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Energy efficiency and renewables for industrial sector

K.Kaygusuz

Karadeniz Technical University, Department of Chemistry, Trabzon, Turkey.

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Abstract

Global industrial energy consumption has increased stable at global level between 2000 and 2017 and has decreased rapidly since then with a contraction twice faster than the industrial activity. As a result, industrial consumption was in 2017 53% above its 2000 level at global level and only represented 25 % of the energy used by final consumers, compared to 29% in 2000. This article discusses a comprehensive review of energy efficiency and renewables for industrial sector. This includes all the renewable energy technologies, energy efficiency systems, energy conservation scenarios, energy savings and other mitigation measures necessary to reduce climate change and sustainable development.

Keywords: Energy efficiency; renewable energy sources, sustainable development, industry.

1. Introduction

Energy is needed in industry for a number of technologies and processes, including cross-cutting technologies such as steam, motors, compressed air, pumps, heating and cooling, as well as specific processes in energy-intensive sectors (Chemicals, Iron and Steel, Cement, Pulp and Paper, Non-Ferrous Metals, and Food). Greenhouse gas emission reductions in industry can be achieved in different ways. One option is to reduce the energy consumption of processes and technologies by implementing specific energy efficiency measures and state-of-the-art energy management systems, or by generating energy reusing industrial by-products. Besides investing in energy efficiency measures, CO_2 emissions can also be reduced substantially through increased material efficiency. This includes various options such as fuel substitution as well as the substitution and reuse of production materials [1-4].

Industrial heat makes up two-thirds of industrial energy demand and almost one-fifth of global energy consumption. It also constitutes most of the direct industrial CO_2 emitted each year, as the vast majority of industrial heat originates from fossil-fuel combustion. Yet despite these impressive figures, industrial heat is often missing from energy analyses. While industrial heat demand grows in the central global energy scenario, the underlying drivers are different depending on temperature requirements. Low- and medium-temperature heat (below 400 ^oC) accounts for three-quarters of the total growth in heat demand in industry by 2040, driven by less energy-intensive industries [5-8].
This is a reversal of historical trends: in the last 25 years, high-temperature heat represented two-thirds of overall heat demand growth, driven by China's rapid development of heavy industries such as steel and cement. On the other hand, developing Asia continues to drive industrial heat demand growth. The growth in low- to medium-temperature needs in this region also alone represents about half of the global industrial heat demand increase [9-12].

Low-temperature heat use grows in most regions through 2040, except in the European Union and Japan. The outlook for high-temperature heat varies even more across regions, including among developing countries. It decreases in China with the country's shift to a less energy-intensive development pathway, while it increases in India as the country becomes, by large distance, the main global driver [6, 8, 13].

As industrial heat demand continues to grow, so does its share in energy-related CO_2 emissions. First, industrial heat is often generated on-site, making it more difficult to regulate than a more centralized sector such as large thermal power generation. There is also limited policy focus in this area compared with other sectors [1]. Second, while heating needs for residential and commercial buildings are fairly standard, industrial heat encompasses a wide variety

Corresponding author; kamilk@ktu edu.tr

of temperature levels for diverse processes and end-uses. For instance, cement kilns require high-temperature, while drying or washing applications in the food industry operate at lower temperatures. Different technology and fuel options are available depending on the required temperature level. For example, low-temperature heat from a heat pump cannot be substituted for high-temperature heat from a gas boiler [14].

Today’s industrial heat demand relies mainly on fossil fuels, biomass and electricity, and only very small shares of renewables in certain sectors. Therefore, decarbonization would require a dramatic shift in how industrial heat is generated. Yet this goal is instrumental to following a low-carbon development pathway as defined in the Sustainable Development Scenario, a new global scenario providing an integrated way to achieve three critical policy goals simultaneously: climate stabilization, cleaner air and universal access to modern energy. The best option for reducing energy use of industrial heat will depend on the specific use and required temperature [1, 14].

Fuel switching can provide some benefit, for instance substituting gas for coal, but for more ambitious climate targets more transformative solutions are needed. For example, under certain conditions, electrification can be a low-cost and sustainable option. Therefore, heat pumps can be economical solutions for low- and medium-temperature needs. Electrification may also be possible for specific high-temperature industrial processes, such as electricity-based steel production [1]. On the other hand, direct renewable heat sources such as solar and geothermal can also be economical for applications below 400^{o}C, but they are not easy to integrate in all industrial facilities. Bioenergy can be used for high-temperature heat demand, but is resource-constrained and only economical and sustainable under certain operating conditions and in certain regions [6-9].

Industrial heat can be decarbonized through the deployment of carbon capture, utilization and storage (CCUS). This can include, for instance, technologies to remove CO_2 emissions from flue gas before recycling the CO_2 in industrial processes, such as for methanol production, or storing it permanently. Finally, end-use efficiency, through the use of modern equipment, improved insulation or heat recovery, can reduce final demand before the heat is even generated – often, limiting overall heat requirements is the first strategy adopted, before taking actions to decarbonize remaining heat use [15-26].

2. Energy consumption and emissions in industry

2.1. General trends

The total global final energy consumption in 2017 amounted to 13,972 million tons of oil equivalent (Mtoe) (see Figure 1, Table 1 and 2). With a share of approximately 37%, the industrial sector consumes more energy than any other end-use sector [13]. In developing and emerging economies the share can even be up to 50% [2]. Most of the worldwide industrial energy consumption increase in 2017 was caused by China and India (64%). In those two countries energy consumption in industry grew by 3.6% in 2017 and in Africa by 3.3%, whereas industrial energy consumption declined in the Middle East by 1.9% and in Latin America by 0.1% [13].

