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Assessment of the Integration of Renewable Energy in Industrial Processes

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Abstract
There are several chances for both technological and financial breakthroughs when renewable energy is included in industrial processes. When used as process heat, biomass exhibits a feasible economic potential of 15–19 EJ annually for ambitious deployment scenarios and 13–14 EJ annually under accelerated deployment scenarios. With an estimated 81 EJ annually for aggressive deployment and 41 EJ annually for rapid deployment, its technically achievable potential is noticeably greater. When used as feedstock, biomass provides an extra economic potential of 1 to 2 EJ annually in ambitious scenarios and 0.5 to 1 EJ annually in accelerated scenarios. With a technological potential of 14.9 EJ per year, solar thermal energy has an economic potential of 0.9 to 3.8 EJ annually. In line with its technical capability of 1.9 EJ annually, geothermal energy has an economic potential of 1.7 to 1.9 EJ annually. Heat pumps have a technical potential of 2.3 EJ annually and an economic potential of 1.2 to 1.9 EJ annually. As a renewable energy source, electricity continues to have 1.1 EJ of annual economic and technical potential. These numbers highlight the significant contribution renewable energy sources can make to improving industrial sustainability and energy efficiency.

Keywords: ***Production costs; heat pump; biomass; solar thermal; Non-ferrous metals.***

1.0 Introduction

A significant shift is occurring in the global energy landscape, with a growing focus on renewable and sustainable energy sources. In this regard, it has become clear that incorporating renewable energy into industrial processes is essential to lowering carbon footprints and promoting sustainable growth. This study explores the experiences of many African countries, revealing the difficulties, achievements, and distinctive dynamics of incorporating renewable energy into their distinct industrial sectors.

Mitigating climate change and securing a resilient and sustainable energy future emphasize how urgent it is to switch to greener energy sources (Akpan & Olanrewaju, 2023; Cherian, 2015). The industrial sector is essential to this shift because of its high energy use (Fouquet, 2016). Understanding the methods and results of integrating renewable energy in various industrial settings is crucial as nations throughout the world struggle to strike a balance between environmental stewardship and economic growth (Gawusu *et al*., 2022). Africa offers a case study on the efficient application of renewable energy in industrial processes. Africa is known for its abundance of natural resources and dedication to environmental sustainability (Richards *et al*., 2012).

Roughly one-third of the world's energy was used by the industrial sector, which saw its total final energy consumption reach 128 exajoules (EJ)[2] in 2009. To produce process heat, 78 EJ of fuels were consumed. For the manufacturing of iron and steel, blast furnaces and coke ovens used an additional 9 exajoules. Approximately 16 exajoules of petrochemical feedstock were used to produce chemicals and polymers, which were referred to as "materials" in a study (World Bioenergy Association). The remaining energy used by the industry was electricity demand (24 exajoules) for a variety of applications, including motor drives, cooling, refrigeration, and electrolysis (IEA, 2012a).

Sixty-four percent of the world's final industrial energy usage comes from non-OECD nations (81 exajoules), mostly emerging and transitioning economies. The OECD, or industrialized and high-income countries, accounted for 36 percent of global final energy usage, or 47 exajoules. Fossil fuels, coal, petroleum products, and natural gas account for 44%, 26%, and 21% of the sector's overall energy usage today, accounting for 91% of the total energy use (not including feedstock use and the need for power).

About 9% of the energy used in industry comes from renewable sources, primarily trash and biomass (the proportions are the same in OECD and non-OECD nations), varying areas have very varying fuel mixes while natural gas makes up at least 40% of the fuel mix in the OECD Americas and Europe, coal supplies 80% and 35% of the total demand in China and the OECD Pacific, respectively. Certain regions, such as Latin America (35%), Africa (42%), and India (24%), have a significant percentage of renewable energy in their fuel mix. In contrast, less than 1% of energy comes from renewable sources in the Middle East and in economies that are transitioning.

The temperature range in which industrial manufacturing processes operate is broad. For instance, the chemical industry's distillation processes, boilers, and reactors operate above 250 ºC, and the temperatures are even higher for the processes involved in the production of iron and steel. In contrast, the food industry uses these processes for drying, washing, and heat treatment, and the textile industry uses them for cleaning, dyeing, and bleaching. Whereas steam is usually used for low-temperature (<150 ºC) and medium-temperature (150-400 ºC) process heat supply, direct heat is used for high-temperature (>400 ºC) applications (e.g., in cement kilns or iron and steel industry).

In steam boilers, fossil fuels normally provide steam at a high conversion efficiency of about 90%. But steam may also be produced using biomass. Currently, the pulp and paper industry uses wood waste (such as bark and black liquor) and small-scale blast furnaces employ charcoal (Taibi *et al*., 2012). The efficiency of bio-based steam generation from feedstocks such as rice husk, wood pellets or wood chips is generally slightly lower (75-90%) (IEA, 2007a; Börjesson & Ahlgren, 2010) than that of fossil fuels (85-90%) (Einstein, *et al*., 2001). The difference in efficiencies between bio-based gasifiers from wood, briquette, and residues such as coconut shells (40-50%) and fossil fuel-fired furnaces, kilns and stoves could be higher (50-60%) (Shivakumar *et al*.,2008).

