IRENA
International Renewable Energy Agency

RENEWABLE ENERGY OPTIONS FOR THE INDUSTRY SECTOR: GLOBAL AND REGIONAL POTENTIAL UNTIL 2030

Background to "Renewable Energy in Manufacturing" Technology Roadmap (IRENA, 2014a)

BACKGROUND PAPER

About IRENA

The International Renewable Energy Agency (IRENA) is an intergovernmental organisation that supports countries in their transition to a sustainable energy future and serves as the principal platform for international cooperation, a centre of excellence, and a repository of policy, technology, resource and financial knowledge on renewable energy. IRENA promotes the widespread adoption and sustainable use of all forms of renewable energy, including bioenergy, geothermal, hydropower, ocean, solar and wind energy, in the pursuit of sustainable development, energy access, energy security and low-carbon economic growth and prosperity.

This report, and other REmap material are available for download through www.irena.org/remap.

For further information or to provide feedback, please contact the REmap team at remap@irena.org

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This is a background paper to "Renewable Energy in Manufacturing" (IRENA, 2014a), a technology roadmap developed as part of IRENA's global renewable energy roadmap, REmap 2030.

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Executive summary

In June 2014, the International Renewable Energy Agency (IRENA) released a global renewable energy roadmap – REmap 2030 – aimed at doubling the share of renewables in the global energy mix by 2030 (IRENA, 2014a). The aspirational target for this roadmap is derived from the Sustainable Energy for All (SE4ALL) initiative, which is currently chaired by the United Nations Secretary-General and the World Bank President. REmap 2030 is the result of a collaborative process between IRENA, national REmap experts within the individual countries, and other stakeholders.

IRENA's approach in REmap 2030 uses two parallel tracks:

- A country-based analysis to identify actions relevant to technology deployment, investment and policies in collaboration with IRENA Members and other key entities; and
- A series of technology roadmaps to identify cross-country insights on actions needed to achieve the target of doubling the share of renewables in the global energy mix.

REmap 2030 suggests that existing and future renewable energy expansion, as currently planned, will result globally in a 21% share of renewables in the global energy mix by 2030 (IRENA, 2014a). This leaves a 15% point gap to achieve the 36% target cited in the SE4ALL Global Tracking Report (Banerjee *et al*., 2013). Furthermore, the results of country-based analyses suggest that there are very few countries that have explicit policies to support renewables deployment in the manufacturing sector.

To complement and support the country-based analyses and to help bridge the gap towards doubling renewables globally, IRENA has developed a technology roadmap for the global manufacturing sector. The technology roadmap is called "Renewable Energy in Manufacturing – A Technology Roadmap for REmap 2030" and was published in June 2014 (IRENA, 2014b). This roadmap is based on the quantitative study presented in this working paper and two stakeholder workshops ("Renewables for a New Product Mix" convened in Brussels, Belgium on 19 April, 2012 (IRENA, 2012a) and "Renewables for Small and Medium Enterprises in South Asia" held in New Delhi, India on 21-22 November, 2012 (IRENA, 2012b), as well as feedback from industry stakeholders at meetings held at the International Energy Agency (IEA) and the World Business Council for Sustainable Development (WBCSD).

This working paper provides details of the background data and analysis for IRENA's technology roadmap (IRENA, 2014b). This first-of-its-kind analysis includes detailed data on energy demand projections in the energy-intensive sectors (*e.g.*, iron, steel and non-metallic minerals), as well as a number of less energy-intensive sectors (*e.g.*, food, tobacco and textiles). The analysis also differentiates between renewable energy deployment in existing and newly-built plants. Feedstock use for material production is analysed as a separate category and included as an option to increase the share of renewable energy in this sector. Energy efficiency improvements, production capacity growth estimates, local availability of resources, local fossil fuel prices and the role of policies to promote renewable energy deployment have been considered as part of the analysis, including the option to relocate industries to resource-rich areas. Individual technology options (*e.g.*, bio-ethylene and bio-methanol production from biomass, heat pumps, solar thermal applications and biomass co-generation) are analysed in detail based on IRENA's technology briefs (IRENA/IEA-ETSAP, 2013a-d).

Comprising a third of the total global energy demand, the manufacturing industry is a crucial end-use sector that must be engaged to achieve a doubling of the share of renewable energy. Earlier analyses by the International Energy Agency (IEA) and the United Nations Industrial Development (UNIDO) show that improving industrial energy efficiency by implementing best practices and new technologies is a prerequisite to achieving the SE4ALL targets. According to another UNIDO analysis, developing and deploying a suitable carbon capture and storage (CCS) technology may contribute to a further reduction of carbon dioxide (CO_2) emissions by the manufacturing industry. Still, CCS technology is an expensive option compared to other low-carbon technologies. Even so, these measures do not reduce the reliance on fossil fuels. Achieving higher penetration levels for renewable energy will be crucial to achieving higher long-term reductions in industry sector's fossil fuel demand and related CO_2 emissions. Accelerated action will be required in all regions and industry sub-sectors to achieve this goal.

The extent to which renewable energy technologies can contribute to reduction of the industry sector's fossil fuel demand has so far not attracted sufficient attention. This study seeks to close this knowledge gap by providing a comprehensive and detailed techno-economic analysis of the regional and sectoral renewable energy potential. This quantitative analysis includes detailed data on energy-intensive sectors (*e.g.*, iron, steel and non-metallic minerals), as well as a number of light industry sectors (*e.g.*, food, tobacco and textiles). Feedstock use for materials production is analysed as a separate category. Energy efficiency improvements, production capacity growth estimates, local availability of resources, local fossil fuel prices and the role of policies to promote renewable energy deployment have been considered as part of the analysis. More information on the individual technology options (*e.g.*, bio-ethylene and bio-methanol production from biomass, heat pumps, solar thermal applications and biomass co-generation) can be found in IRENA's technology briefs (IRENA/IEA-ETSAP, 2013a-d).

The global industry sector between 2009 and 2030

The global industry sector used in total 128 exajoules (EJ) of final energy in 2009, which represents about a third of all global energy use. A worldwide total of 78 EJ of fuels were used to generate process heat via steam and direct heat and another 9 EJ was used by blast furnaces and coke ovens for iron and steel production (together referred to as "process energy"). Petrochemical feedstock use for the production of chemicals and polymers (together referred to as "materials") was about 16 EJ. The sector's remaining energy use was to cover electricity demand (24 EJ) for various uses, such as electrolysis, motor drives, cooling or refrigeration. Analysis of the renewable energy potential in the industrial electricity demand is, however, beyond the scope of this paper.

Approximately two-thirds of the total final industrial energy use worldwide comes from developing countries and economies in transition (81 EJ) (represented by non-OECD countries in this study). The fuel mix varies substantially across different regions. Natural gas accounts for at least 40% in regions, such as the OECD Americas and Europe, while China and the OECD Pacific use coal to meet industrial energy demand (80% and 35%, respectively). A few regions use a high share of renewable energy in their fuel mix, such as India (24%), Latin America (35%) and Africa (42%), while Middle Eastern countries show only negligible renewable energy use shares.

In 2030, global industrial process energy use is estimated to have grown by about 20% compared to current levels of 152 EJ. Industrial energy use in OECD countries will decrease by about 15% in this time period while non-OECD countries will increase their energy use by 20%. With the exception of China and non-OECD Europe, energy demand in non-OECD countries is estimated to grow by between 50-100% depending on the region's production growth projections and energy efficiency improvement potential.

About half of the global industrial energy use in 2030 would come from new capacity (40 EJ), which also offers important potential to deploy renewable energy technologies. Substantial stock turnover is estimated for the OECD Americas where replacement capacity will account for 60% of their total industrial energy use due to ageing energy-intensive sectors. Non-OECD countries will be similar to the world average with about half of the total energy demand coming from new capacity.

The potential of renewable energy technologies

The potential of renewable (RE) technologies for 2030 is estimated on two levels in descending order; namely, their realisable technical and realisable economic potential[1].

Realisable technical potential: The largest realisable technical potential are estimated for biomass, which could substitute two-thirds of the industrial fossil fuel demand as fuel and feedstock (40-80 EJ). More than 60% of the potential is located in high-temperature applications and as feedstock for materials production. Solar thermal has a realisable technical potential of 15 EJ with more than 85% coming from new capacity. With a similar share in new capacity, geothermal can provide 1.9 EJ of renewable energy for industrial process heat generation. Heat pumps have similar potential estimated at 2.3 EJ, dispersed across existing and new capacity.

Realisable economic potential: The realisable economic potential depends on the availability of low-cost biomass resources (mainly residues) and fossil fuels, as well as economic policies that promote the role of renewable energy. The results presented here are based on policies that favour the deployment of renewable energy technologies where fossil fuel price increases between today and 2030 is relatively low due to decreasing demand, and technological learning takes place for solar thermal systems and heat pumps. Furthermore, this scenario assumes that governments will introduce CO_2 prices to stimulate the deployment of renewable energy technologies. According to the IEA's World Energy Outlook for OECD regions, CO_2 prices of more than US dollars (USD in real 2010 terms) 85/tonne CO_2 are assumed while in some non-OECD regions, the CO_2 prices are projected to reach to USD 65/tonne.

In this scenario, biomass will play a key role for high-temperature (HT; >400 ^{o}C) heat applications in the iron and steel, non-metallic minerals and chemical and petrochemical sectors where other technologies do not provide alternatives. Assuming that the economic potential of low cost biomass sources will be

[1] In this IRENA analysis, the "Realisable technical potential" refers to the share of energy demand that can be technically provided by renewable energy sources, considering capital stock turnover and temperature levels, but not resource availability or cost barriers. "Realisable economic potential" considers renewable energy sources based on their costs and regional/national resource availability.

exploited in both existing and new capacity, biomass demand is estimated to increase to 6.5-8 EJ by 2030. Together with medium (MT; 150-400 ^{o}C) and low temperature (LT; <150 ^{o}C) applications where biomass can play a further role, total biomass potential for process heat generation is estimated at 15-20 EJ. Biomass demand for feedstock is estimated at 1-2 EJ. About 80% of the total realisable economic potential of renewables in industry worldwide will come from biomass (23-28 EJ). Low cost biomass sources will provide the basis for a large share of its potential.

The potential for solar thermal and geothermal technologies in low and medium temperature applications in new capacity is estimated at 2.3 EJ and 1.1 EJ, respectively. Potential exists in the chemical and petrochemical and food and tobacco sectors of OECD countries, China, Latin America and India. In addition to new capacity, heat pumps are also estimated to offer potential for existing capacity with total potential estimated at 1.5 EJ across all regions worldwide.

Relocation of primary aluminium smelters next to renewable energy power plants (1 EJ) and substituting electricity-intensive refrigeration equipment in the food and tobacco sector with solar cooling (0.1 EJ) could contribute in total to another 1.1 EJ potential for the industry sector. Electricity demand for other production processes (*e.g.*, electrolysis, motor drives) is estimated to reach at least 26 EJ by 2030 (excluding additional 3-5 EJ demand from heat pumps). According to the BAU scenario, fossil fuels would be used to generate this demand. Increasing the share of renewable energy in the power sector is already cost-effective in some regions. This could contribute further to increasing the share of renewable energy use in the industry sector. Therefore, it deserves further research that is currently outside the scope of this analysis.

From a regional perspective, Asian countries have the highest realisable economic potential. Biomass as feedstock for material production is an important opportunity. Also, the OECD Americas have a high potential due to the capital stock turnover that will take place over the next 20 years but also due to high CO_2 prices. Despite the highest resource availability, the technical and realisable economic potential in Africa is low due to the limited production capacity predicted for 2030.

The most substantial potential worldwide is estimated for the largest industrial energy user: the chemical and petrochemical sector (5-7 EJ). Other energy-intensive iron and steel and non-metallic minerals sectors follow with 5-6 EJ. Among the less energy-intensive sectors, the largest potential is in the food and tobacco sector (2-3 EJ) with a wide range of technologies offering potential. Other smaller sectors offer potential up to 9-11 EJ.

Achieving the total realisable economic potential of 28 EJ could raise the renewable share in the fuel mix of the industry from 10% to 34% worldwide. The results show that about two-thirds of the total global potential is estimated to have an average incremental cost of less than USD 1 per gigajoule (GJ) of fossil fuel substituted. Potentials of geothermal heat, heat pumps and low and high-temperature biomass applications fall within this category. The most expensive option is solar thermal in low temperature applications (USD 2/GJ). Biomass for medium temperature applications costs between USD -4 and USD 0/GJ. Pricing of CO_2 emission and access to available biomass residues determine whether these potentials can be reached. In the case where no CO_2 prices are assumed, the incremental costs would increase with USD 4-6/GJ and reduce the total realisable economic potential to about 27%. Limited biomass availability for industrial use would not necessarily increase the incremental costs but reduce the total renewable energy share to around 15%.

Key areas for exploiting the potentials and conclusions

So far, the potential of renewable energy technologies in the industry sector has received scant attention. This study closes this knowledge gap and shows how the current renewable energy share in the industry sector could be raised to contribute to doubling the share of renewable energy in the global energy mix by 2030. Based on the findings of this study, a number of key priority areas are identified. These are:

- **Energy-intensive sectors:** With 75% of the total industrial energy demand and long lifetimes for these types of plants, the energy-intensive sectors need to consider renewable energy options not only as an integral part of their new build capacity, but also as part of their existing capacity.
- **Small and medium enterprises (SMEs):** Accounting for more than 90% of all manufacturing businesses, SMEs play a crucial role in increasing the deployment rate of renewable energy technologies, providing local manufacturing opportunities and stimulating cost reductions through learning by doing.
- **Biomass:** Among the renewable technology options, biomass has the largest substitution potential in the manufacturing industry, but immediate and internationally coordinated action is required to alleviate the serious supply constraint of sustainable sourced and low-cost biomass resources, and to deploy the most resource efficient biomass use applications.
- **Solar thermal systems:** Solar thermal heat systems have a large technical and realisable economic potential in small scale plants and less energy-intensive industries like the textile and food sectors, but the vicious circle of high initial capital costs and low deployment rates needs to be broken.
- **Electrification:** With increased electrification in the industry sector, renewable energy deployment can only be achieved through technology development in both the industry and power sectors.
- **Regional aspects:** Regional potential depends on production growth, ratio of existing and new capacity, and renewable resource availability. Energy pricing and climate policies can ensure a level playing field and biomass resource constraints may be elevated by trade, but equally important will be specific policies to support the different industries in deploying renewable energy.

Next steps

This study provides first order estimates of the potential of renewable energy technologies in the industry at the sectoral and regional level. It also develops technical and economic scenarios showcasing how the industry sector can contribute to raising the share of renewable energy in the global energy mix. These findings should, however, only be regarded as indicative due to the numerous assumptions, as well as uncertainties in the underlying data. Therefore, many issues require further research to improve the findings of this report.