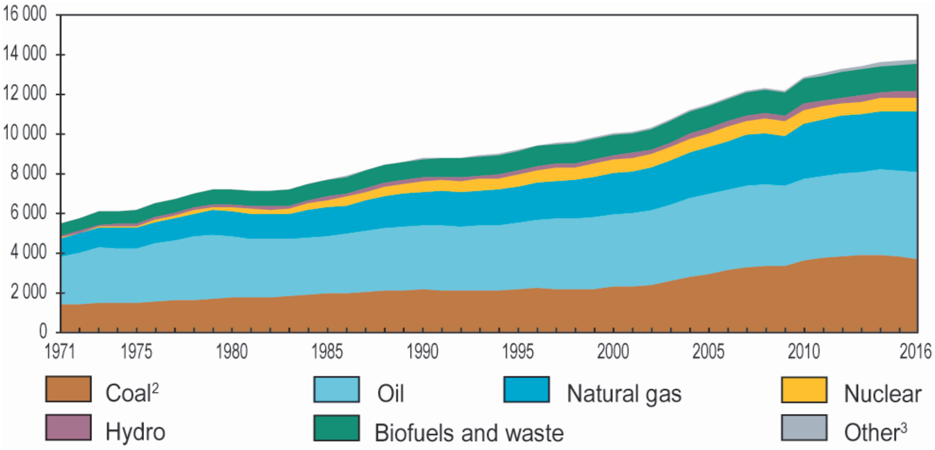

Figure 1. World Total Primary Energy Supply (TPES) from by fuel (Mtoe) [8].

Table 1. World primary energy demand by fuel and industry (Mtoe)

	2000	2017	2030
Total Primary Energy Demand	10 027	13 972	16 167
Coal	2 308	3 750	3 783
Oil	3 665	4 435	4 830
Gas	2 071	3 107	3 820
Nuclear	675	688	848
Hydro	225	353	458
Bioenergy	1 022	1 385	1 691
Other renewables	60	254	736
Energy Consumption by Industry	1 863	2 855	3 460
Coal	400	803	876
Oil	326	321	335
Gas	412	618	851
Electricity	462	768	987
Heat	101	140	148
Bioenergy	162	204	258
Other renewables	0	1	5

Mtoe: Million tons of oil equivalent

Table 2. World renewable energy consumption in 2017 and 2030

	2017	2030
Primary demand (Mtoe)	1 334	2 056
Share of global TPED	10%	15%
Tradition use of solid biomass (Mtoe)	658	596
Share of total bioenergy	48%	38%
Electricity Generation (TWh)	6 351	10 917
Bioenergy	623	1 039
Hydropower	4 109	5 012
Wind	1 085	2 707
Geothermal	87	162
Solar PV	435	1 940
Solar CSP	11	54
Marine	1	4
Share of total generation	25%	38%
Heat consumption (Mtoe)	478	653
Industry	236	302
Buildings and other	242	351
Share of total heat demand	10%	13%
Biofuels (mboe/d)	1.8	4.4
Road transport	1.8	3.9
Share of total transport demand	3%	7%

Figure 2 shows world electricity generation by fuel (TWh). As shown in Figure 2, most of the electricity generation comes from non-renewables and waste sources. The second fuel is hydropower. Electricity is increasingly the "fuel" of choice for society, but a dramatic transformation of the power sector is underway. Innovative technologies are disrupting traditional ways of producing, transporting and storing electricity, creating opportunities for new actors and business models. Ensuring the reliable and secure provision of affordable electricity, while meeting environmental goals, is at the heart of the 21st century economy and is increasingly a central pillar of energy policy making.

Energy is needed in industry for a number of processes such as steam, cogeneration, process heating and cooling, lighting, etc. Depending on economic and technological development, the composition of industries and other factors, the intensity and mix of fuels therefore differs across countries. According to the IEA's International Energy Outlook 2017 reference case, worldwide industrial sector energy consumption is assumed to increase on average by 1.3% per year between 2017 and 2040, where the average annual change in OECD countries is projected to be lower with around 0.8% and in non-OECD countries higher with around 1.5%. Nevertheless, in non-OECD countries the industry share of energy consumption is projected to decrease from 64% in 2017 to 59% in 2040, as many emerging countries are likely to shift their economic activities away from the energy-intensive manufacturing industry to other end-use sectors where energy use is more rapidly increasing [8, 13, 20].

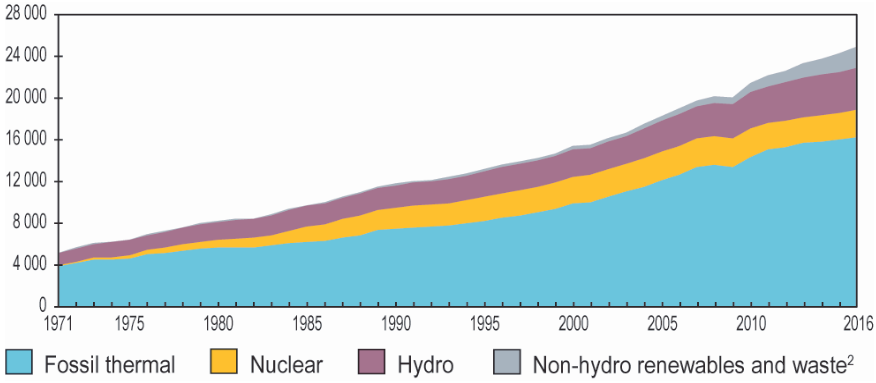

Figure 2. World electricity generation by fuel (TWh) [8].

The worldwide industrial CO_2 emissions were 14.39 $GtCO_2$ in 2014 (Figure 3, Table 3), comprised of direct energy-related emissions, indirect emissions from electricity and heat production, process emissions and emissions from wastes, accounting for 45% of total global CO_2 emissions [8]. In industry, energy efficiency potentials exist in cross-cutting technology systems, sector-specific processes, energy generation, and control systems for performance optimization [13].