2.0 Production Growth Assumptions Methods

The production growth assumptions of the IEA (2012) and the potential for energy efficiency improvement of Saygin et al. (2010), based on Equation (1), were used to predict the fossil fuel use of each industry between 2009 and 2030.

$$TPEU_{s.f.t} = TPEU_{s.f.t}\,2009 \times (1 + r_{s.c.f.t})^{t-2009} \times (1 - EE_{s.f.t}) \qquad (1)$$

Where $TPEU_{s.f.t}$ is the total primary energy use

$r_{s.\,c.f.t}$ is the production growth rate.

$EE_{s.f.t}$ is the energy efficiency improvement potential of sector s in region c for energy carrier f in year t. The EE potential is the same for all energy carriers.

One of the objectives of the SE4ALL initiative is to double the rate of energy efficiency improvements between 2010 and 2030. In this analysis, energy efficiency improvement potential for each sector is the sum of improvements achievable by retrofits in the existing capacity and implementing best practice technology in all new investments.

The improvements achievable by retrofits depend on the average age of the stock and the capacity turnover. BPT improvement potential depends on the production growth and the share of capacity retired each year (Table 1). An overview of the production growth and energy efficiency improvement potential of the energy-intensive sectors is provided in Table 2. Production growth is assumed to be equivalent to demand growth according to the IEA (2012c) and trade analyses were excluded from the scope of this paper.

Production growth is available for energy-intensive sectors only. For other sectors, production is assumed to grow at the average rate of the energy-intensive sectors analyzed. Early retirement of existing capacity is not considered in this study. According to this analysis, improving energy efficiency can reduce total global industrial energy use by at least 23% by 2030 compared to frozen efficiency (equivalent to an annual savings of 1.2%).

Table 1: Average Age of Capacity in Industry Sectors (Worrell and Biermans (2005))

	OECD	**Developing Countries**	**Economies In Transition**	**Average Lifetime**	**References for Average Ages**
	(Years)	**(Years)**	**(Years)**	**(Years)**	
Iron and steel	25-35	15-20	40	65	Assumption
Chemical and petrochemical	20-30	10-15	25-30	40	IEA (2009)
Pulp and paper	20-25	10-25	20-30	40	IEA (2009)
Non-ferrous metals	25-35	15-25	30-35	50	UNCTAD (2000); Turton (2002)
Non-metallic minerals	25-35	15-20	35-45	50	Saygin, Patel and Gielen (2010); Moya, Pardo and Mercier (2010)

Table 2: Production Growth and Energy Efficiency Improvement Potential of Energy-Intensive Sectors (Phylipsen et al. (2002); Saygin et al. (2010); IEA (2012c))

Sector	Production Growth Between 2009 and 2030	BPT Energy Efficiency Improvement Potential In 2009	Retrofit of Existing Capacity	Energy Efficiency Improvement Potential In 2030 Compared To 2009
	(%/yr)	**(%)**	**(%/yr)**	**(%)**
Iron and steel	1.0 (0-5.5)	24	0.5	29
Non-ferrous metals	1.3 (1.0-1.5)	25	0.5	20
Chemical and petrochemical	2.5 (0-5.4)	37	0.5	23
Pulp and paper	1.3 (0-5.9)	28	0.5	23
Cement	0.9 (0-4.7)	24	0.5	29
Total industry	1.7 (0.0-5.0)	27	0.5	23

Note: For all other sectors, production growth and energy efficiency improvement potential are estimated based on the average of the energy-intensive sectors.

Values refer to the global average. Ranges in brackets refer to the lowest and highest values in each region.

Feedstock use in the chemical and petrochemical sector is estimated by applying the same methodology as for fuels used to generate process heat (Equation 1). However, EE is equal to 0 since feedstock use cannot be reduced by energy efficiency improvements. Material efficiency improvements such as recycling, or process yield improvements are not considered.

3.0 Production Costs of Heat Generation

For each renewable process heat generation technology, its production cost is estimated based on Equation (2):

$$PC_{i,t,c} = (\alpha \times I_{i,t,c} + (S_{i,t,c}/\eta_{i,t,c}) \times F_{t,c} + O_{i,t,c})/S_{i,t,c} \quad (2)$$

Where $PC_{i,t,c}$ is the production cost of heat (in US Dollars per GJ_{th}), α is the annuity factor in years (estimated as $r_c/(1-(1+r_c)^{-L}$, r_c is the discount rate in country c (in %) and L is the economic lifetime (in years), $S_{i,t,c}$ is the annual heat production (in PJ/yr), $\eta_{i,t,c}$ is the conversion efficiency, $F_{t,c}$ is the fuel price and $O_{i,t,c}$ is the annual operation and maintenance (O&M) costs of heat generation technology i in year t and region c.

