacture, 63% of global nitrogen fertilizer production, about 50% of global primary aluminium production, and 48% of global steel production.

In 2006 developing countries accounted for 49% of final energy use by industry, developed countries, 40%, and economies in transition, 11%. Since many facilities in developing nations are new, they sometimes incorporate the latest technology and have the lowest specific emission rates [3]. Many older, inefficient facilities remain in both industrialised and developing countries. However, there is a huge demand for technology transfer (hardware, software and know-how) to developing nations to achieve energy efficiency and emissions reduction in their industrial sectors. Though large scale production dominates these energy intensive industries globally small and medium sized enterprises (SMEs) have significant shares in many developing countries which create special challenges for mitigation efforts.

Total industrial sector GHG emissions are currently estimated to be about 12 $GtCO_2$-eq/yr. Global and sectoral data on final energy use, primary energy use, and energy-related CO_2 emissions including indirect emissions related to electricity use, for 1971 to 2005 are shown in Table 1. In 1971, the industrial sector used 91 EJ of primary energy, 40% of the global total of 227 EJ. By 2005, industry's share of global primary energy use declined to 38%.

Table 1. Industrial sector final energy, primary energy and energy-related carbon dioxide emissions, nine world regions, 1971–2005

	Final Energy (EJ)			**Primary Energy (EJ)**			**Energy-Related Carbon Dioxide, including indirect emissions from electricity use ($MtCO_2$)**		
	1971	**1990**	**2005**	**1971**	**1990**	**2005**	**1971**	**1990**	**2005**
Pacific OECD	6.02	8.04	10.09	8.29	11.47	14.29	524	710	821
North America	20.21	19.15	21.89	25.88	26.04	28.06	1,512	1,472	1461
Western Europe	14.78	14.88	16.69	19.57	20.06	21.83	1,380	1,187	1144
Central and East Europe	3.75	4.52	2.80	5.46	7.04	3.85	424	529	246
Former Soviet Union	11.23	18.59	10.81	15.67	24.63	15.00	1,095	1,631	873
Developing Asia	7.34	19.88	37.88	9.38	26.61	60.47	714	2,012	4505
Latin America	2.79	5.94	8.39	3.58	7.53	11.16	178	327	480
Sub-Saharan Africa	1.24	2.11	2.44	1.7	2.98	3.56	98	178	203
Middle East & North Africa	0.83	4.01	6.72	1.08	4.89	8.65	65	277	468
World	68.2	97.1	117.7	90.6	131.3	166.9	5,99	8,32	10,19

Notes

1) Biomass energy included

2) Industrial sector 'final energy' use excludes energy consumed in refineries and other energy conversion operations, power plants, coal transformation plants [4,5]. However, this energy is included in 'primary energy'. Upstream energy consumption was reallocated by weighting electricity, petroleum and coal products consumption with primary factors reflecting energy use and loses in energy industries. Final energy includes feedstock energy consumed, for example in the chemical industry. 'CO_2 emissions' in this table are higher than in IEA's Manufacturing Industries and Construction category because they include upstream CO_2 emissions allocated to the consumption of secondary energy products, such as electricity and petroleum fuels. To reallocate upstream CO_2 emissions to final energy consumption, we calculate CO_2 emission factors, which are multiplied by the sector's use of secondary energy [6].

Energy use represents the largest source of GHG emissions in industry (83%). In 2005, energy use by the industrial sector resulted in emissions of 10.2 $GtCO_2$, 38% of global CO_2 emissions from energy use. Direct CO_2 emissions totalled 5.2 Gt, the balance being indirect emissions associated with the generation of electricity and other energy carriers. The developing nations' share of industrial CO_2 emissions from energy use grew from 18% in 1971 to 55% in 2005. In 2000, CO_2 emissions from non-energy uses of fossil fuels (e.g., production of petrochemicals) and from non-fossil fuel sources (e.g., cement manufacture) were estimated to be 1.7 $GtCO_2$ (Olivier and Peters, 2005). Industrial emissions of non-CO_2 gases totalled about 0.4 $GtCO_2$-eq in 2000 and are projected to be at about the same level in 2010. Direct GHG emissions from the industrial sector are currently about 7.3 $GtCO_2$-eq, and total emissions, including indirect emissions, are about 12.3 $GtCO_2$-eq.