1. Introduction

The global industry sector accounted for about a third of the global energy use and in 2009 when the sector's total final energy demand reached 128 exajoules (EJ)[2]. A total of 78 EJ of fuels were used to generate process heat. Another 9 EJ was used by blast furnaces and coke ovens for iron and steel production. Petrochemical feedstock use for the production of chemicals and polymers (together referred to as "materials" throughout this study) was about 16 EJ. The sector's remaining energy use was electricity demand (24 EJ) for various uses such as electrolysis, motor drives, cooling or refrigeration (IEA, 2012a).

Approximately 64% of the total final industrial energy use worldwide came from non-OECD countries (81 EJ), the majority which are developing countries and economies in transition. Industrialised and high-income countries (*i.e.*, OECD countries) used in total 47 EJ final energy (36%). Today, 91% of the sector energy use originates from fossil fuels, coal, petroleum products and natural gas accounting for 44%, 26% and 21% of the total final energy use, respectively (excluding the demand for electricity and feedstock use). Renewable energy sources account for about 9% of the industrial energy use, which is mostly biomass and waste (the shares are the same in both OECD and non-OECD countries). The fuel mix varies substantially across different regions. While in the OECD Americas and Europe, natural gas accounts for at least 40% of the total fuel mix, in China and the OECD Pacific, 80% and 35%, respectively of the total demand is met by coal. A few regions use a high share of renewable energy in their fuel mix, such as India (24%), Latin America (35%) and Africa (42%). In comparison, the share of renewable energy use in economies in transition and the Middle East is less than 1%.

Since 2009, energy demand in the global industry sector has recovered from the financial crisis and grown with 2.7% per year (including demand as feedstock use). The share of energy consumption in non-OECD countries has also continued to grow and they account for more than two thirds of the total global in 2012. In most countries, industry is a key sector or the economy and it will remain so in the next decades as well since the demand for materials (*e.g.*, steel, plastics, bricks) will continue to increase as a consequence of population and economic growth. In turn, this growth will have important effects on the sector's demand for energy. Increasing energy use will lead to the release of more carbon dioxide (CO_2) emissions, which are regarded as the main driver of climate change. Increasing concerns about climate change has created different policy responses. In 2011, the Sustainable Energy for All (SE4ALL) initiative was launched by the United Nations Secretary-General. It seeks commitment from all countries to meet three objectives by

[2] Data include the petrochemical feedstock for the production of chemicals and blast furnaces and coke ovens. Petroleum refineries are excluded. In IEA energy statistics, data are provided according to International Standard Industrial Classification (ISIC) of All Economic Activities, Rev.3.1; UNSD, 2010 for all manufacturing industry Divisions (*i.e.*, 13-37), except for Divisions 23, 25, and 36. Division 23 is reported under the "own use" item of the transformation and energy sector. The other ISIC Divisions are reported under the non-specific item of the industry sector. However, some countries, particularly those outside the OECD, may deviate from this reporting approach. In these countries, a share of the energy use or the entire energy demand of an industry sector, despite the availability of a specific item in IEA energy statistics, may have been reported to the non-specific item. In this study, it is assumed that the total energy use of the industry sector reported in the energy statistics of each country is not subject to any reporting differences, and the energy use related to all production activities is covered. However, for two sub-sectors an exception is made and data is adjusted based on bottom-up estimates; namely, the non-metallic minerals sector and the chemical and petrochemical sector.

2030: 1) ensuring universal access to modern energy services; 2) doubling the rate of improvement in energy efficiency; and 3) doubling the share of renewable energy in the global energy mix. The third objective is addressed by the International Renewable Energy Agency (IRENA) in its renewable energy roadmap – REmap 2030 - to double the share of renewable energy in the global energy mix (IRENA, 2014a). Given its large energy share, the industrial sector has an important role to play in meeting these targets.

A number of measures exist to reduce the industry sector's increasing demand for fossil fuels and the related CO_2 emissions. Among them, conservation of energy use by improving energy efficiency is the first step as it is cost-effective and various technologies exist which are suitable for different production processes (Worrell *et al*., 2009; Alcorta *et al*., 2014). According to Saygin, Patel and Gielen (2010), improving industrial energy efficiency by implementing best practice technologies (BPT) could reduce total final industrial energy demand more than 25%. However, even more reductions in industrial energy demand would be required to meet ambitious targets in the long term.

Another measure is carbon capture and storage (CCS) technology, but it has not yet proven successful on a commercial scale, its costs for the industry sector are too high and the capture processes (*e.g.*, heat regeneration, compression) require additional energy, which would increase industrial energy demand and reduce the gains achieved from improving energy efficiency (UNIDO, 2011).

The third option is renewable energy which has so far not received much attention, especially compared to the power and transport sectors (Taibi, Gielen and Bazilian, 2012). Suitable policies could also help the industrial sector to increase its share of renewable energy in the next decades as there are already many commercial scale examples of biomass use technologies as fuel and feedstock, as well as solar thermal or geothermal energy use to provide process heat (IEA-SHC, 2014a). The share of renewable energy in 2009 was about 10%, and it has grown from around 5.5% in 1971 (IEA, 2012a). The share of renewable energy can continue to increase, as there is large potential to substitute the fossil fuel-based fuel use for process heat generation and feedstock use for materials production. With new climate policies, development in fossil fuel prices, and the introduction of efficient conversion technologies and learning from the deployment of renewable energy technologies could result in increased cost-competitiveness.

A technology roadmap specific to the industry sector, encompassing the technology and cost aspects of renewable energy technologies, as well as their respective potential, can provide valuable insights. Under the REmap umbrella, IRENA published its renewable energy roadmap for the manufacturing industry sector in June 2014 (IRENA, 2014b). This working paper provides detailed analyses and background information to this roadmap. With this paper, IRENA also aims to support policy makers in the development of effective policies to promote renewable energy technologies in the industry sector by identifying the most important sub-sectors and regions where renewable energy technologies can play a role.

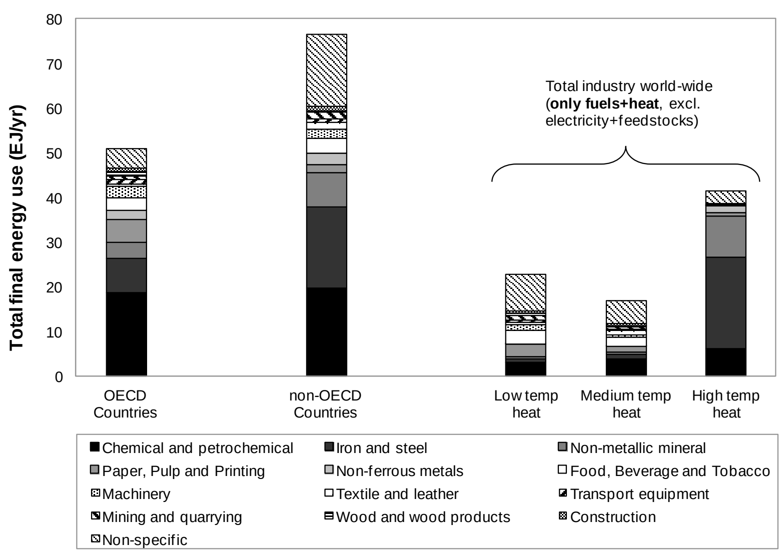
In the next section, various technology options are described. Section 3 covers the methodology and provides an overview of the input data. Section 4 quantifies the potential of renewable energy technologies in the global industry at the sectoral and regional level. The validity of the report's findings are discussed in Section 5. The report concludes with a range of recommendations to governments and industry associations.

2. Options for doubling the share of renewable energy

This section provides a brief explanation of the renewable energy technologies considered in this study for the industry sector. Readers are provided with information on the current status of the technologies, the extent to which they have been applied for the industry sector and, based on a literature review, the sectors that could deploy the most by 2030.

Industrial production processes operate across a wide temperature range. For example, while drying, washing, and heat treatment in the food industry and cleaning, dyeing and bleaching activities in the textile industry operate below 150 °C, distillation processes, boilers and reactors in the chemical industry operate above 250 °C and temperatures are even higher for iron and steel production processes (see Figure 1). While low (<150 °C) and medium temperature (150-400 °C) process heat is typically supplied via steam, high-temperature (>400 °C) applications are provided in the form of direct heat (*e.g.*, in cement kilns or in the iron and steel sector).

Figure 1: Total final industrial energy use in OECD and non-OECD countries (including feedstock, electricity use) and total process fuel use by temperature level of process heat with a breakdown by sectors, 2008



Source: Saygin *et al.* (2014)

2.1.Biomass

2.1.1. Fuel for process heat

Steam is typically generated by fossil fuels in steam boilers at high conversion efficiencies of about 90%. However, biomass can also be used to generate steam. Today typical sources are wood waste (*e.g.*, bark, black liquor) used in the pulp and paper sector and charcoal use in small-scale blast furnaces (Taibi, Gielen and Bazilian, 2012). Although biomass combustion for steam production is currently limited, there are large potential to provide low and medium temperature steam (<400 ^{o}C) by fixed or fluidised bed boilers and combined heat and power (CHP) plants. High-temperature process heat can be provided by biomass gasification. Co-firing of biomass with coal is another option. 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 and Ahlgren, 2010; SCI-PAK, 2013) than that of fossil fuels (85-90%) (Einstein, Worrell and Khrushch, 2001). The difference in efficiencies between bio-based gasifiers from wood, briquette, residues such as coconut shells (40-50%) and fossil fuel fired furnaces, kilns and stoves could be higher (50-60%) (UNEP, 2006; Shivakumar, Jayaram and Rajshekar, 2008). In this roadmap, a total of six heat production technologies are evaluated that can substitute the fossil fuel-based heat demand for varying temperature levels (see Table 1).

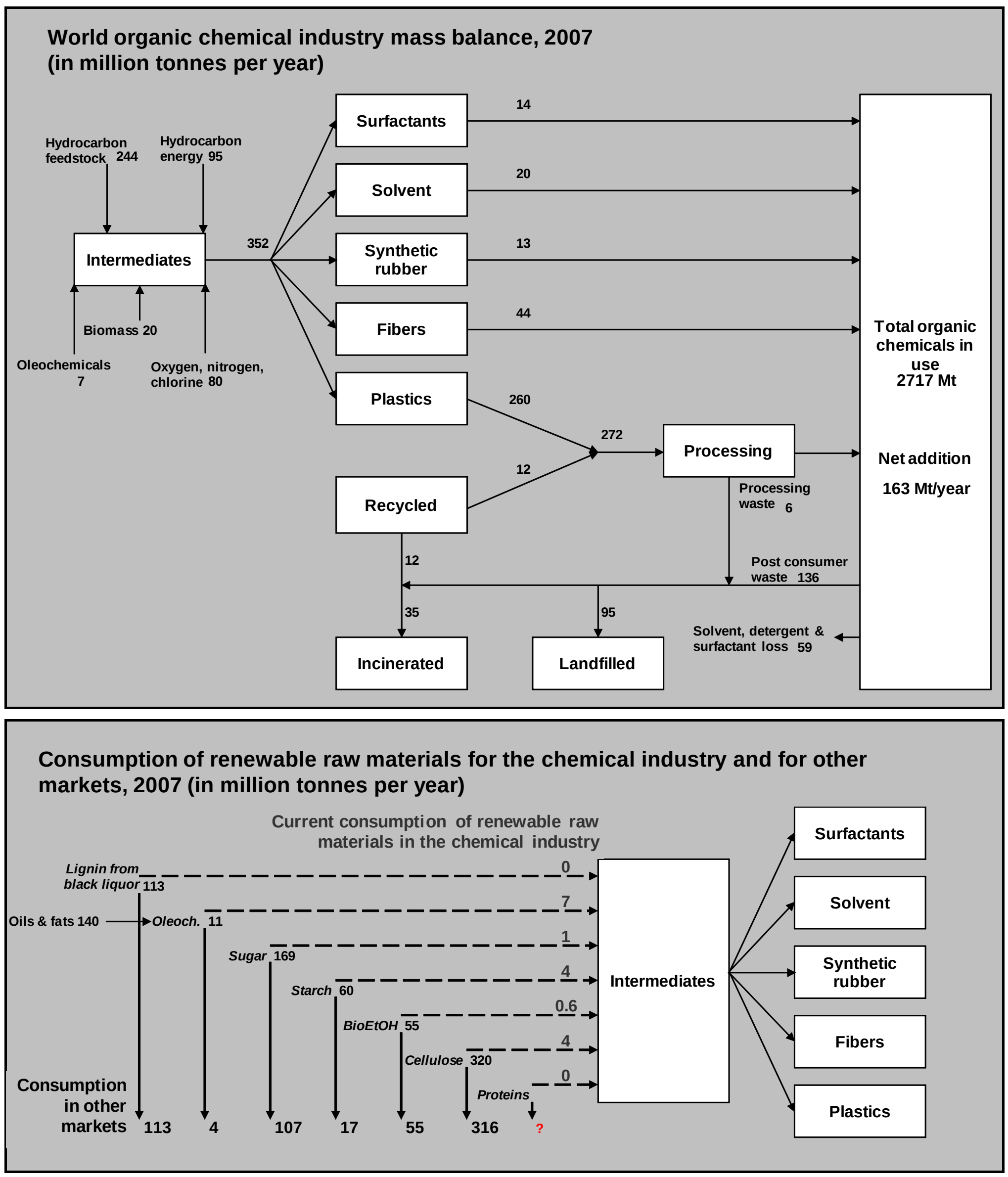
Table 1: Bio-based heat production technologies assessed in this study

	Temperature level (in ^{o}C)	Regions/sectors where technology already deployed	Sectors with large potential by 2030
Biomass fired boilers for steam	100-400	Non-metallic minerals, wood and wood products, pulp and paper and food and tobacco sectors of most non-OECD countries	All sectors with the exception of iron and steel and non-metallic minerals sectors
Biomass fired CHP plants for steam and direct heat	100-400		
Biogas fired CHP for steam	100-150	Food and chemical and petrochemical sectors in OECD countries	Transport equipment, machinery, textile, pulp and paper, mining and quarrying, food and tobacco, pulp and paper sectors
Biomass gasification and direct heat applications	150-800	Various sectors in India	Non-metallic minerals and iron and steel sectors
Charcoal for direct heat	1,000	Iron and steel sector in Brazil	Iron and steel sector

2.1.2. Feedstock for chemicals and polymers

Feedstock energy refers to the use of fuels as raw material in the production of organic chemicals and polymers (*i.e.*, materials). There are five feedstock consuming processes in the chemical and petrochemical sector that convert fossil fuels into basic chemicals. These are the steam cracking process (for ethylene, propylene, butadiene and aromatics production) and ammonia, methanol, carbon black and carbides production processes. The steam cracking process uses large amounts of naphtha (in Europe, Japan, Latin America and non-OECD Asian countries) and ethane/propane (in the US, the Middle East and North Africa). In comparison, methanol and ammonia production processes use mainly natural gas worldwide, with the exception of India and China, which use in large quantities of petroleum products and coal, respectively. The main feedstock for carbon black and carbides production are oil and petroleum coke, respectively. About 60% of the total feedstock use in the chemical and petrochemical sector is for the steam cracking process and the remainder 40% is shared between ammonia production (32%) and other processes (8%) (Daioglou *et al*., 2014). Total fossil fuel-based feedstock use reached 21 EJ in 2009 (IEA, 2012b). Today only a small share of the total feedstock demand originates from biomass (0.6 EJ) (Saygin *et al*., 2014). The basic chemicals are converted into plastics and fibers which account for about ~85% of the total synthetic organic materials production (~290 megatonnes (Mt) per year) and their production is expected to continue growing (IEA, 2009) (see Figure 2:). Technically, 90% of all polymers and fibers can be produced from bio-based feedstocks (Shen, Worrell and Patel, 2010).