4.0 Developments in the energy use of global industry

The developments in the energy use of the global industry between 2009 and 2030 are presented. The costs of each renewable energy technology are provided for the global situations also the key results of the renewable energy technology potential for the global industry sectors are provided.

5.0 Industrial Energy Use Growth

By accounting for the production rate according to the IEA (2012c) and the energy efficiency improvement potential according to Saygin, Patel and Gielen (2010), it is estimated that global industrial fossil fuel use will grow from 79 EJ in 2009 to 87 EJ in 2030 (see figure 1). Even where there are no energy efficiency improvements, total global fossil fuel use would be equal to 113 EJ/yr by 2030 due to total worldwide industrial production growing by 1.7 %/yr on average. By improving the energy efficiency of existing capacity and implementing BPTs in new capacity, the increase related to production growth is reduced and the total industrial fossil fuel use grows only limited in the entire period analysed (at an annual rate of 0.5% per year) (1). Chemical and petrochemical (1.2 %/yr), pulp and paper (0.4 %/yr), food and tobacco (0.3 %/yr) and some of the less energy-intensive sectors (0.2 %/yr) are all projected to increase their total energy use. In comparison, the energy use of all other sectors is expected to decrease by between -0.3% and -1.3 per year.

Based on the production growth of basic chemicals, it is estimated that feedstock used in the industry sector will grow from 16 EJ in 2009 to 27 EJ in 2030 (based on the *net definition* of non-energy use). This is equivalent to an annual increase in feedstock energy use of 2.4%. The share of feedstock use over the total fuel demand of the industry sector is estimated to grow from 15% in 2009 to 22% in 2030. In the chemical and petrochemical sector, the demand for fuels to generate process heat and materials production will grow by only 1.1%/yr between 2009 and 2030.

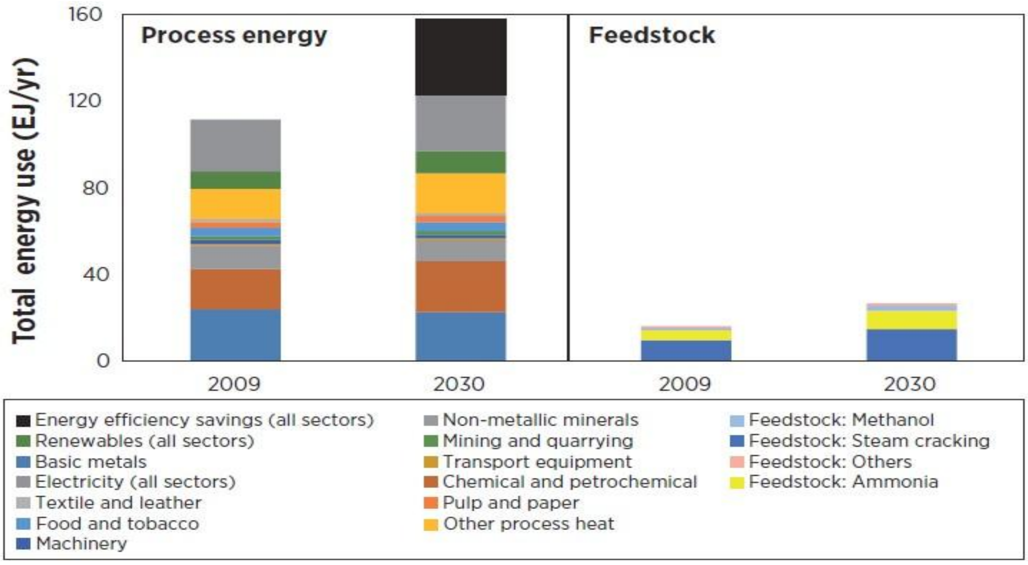

Figure 1: Total Final Energy Use in Global Industry With A Breakdown by Sectors, 2009-2030

The breakdown of industrial energy use by temperature levels is estimated to remain unchanged between 2009 and 2030. Thus, about half of the total industrial energy use in 2030 will still be operated at high-temperature levels (44 EJ). The remaining energy use will be covered by low- and medium-temperature applications with a share of 27% (23 EJ) and 23% (19 EJ) of the total industrial energy use, respectively.

6.0 Production costs of heat and materials

Figure 2 provides estimates of heat generation production costs from fossil fuels and various renewable energy technologies for the year 2009. Key findings are summarised below:

In 2009, fossil fuel-based steam generation for low and medium-temperature applications cost an average of USD 115 per GJ_{th} (range: USD 8-16 per GJ_{th}) from steam boilers (first column from left) [2]. High-temperature direct heat applications are estimated to be slightly more expensive at USD 13 per GJ_{th} (range: USD 7-2 per GJ_{th}). This is explained by the lower combustion efficiency (Second column from left).