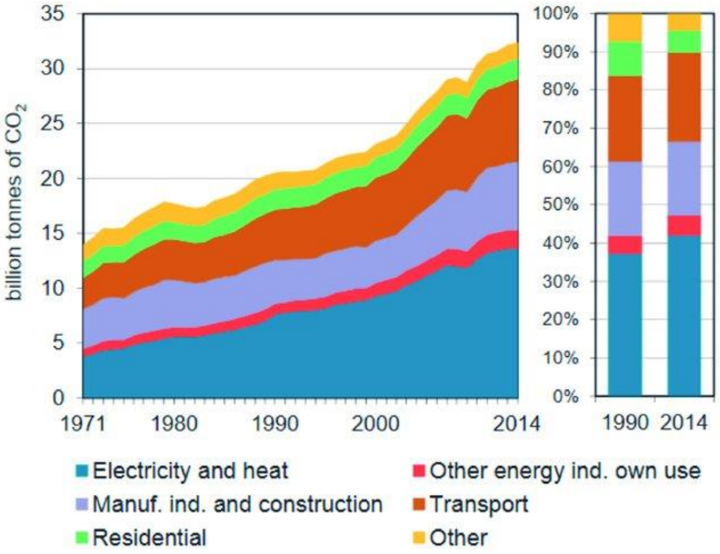

Figure 3. The CO_2 emissions by sector [13].

Table 3. Global energy-related CO_2 emissions (Million Tons)

	2000	2017	2030	2040
By sector				
Power	9 305	13 587	7 839	3 292
Industry	3 922	6 154	5 936	5 081
	5 757	7 986	7 326	5 563
Transport	2 714	2 997	2 593	2 202
Buildings	1 424	1 856	1 788	1 510
Other				
By fuel				
Coal	8 951	14 448	8 335	3 855
Oil	9 620	11 339	9 501	6 886
Gas	4 551	6 795	7 645	6 906
Total	23 123	32 581	37 748	42 475

Figure 4 shows the World CO_2 emissions from fuel combustion by fuel (Mt of CO_2) [8]. As shown in Figure 4, the most of CO_2 emissions comes from coal burning and the second from oil. In 2016, GHG emissions from energy and industrial processes amounted to about 34 gigatonnes of CO_2 equivalent (Gt CO_2-eq). Three-quarters of this is accounted for by only eight source categories. The largest category by far is coal-fired power generation, with 2 053 gigawatts (GW) of capacity accounting for 27% of emissions. Buildings made up nearly 9% in 2017, followed by about 8% each for gas-fired power generation and petroleum-fueled cars (more than one billion cars). Emissions from cement production and oil and gas operations accounted for 7% each, with trucks (202 million vehicles) making up 6% and steel around 5% of the total.

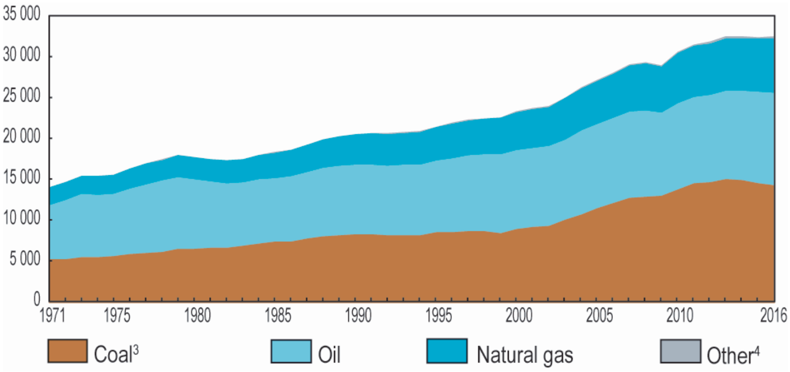

Figure 4. World CO_2 emissions from fuel combustion by fuel (Mt of CO_2) [8].

2.2. Energy and carbon intensive industrial sectors

The industrial sector includes a wide range of manufacturing activities, from the production of bulk materials such as crude steel or cement to the fabrication of electronic devices and food products. Industry overall accounts for 156 exajoules (EJ) (about 40% of total final energy demand) and for 8.5 Gt CO_2 (or about 25%) of the total energy system's CO_2 emissions. Energy-intensive industrial sub-sectors represent about two-thirds of total final industrial energy demand, with just chemicals, iron and steel and cement production accounting for almost 60% of the industrial total. The significant contribution of these three sub-sectors to industrial energy demand, together with the release of CO_2 emissions that are inherently produced as part of the reactions taking place in these processes, result in these industrial activities being responsible for almost 70% of total industrial CO_2 emissions. Each of these industrial segments has specific characteristics that lead to differing starting levels of energy consumption and CO_2 emissions: raw material needs, processing conditions, and product quality requirements. The singularities of each industrial sub-sector need to be well understood to identify sustainable strategies that can drastically reduce its emissions footprint. For instance, while the chemical sector is the highest industrial energy consumer, it is only the third-largest industrial CO_2 emitter, after cement and iron and steel, as a result of a lower dependency on coal and the energy consumed as raw material being locked into the product and not resulting in CO_2 emissions until the product decomposes (Fig. 5).