Figure 2: World organic chemical industry mass balance and current consumption estimates of renewable raw materials for the chemical industry and other markets, 2007



Source: Saygin *et al*. (2014) based on Gielen, Newman and Patel (2008) and Shen, Worrell and Patel (2010). Note: Net addition is the total production of surfactants, solvents, synthetic rubber, fibers and processed plastics minus the total of post-consumer waste and materials loss. Total quantities of starch and sucrose consumed for bioethanol production are excluded

According to Gielen, Newman and Patel (2008), there are four principal ways to produce materials from biomass:

(i) Direct use of naturally occurring polymers;
(ii) Thermo-chemical conversion of biomass;
(iii) Industrial biotechnology; and
(iv) "Green" biotechnology using genetically modified crops tailored to the needs of material production.

The first three technologies are already applied (Manzer, van der Waal and Imhof, 2013). The fourth option is still under development. In this study, two categories of bio-based materials are identified: 1) the same compound made from renewable feedstocks instead of petrochemicals (*e.g.*, bio-based ethylene) via thermo-chemical conversion or industrial biotechnology (*e.g.*, biomass gasification); and 2) materials with comparable functionality (*e.g.*, polylactic acid (PLA) to substitute polyethylene terephthalate (PET) via industrial biotechnology. From an energetic point of view (total of renewable and non-renewable primary energy on cradle-to-factory gate basis), the demand for feedstock to produce one tonne of chemical is higher than the demand for fossil fuels. Depending on the crop type (*i.e.*, different biomass yields, land use and calorific values), production of bio-based ethylene requires between 93-125 gigajoules (GJ) per tonne (total or renewable and non-renewable energy use) compared to the petrochemical route which require 66 GJ/t (Patel *et al*., 2006). In Table 2, the bio-based materials assessed in this study are shown.

Table 2: Bio-based chemicals and polymers production technologies assessed in this study

<table>
<tr><th></th><th>Petrochemical counterpart</th><th>Regions where technology already deployed</th><th>Regions with large potential in 2030</th></tr>
<tr><td>Bio-based ethylene</td><td>Ethylene</td><td>Brazil and India from sugar cane</td><td rowspan="3">Regions where sugar and starch crops are affordable such as Latin America, Asia and parts of Africa</td></tr>
<tr><td>Bio-based methanol</td><td>Methanol</td><td>Canada from wood, Netherlands from glycerine</td></tr>
<tr><td>PLA</td><td>PET (today) and polyethylene, polystyrene and other polymers (medium term)</td><td>In Thailand from sugar cane, in the US from corn</td></tr>
</table>

This working paper focuses on separate systems of heat and chemicals production from biomass. In addition, there are also bio-refinery concepts that combine the production of various products including biofuels, heat, electricity, chemicals and paper. However, the assessment of these systems lies beyond the scope of this analysis.

2.2. Solar thermal

In addition to biomass combustion for process heat generation, solar thermal technologies can also provide low and medium temperature process heat (see Figure 1). In early 2014, there were around 130 solar thermal plants for industrial process heating worldwide, comprising a combined 93 megawatt-thermal (MW_{th}) of total capacity (IEA-SHC, 2014b). Today most applications in the industry sector concern low temperature heat generation from glazed and unglazed flat plate and evacuated tubular collectors (IEA-SHC, 2014a). For higher temperature process heat applications, solar concentrator technologies offer alternatives, such as parabolic trough concentrators, parabolic dishes (with fixed or moving focuses) or vacuum tube collectors with compound parabolic concentrators (UNDP, 2008). Industry sectors that employ solar thermal technologies in their processes are typically the food and beverages (drying, washing, pasteurising processes) and the textile sectors (washing and bleaching processes) (Vannoni, 2007; Weiss, 2010; Hennecke, 2012). Heating make-up water for steam systems and for washing and cleaning in various other industry sectors are other examples, *e.g.* chemical and petrochemical and pulp and paper sectors (Hess and Oliva, 2010). The conversion efficiencies depend on the annual solar yield of the region, the temperature of the process heat and the type of collector (*i.e.*, conversion factor, loss coefficients). In Table 3, the solar thermal technologies in this study are assessed.

Table 3: Solar thermal heat production technologies assessed in this study

	Temperature level (in °C)	Regions/sectors where technology already deployed	Sectors with large potential in 2030
Flat plate collector	<100	Food and tobacco, textiles, pulp and paper, chemical and petrochemical sectors in various countries	All sectors with the exception of iron and steel and non-metallic minerals sectors
Evacuated tubes	<150	Food and tobacco, textiles, pulp and paper, chemical and petrochemical sectors in various countries	All sectors with the exception of iron and steel and non-metallic minerals sectors
Concentrating solar	<200	Food and tobacco sector in India, Germany, Italy, Mexico, Turkey and the US	Transport equipment, machinery, textile, pulp and paper, mining and quarrying, food and tobacco, pulp and paper sectors

2.3. Heat pumps

Heat pumps convert energy from various sources into process heat. Heat sources could be air, river/lake/sea water, ground heat or waste heat. Electricity input is required to operate the heat pump, so it is not a fully a renewable energy but heat pumps can produce up to seven units of thermal energy from one unit of electricity input. For example, the European Commission Directive proposes that if seasonal performance factors (SPF) of heat pumps are higher than the value of $1.15 * 1/\eta$ (where η is the efficiency of power generation estimated based on Eurostat), then they can be considered as renewable energy (EC, 2009). SPF is determined based on temperature lift required, *i.e.* the difference between the temperature of the heat source and the temperature of the process heat, coefficient of performance (COP) and the efficiency of the heat pump[3]. SPF is the ratio of heat delivered to energy consumed over the season.

So far only a few heat pumps are installed in industry. Industrial heat pumps are typically used for space heating and cooling, simultaneous heating and cooling, refrigerating, low temperature steam production, cleaning, drying, evaporation and distillation processes in various sectors. In this study two heat pump settings are evaluated based on this brief, one which delivers process heat up to 60 ^oC and the other up to 100 ^oC. Thus, one sees the largest potential in all industry sectors with the exception of chemical and petrochemical and iron and steel sectors where medium- and high-temperature process heat dominate the demand.

There are opportunities for heat pumps above 100 ^oC as well. This could be done through mechanical vapour recompression by integrating excess heat to temperatures above 120 ^oC and could also result in higher COP values. Furthermore, some heat pumps can deliver steam at 160 ^oC (Wolf *et al.*, 2012). The assessment of these systems lies beyond the scope of this analysis. However, if these were also accounted for, the heat pump potential estimates of this study would be much higher.

In addition to the manufacturing industry, heat pumps have a potential in wastewater treatment facilities as well which are located on-site or close to most industrial plants. In anaerobic wastewater treatment process, the wastewater is usually heated by steam supplied by boiler where heat pumps can be used as an alternative.

Heat pump options in the food processing industry

In the particular case of the food processing industry, there are plenty of cases where heat pumps are being applied today.

For example in Japan, heat pumps are being used in brewing sake. Brewing process starts by steaming rice, the main raw ingredient. This is followed by a fermentation process, and several others, such as storage and bottling. In all of these processes, heating and cooling energy is required.

In a sake bottling and packaging factory in Japan, during the bottling process, sake is pre-heated for sterilisation before bottling, after which it is cooled immediately to prevent maturation. Since the heating and cooling load exist side by side, a CO_2 recovery heat pump system, which is capable of simultaneously producing hot and cold water was installed. This has improved the operational efficiency dramatically, as a result the COP has reached 5.7.

There are also examples of industrial applications of heat pumps in other countries. For example, India has been demonstrating the use of heat pumps in the dairy industry.

[3] SPF = COP * efficiency. Efficiency is the ratio between actual and ideal COP and it is generally around 70% for industrial heat pumps delivering low temperature heat (ITP, 2003).

2.4. Geothermal

Geothermal heat (excluding geothermal source heat pumps) can be used as a source for low temperature process heat applications. Today less than one percent of the total industrial heat use is provided from geothermal sources (IEA, 2012b). About half of the demand comes from the pulp and paper sector and the remainder from drying, evaporation, distillation or washing applications in various other sectors (EGEC, n.d.; IEA, 2012b). In Iceland as an example, geothermal heat is typically used for fish drying (Arason, 2003). Similarly, the drying of tomatoes is done with geothermal heat in Greece (EGEC, n.d.). Geothermal heat can be directly applied to the industrial processes if the distance between the heat source and the end-user is sufficiently close (IEA-ETSAP, 2010). In this analysis, conventional deep geothermal heat-production technology for low-temperature heat applications is considered. These application offer the largest potential in all industry sectors with the exception of the chemical and petrochemical and the iron and steel sectors, where medium- and high-temperature process heat dominates the demand.

2.5. Potential of renewable energy technologies for industrial electricity use

Estimating the potential of renewable electricity technologies for the industry sector is beyond the scope of this study. Renewable electricity generation from investing in own capacity (*i.e.*, autoproducers) and off-grid plants is also excluded from this study. However, some renewable energy technologies which have a dual function to substitute heat and electricity (*e.g.*, solar cooling), as well as the potential which could arise through sectoral changes in the industry, are discussed in this study.

There are a number of electricity-intensive industrial production processes. These include the production of non-ferrous metals, such as aluminium (~56 GJ/t), copper (~14 GJ/t) and zinc (24 GJ/t), as well as the chlor-alkali (12 GJ/t chlorine) process (Saygin *et al*., 2011a;b). When the size of production plants is considered, primary aluminium smelters consume the largest quantities of electricity per plant (~14 PJ/yr) (UNCTAD, 2000; Turton, 2002; Saygin *et al*., 2011b). It is therefore already common in the primary aluminium sector that smelters are located next to hydro power plants, which ensure the continuous supply of cheap electricity, *e.g.* in Iceland, Norway or Brazil (Reinaud, 2008). In regions where aluminium production is expected to grow, relocation of plants next to renewable electricity plants is an option considered in this study.

Electrification of production processes is another option if electricity is generated from renewable energy sources. Industrial production processes typically operate based on process heat, with the exception of a few processes, such as smelting or electrolysis. Some of these heat-based production processes can also operate via novel process routes running based on electricity. One example originates from Iceland where hydrogen is produced from water via electrolysis and is subsequently combined with CO_2 to produce bio-based methanol (IRENA/IEA-ETSAP, 2013c). This process substitutes the fossil fuel-based steam reforming or partial oxidation process. However, since electrolysis is an electricity-intensive process, such transition is only possible in regions where electricity is cheap.

Solar thermal technology can also provide an alternative to cooling processes in sectors, such as the food and tobacco sector (IEA, 2007a; Taibi, Gielen and Bazilian, 2012). Table 4 shows the renewable energy technologies for industrial electricity use assessed in this study.

Table 4: Technologies assessed in this study

	Regions/sectors where technology already deployed	Sectors with large potential by 2030
Relocation of electricity-intensive plants	Primary aluminium sector in Brazil, Iceland, Norway	EAF and non-ferrous metals production sector
Solar cooling	Food and tobacco sector	Food and tobacco sector in various regions of the world with good solar income

3. General methodology and the data sources

In this section, the methodology to estimate industrial energy use (Section 3.1), costs of renewable energy technologies (Section 3.2) and the potential of renewable energy in the industry sector (Section 3.3) for the period between 2009 and 2030 is described. Where relevant, a key data related to each methodological step is provided. Detailed data are provided in Appendix A.

3.1. Industrial energy use growth

The main objective of this study is to estimate the potential of renewable energy to substitute fossil fuel use in the industry sector. For this purpose, the growth of fossil fuel use in each industry sector between 2009 and 2030 is estimated, based on the IEA's energy balances (IEA, 2012a;b) and demand growth estimates (IEA, 2012c). The sectors included in the analysis are as follows:

- Basic metals: iron and steel and non-ferrous metals, including blast furnaces and coke ovens;
- Chemical and petrochemical (process heat);
- Chemical and petrochemical (feedstock);
- Non-metallic minerals;
- Food and tobacco;
- Pulp and paper; and
- Textile and leather; and
- Others, including transport equipment, machinery, mining and quarrying, and non-specified.

For the year 2009, the IEA (2012a;b) provides the fossil fuel use with a breakdown by energy carriers for each sector. In addition, the heat use (in final energy terms) of each sector is reported. The conversion heat use to primary fuel use equivalents based on 90% boiler conversion efficiency and by assuming that the same fuel mix is used to generate this heat as for the rest of the sector. The analysis of industrial electricity use is excluded as the potential of renewable energy in the power sector are analysed in a separate study by IRENA (IRENA, 2014a). However, as mentioned earlier in Section 2.5, the potential of a number of technologies is briefly analysed.

We estimate the fossil fuel use of each sector between 2009 and 2030 based on the production growth scenarios of IEA (2012c) and the energy efficiency improvement potential of Saygin, Patel and Gielen (2010) based on Equation 1:

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

where $TPEU_{s,c,f,t}$ is the total primary energy use (in PJ/yr), $r_{s,c,f,t}$ is the production growth rate (in %/yr) and $EE_{s,c,f,t}$ is the energy efficiency improvement potential of sector *s* in region *c* for energy carrier *f* in year *t* (in %). The EE potential is the same for all energy carriers.

As mentioned earlier, one of the objectives of the SE4ALL initiative is to double the rate of energy efficiency improvements between today (2010) and 2030. In this analysis, energy efficiency improvement potential for each sector are the sum of improvements achievable by 1) retrofits in the existing capacity and 2) 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 depend on the production growth and the share of capacity retired each year (see Table 5). An overview of the production growth and energy efficiency improvement potential of the energy intensive sectors is provided in Table 6. 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 analysed. 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 5: Average age of capacity in industry sectors

	OECD	Developing countries	Economies in transition	Average lifetime[1]	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)

[1] Average lifetimes are assumed based on Worrell and Biermans (2005).

Table 6: Production growth and energy efficiency improvement potential of energy-intensive sectors

Sector	Production growth between 2009 and 2030	BPT energy efficiency improvement potential in 2009[1]	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

Sources: Phylipsen *et al*. (2002); Saygin, Patel and Gielen (2010); IEA (2012c)

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.