In 2009, heat production from the steam boiler and CHP plants was estimated to cost on average USD 9 and USD 11 per GJ_{th}, respectively, from cheap sources of biomass (third and seventh columns respectively from the left). These technologies are cost-competitive compared to fossil fuel-based technologies. In comparison, the production of steam from expensive biomass sources costs on average USD 20 and USD per GJ_{th} from boilers and CHPs, respectively. This is some 60-100% higher compared to fossil fuel-based heat production. Production costs of steam from CHP are slightly higher than from boilers based on the energy allocation method. However, the true cost of steam is highly dependent on the electricity price, which is excluded in this analysis.

Similarly, biomass heat generation for high-temperature applications is cost-competitive from cheap sources of biomass, with production costs estimated at USD 10 ± 5 per GJ_{th} (fifth column from the left). However, heat production from expensive sources costs on average two times more (USD 33 ± 22 per GJ_{th}) compared to fossil fuel-fired furnaces.

CHPs fired with low-cost biogas produce low-temperature heat at an average cost of USD 24 ± 7 per GJ_{th} (range: USD 19-32 per GJ_{th}). Despite low fuel costs, heat generation costs are high due to the high capital costs of anaerobic digestion and CHP systems.

Heat production from low- and medium-temperature solar thermal systems costs on average USD 55 ± 14 per GJ_{th} (range: USD 8-69 per GJ_{th}) (third and fourth columns from right).

Heat pumps (depending on the electricity price) and geothermal energy offer cost-competitive heat production costs compared to fossil fuels with heat generation costs estimated at USD 16 ± 3 USD/GJ_{th} (range: USD 10-22 per GJ_{th}) and USD 7 ± 2 per GJ_{th} (range: USD 5-13 per GJ_{th}), respectively (last two columns from the left, respectively).

Based on heat production cost analyses, it is shown that boilers, CHPs and anaerobic digestion fired with residues and other cheap sources of biomass offer cost-competitive alternatives to fossil fuel-based steam generation for varying temperature levels of process heat used in the industry sector. Other cost-competitive alternatives are presented only for low-temperature applications, heat pumps and geothermal heat.

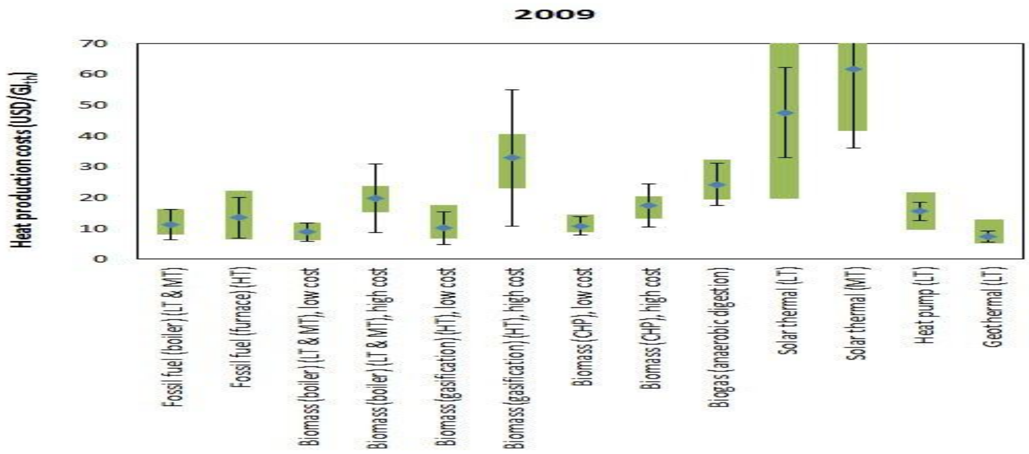

Figure 2: Heat Production Costs of Fossil Fuel-Based and Renewable Energy Technologies (2009).

Note: The high and low ends of the green bars refer to the range of production costs in the ten different regions analyzed. The blue dots refer to the average for the total global industry. LT: low temperature, MT: medium temperature, HT: high temperature. Error bars refer to the estimated uncertainty margins of the mean values for the global situation.

The heat production cost estimates for 2030 for low and high energy price (and technological learning) scenarios are provided in Figure 2. Given the current situation and developments between 2010 and 2030, the findings for 2030 are summarized below:

Based on IEA data (2011a), it is assumed that fossil fuel prices will increase by between 0.6 %/yr (coal) and 3.1 %/yr (natural gas) for the high energy price increase scenario and between -1.5 %/yr (coal) and 1.0 %/yr (crude oil) for the low energy price increase scenario. As a result of these changes, process heat production costs for varying temperature levels should increase from about USD 12 per GJ_{th} in 2010 to approximately USD 15 per GJ_{th} by 2030. CO_2 prices will add 25-45% additional costs to fossil fuel-based routes in the low energy price scenario in comparison to 510% increase in the high energy price scenario.