3. Energy Efficiency and GHG Emission Mitigation

The International Energy Agency [7] found, "The energy intensity of most industrial processes is at least 50% higher than the theoretical minimum." This provides a significant opportunity for reducing energy use and its associated CO_2 emissions. A wide range of technologies have the potential for reducing industrial GHG emissions, of which energy efficiency is one of the most important, especially in the short- to mid-term. Other opportunities include fuel switching, material efficiency, renewables and reduction of non-CO_2 GHG emissions. Within each category, some technologies, such as the use of more efficient motor systems, are broadly applicable across all industries; while others are process-specific.

As the largest part of industrial energy consumption is used to process materials and manufacture a huge diversity of products out of these materials, the way that materials are used is also an important driver for industry's energy use and emissions. Hence, improving material efficiency, the total amount of materials used to provide a service (or product), is important.

3.1. Cross-Cutting Technologies

Approximately 65% of electricity consumed by industry is used by *motor systems*. The efficiency of motor-driven systems can be increased by reducing losses in the motor windings, using better magnetic steel, improving the aerodynamics of the motor and improving manufacturing tolerances. However, maximizing efficiency requires properly sizing of all components, improving the efficiency of the end-use devices (pumps, fans, etc.), reducing electrical and mechanical transmission losses, and the use of proper operation and maintenance procedures. Implementing high-efficiency motor driven systems, or improving existing ones, in the EU-25 could save about 30% of the energy consumption, up to 202 TWh/yr [8], in the USA, over 100 TWh/yr by 2010 [9].

The IEA [7] estimates that *steam generation* consumes about 15% of global final industrial energy use. The efficiency of current steam boilers can be as high as 85%, through general maintenance, improved insulation, combustion controls and leak repair, improved steam traps and condensate recovery. Studies in the USA identified energy-efficiency opportunities with economically attractive potentials up to 18–20% [10,11].

Large potentials still exist for *energy recovery* techniques. It can take different forms: heat, power and fuel recovery. The discarded heat can be re-used in other processes onsite, or used to preheat incoming water and combustion air. New, more efficient heat exchangers or more robust (e.g., low-corrosion) heat exchangers are being developed continuously, improving the profitability of enhanced heat recovery. Waste heat conversion by heat transformers or by thermo-electrical conversion, and power electronics to electricity poses great potential. Typically, cost-effective energy savings of 5 to 40% are found in process integration analyses in almost all industries [12].

Power can be recovered from processes operating at elevated pressures using even small pressure differences to produce electricity through pressure recovery turbines. Examples of pressure recovery opportunities are blast furnaces, fluid catalytic crackers and natural gas grids. Power recovery may also include the use of pressure recovery turbines instead of pressure relief valves in steam networks and organic Rankine cycles from low-temperature waste streams. Bailey and Worrell [13] found a potential savings of 1 to 2% of all power consumed in the USA, which would mitigate 21 $MtCO_2$.

Cogeneration (also called Combined Heat and Power, CHP) involves using energy losses in power production to generate heat and/or cold for industrial processes and district heating, providing significantly higher system efficiencies. Industrial cogeneration is an important part of power generation in Germany and the Netherlands, and in many countries. Mitigation potential for industrial cogeneration is estimated at almost 150 $MtCO_2$ for the USA [14], and 334 $MtCO_2$ for Europe [15].

3.2. Sector-Specific Technologies and Measures

This section discusses process specific mitigation options, focusing on energy intensive industries: iron and steel, chemicals, petroleum refining, minerals (cement, lime and glass) and pulp and paper. These industries (excluding petroleum refining) accounted for almost 70% of industrial final energy use in 2003 [7]. With petroleum refining, the total is over 80%. All the industries discussed in this section can also benefit from application of the technologies and measures described above.