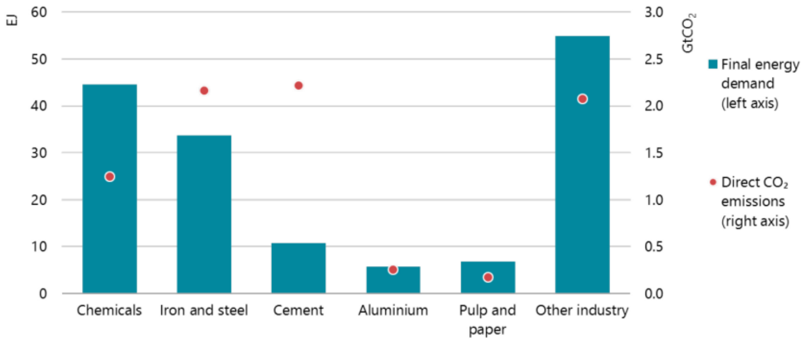

Figure 5. Final energy demand and direct CO_2 emissions by industrial subsector, 2017

According to IPCC's Fifth Assessment Report [15], the major emitting industrial sectors are Chemicals (plastics, fertilizer and others), Iron and Steel, Cement, Pulp and Paper, Non-Ferrous Metals (aluminum and others), and Food Processing given as [1, 15]:

- ***Chemicals:*** The largest energy-consuming industry sector is the basic chemicals industry with a share of 15-20% of the total delivered energy consumption in industry for non-OECD and OECD countries respectively. Petrochemical feedstocks, such as ethylene, ammonia, adipic acid and caprolactam used in producing plastics, fertilizer, and synthetic fibers, account for around 60% of the energy consumption [20].
- ***Iron and Steel:*** Iron and Steel is the second largest energy consumer in industry. With nearly half of the world's steel production, China is the world's biggest steel-producing country (49.6% in 2015), followed by EU-28 with 10.2%, Japan with 6.5%, India with 5.5% and the US with 4.9% [10]. The energy intensity of the steel production varies across regions depending on the technology used. Due to the use of coal and coke, the conventional iron making process is the most emission-intensive part of steel production, accounting for 70-80% of the emissions [13]
- ***Cement:*** As the demand for cement is correlated with the construction industry, an increase of building and infrastructure construction induces a rise in the cement industry's energy use [20]. On the other hand, the CO_2 emissions in the cement sector are composed of emissions from fuel combustion for limestone, clay and sand heating (around 40%), of process emissions from the calcination reaction (around 50%), and of emissions arising from grinding and transport (around 10%) [15].
- ***Pulp and Paper:*** The global demand for paper and variety of paper products is mainly driven by developing countries leading to a steadily growing worldwide paper production [15]. Although the paper producing process is very energy-intensive, nearly half of the needed electricity is provided through co-generation in paper mills with wood waste products [20].
- ***Non-Ferrous Metals:*** The production of non-ferrous metals, primarily aluminum, is very energy-intensive because of a high electricity demand. More than 80% of total GHG emissions in aluminum production are indirect electricity-related emissions [15]. Aluminum can be produced from raw materials or recycling, where the latter one can save up to 95% of energy needed for primary aluminum production. China currently produces more aluminum than any other country in the world, however, with recycling rates much lower (21% in 2012) than in the US (57%) [20].
- ***Food:*** In food processing, most energy is used for drying, cooling, storage, and food and beverage processing purposes [12]. Due to a growing world population the demand for food keeps rising, making the food industry one of the major GHG emitting industry sectors. However, the demand for food and hence energy use and emissions could be drastically reduced by avoiding wasted food, which is estimated at around one third of the food produced.

3. Energy efficiency in industry

As greenhouse gas emissions reach a new record high in 2018 according to World Meteorological Organization, our time to switch to low-carbon energy systems is running out. Our energy system has to change rapidly to adapt to the actions and new policies to be taken according to 1.5°C Paris agreement on climate change. Common target of the countries around the world should be low-carbon energy system that will replace fossil fuels by renewable energy sources [8]. Increasing energy demand by industrial sectors makes reaching this target even more variable. Another challenge is matching the variable renewable production to different load profiles in energy consumption. Energy storage is the key technology to bridge the gap between supply and demand of such intermittent energy sources and realize ambitious goals of the low-carbon future. However, the potential of energy storage sometimes is underestimated, because it can be a hidden technology in the whole energy system. The environmental and economic benefits of energy storage need to be emphasized and demonstrated more [8, 11].

3.1. The need for innovation

Fossil fuel use in industry and its associated CO_2 emissions can be reduced by various means, from improved energy efficiency to carbon capture and reuse or storage, as well as by novel manufacturing processes and ultimately by using different materials in industry and other end-use sectors – for example, more wood in construction. However, increased uptake of energy from renewables appears to be an ideal means to reduce fossil fuel consumption and emissions in a variety of industrial sectors of growing relevance [11].

Various renewable sources, such as bioenergy, solar radiation, and geothermal energy, can be used to produce heat for industrial purposes, but the availability of these resources is neither spatially nor temporally uniform [1]. For example, in both temperate and hot but humid areas, the opportunities to cost-effectively collect solar heat at temperatures beyond ~150°C are scarce, but biomass resources can be important [3]. Conversely, in hot and arid areas biomass resources are usually scarce, but concentrating solar power systems are able to efficiently collect the sun's energy at high temperatures [13].

The energy used in industry can also be sourced from renewables through electricity generation, either from dedicated facilities or from the grid, or any combination of both. For remote, off-grid industrial facilities, these sources can replace the fossil fuels used to generate power. Furthermore, heat can be generated from electricity using a variety of technologies. The pillars of industrial emissions reductions in the energy technology scenarios are energy efficiency, innovative processes and energy storage technologies. Fuel and feedstock switching, and material efficiency, combining manufacturing material efficiency, inter-industry material synergies, decreased end-use material intensity, and post-consumer recycling, also make small contributions [20, 22, 24, 26].

Innovative processes account for 19% of cumulative CO_2 reductions in the industrial sectors. But, these processes, not yet fully commercialized, include new steelmaking processes, inert anodes for aluminum smelting, oxy-fuelling kilns for clinker production in cement manufacturing, enhanced catalytic and biomass-based processes for chemical production, and integration of CCS in energy-intensive industrial processes [13]. Figure 6 shows the global industry direct CO_2 emissions.