Assuming that biomass prices are coupled to the increase in fossil fuel prices, heat production costs for steam boilers and CHPs of USD 9 ± 3 and 10 ± 3 per GJ_{th} from cheap sources of biomass by 2030, respectively, are forecast for low price scenario. For expensive sources of biomass, heat production costs from these technologies are estimated to be higher at USD 20 ± 12 and 24 ± 12 per GJ_{th}, respectively. Low- and medium-temperature heat generation from biomass will still remain a cost-competitive alternative, in particular if cheap biomass sources such as residues are used. This is also valid for the high price scenario projections.

High-temperature heat production from biomass costs on average USD 10 ± 5 (low-cost) and USD 32 ± 22 (expensive) per GJ_{th} by 2030 for low and high price scenarios, respectively. Compared to high-temperature heat production from fossil fuels, this remains an expensive option except when low-cost biomass sources are used or if CO_2 prices are high.

For biogas, the increase in biomass prices is partly levelled off by the decrease in its capital costs (~10%) between 2010 and 2030. Relative to other bio-based alternatives, its production costs are still high, estimated at USD 26 ± 9/GJ_{th} for low and USD 29 ± 10/GJ_{th} for high price scenarios.

As a result of the increase in conversion efficiencies and the decrease in capital costs of solar thermal technologies, heat production costs should decrease by 40-60% between 2010 and 2030. Solar thermal for low- and medium-temperature applications can be cost competitive (USD 20 ± 10 and USD 48 ± 24/GJ_{th}; respectively; for the low-price scenario) in some regions compared to fossil fuel-based technologies. For the high-price scenario with low technological learning, solar thermal-based heat generation costs are estimated to remain expensive compared to fossil fuel counterparts.

Heat pumps (USD 14 ± 5/GJ_{th}) and geothermal energy (USD 10 ± 4/GJ_{th}) will remain as cost-competitive alternatives in 2030.

If the increase in steam coal prices also applies to coking coal, USD 4-7/GJ and USD 7-10/GJ for coking coal prices are estimated, according to the low- and high-energy price scenarios, respectively. Accounting for CO_2 pricing, coking coal prices would increase to USD 915/GJ. In comparison, the charcoal price is estimated to be on average USD 5/GJ higher.

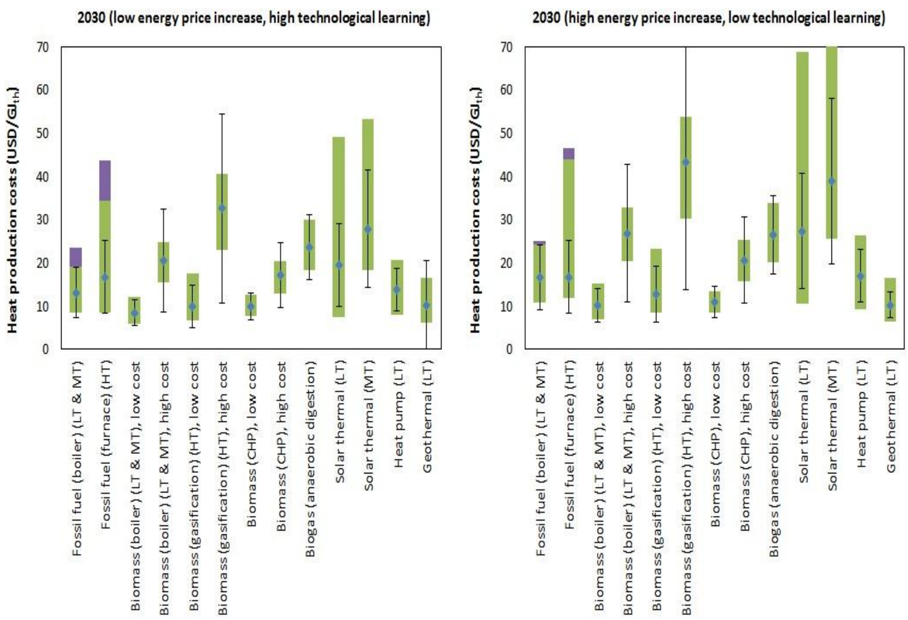

Figure 3: Heat Production Costs of Fossil Fuel-Based and Renewable Energy Technologies for Low (Left-Figure), and High (Right-Figure) Energy Price Increase and Technological Learning Scenarios, 2030.

Note: The high and low ends of the green bars refer to the range of production costs in the ten different regions analysed. The blue dots refer to the average for the total global industry. Purple bars indicate the additional costs of heat production from fossil fuel-based technologies due to CO_2 prices. LT: low temperature, MT: medium temperature, HT: high temperature. Error bars refer to the estimated uncertainty margins of the mean values for the global situation.