Iron and Steel. Global steel industry with production of 1129 Mt in 2005 emits 2200 to 2500 $MtCO_2$ or about 6 to 7% of global anthropogenic emissions, including emissions from coke manufacture and indirect emissions due to power consumption. Emissions per tonne of steel vary widely between countries: 1.25 tCO_2 in Brazil, 1.6 tCO_2 in Korea and Mexico, 2.0 tCO_2 in the USA, and 3.1 to 3.8 tCO_2 in China and India [16]. These differences are due to a range of factors including fuel mix, different degrees of integration but mainly due to the age, type of technology, and levels of retrofitting.

Iron and steel production is a combination of batch processes. Steel industry efforts to improve energy efficiency include enhancing continuous production processes to reduce heat loss, increasing recovery of waste energy and process gases, and efficient design of electric arc furnaces, for example scrap preheating, high-capacity furnaces, foamy slagging and fuel and oxygen injection. The potential for energy efficiency improvement varies based on the production route used, product mix, energy and carbon intensities of fuel and electricity, and the boundaries chosen for the evaluation. Kim and Worrell [16] benchmarked the energy efficiency of steel production to the best practice performance in five countries with over 50% of world steel production, finding potential CO_2 emission reductions due to energy efficiency improvement varying from 15% (Japan) to 40% (China, India and the US). A study in 2000 estimated the 2010 global technical potential for energy efficiency improvement with existing technologies at 24% [17] and that an additional 5% could be achieved by 2020 using advanced technologies such as smelt reduction and near net shape casting. Economics may limit the achievable emission reduction potential. A recent analysis of the efficiency improvement of electric arc furnaces in the US steel industry found that the average efficiency improvement between 1990 and 2002 was 1.3%/yr, of which 0.7% was due to stock turnover and 0.5% due to retrofit of existing furnaces [18].

Chemicals and Fertilizers. The chemical industry is highly diverse, with thousands of companies producing tens of thousands of products in quantities varying from a few kilograms to thousand of tons. Separation, chemical synthesis and process heating are the major energy consumers in the chemical industry, and include technology advances that could reduce energy consumption in each area, for example improved membranes for separations, more selective catalysts for synthesis and greater process integration to reduce process heating requirements. *Ethylene*, which is used in the production of plastics and many other products, is produced by steam cracking hydrocarbon feedstocks, from ethane to gas oil. The heavier the feedstock, the more and heavier the byproducts, and the more energy consumed per tonne of ethylene produced. Ren *et al.* [19] report that steam cracking for olefin production is the most energy consuming process in the chemicals industry, accounting for emissions of about 180 $MtCO_2$/yr and that significant reductions are possible. Cracking consumes about 65% of the total energy used in ethylene production, but use of state-of-the-art technologies (e.g., improved furnace and cracking tube materials and cogeneration using furnace exhaust) could save up to about 20% of total energy. The remainder of the energy is used for separation of the ethylene product, typically by low-temperature distillation and compression. Up to 15% total energy can be saved by improved separation and compression techniques (e.g. absorption technologies for separation).

The *fertilizer industry* uses 1.2% of world energy consumption. More than 90% of this energy is used in the production of ammonia (NH_3). However, as the result of energy efficiency improvements, modern ammonia plants are designed to use about half the energy per tonne of product than those designed in 1960s, with design energy consumption dropping from over 60 GJ/t NH_3 in the 1960s to 28 GJ/t NH_3 in the latest design plants, approaching the thermodynamic limit of about 19 GJ/t NH_3. Benchmarking data indicate that the best-in-class performance of operating plants ranges from 28.0 to 29.3 GJ/t NH_3 [20,21]. The newest plants tend to have the best energy performance, and many of them are located in developing countries, which now account for 63% of nitrogen fertilizer production. Individual differences in energy performance are mostly determined by feedstock (natural gas compared with heavier hydrocarbons) and the age and size of the ammonia plant [20, 22].