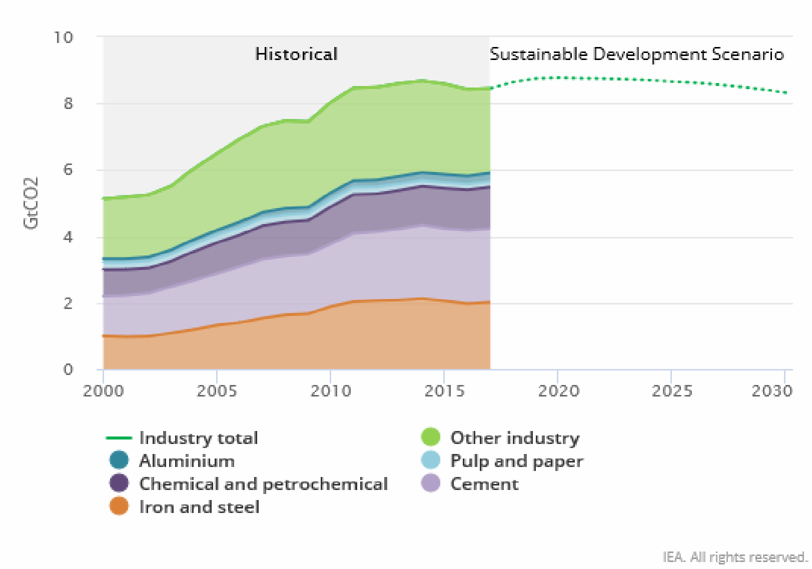

Figure 6. Global industry direct CO_2 emissions.

Climate-friendly scenarios rely particularly on ambitious development of bioenergy resources, CCS and carbon capture and use (CCU) technologies, or on the combination of both technology families with bioenergy carbon capture and storage (BECCS) [3]. Bioenergy is sourced from organic material that stores sunlight as chemical energy as it grows through photosynthesis, which removes CO_2 from the atmosphere; therefore, capturing and storing the CO_2 that is emitted when the bioenergy is consumed could possibly make the life-cycle emissions of BECCS negative. For this to happen, the combined amount of GHGs present in the entire supply chain and the GHGs that cannot be captured by CCS must total less than the amount that is captured and permanently stored [1, 3, 4, 7]. Figure 7 shows the global industrial demand by temperature level and sector.

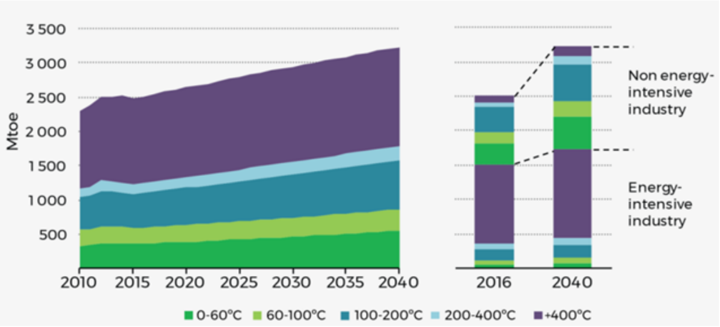

Figure 7. Global industrial demand by temperature level and sector

Achieving negative emissions in power and industry could compensate for temporary “overshoots” in emissions particularly hard-to-suppress emissions from other sectors (e.g. transport and industry), or both. However, CCS is proving slow and difficult to deploy, and it clearly does not reduce reliance on fossil fuels. Economic conditions for other low-carbon technologies may improve more rapidly than expected. Furthermore, BECCS is as yet an unproven technology at scale and there is a great degree of uncertainty surrounding its viability, although the uncertainties do not necessarily pertain to the CCS technology itself. Another question is what level of bioenergy resources might be sustainably available for use on a large scale by the energy sector [9, 10, 13, 14], as all studies lead to the conclusion that the extensive application of BECCS needed to achieve Paris Agreement objectives would stretch the possibilities offered by bioenergy to their maximum. The supply of sustainable bioenergy will need to grow from today’s 1512 Mtoe to around 3480 Mtoe under the sustainable development scenarios [1, 13, 20].

The role of renewables in the power sector, and to some extent in the buildings sector, has been investigated extensively. This is less the case for industry, for which renewables have been the topic of only a limited number of studies. To date, most energy-related innovation in the industry has been to improve energy efficiency rather than to reduce GHG emissions, as energy has always had a cost whereas emissions have not [1]. Moreover, industries have considered electricity a costly source of heat, and rightly so, as electricity has been produced mostly in thermal plants from combusting fossil fuels at an efficiency rarely exceeding 50%. Electricity could thus compete with fossil fuels only if it were running more efficient devices such as heat pumps. However, recent and rapid cost reductions in some renewable electricity generating technologies have led to the emergence of new, affordable options that have not been considered in many studies [17-24].

4. Energy efficiency and renewable sources in industry

The combined application of renewable energy and energy efficiency in industry is a natural marriage insofar as industry operators who have the foresight to convert their plants from using fossil fuels to renewable fuels are very likely to maximize the value of the renewable fuel by maximizing the efficiency of its use in their plants. Governments can create regulatory and business environments that promote development of renewable energy and energy efficiency in industry and industry will respond by developing business models configured to extract maximum value for the business from the opportunity available. There is, therefore, a need to broaden our thinking to include the goal of efficient use of renewable energy in industry to achieve maximum value. This value flows through to the whole economy and, ultimately, the planet and its inhabitants [1, 10, 14].