The production costs of materials (selected for this analysis are ethylene, methanol, and PET) are presented for the situation in 2030 in Figure 4. Compared to petrochemical equivalents, the production costs of ethylene from biomass feedstock are on average 30% higher. In a few regions, the production cost of bio-ethylene is cost-competitive (similar or about 10% lower), but in most regions, the production costs could be doubly more expensive. Similar relationships are estimated for PLA with its production costs on average 10% higher than its petrochemical equivalent PET. Based on IRENA/IEA-ETSAP (2013c) estimates, bio-methanol is not cost-competitive in all regions of the world and by a factor of 2-3 higher than the petrochemical route. Due to the lack of bottom-up production cost estimates, there is no further information on the possible future developments in material production costs. However, with increasing fossil fuel prices and technological developments (*i.e.*, increasing conversion efficiencies of sugar to chemicals/polymers), bio-ethylene and PLA are expected to be cost-competitive in more regions (Saygin *et al.*, 2014). For the same reasons, the economic viability of bio-methanol production could improve in the long term, if waste (*e.g.*, black liquor, glycerine) feedstocks are utilized in its production.

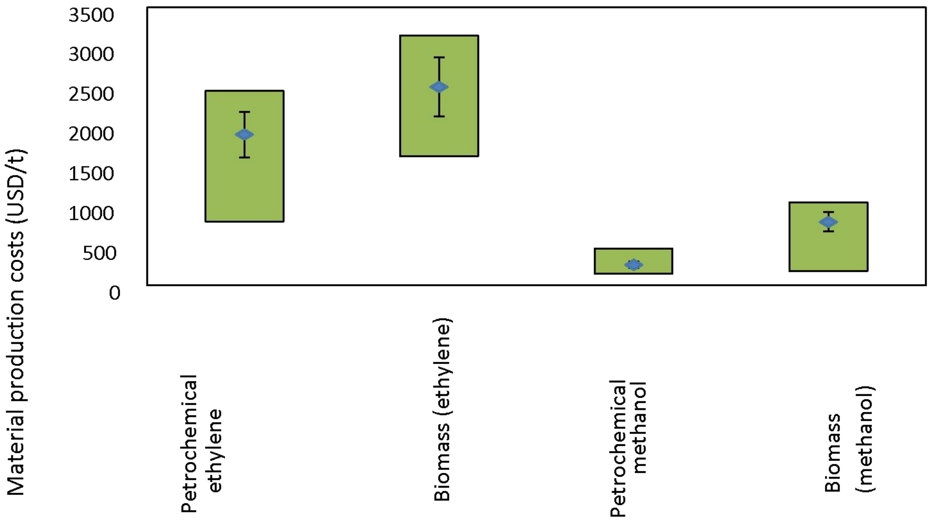

Figure 4: Material Production Costs from Petrochemical and Biomass Feedstocks (2030)

Note: The high and low ends of the green bars refer to the range of production costs in the ten different regions analysed. The blue dots refer to the average for the total global industry. Error bars refer to the estimated uncertainty margins of the world average.

7.0 Potential of Renewable Energy Technologies in The Total Global Industry Sector

The summary of the realizable technical potential of the four renewable energy technologies is presented for the global industry in the year 2030. The largest potential is estimated for biomass, with a total potential of 41 EJ and 81 EJ according to the AccD and AmbD scenarios, respectively. Approximately 40% of the potential exists in the chemical and petrochemical sector as fuel for heat generation (10%) and as feedstock to produce materials (30%). High-temperature applications in non-metallic minerals and iron and steel sectors account for another 25% of the total biomass demand (11-20 EJ). The total biomass demand for high-temperature applications is about 45% of the total biomass demand as fuel. This shows the importance of biomass for the total industry to substitute fossil fuels used in high-temperature applications. The total realisable potential of biomass could replace between 30-60% of the total industrial fuel demand for heat generation, depending on technological developments.

The total potential for solar thermal, geothermal and heat pumps are estimated at 15 EJ, 2 EJ and 2.3 EJ, respectively (in both AccD and AmbD scenarios). The chemical and petrochemical sector accounts for about half of the total potential of the solar thermal process heat technology. This sector has the potential to replace more than half of its existing capacity by 2030, providing the opportunity for deploying solar thermal process heat capacity, and it has a high share (>50%) of low- and medium-temperature heat demand in its production processes.

The pulp and paper, food and tobacco and other small sectors account for the largest potential for geothermal and heat-pump technologies, as well as the remainder of the solar thermal (*i.e.*, sectors with high shares of low- and medium-temperature heat demand in their production processes). Total realisable potential of solar thermal and geothermal energy is estimated to substitute about 21% and 3% of the total industrial energy use, respectively. These potentials would increase the share of renewable energy use in the industry sector from 10% to 27% and 16%, respectively.