Petroleum Refining. As of the beginning of 2004, there were 735 refineries in 128 countries with a total crude oil distillation capacity of 82.3 million barrels per day. Petroleum industry operations consume up to 15 to 20% of the energy in crude oil, or 5 to 7% of world primary energy, with refineries consuming most of that energy . Worrell and Galitsky [23], based on a survey of US refinery operations, found that most petroleum refineries can economically improve energy efficiency by 10–20%, and provided a list of over 100 potential energy saving steps. The petroleum industry has had long-standing energy efficiency programmes for refineries and the chemical plants with which they are often integrated. These efforts have yielded significant results. Exxon Mobil reported over 35% reduction in energy use in its refineries and chemical plants from 1974 to 1999, and in 2000 instituted a programme whose goal was a further 15% reduction. Chevron reported a 24% reduction in its index of energy use between 1992 and 2004.

Cement. Global cement production grew from 594 Mt in 1970 to 2550 Mt in 2006. In 2006 developed countries produced 529 Mt (21% of world production) and developing countries 1886 Mt (74%). The production of clinker emits CO_2 from the calcination of limestone. The major energy uses are fuel for the production of clinker and electricity for grinding raw materials and the finished cement. Based on average emission intensities, total emissions in 2005 are estimated at 1800 $MtCO_2$ to 2000 $MtCO_2$, or about 7% of global CO_2 emissions, half from process emissions and 40% from direct energy use, and 10% from used electricity. Global average CO_2 emission per tonne cement production is estimated by Worrell *et al*. [24] at 814 kg. CO_2 emission/t cement vary by region from a low of 700 kg in Western Europe and 730 kg in Japan and South Korea, to a high of 900, 930, and 935 kg in China, India and the United States [24,25]. This reflects differences of fuels mixes, cement types but also kiln technologies, with age and size being critical parameters.

Emission intensities have decreased by approximately 0.9%/yr since 1990 in Canada, 0.3%/yr (1970–1999) in the USA, and 1%/yr in Mexico [26,27,28]. Benchmarking and other studies have demonstrated a technical potential for up to 40% improvement in energy efficiency [29,30]. Countries with a high potential still use outdated technologies, like the wet process clinker kiln.

Pulp and Paper. Direct emissions from the pulp, paper, paperboard and wood products industries are estimated to be 264 MtCO2/yr [31]. The industry's indirect emissions from purchased electricity are less certain, but are estimated to be 130 to 180 MtCO2/yr [32]. Mitigation opportunities in the pulp and paper industry consist of energy efficiency improvement, cogeneration, increased use of (self-generated) biomass fuel, and increased recycling of recovered paper. As the pulp and paper industry consumes large amounts of motive power and steam, the cross-cutting measures discussed above apply to this industry.

Because of increased use of biomass and energy efficiency improvements, the GHG emissions from the pulp and paper industry have been reduced over time. Since 1990, CO_2 emission intensity of the European paper industry has decreased by approximately 25% [32], the Australian pulp and paper industry about 20%, and the Canadian pulp and paper industry over 40%. Fossil fuel use by the US pulp and paper industry declined by more than 50% between 1972 and 2002. However, despite these improvements, Martin *et al*. [33] found a technical potential for GHG reduction of 25% and a cost-effective potential of 14% through widespread adoption of 45 energy-saving technologies and measures in the US pulp and paper industry. Inter-country comparisons of energy-intensity in the mid-1990s suggest that fuel consumption by the pulp and paper industry could be reduced by 20% or more in a number of countries by adopting best practices [34].

3.3. Material Efficiency Opportunities

Re-designing products so that they require less material throughout the production chain, without reducing quality, is an important area for GHG emissions reductions, which has not yet been sufficiently addressed in technology and policy. Yet, the impact can be large. In fact, a large part of the energy savings realized in the iron and steel industry are due to improved material efficiency as material losses between different production steps (e.g. continuous casting to replace ingot casting) were reduced.