Figure 8 shows the share and breakdown of heat demand in industry. As shown in Figure 8, three-quarters of the energy used in industry is process heat: the rest is for mechanical work and electricity (computers, lighting, etc.). About 30% of process heat is “low-temperature” (below 150 °C), 22% is “medium-temperature” (150 °C-400 °C) and 48% is “high-temperature” (above 400 °C) as shown in Figure 9. About 10% of process heat is estimated to be electricity-based.

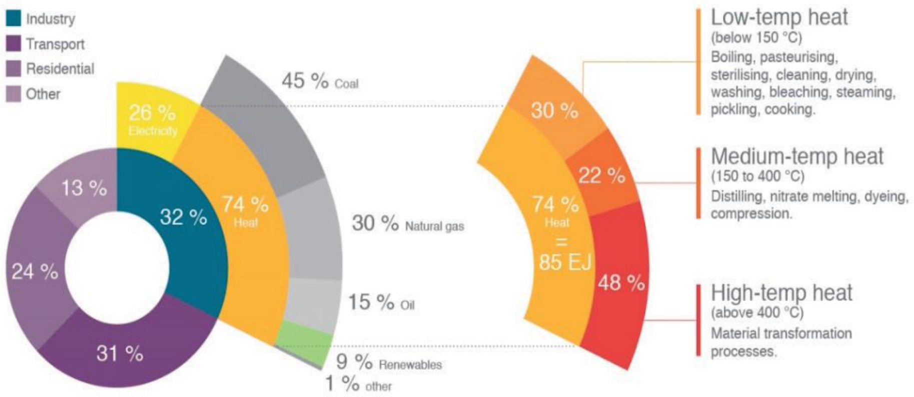

Figure 8. Share and breakdown of heat demand in industry [8, 13].

While there are many examples of the combined application of renewables and efficiency in industry, their penetration to date has not been extensive. The applications considered most likely to achieve significant penetration in the middle term are the use of [1, 8, 10, 14]:

- biomass energy for process heat,
- biomass as a petrochemical feedstock,
- solar thermal systems for process heat,
- heat pumps for process heat,

and it has been suggested that renewable energy, if used efficiently, has the potential to supply 23% of final energy use in the global manufacturing industry and up to 14% of fossil feedstock can be replaced by biomass. Together, this equates to 21% of total final energy use.

The combined application of renewable energy and energy efficiency in industry is a natural marriage insofar as industry operators who have the foresight to convert their plants from using fossil fuels to renewable fuels are very likely to maximize the value of the renewable fuel by maximizing the efficiency of its use in their plants. There are also a number of synergies and similarities that include [1, 10, 14]:

- improvements in end-use energy efficiency reduce the cost of delivering end-use services by renewable energy. The money saved through can help finance additional efficiency improvements and deployment of renewable energy technologies,
- lower end-use energy requirements increase the opportunity for renewable energy sources that have low energy density, such as solar, or of low energy content, such as low-temperature solar heat, to meet full energy-service requirements,
- achievement of targets for increasing the share of renewables in an economy's energy portfolio by reducing total energy consumption as well as by increasing the percentage of renewable energy,
- reduction of the energy intensity in an industrial plant, both through the introduction of new technology and energy end use efficiency gains, enhances the opportunity to introduce renewable energy,
- similarity of the obstacles to implementation that are often encountered and the regulatory frameworks and incentives required to ensure successful development of both renewable energy and energy efficiency technologies in industry.

While renewable energy and energy efficiency may be the twin pillars of a sustainable energy future, they are in fact fundamentally different concepts. Thus, renewable energy is energy that either renews itself. Energy Efficiency also involves using the least amount of energy to do a job or achieve an objective. There is, therefore, a need to broaden our thinking to include the efficient use of renewable energy in industry to achieve maximum value for the industrial end user, the community, the economy and, ultimately, the planet and its inhabitants.

To this end, we believe that the combined use of renewable energy and energy efficiency in industry needs to focus on how such combination can maximize the benefits that can be achieved. Such benefits include, but are not necessarily limited to [1]:

- minimizing the specific energy consumption (SEC) required for production,
- maximising revenues and economic value for an industrial company,
- minimizing the use of fossil fuels,
- reducing GHG emissions,
- managing waste disposal,
- minimizing environmental impacts,

- job creation,
- improvement of industrial working conditions and safety.

The ways in which renewable energy and energy efficiency initiatives can be combined to achieve these objectives may be quite different depending on which are targeted by a particular industry or industrial plant.

4.1. Bioenergy

With an estimated consumption of 196 Mtoe in 2017, biomass is by far the largest renewable energy source in industry today. Of this consumption, 58 Mtoe were used by the pulp and paper industry, 29 Mtoe by the food and tobacco branch, 7.7 Mtoe by the wood and wood products industry, 5.1 Mtoe by non-metallic minerals such as the cement industry, 3.2 Mtoe by the iron and steel industry, and 2.71 by the chemical industry. Bioenergy consumption is most evident in industry sectors that produce biomass residues onsite suitable for fuel use. In other industries where this is not the case, bioenergy is less used because biomass fuel supply chains need to be mobilized [13].

Brazil, India, the USA, some developing countries and the European Union are the largest industrial consumers of bioenergy. The power sector led the growth, with renewables-based electricity generation increasing by 7%, almost 450 TWh, equivalent to Brazil’s entire electricity demand. This was faster than the 6% average annual growth since 2010. Shares shown in Figure 9 do not, however, include biomass used to generate electricity (total 720 Mtoe) and commercial heat (total 120 Mtoe) consumed globally by industries. Neither do they include the share of bioenergy consumed onsite to transform biomass into biofuels [13].