The majority (>90%) of the potential for solar thermal and geothermal technologies lies in new capacity, assuming that new plants would be constructed in regions that can accommodate the space requirements of solar thermal technologies, either on roofs or land near geothermal energy sources. However, the potentials of solar thermal and geothermal technologies are clearly lower than those of biomass and this is explained by the fact that biomass combustion is the only alternative to fossil fuel-based high temperature heat generation and feedstock use for materials production. Excluding biomass use, it may be challenging to increase the share of renewable.

In a low-cost scenario, Table 3 compares various heating systems based on the fuel type, applicable temperature ranges, and cost-effectiveness. For the type of Fuel and Technology, the Boiler, biomass residues make use of organic waste products including wood trash and forestry residues and also provide substantial cost reductions of -85 to -60 units in applications involving low and medium temperatures, while crops use energy crops that are grown especially for the generation of biomass energy and produce extra expenses, between 82 and 110 units, suggesting that the cost of using energy crops specifically is higher than that of residues.

The high temperature and biomass residues like the previous one but made for uses that call for greater temperature outputs offer significant cost savings of -79 to -61 units, while the energy crops are used in applications requiring high temperatures and have higher prices, between 105 and 126 units, which is comparable to the pattern seen in biomass boilers. For the combined heat and power (CHP), Biomass using organic waste materials, and residues produces heat, and electricity and provides moderate cost reductions of -62 to -44 units in applications at low and medium temperatures while crops use energy crops to generate both power and heat, it comes with extra expenses, between 45 and 59 units.

For Anaerobic digestion and biogas, anaerobic digestion of organic leftovers yields biogas, which is subsequently utilized for low-temperature heating in the low-price scenario, this technology is more costly due to its higher expenses, which range from 116 to 154 units. For the solar-thermal, evacuated tubes and flat plates are solar collectors made for applications requiring low to medium temperatures incurring additional expenditures of 70 to 93 units. General solar thermal is a broad category that includes a variety of solar thermal technologies for heating at low to medium temperatures having a cost between 162 and 214 units.

Particularly in high-temperature environments, using biomass leftovers for heating purposes typically saves money in this low-cost situation. On the other hand, using certain energy crops usually results in higher expenses for a range of uses. In low-temperature applications, technologies like heat pumps and geothermal systems show potential with little to no additional expenses or moderate savings. But in this case, solar thermal methods are more expensive.

Table 3: Estimated CO_2 Abatement Costs of Heat Generation Technologies, 2030 (in USD/t CO_2)

	Fuel type	Temperature level of heat	Low price scenario
Biomass, boiler	Residues	Low, medium	-75 (-85 - -60)
	Crops		99 (82 - 110)
Biomass, high-temperature	Residues	High	-70 (-79 - -61)
	Crops		115 (105 - 126)
Biomass, CHP	Residues	Low, medium	-55 (-62 - -44)
	Crops		54 (45 - 59)

Biogas, anaerobic digestion	Residues	Low	138 (116 - 154)
Solar thermal, flat plate, evacuated tube	N/A	Low, medium	84 (70 - 93)
Solar thermal	N/A	Low, medium	193 (162 - 214)
Heat pump	N/A	Low	8 (7 - 9)
Geothermal	N/A	Low	-38 (-43 - -32)

8.0 Realizable Economic Potential

The technological and economic potential of several renewable energy sources under the AmbD and AccD scenarios are compared in Table 4. Under the AmbD scenario, biomass (process heat) has a technological capacity of 81 EJ/yr and an economically feasible potential of 15–19 EJ/yr. The technical potential falls to 41 EJ/yr and the economic potential to 13–14 EJ/yr in the AccD scenario. The economic potential of biomass (feedstock) is 1-2 EJ/yr under AmbD and 0.5-1 EJ/yr under AccD. There is no technical potential data given. Solar thermal: Under AmbD, the economic potential is between 0.9 and 3.8 EJ/yr, whereas under AccD, it rises to 14.9 EJ/yr.

There is no technical potential data given. Geothermal: Under AmbD, the economic potential is 1.7–1.9 EJ/yr, while under AccD, it is 1.9 EJ/yr. There is no technical potential data given. The economic potential of a heat pump is 1.2-1.9 EJ/yr under AmbD and 2.3 EJ/yr with AccD. There is no technical potential data given. Electricity: In both cases, the economic potential stays at 1.1 EJ/yr. There is no technical potential data given. Although the technical potential of biomass (process heat) is substantial, the commercially viable component is much smaller, suggesting that there are financial barriers to fully utilizing the technical capacity.

The economic potential of heat pumps and solar thermal systems rises significantly in the AccD scenario, indicating that intensified decarbonization initiatives may boost the economic appeal of these technologies. Regardless of the decarbonization strategy, electricity's economic potential is consistent across both scenarios, suggesting that its viability is unaffected. To close the gap between what is technically conceivable and what is economically feasible, this table emphasizes the significance of cost reductions, technological developments, and supportive policies.