Recycling is the best-documented material efficiency option for the industrial sector. Recycling of steel in electric arc furnaces accounts about a third of world production and typically uses 60–70% less energy. Recycling aluminium requires only 5% of the energy of primary aluminium production. Recycled aluminium from used products and sources outside the aluminium industry now constitutes 33% of world supply and is forecast to rise to 40% by 2025. Recycling is also an important energy saving factor in other non-ferrous metal industries, as well as the glass and plastics industries.

Materials substitution, for example the addition of wastes (blast furnace slag, fly ash) and geo-polymers to clinker to reduce CO_2 emissions from cement manufacture, is also applicable to the industrial sector. Use of granulated slag in Portland cement may increase energy use in the steel industry, but can reduce both energy consumption and CO_2 emissions during cement production by about 40%.

Co-siting of industries can achieve GHG mitigation by allowing the use of byproducts as useful input and by integrating energy systems. In Kalundborg (Denmark) various industries (e.g., cement and pharmaceuticals production and a CHP plant) form an eco-industrial park that serves as an example of the integration of energy and material flows. Heat-cascading systems, where waste heat from one industry is used by another, are a promising cross-industry option for saving energy. Based on the Second Law of Thermodynamics, Grothcurth et al. [34] estimated up to 60% theoretical energy saving potential from heat cascading systems. However, as the potential is dependent on many site-specific factors, the practical potential of these systems may be limited to approximately 5% [35]. Other examples are the use of (waste) fuels generated by one industry and used by another industry, while this results in GHG emission reductions, this may not result in energy-efficiency improvement.

Some materials substitution options, for example the production of lightweight materials for vehicles, can increase GHG emissions from the industrial sector, which will be more than offset by the reduction of emissions from other sectors. Realizing opportunities for material efficiency will require the re-thinking of supply chains, but also a new vision and tools for the product design that include these elements in the design of products and production processes.

3.4. Realizing the Potential: Energy Management

Changing how energy and material is managed by implementing an organization-wide energy management program is one of the most successful and cost-effective ways to bring about efficiency improvements. Continuous improvements to energy efficiency typically only occur when a strong organizational commitment exits. A sound energy management program is required to create a foundation for positive change and to provide guidance for managing energy throughout an organization. Energy management programs help to ensure that energy efficiency improvements do not just happen on a one-time basis, but rather are continuously identified and implemented in an ongoing process of continuous improvement. Without the backing of a sound energy management program, energy efficiency improvements might not reach their full potential due to lack of a systems perspective and/or proper maintenance and follow-up.

In companies without a clear program in place, opportunities for improvement may be known but may not be promoted or implemented because of organizational barriers. These barriers may include a lack of communication among plants, a poor understanding of how to create support for an energy efficiency project, limited finances, poor accountability for measures, or organizational inertia to changes from the status quo. Even when energy is a significant cost, many companies still lack a strong commitment to improve energy management.

A successful program in energy management begins with a strong organizational commitment to continuous improvement of energy efficiency. This involves assigning oversight and management duties to an energy director, establishing an energy policy, and creating a cross-functional energy team (see the section on energy teams below). Steps and procedures are then put in place to assess performance through regular reviews of energy data, technical assessments, and benchmarking. From this assessment, an organization is able to develop a baseline of energy use and set goals for improvement. Performance goals help to shape the development and implementation of an action plan.

An important aspect for ensuring the success of the action plan is involving personnel throughout the organization. Personnel at all levels should be aware of energy use and goals for efficiency. Staff should be trained in both skills and general approaches to energy efficiency in day-to-day practices.

Evaluating performance involves the regular review of both energy use data and the activities carried out as part of the action plan. Information gathered during the formal review process helps in setting new performance goals and action plans and in revealing best practices. Establishing a strong communications program and seeking recognition for accomplishments are also critical steps. Strong communication and recognition help to build support and momentum for future activities. The successes of plant-wide energy-efficiency assessments and the implementation of energy management programs in reducing energy use and CO_2 emissions have been proven in a large number of cases like the ones discussed below.