[1] Due to technology developments, the energy efficiency of BPTs is assumed to improve by 0.3 %/yr between 2009 and 2030.

Feedstock use of the chemical and petrochemical sector is estimated by applying the same methodology as for fuels used to generate process heat (see 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[4].

As a next step, the key products/sub-processes of the energy-intensive sectors, which are the highest energy users (see Table 7), are identified. Based on process information available from the literature the temperature level of these production processes is also estimated. By doing so, a higher level of detail of the sector's energy use can be attained when estimating the potential of renewable energy technologies. For the share of energy use for which individual processes cannot be identified, temperature levels are used to determine the characteristics of process heat.

Table 7: Overview of sub-processes of the sectors analysed in this study

<table>
<tr><td rowspan="2">Sector</td><td rowspan="2">Sub-processes</td><td colspan="2">References</td></tr>
<tr><td>Production</td><td>Specific energy consumption</td></tr>
<tr><td rowspan="6">Iron and steel</td><td>Blast furnace coke use</td><td>WSA (2012)</td><td>IEA (2007b); Norgate et al. (2012)</td></tr>
<tr><td>Blast furnace pulverised coal injection</td><td>WSA (2012)</td><td>IEA (2007b); Norgate et al. (2012)</td></tr>
<tr><td>Sintering/pelletising</td><td>IEA (2007b); WSA (2012)</td><td rowspan="2">Corsten (2009); IPTS/EC (2013a)</td></tr>
<tr><td>Rolling</td><td>WSA (2012)</td></tr>
<tr><td>Steel re-rolling (mini)</td><td>Banerjee et al. (2012)</td><td>Banerjee et al. (2012)</td></tr>
<tr><td>Electric arc furnace</td><td>WSA (2012)</td><td>Corsten (2009); IPTS/EC (2013a)</td></tr>
<tr><td rowspan="4">Chemical and petrochemical</td><td>Steam cracking</td><td>OGJ (2012)</td><td rowspan="3">Weiss et al. (2008)</td></tr>
<tr><td>Ammonia</td><td>USGS (2012a)</td></tr>
<tr><td>Methanol</td><td>MI (2011)</td></tr>
<tr><td>Synthetic organic materials</td><td>PEMRG (2011)</td><td>Patel et al. (2006)</td></tr>
<tr><td rowspan="2">Non-ferrous metals</td><td>Alumina</td><td>IAI (2012a)</td><td rowspan="2">Saygin, Patel and Gielen (2010)</td></tr>
<tr><td>Aluminium</td><td>IAI (2012b)</td></tr>
<tr><td rowspan="5">Non-metallic minerals</td><td>Clinker</td><td colspan="2">CSI (2012)</td></tr>
<tr><td>Cement</td><td>USGS (2012b)</td><td>N/A</td></tr>
<tr><td>Lime</td><td>IPTS/EC (2012)</td><td>Saygin, Patel and Gielen (2010)</td></tr>
<tr><td>Brick</td><td colspan="2">Saygin, Patel and Gielen (2010)</td></tr>
<tr><td>Glass</td><td colspan="2">Saygin, Patel and Gielen (2010)</td></tr>
</table>

Based on this methodology, the breakdown of industrial energy use is estimated in each region by fuel type, sector and contribution to total demand from the existing and new capacity covering the period 2009-2030. This analysis covers a total of ten world regions: OECD Americas, OECD Europe, OECD Pacific, Other Europe, China, India, Other Developing Asia, Africa, Middle East and Latin America.

[4] Although IEA requests countries to report the fuel and feedstock used for materials production *separately* (*i.e.*, *net* definition of non-energy use), they generally tend to combine the two (*i.e.*, *gross* definition of non-energy use). Therefore, *net* feedstock used for each energy carrier is estimated and this amount is subtracted from the reported values in IEA energy balances. Subsequently, the difference is allocated as process energy to the chemical and petrochemical sector. One exception is coal use for the production of ammonia and methanol in China and India, which is not reported in the *memo-item* (Saygin *et al*., 2011a). There, the bottom-up estimates of coal use in these countries is added as additional energy use to the *memo-item* feedstock use.

3.2. Production costs of heat generation

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

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

where $PC_{i,t,c}$ is the production cost of heat (in US Dollars per GJ_{th}), α is the annuity factor in years^{-1} (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*. CHPs co-produce electricity in addition to heat. Heat production costs are estimated by applying energy allocation, thereby partitioning the fuel input, as well as the investment and O&M costs to heat and electricity based on the gross output of CHPs[5]. As reference, the production costs of steam and direct heat generation from boilers and process heaters are also estimated by respectively applying the same methodology in Equation 2.

For the production costs of materials, literature estimates (Broeren, Saygin and Patel, 2014; Saygin *et al.*, 2014; IRENA/IEA-ETSAP, 2013b;c) are used since the available data for carrying out a detailed cost analysis are limited.

All data used to estimate the production costs are provided in detail in Appendix A. In this study, all costs are expressed in real 2010 USD (1 Euro = 1.3 USD).

Production costs for the years 2009, 2020 and 2030 are estimated by accounting for the developments in fossil fuel, biomass and feedstock energy prices, as well as technological developments (*i.e.*, decrease in capital costs due to technological learning and conversion efficiency improvements of technologies). In this analysis, two energy price growth scenarios are used, namely **high price** (average of *current policies* and *new policies* scenario) and **low price** (*450ppm scenario*) scenarios based on the IEA (2011a). The **high energy price scenario** refers to the case where the demand for all fossil fuels (*i.e.*, natural gas, coal and oil) continue to increase under a mix of current and new climate policies between today (2015) and 2030. In comparison, the **low energy price scenario** refers to the case where climate policy is more ambitious with the aim of limiting global surface temperature increase to 2 ^{o}C, which would require CO_2 concentrations in the atmosphere to stabilise at 450 parts per million (ppm). The price of biomass (*i.e.*, forest residues, agricultural residues, energy crops, pellets) is assumed to be coupled to the developments in fossil fuel prices regardless of the climate policy and biomass demand. For biomass, an average price for each region is assumed by distinguishing between biomass types, namely expensive (*i.e.*, energy crops, wood pellets) and cheap (*e.g.*, waste, forest and agricultural residues) sources of biomass. However, no further breakdown the average prices into detailed price categories by considering supply volumes is

[5] Exergy allocation can be preferred to energy allocation. In this case, the total costs allocated to electricity would be higher since the exergy-energy ratio of process heat is less than 1. An alternative to allocation is to analyse the system's total costs by crediting by-product revenues from surplus electricity sales. However, the quantities of electricity sales for each region are hardly known and forecasting future electricity prices is complex as well since prices vary widely within the regions analysed.

undertaken. An overview of fossil fuel price development in the high and low scenarios is provided in Table 8. More detailed information about the energy price assumptions are provided in Appendix A.

Table 8: Fossil fuel price projections according to the IEA's World Energy Outlook 2011

	Units	2010	Current Policies scenario	New Policies scenario	450 ppm scenario	This study	
						High price	Low price
			2030	2030	2030	2030	2030
IEA crude oil imports	(USD/bbl)	78.1	134.5	117.3	97.0	125.9	97.0
Gas US MBtu	(USD/Mbtu)	4.4	8.4	7.9	8.4	8.2	8.4
Gas imports EU	(USD/Mbtu)	7.5	12.6	11.7	9.7	12.2	9.7
Gas imports Japan	(USD/Mbtu)	11.0	14.8	13.9	12.1	14.4	12.1
OECD steam coal	(USD/t)	99.2	115.9	109.3	13.7	112.6	13.7

Source: IEA (2011b)

Fuels are combusted to produce heat, which releases CO_2 and other GHG emissions into the atmosphere. The pricing of CO_2 emissions creates additional cost burdens which, in turn, may affect investment decisions to substitute heat production technologies fired with emission-intensive fuels with less emission-intensive alternatives. In this study, CO_2 prices according to the IEA (2011a) are considered for the ten regions analysed (see Table 10). The CO_2 prices are applied to the total GHG emissions related to fuel combustion only, expressed in CO_2 emission equivalents (CO_2-eq) based on the global warming potential of CO_2, methane (CH_4) and nitrous oxide (N_2O) over 100 years. Upstream emissions from the extraction of materials, their processing for fuel production and fuel transport are excluded from the system boundaries of this analysis. Burning of all residual biomass is assumed to be carbon neutral. Emission factors are provided in Table 9.

Table 9: Emission factors used in this study for fuel combustion (in kg CO_2-eq/GJ on a lower heating value basis)

	CO_2	CH_4[1]	N_2O[1]
Coal	96.1	0.3	0.5
Coking coal	94.6	0.3	0.5
Oil products	73.3	0.1	0.2
Natural gas	56.1	0.0	0.0

Source: IPCC (2006)

[1] Global warming potential of non-CO_2 GHG over 100 years is 25 for methane and 298 for nitrous oxide (IPCC, 2007).

Table 10: 2030 CO_2 prices applied in this study according to the IEA's World Energy Outlook 2011 (in USD/t CO_2)

Region	High energy price scenario	Region	Low energy price scenario
OECD Americas	-	OECD Americas (only the US & Canada)	87
OECD Europe (only EU)	40	OECD Europe (only EU)	95
OECD Asia/Pacific (excl. Japan)	36	OECD Asia/Pacific	90
Other Europe (only Russia)	-	Other Europe (only Russia)	65
China	23	China	65
Africa	-	Africa (only South Africa)	65
Latin America	-	Latin America (only Brazil)	65

Source: IEA (2011b)

Note: According to the IEA (2011b), CO_2 prices are assumed for specific countries of the regions only as provided in brackets. In this study, CO_2 prices are assumed to apply to the entire region, which is more stringent.

Capital costs of renewable energy technologies depend on technological learning, which, in its turn, depends on global cumulative investments. Typically, a doubling of cumulative investments results in a 10-20% reduction in capital costs (Weiss *et al*., 2010). The IEA (2007a) provides the capital cost reductions for each renewable technology between 2005 and 2030 and this provides principle background data for the purpose of this analysis (see Table 11). Capital cost reductions are directly applied to the 2009 data without separately estimating the cumulative capacity installed worldwide.

Table 11: Capital cost reduction assumptions for heat generation technologies, 2005 to 2030

Technology	Installed capacity worldwide in 2005	Capital cost reductions by 2030	References
	(GW_{th})	(%)	
Biomass fuel	2,000-4,000	15	IEA (2007a)
Biogas (anaerobic digestion)		15	IEA (2007a)
Solar thermal heat	100-110	35-50	IEA (2007a)
Solar thermal cooling		35-45	IEA (2007a)
Geothermal heat	25-30	20	IEA (2007a)
Heat pumps	N/A	20	N/A

Note: Global capacity investments are not separately modelled in this study.

An uncertainty analysis was separately conducted in order to account for ranges in the background data (*e.g.*, energy prices, interest rates, capital costs) used to calculate the production costs. These uncertainties are reported as ranging (±) around the mean value where relevant.

3.3. Estimation of the potential of renewable energy technologies

For each renewable technology, the potential is estimated based on a hierarchical analysis of the following: 1) realisable technical; 2) economic, and (3) realisable economic potential to substitute fossil fuels used to generate heat and produce materials. For each level of assessment, the following criteria are considered:

Realisable technical potential: The industrial energy use of each region is disaggregated into its sub-sectors, fuel types, temperature level and sub-processes based on the energy use reported in the IEA's Energy Balances (IEA, 2012a;b). Subsequently, capital stock turnover rates to disaggregate industrial energy use in 2020 and 2030 by new and existing capacity are considered. This allows a differentiation between new investments and retrofits. Based on these two criteria and specific process characteristics (*e.g.*, the extent to which biomass can be injected into blast furnaces), the total substitution potential of fossil fuels with renewable energy technologies is estimated. For each substitution, the differences in conversion efficiency between the renewable technology and the conventional fossil fuel based counterpart is evaluated. Realisable technical potential considers neither the costs of technologies nor the availability of resources to reach the related potential. Rather, they serve as an indication of the maximum extent to which renewable energy technologies can be deployed given their existing technical constraints.

Technical, all low and medium temperature and, to a large extent, high-temperature process heat can be provided by biomass (Saygin *et al*., 2014) and up to 90% of fossil fuel feedstocks can be substituted with bio-based equivalents (Shen, Worrell and Patel, 2010). However, the extent to which this potential can be achieved depends on the development and availability of technologies between 2009 and 2030. Furthermore, there are more important characteristics of plants besides their process heat temperature levels. For example, the processes of the chemical and petrochemical plants are highly integrated, which allows the use of by-products (materials and energy) in other processes. In comparison, not all pulp and paper mills will be integrated in future although this would provide advantages from an energy use point of view since there will be stand-alone paper mills processing recovered paper. In view of these sector-specific differences, although there would be technical potential for renewable energy technologies, they may, in reality, never be achieved. Therefore, two cases of realisable technical potential are evaluated in this study; namely, the **"ambitious development scenario" (AmbD)**, which considers the temperature level of process heat and new/existing capacity as the main criteria, and the **"accelerated development scenario" (AccD)**, which, in addition, considers technology development and sector-specific characteristics. Both scenarios, however, refer to realisable technical potential by accounting for the development and deployment of new and emerging renewable energy technologies, which are beyond the business as usual or market trends historically observed. The potential according to the AmbD scenario is higher than that of the AccD scenario.

Economic potential: Subsequent to the estimation of realisable technical potential, the additional costs of heat production by renewable technologies compared to fossil fuel counterparts are taken into account (see Section 3.3)by estimating the CO_2 abatement costs of each renewable technology relative to the fossil fuel-based counterpart, thereby taking into account the fuel mix in each region, heat production costs and regional CO_2 prices.

$$COE_{i,t,c} = \frac{\Delta PC_{i,t,c}}{\Delta C_{i,t,c}}$$

where $COE_{i,t,c}$ is the cost of abating one tonne of CO_2-eq emissions by heat generation technology *t* relative to fossil fuel based technology, $\Delta PC_{i,t,c}$ is the difference in heat production costs between the renewable and fossil fuel-based technology and $\Delta C_{i,t,c}$ is the total abated CO_2-eq emissions per GJ_{th} heat production by renewable energy technology relative to fossil based technology. Abated emissions represent the total

CO_2-eq emission savings from the avoided combustion of fossil fuels. All renewable energy technologies are assumed to be carbon neutral (see Table 9). The system boundary of heat generation is the factory gate-to-factory gate, thus upstream energy use and related emissions for fuel production and transport are excluded from the analysis.