Table 4: Summary of Estimated Realisable Economic Potential of Renewable Energy Technologies and Comparison to The Realisable Technical Potential

	Realisable economic (EJ/yr)		Realisable technical (EJ/yr)	
	AmbD	AccD	AmbD	AccD
Biomass (process heat)	15-19	13-14	81	41
Biomass (feedstock)	1-2	0.5-1		
Solar thermal	0.9-3.8		14.9	
Geothermal	1.7-1.9		1.9	
Heat pump	1.2-1.9		2.3	
Electricity	1.1		1.1	

Note: Potentials provided in this table refer to individual technologies and competition of technologies for the same heat application for a specific sector is not considered. Each technology should therefore be treated separately, and the potentials of all technologies should not be cumulatively added to estimate the total renewable energy technology potential for the industry sector.

According to Figure 6 (referring to the low-price scenario according to the results of the AmbD scenario), the largest potential of renewable energy technologies is in the chemical and petrochemical sector estimated at 7 EJ. The sector is the largest industrial energy user worldwide including fuels used for feedstock and up to 20% of its fossil fuel demand can be substituted with renewable energy. This is followed by the other energy-intensive sectors, namely non-metallic minerals (4.7 EJ) and basic metal sectors (1.8 EJ) with substitution potential reaching 30% in the non-metallic minerals sector.

Among the less energy-intensive sectors, the largest potential is in the food and tobacco sector (2.6 EJ) with a wide range) to 7 EJ. The total potential of th ntensive sectors (14 EJ).

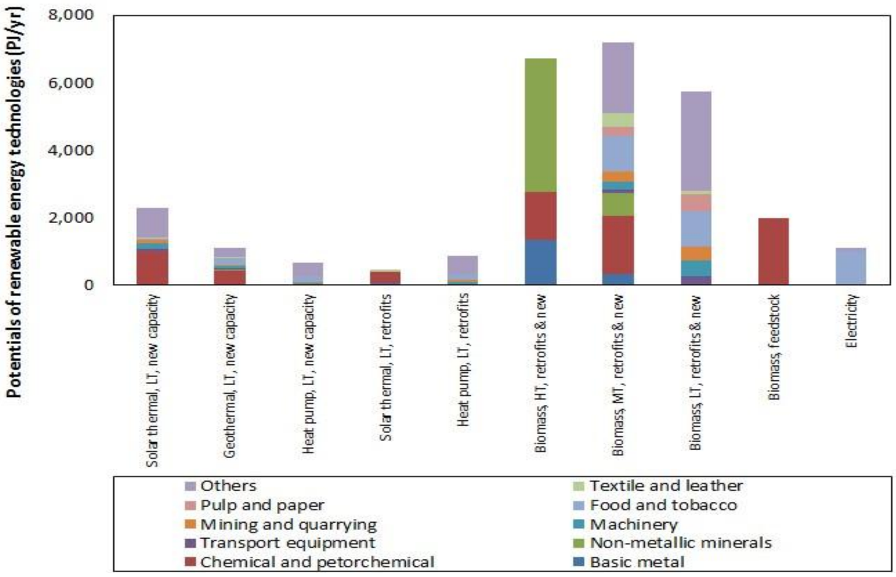

Figure 6: Realizable Economic Potential of Renewable Energy Technologies with a Breakdown by Global Industry Sectors for the Low-Price Increase Scenario (According to AmbD Scenario), 2030

So far, assessment of the renewable energy technologies in the industry sector has received little attention. This paper tried to close this knowledge gap by providing first-order estimates of the potential of renewable energy technologies at sector and region levels, and by developing scenarios to address how the current share of renewable energy in the industry sector could be raised.

Conclusion

There is a great chance to improve sustainability and lower carbon emissions by incorporating renewable energy into industrial processes. According to the statistics, biomass has significant viable economic potential, especially for process heat, with an estimated 13–19 EJ/year and a technical capacity of up to 81 EJ/year under ambient drying conditions. With achievable economic potentials of 0.9 to 3.8 EJ/year and 1.7 to 1.9 EJ/year, respectively, solar thermal and geothermal energy also contribute to this potential, albeit to a lower degree. Additional integration opportunities include electricity and heat pumps, both of which have an annual economic potential of 1.1 to 1.9 EJ. However, careful consideration of technical, financial, and infrastructure aspects is required for the successful deployment of these renewable energy sources in industrial settings. It is necessary to handle issues including the requirement to upgrade current infrastructure, provide a steady supply of energy, and control the sporadic character of some renewable sources. This shift can be facilitated by partnerships with specialists in the integration of renewable energy, guaranteeing that industrial processes are optimized for sustainability and efficiency.

Declarations

Ethics approval and consent to participate

Not applicable

Competing interest

The author declares that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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