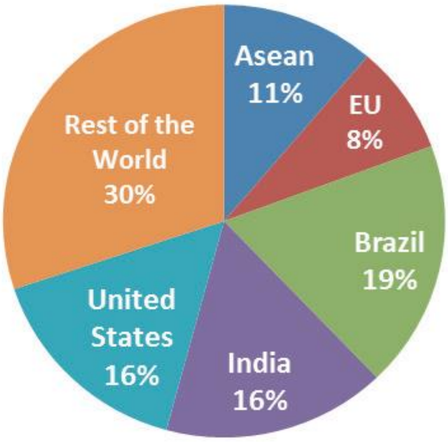

Figure 9. Country/regional shares of global biomass use in industry [13].

4.2. Solar heat

Activity is accelerating with respect to solar heat for industries. While the deployment of small-scale solar water heating systems is slowing, that of large-scale solar-supported district heating systems and industrial applications is quickening. A recent study has identified over 130 companies in at least 22 countries worldwide that have realized more than 500 industrial plants with an overall combined installed collector area of 416 414 m^2 for process heat. This represents an installed capacity of only 280 MW_{th}, likely to produce 560 GWh_{th} of heat per year at most, assuming a relatively high capacity factor of 2 000 full load hours [7, 11].

The vast majority of projects use non-concentrating technologies such as flat-plate collectors or evacuated tubes. These can be installed almost anywhere, as they use global solar irradiance, but they usually do not deliver usable heat above about 100°C. In recent years, however, new high-vacuum flat-plate collectors have been commercialized, which remain relatively efficient at temperatures up to 160°C [12]. On the other hand, concentrating technologies, such as parabolic troughs use direct irradiance only and are geographically limited to areas with good direct normal irradiance (DNI). But as these linear concentrating technologies can reach or even exceed 400°C, they could be a mean of supplying medium high temperature process heat needs. Central receiver systems or “solar towers”, which can achieve higher temperatures still, have so far developed in the power sector only [8, 13].

Another important reason for this prevalence of non-concentrating technologies rests in the relationship between solar heat cost and temperature level that makes competition with fossil fuels easier at low temperatures [23]. The food and beverage industry, the service industry, and the textile industry, all of which mostly need low-temperature heat, are the main areas in which solar heat has been deployed.

Another example of low-temperature solar process heat is the 27.5 MW_{th} system at mining company's Gaby copper mine in northern Chile, the largest such system in service so far: it has 39 300 m^2 of flat-plate collectors and 4 000 m^3 of thermal energy storage, and supplies 85% of the process heat needed to refine copper. It was commissioned in 2013, in one of the world's best areas for concentrating or non-concentrating solar power or heat [7].

5. Policy options

In this section, lessons learned from the recent deployment of renewables in various industrial sectors are considered first to provide useful information to industrial decision/policy makers at national and possibly sub-national levels. With respect to international trade in energy-intensive industries, such as chemicals, iron and steel, and cement, however, the main barrier for most products is likely to be competition from current greenhouse gas emitting technologies, as most substitutions with renewable energy reveal a positive cost of carbon abatement [1].

5.1. Lessons learned

Various barriers still hinder full renewable energy deployment in the industry sector, but industrial decision/policy makers have a wide array of options available to overcome them. Eight issues were identified in the Renewable Energy Technology Deployment (RETD) Industry study [5] that could influence industries in deciding whether to deploy renewable energy production assets in their facilities. Diverse policy options can be implemented to surmount these barriers, which are summarized below [1, 3, 5].

- ***Energy supply regulatory regime:*** In various jurisdictions, it is difficult to supply energy using independent producers and valorise energy through self-consumption and/or the right to sell excess energy produced. These are fundamental requirements for deploying renewables in industry.
- ***Operability and integration:*** Industrial installations and processes might not be adapted to integrate RE assets, especially for renewable heat, including biomass. Deep integration of renewables into processes can provide the best results, but also risks perturbing core processes. Switching from fossil fuels to renewables production can add complexity and cost.
- ***Investment:*** Renewable energy projects require high upfront capital expenditures.
- ***Return on investment:*** Renewables projects often show relatively low returns on investments; moreover, even if the profitability of assets with long technical lifespans is high, the payback time might be long compared with the company's core activities. This commonly-used criterion may dissuade industrial decision makers.
- ***Risk and insurance:*** RE installations that use immature technologies or lack backup generation present a supply continuity risk, but also offer a hedge against fluctuations in market energy prices and often improve energy security. In some cases, faulty equipment can put the safety of the whole facility in jeopardy. More often, long-term continuity of the operation and solvency of the off-taker present a risk for renewable energy investments.
- ***Contractual scheme complexity:*** The complexity of contracts between industrial customers, third-party power (or heat) producers and utilities can deter investment.
- ***Technology maturity:*** While solar, wind, geothermal and various biomass technologies are mature, some other options (power to gas, tri-generation) are less so and carry additional risks.
- ***Awareness:*** Industrial companies often lack awareness about technologies, possible incentives or guarantees, costs and best practices.

RE portfolios and obligations to buy renewable power from independent power producers have been instrumental in ensuring rapid deployment and cost reductions in solar and wind power; similarly, obligations for shares of solar heat in domestic hot water supplies have proven effective in driving deployment of solar water heaters in a number of jurisdictions, where the obligations are now often integrated into strict building codes that either explicitly mandate the use of renewable heat or require it in practice. Such instruments should still be considered by governments and other public authorities at various levels [1].

5.2. International agreements

Energy- and GHG-intensive industries, whose products are traded internationally, may not be in a position to support additional costs for process modification to reduce carbon dioxide (CO_2) emissions. Furthermore, imposing carbon prices or directly regulating emissions potentially puts carbon-constrained industries at a competitive disadvantage relative to their unconstrained competitors. Governments thus fear that uneven carbon constraints could enhance the competitiveness of non-carbon-constrained producers [1].