Equation 3 is applied in order to estimate the potential in both new and existing capacities. While this is justified for new capacity investments where the decision is being made between a new fossil fuel and renewable technology, it may not entirely be the case for existing capacity as the equipment is already partly depreciated. In order to estimate the true cost of process heat production, one would need to know precisely the extent of existing capacity that has been depreciated. Since this value is not known, the comparison is made as if the investment were for new capacity where the approach favours renewable energy technologies for existing capacities since ΔPC is lower. In comparison, when existing capacity is retrofitted, additional equipment may be necessary due to the modifications required at site, which would increase the capital costs compared to the "greenfield" investments. For bio-based process heat technologies and heat pumps, it is assumed that there are no differences in costs for existing and new capacity. For solar thermal and geothermal technologies, most of the potential is attributed to the new capacity. The small potential estimated for existing capacity is assumed to have identical costs with the new capacity.

Technologies with CO_2 abatement costs below the level of CO_2 prices in 2030 are considered to be cost-effective. For bio-based materials, their production costs (based on Saygin *et al*., 2014 and IRENA/IEA-ETSAP, 2013b;c) are compared with those of their petrochemical counterparts instead of estimating CO_2 abatement costs, given the lack of bottom-up cost analysis.

For each renewable energy technology, the different types (*e.g.*, biomass-fired boilers and CHP or flat plate and evacuated tube solar thermal heat plants) are evaluated. Due to lack of insight into the exact shares of various technologies in 2030, the arithmetic mean of all technologies available is used to estimate the average CO_2 abatement costs of the renewable technologies (*e.g.*, average of biomass-fired boiler, CHP and biogas for low-temperature heat production), but the differences in world regions are accounted for and both low and high energy price scenarios are assessed.

By applying the same methodology, the additional cost to substitute fossil fuels by renewable energy technologies (in USD per GJ of primary fuel substituted) is also estimated.

Realisable economic potential: In this step, the demand for renewable energy sources according to the economic potential is compared to the regional resource supply potential. This applies to geothermal and biomass since access to supply could be limited in some regions, in particular because international biomass trade is excluded. The limited solar income in some regions (*e.g.*, Other Europe) is accounted for under the heat production costs, which are a function of the annual energy yields (see Appendix A).

For biomass, a two-step approach is followed. It is assumed that the first cheap sources of biomass (*e.g.*, residues) are available for the industry sector to meet demand. The remainder of biomass demand will be subsequently met through expensive sources (*e.g.*, energy crops). It is assumed that about one-third of the total biomass supply potential in each region will be available to meet the demand in the industry sector (Taibi, Gielen and Bazilian, 2012). Feedstock for materials production is assumed to originate from a mix of cheap and expensive sources, which are still readily available after the demand for process heat generation has been supplied.

Based on the above criteria, the ranking of the different potentials of renewable energy technologies for the industry sector is as follows: **realisable technical (AmbD > AccD) > economic > realisable economic.** The same methodology is re-applied for each renewable energy technology to estimate the related potentials.

In reality, more than one technology will be deployed in the industry sectors of the regions analysed. Therefore, as a final step, the estimated realisable economic potential of each technology (in PJ/yr) are allocated to different applications in various industry sectors by accounting for the regional differences (*e.g.*, shares of new and existing capacity, temperature levels, etc). All potentials estimated in this study are additional to the business as usual combustible renewable and waste use, which is assumed to follow the growth in industrial energy demand. In all countries worldwide, combustible renewable and waste use is considered as a modern form of biomass energy. Therefore, they are not substituted by the renewable energy technologies analysed in this study.

Given the lack of regional bottom-up cost data on some technologies a number of assumptions are made to estimate their realisable economic potential:

- The economic potential of charcoal is based on the difference between the global coking coal and charcoal prices instead of estimating heat generation costs;
- For bio-based materials, regions with low cost sugar prices are regarded as economic feasible. This is a simplification given that, in some parts of the world, bio-based materials are already produced despite high prices. Materials have a longer value chain and a complex cost structure compared to mature heat generation technologies, which are dominated by a single production cost factor. However, bio-based materials are treated solely based on the feedstock cost, which is found to dominate their economic viability (Saygin *et al*., 2014).
- Regarding plant relocation, all realisable technical options are regarded as also realisable economic.

4. Potential of renewable technologies for the global industry

In this section, developments in the energy use of global industry between 2009 and 2030 (Section 4.1) are presented. Then the costs of each renewable energy technology are provided for the global situations in Section 4.2 while Section 4.3 provides the key results of the renewable energy technology potential for the global industry sectors. Details of the ten regions analysed can be found in Appendix C.

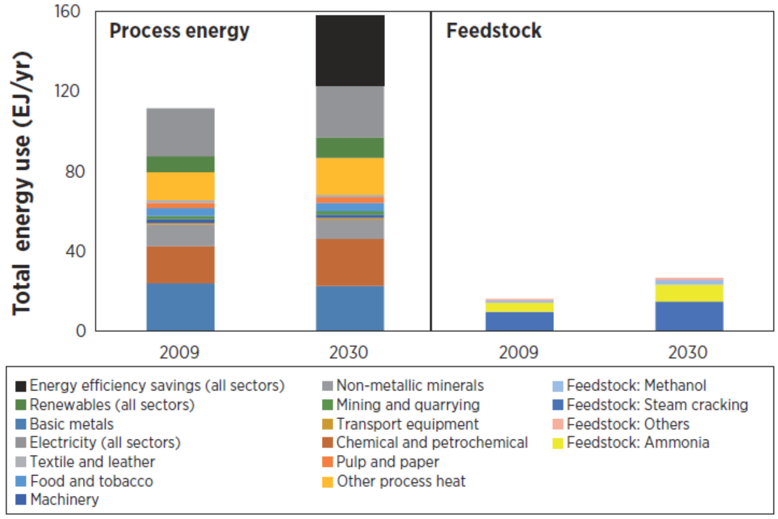
4.1. Industrial energy use growth

By accounting for the production growth 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 3). Even were there 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)[6]. 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 use 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.

[6] Between 2008 and 2012, total industrial energy use has grown by 2.3% per year and the feedstock demand for chemicals production has even grown faster at 3.4% per year. Both of these rates are higher than what is used in this working paper, indicating the lower physical growth rates assumed and the higher energy efficiency improvement potentials estimated. Furthermore, the physical growth rate of the non-energy intensive sectors has been estimated assuming that they would follow the trend of the energy-intensive sectors which is a conservative assumption.

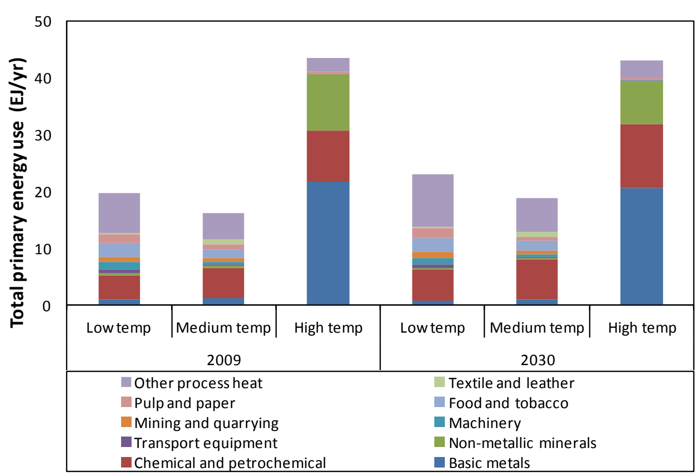
Figure 3: Total final energy use in global industry with a breakdown by sectors, 2009-2030



Note: Renewables refer to combustible renewable and waste

The breakdown of industrial energy use by temperature levels is estimated to remain unchanged between 2009 and 2030 (see Figure 4). 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.

Figure 4: Total primary energy use in global industry with a breakdown by temperature levels, 2009-2030



Note: Excluding electricity use, feedstock use and combustible and renewable and waste

4.2. Production costs of heat and materials

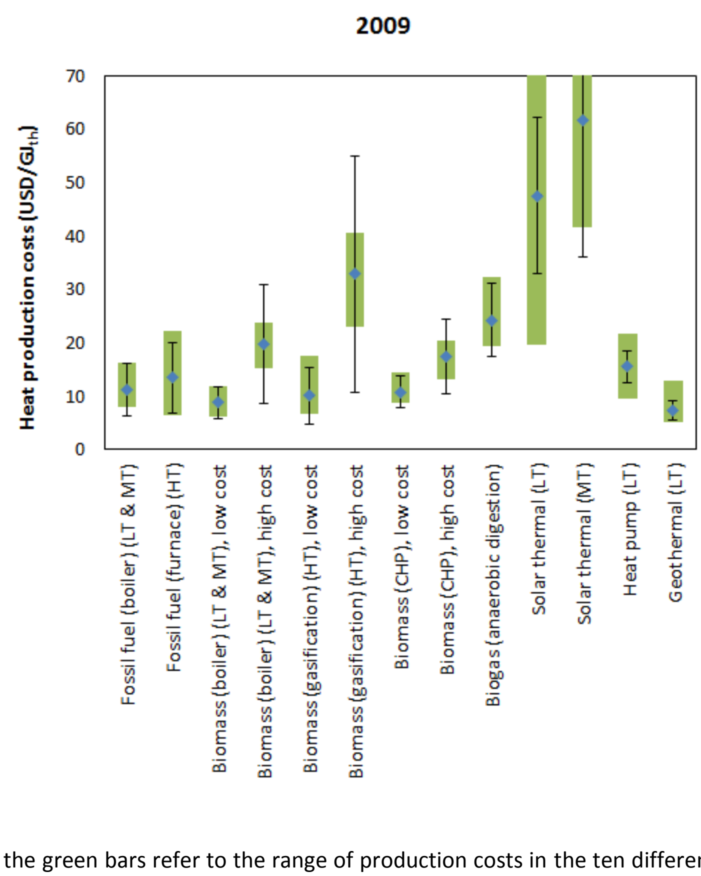
Figure 5 provides estimates of heat generation production costs from fossil fuels and various renewable energy technologies for the year 2009. Key findings are summarised below:

- In 2009, fossil fuel-based steam generation for low- and medium-temperature applications cost on average USD 11 ± 5 per GJ_{th} (range: USD 8-16 per GJ_{th}) from steam boilers (first column from left)[7]. High-temperature direct heat applications are estimated to be slightly more expensive at USD 13 ± 7 per GJ_{th} (range: USD 7-22 per GJ_{th}). This is explained by the lower combustion efficiency (second column from left).
- In 2009, heat production from steam boilers and CHP plants is estimated to cost on average USD 9 ± 3 and USD 11 ± 3 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, production of steam from expensive biomass sources cost on average USD 20 ± 11 and USD 18 ± 7 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. In reality, 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 cost 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 use in the industry sector. Other cost-competitive alternatives are presented only for low-temperature applications, heat pumps and geothermal heat.

[7] Throughout this study, first, the mean value and its error margins followed by the ± sign is presented. Error margins refer to the uncertainties around the mean value due to variations in production cost factors. Ranges provided in brackets refer to the lowest and highest estimates based on the findings of various sectors and regions.

In addition to various forms of biomass used as fuel for combustion in boilers or process heat furnaces, charcoal is also injected in a few blast furnaces at a small scale in the iron and steel sector of Brazil. It can also be used to replace the coke input to blast furnaces. However, for the systems described above, a detailed cost analysis of blast furnaces is not available. Therefore, a comparison of the prices of fuel input to blast furnaces is provided to give an indication of the cost-competitiveness of charcoal today. Australian coking coal prices stood between USD 160-220 per tonne freight-on-board (FOB) in 2012 and cost-and-freight (CFR) prices to China and India was USD 15-20 higher (CBA, 2012; Reuters, 2012). This equals around USD 6-9 per GJ of coking coal (assuming net calorific value of 28.2 GJ/t for coking coal). In comparison, Brazilian charcoal prices ranged between USD 230-310 per tonne in 2012 (1R$=1.95 USD; SAPA, 2012) or USD 8-12 per GJ. For wet wood prices of USD 26-44 per tonne (at a moisture content of 45-50%), which account for more than 70% of the total production costs, charcoal production costs are estimated to range between USD 330-450 per tonne (incl. transportation to the steel mill), or USD 12-16 per GJ (Norgate and Langberg, 2009). Therefore, the additional cost would amount to USD 3-10 per GJ of coal substituted (or by a factor two higher compared to coking coal prices). However, the coking coal prices are instable; therefore, the cost-competitiveness of substituting coal with charcoal could easily vary.

Figure 5: Heat production costs of fossil fuel-based and renewable energy technologies, 2009



Note: 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. 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.

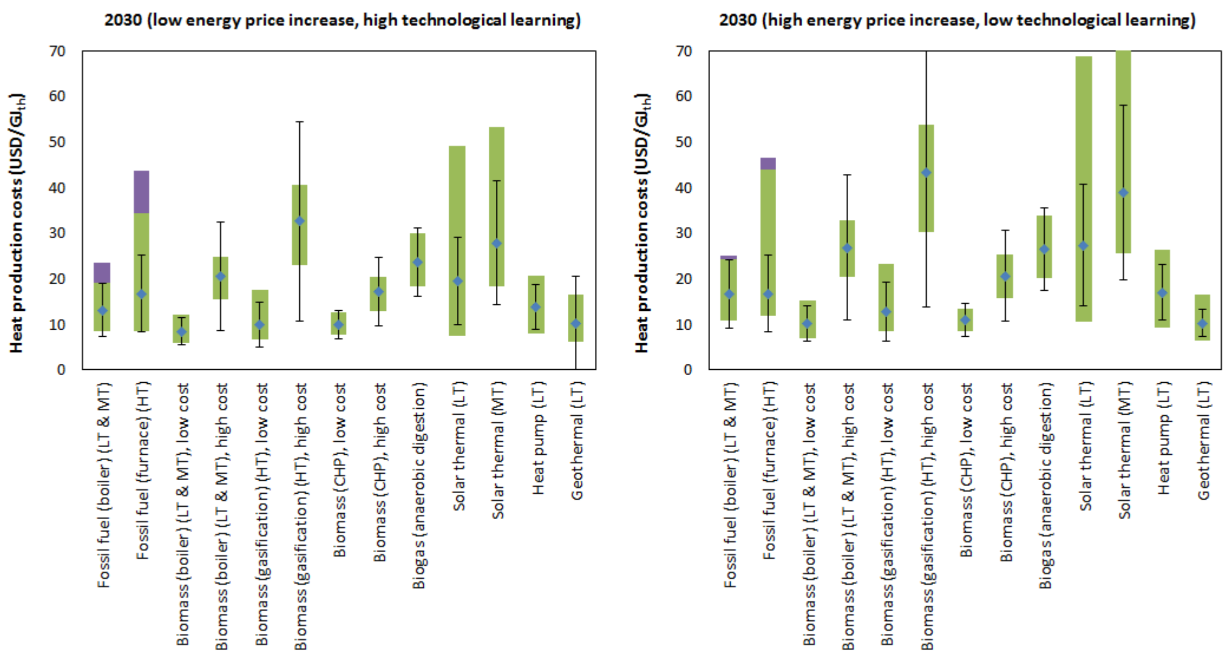
The heat production cost estimates for 2030 for low and high energy price (and technological learning) scenarios are provided in Figure 6. In view of the current situation and developments between 2010 and 2030, the findings for 2030 are summarised below:

- 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 5-10% 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.
- Assuming that 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 9-15/GJ. In comparison, the charcoal price is estimated to be on average USD 5/GJ higher.