Companies can use *benchmarking* to compare their operations with those of others, to industry average, or to best practice, to improve energy efficiency. The petroleum industry has the longest experience with energy efficiency benchmarking through the use of an industry-accepted index developed by a private company. Many benchmarking programmes are developed through trade associations or ad hoc consortia of companies, and their details are often proprietary. However, ten Canadian potash operations published the details of their benchmarking exercise [36], which showed that increased employee awareness and training was the most frequently identified opportunity for improved energy performance. Several governments have supported the development of benchmarking programmes in various forms, for example Canada, Flanders (Belgium), the Netherlands, Norway and the USA.

Application of housekeeping and general maintenance on older, less-efficient plants can yield energy savings of 10–20%. Low-cost/minor capital measures (e.g. combustion efficiency optimisation, recovery and use of exhaust gases, use of correctly sized, high efficiency electric motors and insulation) show energy savings of 20–30%. Higher capital expenditure measures (e.g. automatic combustion control, improved design features for optimisation of piping sizing, and air intake sizing, and use of variable speed drive motors, automatic load control systems and process residuals) can result in energy savings of 40–50%.

3.5. Realizing the Potential: Policy

Industry can respond to the potential for increased government regulation or changes in consumer preferences in two ways: by mitigating its own GHG emissions and by developing new, lower GHG emission products and services. To the extent that industry does this before required by either regulation or the market, it is demonstrating the type of anticipatory, or planned, adaptation. Due to the variety of barriers faced by industrial decision makers there is no “silver bullet”; i.e. no single policy to resolve the barriers for all industries.

Voluntary Programmes and Agreements. Voluntary Agreements are defined as formal agreements that are essentially contracts between government and industry that include negotiated targets with time schedules and commitments on the part of all participating parties. Voluntary agreements by industry have been implemented in industrialized countries since the early 1990s. These agreements fall into three categories: completely voluntary; voluntary with the threat of future taxes or regulation if shown to be ineffective; and voluntary, but associated with an energy or carbon tax [37]. Agreements that include explicit targets, and exert pressure on industry to meet those targets, are the most effective [38].

Voluntary agreements typically cover a period of five to ten years, so that strategic energy-efficiency investments can be planned and implemented.

Independent assessments find that experience with voluntary agreements has been mixed, with some of the earlier programmes appearing to have been poorly designed, failing to meet targets, or only achieving business-as-usual savings [39]. Recently, a number of voluntary agreement programmes have been modified and strengthened, while additional countries, including some newly industrialized and developing countries, are adopting such agreements in efforts to increase the efficiency of their industrial sectors [37]. The more successful programmes are typically those that have either an implicit threat of future taxes or regulations, or those that work in conjunction with an energy or carbon tax, such as the Dutch Long-Term Agreements, the Danish Agreement on Industrial Energy Efficiency and the UK Climate Change Agreements. Such programmes can provide energy savings beyond business-as-usual and are cost-effective.

In addition to the energy and carbon savings, these agreements have important longer-term impacts [40,41] including: changing attitudes, reducing barriers to innovation and technology adoption, creating market transformations , promoting positive dynamic interactions between different actors involved in technology research and development, deployment, and market development, facilitating cooperative arrangements that provide learning mechanisms within an industry.

Financial instruments: taxes, subsidies and access to capital. To date there is limited experience with taxing industrial GHG emissions. The UK Climate Change Levy applies to industry only and is levied on all non-household use of coal, gas, electricity, and non-transport LPG. Fuels used for electricity generation or non-energy uses, waste-derived fuels, renewable energy, including quality CHP, which uses specified fuels and meets minimum efficiency standards, are exempt from the tax. Subsidies are also used to stimulate investment in energy-saving measures by reducing investment cost. Subsidies to the industrial sector include: grants, favourable loans and fiscal incentives, such as reduced taxes on energy-efficient equipments, accelerated depreciation, tax credits and tax deductions. Many developed and developing countries have financial schemes to promote industrial energy savings. Evaluations show that subsidies for industry may lead to energy savings and can create a larger market for energy efficient technologies [42]. Whether the benefits to society outweigh the cost of these programmes, or whether other instruments would have been more cost-effective, has to be evaluated on a case-by-case basis.