This risk is usually characterized as "carbon leakage" as implementing uneven GHG emissions constraints could lead to an increase in emissions outside the given country or region. This could result from short-term deterioration in competitiveness, whereby carbon-constrained industrial products lose international market shares to the benefit of unconstrained competitors. In the longer term, differences in returns on capital associated with uneven emissions mitigation actions provide incentives for firms to relocate their capital to countries with less stringent climate policies. Finally, reduced energy demand and lower prices in some countries may trigger higher energy demand and associated GHG emissions elsewhere [1].

Carbon leakage is formally expressed as the ratio of emissions-increase outside the country that has implemented domestic mitigation policies, over the emissions-decrease within that country. This ratio could be above or below 100%: if below, it means that global GHG emissions increase if emissions in the regions benefitting from a shift in production are greater than the emissions reduction in the regions implementing a constraint of any kind. This could happen, for example, if specific GHG emissions in the regions taking mitigation action were already lower than the specific emissions in the outside regions.

The Paris Agreement is significantly more encompassing than the Kyoto Protocol in including China, India and other emerging economies. However, the heterogeneity of the current national pledges may still not provide enough security for industries in the most exposed sectors. On the other hand, cement is less at risk, as it is traded much less than ammonia and steel. With respect to chemicals, the situation varies according to the cost of shifting to renewables [5]. If it is low, as for ammonia used as an industry feedstock, the risk of carbon leakage is low, while it cannot be ignored for methanol and high-value chemicals; the current shift in production. Finally, international competition and trading are intense in the iron and steel subsector [1].

A global agreement to create a state of equality with respect to GHG emissions, for example with a globally coordinated "single" carbon pricing system, would in principle solve this issue. While some economists consider it to be the "first-best" option, others point out that its adoption is very unlikely from a political standpoint, for it does not take inequalities in economic development into account: a single world price would be too high for some countries and too low for others. Global agreements by sector might be more realistic. Compared with countrywide, quantified targets, sector-wide approaches may [6]:

- require lighter monitoring and enforcement
- more effectively link economic agents in these sectors and international investors
- settle part of the abatement cost uncertainty inherent to uncertain economic growth
- create emissions leakage from sectors covered to those unconstrained
- complicate international negotiations with sector-specific technicalities.

5.3. Procurement

To ensure prompt deployment of innovative clean technologies based on renewables, public and private procurement of clean, carbon-free materials may be the most realistic short-term option. For example, the cost of steel represents only a small fraction of the overall cost of a vehicle. Manufacturers of brand products may want to bolster their green performance image they project to their customers and the general public, including their own stakeholders, whether out of personal conviction. Electric cars and plug-in hybrids could lead the transition towards "green steel", and renewable energy developers could pay attention to the life-cycle emissions of wind turbines [1].

Many developers have done this already, procuring green power and now turning their attention to the “grey energy” embodied in their products and to procuring preferably cleaner materials. It identified six areas in which suppliers can focus their clean-energy efforts: agriculture, waste, packaging, deforestation, and product use and design [1]. Sustainable procurement of wood and paper-based products is not only a project of the World Resources Institute, it is also becoming a mandatory reference in industry and commerce, and for sustainable fisheries [24-26].

Public procurement may play a similar role. Public procurement accounted for 13% of the gross domestic product of OECD countries in 2013, and even more in some emerging and developing economies. All jurisdictions, public services and companies have buildings constructed for their own operations or for the public – schools, hospitals, social housing, etc. They procure vehicles of all sorts, railways, bridges, roads and other infrastructure, and therefore manage concrete, cement and steel in massive quantities [24].

The primary objective of procurement is obviously to find and buy products and services that offer good value for taxpayers’ money. However, as a government-operated instrument, public procurement should also be aligned with a country’s broad policy objectives, balancing these objectives with its primary purpose of finding the best value for public money. Designing public procurement to promote low-carbon innovation can be justified on three grounds [24]:

- Structural inefficiencies in government purchasing, e.g. focusing on upfront acquisition costs when including operating costs could lead to a more environmentally conscious choice.
- Environmental market failure, e.g. the absence of a price on CO_2 emissions due to political constraints, while an individual government may choose to include a CO_2 price to guide its own decisions.
- Insufficient support for innovation in light of positive externalities related to demonstrating and adopting new technologies, learning and network externalities.

6. Conclusions

The combined application of renewable energy and energy efficiency in industry is a natural marriage insofar as industry operators who have the foresight to convert their plants from using fossil fuels to renewable fuels are very likely to maximize the value of the renewable fuel by maximizing the efficiency of its use in their plants. Governments can create regulatory and business environments that promote development of renewable energy and energy efficiency in industry and industry will respond by developing business models configured to extract maximum value for the business from the opportunity available. There is, therefore, a need to broaden our thinking to include the goal of efficient use of renewable energy in industry to achieve maximum value. This value flows through to the whole economy and, ultimately, the planet and its inhabitants.

While there are many examples of the combined application of renewable energy and energy efficiency in industry, their penetration to date has not been extensive. The applications considered most likely to achieve significant penetration in the middle term are the use of: biomass energy for process heat, biomass as a petrochemical feedstock, solar thermal systems for process heat, heat pumps for process heat, and it has been suggested that renewable energy, if used efficiently, has the potential to supply 23% of final energy use in the global manufacturing industry and up to 14% of fossil feedstock can be replaced by biomass. Together, this equates to 21% of total final energy use. Reducing long-term GHG emissions of the industry sector is one of the toughest challenges of the energy transition. Combustion and process emissions from cement manufacturing, iron- and steelmaking, and chemical production are particularly problematic. The main finding of this study is the recent rapid cost reductions in solar PV and wind power may enable new options for greening the industry from electricity or the production of hydrogen rich chemicals and fuels. Simultaneously, electrification offers new flexibility options to better integrate large shares of variable renewables into power grids.

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