For most technologies, energy costs account for a large share of total heat generation costs. For low- and medium-temperature heat applications up to 70% and for high-temperature applications, more than 90%

of the total costs are related to energy for fossil fuel technologies. The shares are comparable for heat generation from energy crops and geothermal sources. For biomass residues, the share of energy costs is lower, estimated on average at 30-60% depending on the biomass price. For CHPs, biogas and heat pumps, capital costs account for an equally important share of the total heat generation costs, estimated to be between 30-60%. For solar thermal, more than 80% of the total costs are related to the capital.

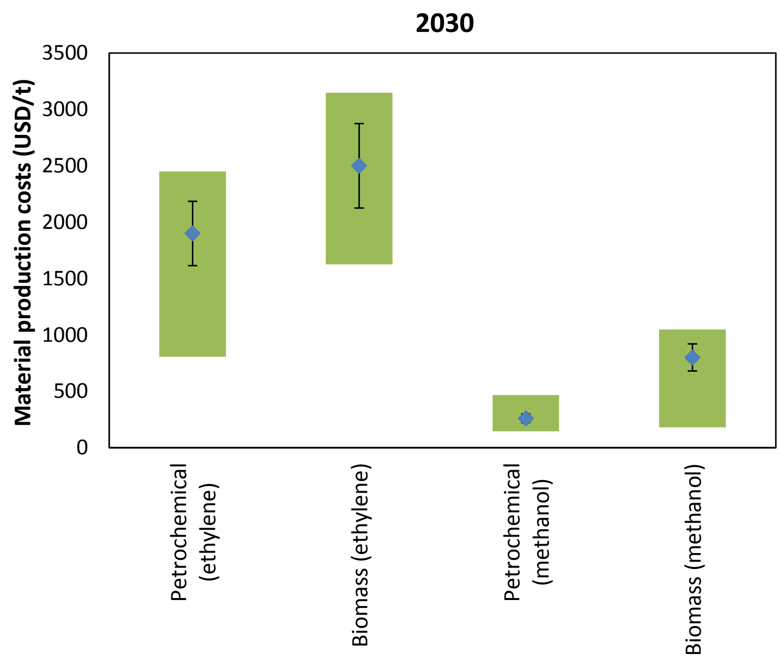
Figure 6: Heat production costs of fossil fuel-based and renewable energy technologies for low (left-figure),and high (right-figure) energy price increase and technological learning scenarios, 2030



Note: 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 the purpose of this analysis are: ethylene, methanol and PET) are presented for the situation in 2030 in Figure 7. Compared to petrochemical equivalents, the production costs of ethylene from biomass feedstock is 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 2-3 higher than the petrochemical route. Due to 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, in particular if waste (*e.g.*, black liquor, glycerine) feedstocks are utilised in its production.

Figure 7: Material production costs from petrochemical and biomass feedstocks, 2030



Note: 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.

The production cost estimates are based on three production cost factors; namely capital, operation and maintenance and energy (*i.e.*, fuels and electricity). Each factor has its own uncertainty. Equipment and material costs, location specific characteristics, discount rates and construction labour costs determine the capital costs and the variations in these parameters determine the uncertainties related to the capital costs. Likewise, operation and maintenance costs, which are a function of capital costs, are subject to uncertainty. There are large variations in fuel and electricity prices over time and across the world, as well as within regions. Based on the variations in each production factor (see Appendix A), the uncertainty margins of the production costs factors are estimated at ± 40% for heat generation technologies and at ± 20% for materials, which were presented around the mean value in the text and expressed as errors bars in the figures.

4.3. Potential of renewable energy technologies in the total global industry sector

Realisable technical potential

In this section, a summary of the realisable technical potential of the four renewable energy technologies are presented for the global industry in the year 2030. A detailed breakdown of the results by sector can be found in the Appendix B.

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 for the production of 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 energy use in the industry sector *solely* through solar thermal, geothermal and heat pumps.

Economic potential

Realising the potential of renewable energy technologies depends on a number of factors, including technology costs and access to resources. These factors are taken into account to further refine technical potential estimates. By accounting for the structure of the industry sectors, fuel mix and production growth in the ten regions analysed, Table 12 provides the ranges of CO_2 abatement costs of renewable heat technologies. In line with the heat production costs presented earlier (see Figure 5 and Figure 6), geothermal and heat pump technologies for low-temperature applications are cost-competitive (*i.e.*, negative CO_2 abatement cost or slightly above zero). If biomass residues are used, biomass-fired heat generation technologies are also cost-competitive. Boilers fired with expensive sources of biomass (*e.g.*, energy crops, wood pellets) are the cheapest among the options that have positive CO_2 abatement costs (USD 116 per tonne CO_2). Medium temperature solar thermal has the highest CO_2 abatement cost (USD 194 per tonne CO_2). Although there are no detailed bottom-up cost estimates for bio-based materials, Saygin *et al*. (2014) indicate abatement costs of USD 150-300 per tonne CO_2 for bio-ethylene and USD -110 to USD 0 per tonne CO_2 for PLA (compared to PET) for high sugar prices. When compared to other polymers, PLA could technically substitute (polyethylene, polypropylene or polystyrene; Shen, Worrell and Patel (2010)) and the abatement costs could increase by USD 10-100 per tonne CO_2 (Saygin *et al*., 2014).

Table 12: 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)

Note: Data outside brackets are the worldwide average corrected for industry structure, fuel mix and regional energy use. Ranges provided in brackets are based on the abatement costs of different sectors worldwide. Charcoal, biomass for materials and electricity-related options are excluded from the table since there are no detailed bottom-up cost estimates for these technologies to estimate their CO_2 abatement costs. For charcoal, developments in steam coal and biomass prices are used as proxy and in a similar way for bio-based chemicals sugar prices are used to estimate their cost-effectiveness. The realisable potential of electricity-related options is regarded as cost-effective.

Only results for the low price scenario are shown since this is estimated to be the most cost-effective for renewable energy technologies. Although due to more investments in renewable energy technologies, the price of fossil fuels does not increase as much as in the high price scenario, capital cost reductions and improvements in conversion from technological learning are estimated to be higher.

Both low and high price scenarios have associated CO_2 pricing policies that vary by region: worldwide on average USD 53 USD per tonne CO_2 for the *low price scenario;* and worldwide on average USD 11 USD per tonne CO_2 for the *high price scenario*. When these policies are taken into account, the cost-competitiveness of these technologies changes. Below the key findings for each technology (see Table 13):

- In both the low and high price scenarios, there is economic potential for biomass residue fired heat generation technologies. This is, however, not the case for expensive sources of biomass. Potential exists only in OECD countries, India, Other Developing Asia, Africa and Latin America. Economic potentials of **23 EJ** (AccD scenario) and **40 EJ** (AmbD scenario) are estimated for biomass residue used to generate process heat generation in both low and high scenarios. The economic potential for expensive biomass sources are about half of this, estimated at **13 EJ** (AccD scenario) and **25 EJ** (AmbD scenario) in the low price scenario and even lower at **11 EJ** (AccD scenario) and **22 EJ** (AmbD scenario) in the high price scenario. The economic potential of biomass residues is half of the realisable technical potential. Energy crops have an economic potential of approximately 25%. Biomass for feedstock could see a similarly high magnitude of potential, estimated at **3 EJ** (AccD scenario) and **6 EJ** (AmbD scenario) by 2030 for both price scenarios (in India, Other Developing Asia, Africa and Latin America). This is 12-24% of the total realisable technical bio-based feedstock potential.
- Solar thermal process heat technologies may be cost-effective, in particular if regional CO_2 prices and fossil fuel prices are high and if regions have good solar income. According to the low price scenario, solar thermal technology can be cost-competitive in India and Latin America, as well as in some OECD countries. Given the relatively low fossil fuel prices in most developing countries, solar thermal may not be cost-competitive although the annual energy yields are high. The economic potential is estimated at **3.8 EJ** for the low price scenario and **1.1 EJ** for the high price scenario. This is equivalent to 7-22% of the realisable technical potential. Most of this potential exists in low-temperature applications. Under both low and high price scenarios, geothermal energy and heat pumps each have estimated economic potential of approximately **1.5-2.0 EJ**. This is identical to their realisable technical potential.

Realisable economic potential

The second most important factor is the availability of resources to meet the estimated economic potential. The annual total technical potential of solar energy ranges from 1 500-50 000 EJ worldwide (Arvizu *et al*., 2011). In comparison to this large supply potential, the total estimated economic potential from the industry sector (3 EJ) is negligible, even when compared to regions where solar energy potential is low, such as Central and Eastern Europe (technical supply potential of 4-154 EJ). For geothermal energy, the technical potential for direct use are estimated to range between 10-312 EJ, with the lowest potential in OECD Europe (0.5-16 EJ) and the Middle East (5-21 EJ) (Goldstein *et al*., 2011). Even with potential competition from heating for the residential sector and the utilisation of these resources for power generation, no limitations are foreseen from deploying the realisable potential of geothermal energy. Therefore, the economic potentials of solar thermal (**0.9-3.8 EJ**) and geothermal (**1.7-1.9 EJ**) technologies are also the realisable economic potentials, in view of regional resource availability estimates. Likewise, the realisable economic potential for heat pumps is **1.2-1.9 EJ**, with additional electricity demand to run heat pumps (**3-6 EJ**) being met from a mix of renewable energy sources.

In comparison to solar thermal and geothermal technologies, the potential of biomass supply depends on a number of factors, such as increases in food demand and developments in the agriculture sector, availability of resources for agriculture (water, land) and development in biomass conversion technologies. Therefore, it is a complex task to provide ranges for the technical potential of biomass supply. IRENA prepared its own estimates in a bioenergy working paper for the year 2030 based on the analysis of more than 100 countries and seven types of biomass feedstocks (IRENA, 2014c). According to the IRENA bioenergy working paper, there is a global biomass supply potential of 95-145 EJ/yr. About 40-65 EJ of this total is from agricultural residues and waste and about 25-40 EJ is from forestry products, including residues. The remainder 30-40 EJ is related to energy crops.

IRENA's (2014a) REmap shows that nearly 20% of the total biomass demand would be related to the industry sector if the global share of renewable energy is to double by 2030. This global average ranges from 0% in Middle East to more than half of the total final industrial energy demand in India. A quarter of all biomass is assumed to be available for the industry sector (total of 18-30 EJ, 8-18 EJ residues and 10-12 EJ energy crops). The realisable economic potential of biomass for the industry sector, in view of resource availability, is equivalent to **19 EJ** and **14 EJ** for low and high price scenarios, respectively, according to the AmbD scenario. About 85-95% of the total potentials are related to process heat generation. The remaining 5-15% is use of biomass as feedstock that is estimated to have approximately **1-2 EJ** in both scenarios, assuming that biomass residues and energy crops are first used for process heat generation and the remaining quantities are only available as feedstock. According to the AccD scenario, the potential is slightly lower, estimated at **14 EJ** and **13 EJ** for the low and high price scenarios, respectively (**0.5-1 EJ** as feedstock).

For electricity, the realisable potentials are **0.6 EJ** and **1.1 EJ** according to the AccD and AmbD scenarios, respectively (0.1 EJ solar cooling, and 0.5-1.0 EJ relocation of primary aluminium smelters).

Table 13: 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 taken into account. Each technology should therefore be treated separately, and the potentials of all technologies should not be cumulatively added in order to estimate the total renewable energy technology potential for the industry sector.

Allocation of the realisable economic potential

Although this study takes into account the regional biomass supply potential as well as the competition from other sectors of the economy at an aggregate level, reaching the economic potential of biomass could still be challenging. For example, at certain biomass prices a higher share of biomass could be allocated to other applications, such as transportation fuels as opposed to low-temperature heat which would limit the availability for the industry sector. Therefore available biomass needs to be allocated to the most cost-competitive applications where other renewable technologies do not provide an alternative for. As earlier mentioned, renewable energy use in high-temperature process heat applications (*i.e.,* iron and steel, non-metallic minerals and chemical and petrochemical sectors) and substituting petrochemical feedstocks can only be achieved by biomass. In comparison, low-temperature heat can be provided by a mix of solar thermal, geothermal and heat pumps. Medium temperature heat applications can be met by solar thermal technology, but as the analysis shows it is economic viable only in few sectors and regions. Therefore medium temperature heat applications would also require biomass as a renewable alternative. Allocating the estimated economic potential of renewable technologies in this way would yield their most optimal and effective use across different applications. Based on this reasoning, the estimated realisable economic potential is now allocated to different applications and present the results for the low price scenario (for both the AmbD and the AccD scenarios in the case of biomass and electricity) where their economic potential is the highest in 2030 (see Figure 8):

- We start with low-temperature heat applications. To substitute low-temperature heat demand, solar thermal and geothermal technologies could play a key role in new capacity investments with total potential estimated at **2.3 EJ** and **1.1 EJ,** respectively (see Figure 9). About half of the total potential for solar thermal heat exist in the chemical and petrochemical sector (1 EJ). The remainder of the potential is distributed across less energy intensive small sectors such as food and tobacco, textile and leather and others (1.2 EJ). Chemical and petrochemical sector accounts for about half of the geothermal energy potential (0.4 EJ) with the remainder being in the food and tobacco sector (0.2 EJ) and other small sectors (0.5 EJ).

  The potential of heat pumps is distributed across new (0.7 EJ) and existing (0.9 EJ) capacity. Food and tobacco account for about 20% of total potential (0.3 EJ), with the remainder being in other less energy intensive sectors (see Figure 9).

  The potential of solar thermal, geothermal and heat pumps combined can substitute in total 27% of the total low-temperature heat demand worldwide in both the AmbD and AccD scenarios (see Figure 9).

- Biomass is estimated to play a key role for high-temperature heat applications where other technologies do not provide alternatives for. In both existing and new capacity, biomass demand is estimated at **6.1 EJ** (AccD scenario) and **6.7 EJ** (AmbD scenario) by 2030. Demand from iron and steel (0.5-1.4 EJ) and non-metallic minerals (4-4.4 EJ) sectors accounts for most demand for high-temperature applications with rest being in the chemical and petrochemical sector (1.2-1.4 EJ). The total potential of biomass can substitute up to 18% of the total high-temperature heat demand by 2030.

The remainder of the economic potential of biomass can be used for medium temperature heat applications in new and existing capacity (total potential of **5.3 EJ** and **7.2 EJ**). The largest potential is seen in the chemical and petrochemical (1.3-1.7 EJ) and food and tobacco (0.8-1.0 EJ) sectors and in other less energy intensive sectors (3.1-4.5 EJ). The total substitution potential of biomass use for medium temperature heat applications reaches as high as 35%.