Technology Research, Development, Deployment and Diffusion (RDD&D). Most industrial processes use at least 50% more than the theoretical minimum energy requirement determined by the laws of thermodynamics, suggesting a large potential for energy-efficiency improvement and GHG emission mitigation [7]. However, RDD&D is required to capture these potential efficiency gains and achieve significant GHG emission reductions. It is important to realize that successful technologies must also meet a host of other performance criteria, including cost competitiveness, safety, and regulatory requirements; as well as winning consumer acceptance. A review of 54 emerging energy-efficient technologies, produced or implemented in the US, EU, Japan and other industrialized countries for the industrial sector, found that 20 of the technologies had environmental benefits in the areas of ‘reduction of wastes’ and ‘emissions of criteria air pollutants’. In addition, 35 of the technologies had productivity or product quality benefits [12]. Inclusion of quantified co-benefits in an energy-conservation supply curve for the US iron and steel industry doubled the potential for cost-effective savings [43]. In many situations a range co-benefits result from improving efficiencies at the useful energy level. Long term efficiency approaches by process substitution relying on major innovations are likely to become increasingly important as existing technology options reach full market penetration.

Industry is not running out of energy-efficient technologies, as new technologies are developed continuously [12]. Technology RDD&D is carried out by both governments (public sector) and companies (private sector). Ideally, the roles of the public and private sectors will be complementary. Flannery [44] argued that it is appropriate for governments to identify the fundamental barriers to technology and find solutions that improve performance, including environmental, cost and safety performance, and perhaps customer acceptability; but that the private sector should bear the risk and capture the rewards of commercializing technology. Studies by Luiten and Blok [45,46] have shown that a better understanding of the technology and the development process cultivating ‘champions’ for technology development and is essential in the design of effective government support of technology development. In its analysis of its Accelerated Technology scenarios, IEA [7], as well as the estimate of the 2030 potential discussed above, found that end-use energy efficiency, much of it in the industrial sector, contributed most to mitigation of CO_2 emissions from energy use. It accounted for 39–53% of the projected reduction. However, IEA countries spent only 17% of their public energy R&D budgets on energy-efficiency.

4. Conclusions

Industry contributes directly and indirectly about 37% of the global greenhouse gas emissions. Total energy-related industrial emissions have grown by 65% since 1971.

Full use of available mitigation options is not being made in either industrialized or developing nations due to a number of barriers like limited access to capital, lack of management attention, insufficient availability of knowledge or qualified service providers. Although industry has almost continuously improved its energy efficiency over the past decades, energy efficiency remains the most cost-effective option for GHG mitigation for the next decades. Reduction of non-CO_2 GHGs and energy efficiency are the least cost options. Energy efficiency is a key opportunity as it not only realizes reductions in GHG emissions, it also reduces (rising) energy costs, and may include many other benefits (e.g. improved productivity, product quality, and environmental performance).

The results also demonstrate that we are not running out of technology. New and emerging technologies and technology applications are developed continuously, providing future opportunities for energy and material efficiency improvements. Thermodynamically, large potentials still exist in most industries, and new materials, technologies, and production process routes will allow capturing part of this potential.

The potential for GHG emission reductions through energy efficiency improvement will vary between 1 and 5 $GtCO_2$/year in 2030, compared to emission levels varying between 14 and 20 Gt CO_2, or equivalent to savings up to 25%. It is hard to provide an exact estimate, as large uncertainties are due to drivers for industrial development and technology innovation.

Industry has a substantial potential to reduce energy and material intensity as well as greenhouse gas emissions. To realize these savings it is essential that companies have effective strategic energy management programs in place to continuously improve energy efficiency. Without such a program, industries will find it hard to identify and realize the energy efficiency measures. We find a large variety in the ability and track record of companies in developing and maintaining energy management programs.

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