Finally biomass can also be used to substitute the remaining fossil fuel use in low-temperature heat applications (after accounting for the quantities substituted by other renewable energy technologies). These potentials – equivalent to **4.3 EJ** (AccD scenario) and **5.7 EJ** (AmbD scenario) – exist in various sectors, with the exception of energy-intensive sectors. Together with biomass, all renewable energy technologies offer a substitution potential of up half of total fossil fuel demand for low temperature heat generation according to the AccD and AmbD scenarios, respectively (see Figure 8).

- The biomass demand as feedstock for the production of materials is estimated at **1-2 EJ**, which is equivalent to a substitution potential of 4-7% according to the AccD and AmbD scenarios (see Figure 8).
- Relocation of primary aluminium smelters offers **0.7 EJ** (AccD scenario) **1.0 EJ** (AmbD scenario) potential related to renewable electricity use worldwide. The potential for solar cooling to substitute electricity-based equipment in the food and tobacco sector is estimated at **0.1 EJ** (see Figure 8).

The potential of renewable energy technologies could reach a total **23 EJ** and **28 EJ** by 2030. Biomass is estimated to contribute to approximately 75% of this potential (17 EJ and 22 EJ) followed by the solar thermal heat (2.5 EJ) and heat pump potential (1.5 EJ). Total potential of renewable energy technologies could raise the share of renewable energy in the fuel mix of the industry sector from 10% to up to 34%.

The total potential for renewable energy is 4 EJ in the high price scenario, and 7 EJ lower according to the AccD and AmbD scenarios, estimated at **19 EJ** and **21 EJ**, respectively. Realising the potential of the high price scenario would increase the share of renewable energy in the fuel mix of the global sector from 11% to approximately 26%. This is also clearly a high share of renewables.

In both price scenarios, the realisable economic potential of biomass is fully exploited. In particular for the high price scenario, all potential originates from biomass residues, since there is only small potential for energy crops. Biomass residues are equally important for the low price scenario, where they also account for most of the potential.

In the low price scenario, more than 80% of the total potential of solar thermal, geothermal and heat pumps needs to be deployed in new capacity which will be built between 2010 and 2030. Biomass can be applied to both new and existing capacity.

Exploiting the potential quantified in this study relies on the availability of biomass residues since it is assumed that they are first used to meet the demand from the industry sector. If a lower share of biomass residues is available, the demand for energy crops would increase. However given their low cost-competitiveness, the biomass potential would be clearly lower although supply from energy crops is more.

Furthermore, access of production plants needs to be ensured to the biomass resources. Although there could be large supply potential within regions, if access to plants is limited due to lack of transportation infrastructure or for other reasons, the potential quantified in this study may not be reached. It is therefore important to smartly position new capacity by considering access to resources as well as to the supply of raw materials required for production processes.

Figure 8: Comparison of the realisable economic potential of renewable energy technologies according to the AmbD and AccD scenarios, 2030

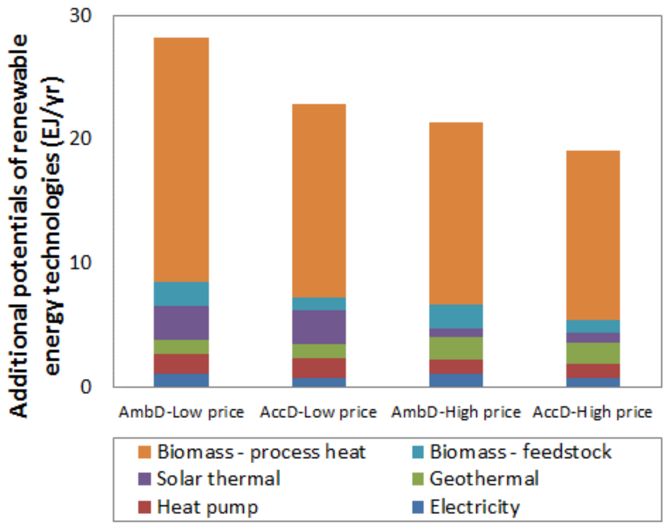
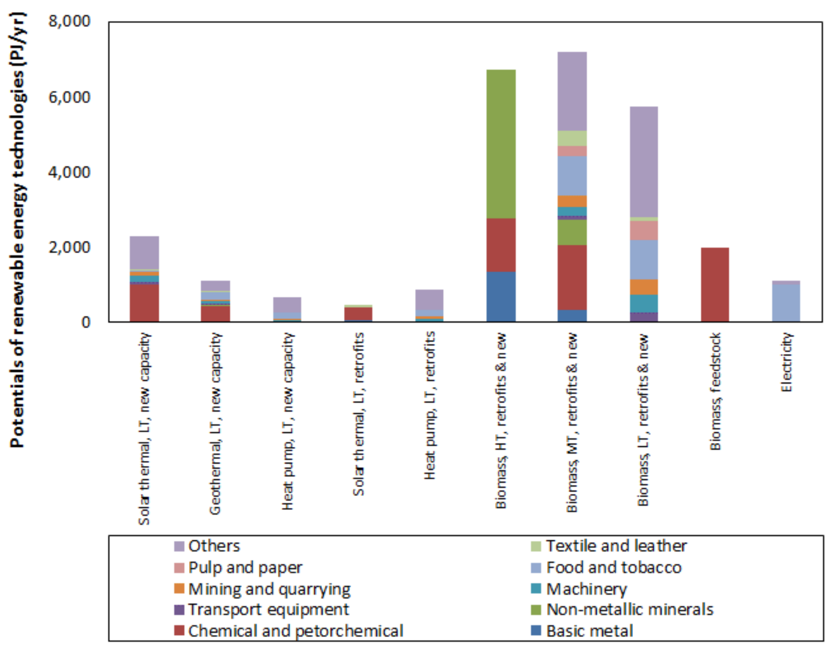
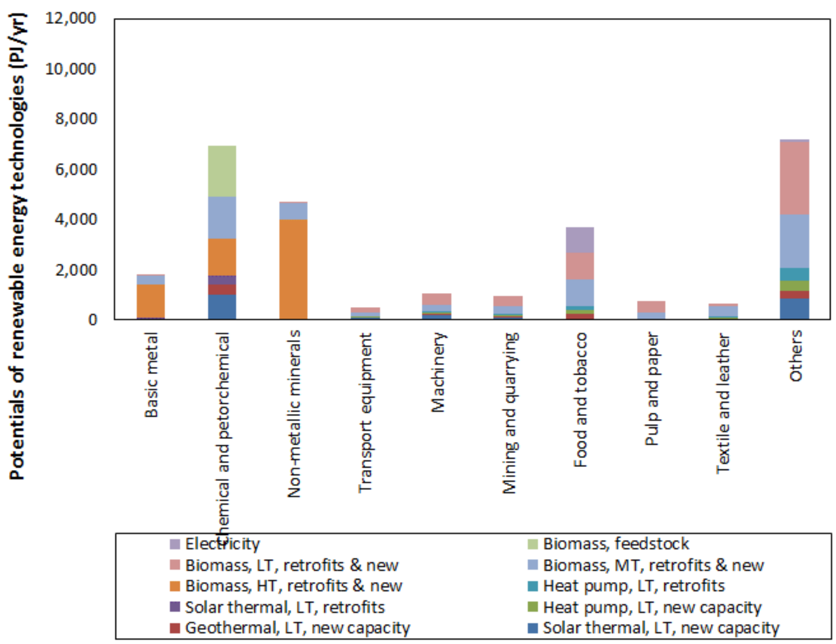


Figure 9: Realisable economic potential of renewable energy technologies in the global industry sectors for the low price increase scenario (according to the AmbD scenario), 2030



According to Figure 10 (referring to the low price scenario according to the results of the AmbD scenario), largest potential of renewable energy technologies is located 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 of technologies offering potential. Other small sectors offer potential up to 7 EJ. The total potential of the energy-intensive sectors (14 EJ) is equal to the potential in less energy-intensive sectors (14 EJ).

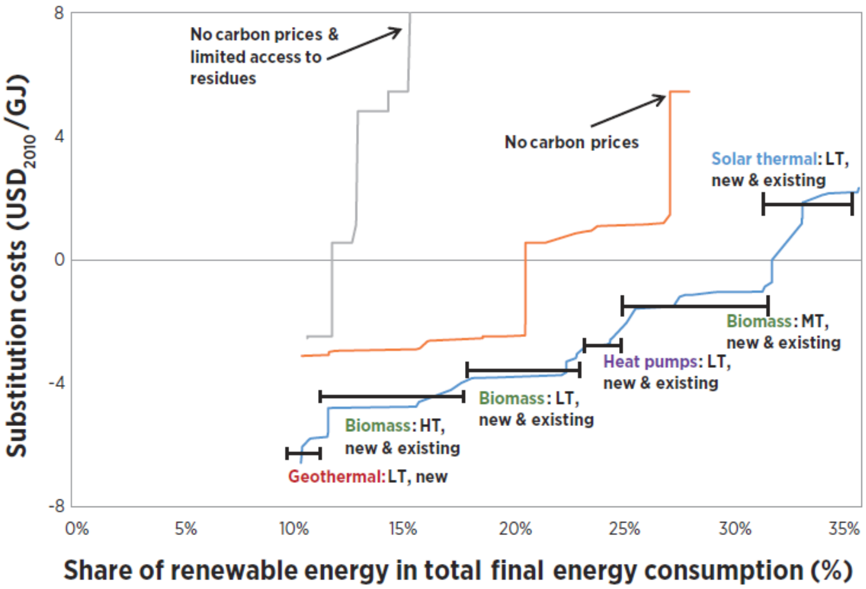
Figure 10: Realisable economic potential of renewable energy technologies with a breakdown by global industry sectors for the low price increase scenario (according to AmbD scenario), 2030



In Figure 11, the average incremental costs of substituting industrial fossil fuel use by renewable energy technologies are presented for the low price scenario where the additional potential of 25 EJ renewable energy use in process heat generation raises its share in 2030 to 34% worldwide (according to the AmbD scenario; blue line). The results show that about 80% of the total potential worldwide are estimated to have negative incremental costs of fossil fuel substitution (<USD 0 per GJ fossil fuel substituted). Potential from geothermal heat, heat pumps and low- and high-temperature biomass applications falls under this cost category. The most expensive option is solar thermal in low-temperature applications (USD 2 per GJ of fossil fuel substituted). In the case where there is no pricing scheme for CO_2 emissions, the incremental costs would increase by USD 4-6 per GJ and reduce the realisable economic potential for most options, thereby reducing the total renewable energy share from 34% to about 27% (orange line, AmbD scenario).

Limited access to biomass residues for industrial use would reduce the total share of renewable energy use would to around 15% (grey line).

Figure 11: Potential of renewable energy technologies in the industry sectors in 2030 for low-price increase scenario, according to the AmbD scenario



Note: Data for process heat only

5. Discussion

So far, assessment of the renewable energy technologies in the industry sector has received little attention. This study makes an attempt 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.

The findings quantified in this study are subject to uncertainty due to quality of background data and the numerous assumptions made in the analysis. The comparative potentials assessed in this study, therefore, are only indicative, with many issues requiring further research to improve these estimates. First, the main uncertainties in the results due to data quality and methodological limitations are discussed in Section 5.1. This is followed in Section 5.2 by quantifying the effects of key assumptions and methodological components on the results, based on a sensitivity analysis.

5.1. Data and methodology

Uncertainties in industrial energy use projections and heat generation costs due to data issues

Data used to project industrial energy use and estimate the heat generation costs of process heat are based on three sources: (i) IEA's energy balances which provide the breakdown of industrial energy use for each of the 10 regions (IEA, 2012a;b), (ii) physical production growth data based on IEA (2012c) and the underlying data to breakdown the industrial energy use to temperature levels and new capacity versus existing capacity, and (iii) technology and energy price data used to estimate the costs of renewable energy technologies (see Appendix A). Uncertainties related to each dataset are discussed in more detail below.

Energy statistics

The quality of process energy use data reported in IEA's energy balances (IEA, 2012a;b) is workable for most regions. There are some limitations for Middle East and Africa and some of the Other Developing Asia countries. The energy use of the less energy intensive sectors of these countries is often grouped under the *non-specified sector* without a detailed breakdown of the sectors which actually consume this energy. However, given similarity of the process heat temperature breakdown of these sectors with other less energy intensive ones (majority low- and medium-temperature heat), potential estimates are not expected to be too different unless there are major differences in the types of production process applied.

A more important issue is the reporting of the energy use of some of the energy-intensive sectors, notably for non-metallic minerals sector, under the item *non-specific sector*. This introduces a larger magnitude of uncertainty to the analysis. An effort was made to improve the data based on the bottom-up analysis of the non-metallic minerals sectors energy use in all regions, but if the energy use of the sectors is not reported at all to the energy statistics then the potential estimates are underestimation in some regions. This is found to be the case in China and India as the additional energy use estimated for the non-metallic minerals sector is higher than what is reported in the non-specific sector.

In a similar way, an effort was made to improve the energy use of the chemical and petrochemical sector of all regions based on bottom-up data. It was found that in China and India coal use for chemicals production is most likely not reported in the IEA energy balances (Saygin *et al*., 2011a). This could be the case for the production of other materials in other regions as well. Hence accounting for the uncovered industrial energy use would increase the potential for biomass. It is expected that this would not be more than 5-10% of the total estimates (1-3 EJ).

Production growth estimates and breakdown of industrial energy use

We assume the production growth to be equivalent to the demand growth according to the IEA's high and low estimates by excluding trade of materials (IEA, 2012c). In the absence of energy efficiency improvements, industrial energy use is estimated to reach more than 185 EJ. This is in line with the scenario estimates of IEA (2012c) where no new policy action is taken to address climate change between 2010 and 2050. Compared to IEA's most ambitious climate policy scenario where industrial energy use grows on average by 1 %/yr between 2010 and 2050 (for 2030 equivalent to total energy use of 155 EJ), a similar growth of 0.9 %/yr is estimated (equivalent to 150 EJ by 2030).

In reality industrial growth can be much different than what is estimated in this study. This would depend on cost-competitiveness of production across regions or the changes in demand for bulk materials (*e.g.,* steel, cement, paper, polymers). If production of bulk materials would not be economically viable anymore in OECD regions due to various policy choices, production could be re-located to other regions. Conversely, increase in raw material or other production cost factors could be more important than energy prices or the pricing of CO_2 in some sectors since the share of energy costs are low. In such cases, businesses may choose to remain in a certain region to improve their cost-competitiveness (*e.g.,* regions with low interest rates, thereby lower annual depreciation costs). Moreover, OECD regions may continue to increase their capacity as is partly the case today in the US due to availability of cheap shale gas. These aspects which are excluded from this study, should be accounted for with more production growth scenarios since potential of renewable energy technologies could change compared to this study's estimates.

The breakdown of the temperature levels of industrial energy use is based on the data collected a decade ago for the EU countries. Although it is unlikely that the temperature levels of production processes across different countries would show major differences, a further breakdown of low and medium temperature levels by accounting for the differences in production processes would help to improve the estimates.

Another issue concerns the approach to model the share of new and existing capacity. While the energy intensive sectors were modelled rather in detail, non-energy intensive sectors were estimated based on the developments in the energy intensive sectors due to lack of data availability. Furthermore, lifetime of plants could be much different than what is assumed in this study as today's examples already show. In reality, in most sectors, lifetime of plants exceed their technical lifetime which means that the share of existing capacity could be more than what is estimated in this study. Also, total energy efficiency improvements would be lower since retrofits have a lower improvement potential compared to implementing BPTs in new capacity. Although it is considered as a costly option, early retirement of existing capacity could be an option to accelerate new capacity investments. This would favour the deployment of solar thermal and geothermal technologies.

It is also important to analyse the energy balances of plants when renewable energy technologies substitute fossil fuels (*e.g.,* charcoal use in iron making). Although the differences in fuel demand to deliver the same amount of heat between fossil fuels and renewables are accounted for, substantial changes in energy balances of plants may present technical constraints to the large deployment of technologies. Based on actual plant experiences, this should be incorporated in future assessments.

Finally, reaching renewable energy shares of up to 34% by 2030 in the manufacturing industry also depends on energy efficiency improvements. With the same amount of renewables, higher renewable energy shares can be reached if the total industrial energy demand is lower.

Technology data

Heat generation costs for 2009 and 2030 are estimated based on capital cost and O&M cost data specific to each renewable energy technology. For biomass related technologies and heat pumps, energy prices also account for a large share of the total production costs. Technology data for 2009 originates from literature and information received via industry associations. Based on variations in the data, errors were estimated at ± 40% for heat generation technologies and as ± 20% for materials around the mean value. However, actual capital and O&M costs could be different than what is estimated in this study since each industrial production plant is different in its configuration and energy use setting. Therefore additional equipment requirements, sizing of capacity, space requirements at site and process modifications will differ from plant to plant. This argument is valid for technologies considered for both new and existing capacity. While for solar thermal and geothermal heat generation technologies, a distinction was made for biomass that it could be applied to both existing and new capacity. With real life examples from production plants, potential differences in costs of technologies need to be quantified and included in the analysis to arrive plausible cost estimates.

Another critical parameter is the capital cost reductions assumed based on technological learning. This determines whether solar thermal technology is cost-competitive by 2030 or not. More data is needed to support the assumptions underpinning the analysis. The effects of these changes over the results are quantified in Section 5.2.

Energy prices

Development of energy prices are subject to large uncertainties. Current prices of different fossil fuel energy carriers are collected from literature and industry databases and therefore found to be reliable. Moreover, projections are based on IEA (2011b) which is regarded as an authoritative source for the energy industry. However, average prices of biomass at region level for today and their future developments are less certain. Projections are assumed to be coupled to the developments in fossil fuel prices. Developments could deviate from this assumption for various reasons. With increasing demand, biomass will reach the limits of its supply. In this case, the production costs and prices of biomass will be higher in comparison to the average prices used. Furthermore, prices will increase along with the distance to the plants which is excluded from this study. These are important aspects, especially for large scale consumers of the energy-intensive sectors where most potential is estimated. Prices of biomass will also be driven by the developments in the global power, heat and transport sectors. An integrated assessment of the developments in all sectors is necessary to address these issues.

Uncertainties in realisable economic potential estimates

We combined industrial energy use projections with the heat generation costs of renewable energy technologies to estimate the realisable economic potential based on a number of technical and economic criterion. Now the uncertainties in these estimates are discussed by identifying the main data issues and methodological simplifications.

Realisable technical and economic potential

Some of the potential trends in renewable energy use in the manufacturing industry are accounted for by developing the AmbD and AccD scenarios. However, the approach is still limited to considering developments in the industry's structure, as well as identifying sector-specific characteristics and assessing the availability of new technologies to fulfil potential. Therefore the realisable technical potential estimates could be too optimistic. For example, if bio-ethylene production from bio-ethanol substitutes a large share of ethylene from naphtha steam crackers, other olefins and aromatics would need to be increasingly produced from other fossil fuel routes (*e.g.,* as by-product of refineries, direct propane conversion) unless bio-based processes are developed for their production. So far the developments of such processes are, however, lagging behind bio-ethylene technology, and the chemical and petrochemical sector may not choose to invest in other fossil fuel feedstocks for cost reasons. Hence, due to lack of technology deployment, the existing technical potential may never be reached. Estimates under both AmbD and AccD scenarios should be supported by examples of research and development in emerging technologies.

The economic potential of technologies is determined based on whether the abatement costs of technologies are below the CO_2 price in 2030 according to the IEA (2011b). Although no economic potential is estimated for some technologies according to this study, in reality they may still be deployed. Application of solar thermal for medium-temperature heat applications which is estimated to have limited economic potential is for example implemented in various sectors in India and Mexico. There are also new types of solar thermal process heat technology which are being developed and shown to be cost-effective (GlassPoint, 2013). In comparison, biomass for process heat generation is estimated to be cost-effective in most regions, in particular if low-cost biomass sources are used. However, the share of biomass use for process heating is currently low due to barriers such as limited access to low-cost resources, transportation to plant and site requirements for storage. Thus other factors beyond costs could play a role to limit the uptake of technologies despite their economic viability. These need to be incorporated to future assessments when estimating the potential of renewable energy technologies. The CO_2 prices according to the IEA (2011b) may also be too high. As a result the estimated economic potential of process heat technologies could be too optimistic.

It is assumed that biomass will first be deployed for process heat generation and the remaining resources would be available for feedstock use. However, today already bio-based feedstock technologies for materials production are increasingly being developed and deployed. Although the economic viability of bio-based feedstocks are lower compared to biomass fired process heat technologies (based on CO_2 emission abatement costs), it would still be more important to give importance to investments for bio-based materials production since the value added of end products are higher and innovation possibilities are more (Saygin *et al*., 2014). Furthermore, the chemical and petrochemical sector can invest in regions where biomass feedstocks are cost-competitive and subsequently import the bio-based basic chemicals (*e.g.,* ethylene) and their derivatives for further processing since the sector is globalised with respect to its trade flows. This is also an aspect which is left out from the assessment, but requires further attention. Compared to the case of biomass use for process heat generation, the potential of biomass as feedstock should be regarded as conservative.

Biomass supply estimates

A large share of biomass potential is estimated to originate from low-cost biomass sources assuming that agricultural and forestry residues as well as waste (including animal manure and municipal solid waste) would be available by 2030. Furthermore, it is assumed that about twenty percent of all biomass supply potential in 2030 would be available for the industry sector. These are the two critical assumptions to increase the share of renewable energy in the fuel mix of the industry sector; however, they are both subject to large uncertainty. The biomass potential quantified in this study for process heat should therefore be regarded as optimistic.

The objective of this study is to compare cost-effective deployment potential with bioenergy supply estimates, to arrive at techno-economic potential. IRENA (2014c) discusses in greater detail the challenges in realising the biomass supply estimates used in this study. From a bioenergy demand perspective, developments other than what is assumed for different end-use sectors may result in a higher or lower share of biomass available for the industry sector. This will be an important factor determining how much biomass can be deployed realistically in the industry sector.

Accounting of greenhouse gas emissions

A detailed analysis of emissions is excluded from this study. However, production and transport of biomass as well as increasing demand for land for energy crops introduce additional GHG emissions. Several studies showed that when emissions related to land use change (direct and indirect) for biomass production are accounted for, life cycle CO_2 emissions of bioenergy technology options increase (Searchinger *et al*., 2008; Fargione *et al*., 2008). Furthermore, upstream emissions from biomass production could be high (*e.g.,* methane from charcoal production), especially if the technology for fuel production is rather inefficient. Realising the potential estimated in this study will also increase the transportation of biomass across different countries since it will not be possible to deploy all supply potential in that region. Moving large quantities of biomass across countries will increase emissions which should be accounted for. In the next step, the boundaries of the emissions should be extended to cover such upstream activities.

5.2.Quantifying the effects of uncertainties over results

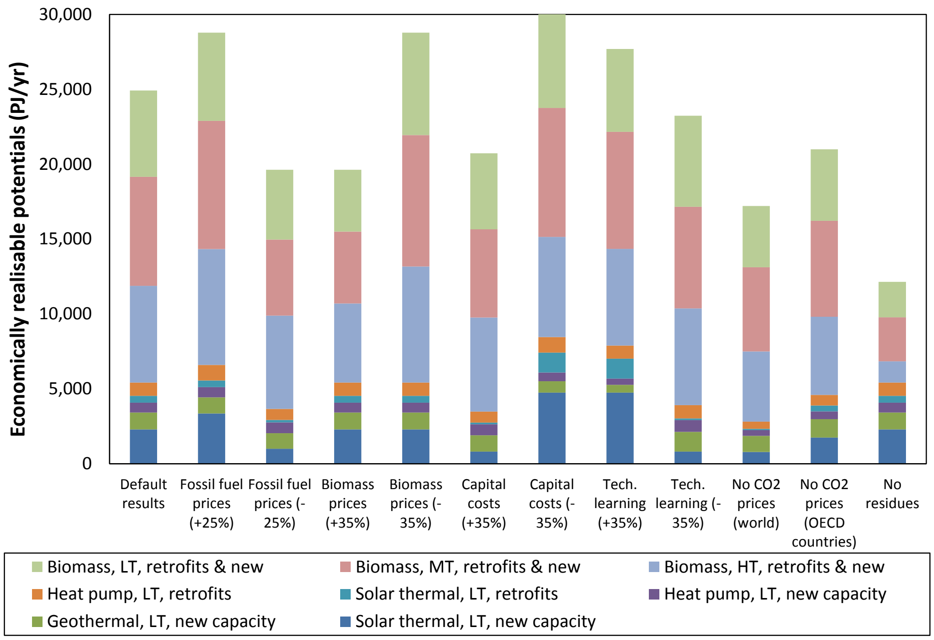
Based on the most important production cost factors as well as global issues which may influence the potential estimates, the changes in the realisable economic potential estimates for 2030 are estimated. Figure 12 shows the changes due to energy prices, capital costs (including technological learning), CO_2 prices and the share of biomass residues over the total biomass supply potential (for the low price scenario, AmbD scenario).

High fossil fuel and low biomass prices are the most important factors for the higher deployment of renewable energy technologies in the industry sector. Keeping all other factors same, increasing fossil fuel prices by +25% or decreasing biomass prices by -35% increase the renewable energy potential by approximately +15% (from 25 EJ to 29 EJ) (excluding feedstock and electricity-related potentials). Higher fossil fuel prices increase the potential for all technologies, notably for solar thermal by +45%. With lower biomass prices, potential for biomass could increase by +20%. Reducing the cost-competitiveness of renewable energy technologies either by increasing biomass prices or by reducing fossil fuel prices has a larger magnitude of effect over the potential of approximately -25% (from 29 EJ to 20 EJ). This is explained by the fact that reaching higher potential is constrained by availability of low cost biomass supply.

Changes in capital costs have a similar effect (within +/-15%) over potential compared to that of energy prices, although energy costs account for a large share of the heat-generation costs with most technologies. Capital costs dominate the total costs of low-cost biomass fired technologies and the solar thermal. In particular, solar thermal potential doubles when capital costs are reduced by -35% (from 2.8 EJ to 6 EJ). There are similar effects over the estimates when technological learning assumptions are altered by ±35%.

The largest change is observed in estimates when the effect of CO_2 prices from all world regionsare removed. In this case, the potential of renewable technologies is almost halved, from 25 EJ to 17 EJ. The effects are largest for solar thermal (most expensive option) and lowest for geothermal and biomass applications some of which already economically viable. The decrease in potential is lower, from 25 EJ to 21 EJ, when CO_2 prices are removed in OECD regions only.

Figure 12: Sensitivity of economically realisable potential of renewable heat generation technologies to the changes in production cost factors and other assumptions, 2030



Note: Data for process heat only

6. Priority areas for action

Although there are many issues which need further research and the findings should be improved, this study show that the current renewable energy share in the industry sector could be substantially raised. This can make an important contribution to doubling the share of renewable energy in the global energy mix objective of the SE4ALL. Based on the findings of the techno-economic analysis and the feedback from the stakeholder workshops, IRENA identified six priority areas that warrant action from both policy makers and industrial stakeholders. These are:

(i) Energy-intensive Sectors: With 75% of the total industrial energy demand and long lifetimes for these types of plants, the energy-intensive sectors need to consider renewable energy options not only as an integral part of their new build capacity, but also as part of their existing capacity.

(ii) Small- and medium-sized enterprises (SMEs): Accounting for more than 90% of all manufacturing businesses, SMEs play a crucial role in increasing the deployment rate of renewable energy technologies, providing local manufacturing opportunities and stimulating cost reductions through learning by doing.

(iii) Biomass: Among the renewable technology options, biomass has the largest substitution potential in the manufacturing industry, but immediate and internationally coordinated action is required to alleviate the serious supply constraint of sustainable sourced and low-cost biomass resources, and to deploy the most resource efficient biomass use applications.

(iv) Solar thermal systems: Solar thermal heat systems have a large technical and realisable economic potential in small scale plants and less energy-intensive industries like the textile and food sectors, but the vicious circle of high initial capital costs and low deployment rates needs to be broken.

(v) Electrification: With increased electrification in the industry sector, renewable energy deployment can only be achieved through technology development in both the industry and power sectors.

(vi) Regional aspects: Regional potential depends on production growth, ratio of existing and new capacity, and renewable resource availability. Energy pricing and climate policies can ensure a level playing field and biomass resource constraints may be elevated by trade, but equally important will be specific policies to support the different industries in deploying renewable energy.

In view of these key priority areas, new policies will be required. As a consequence of regulatory and fiscal instruments in some countries, renewable energy use is already taking off in the power and transport sectors. Suitable policies are also required for the industry sector to increase its share of renewable energy in the next decades. Quotas, incentives in emission trading schemes and green procurement programs can accelerate biomass use in materials production. Target setting for increasing the share of renewable energy use for process heat generation is required. These targets should be tailored to address the characteristics of both energy-intensive sectors and SMEs and by considering the regional differences in resource availability. Biomass is at the heart of nexus of energy, food, water and land use; therefore it needs to be sourced in a sustainable manner. This requires the development of integrated policies on energy, material, agriculture and resource use.

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List of abbreviations

BAU	Business as Usual
BPT	best practice technologies
^{o}C	degree celcius
CFR	cost-and-freight
CH_4	methane
CHP	combined heat and power plant
CO_2	carbon dioxide
COE	cost of abating one tonne of CO_2-eq emission
COP	coefficient of oerformance
EAF	electric Arc furnace
EE	energy efficiency improvement potential
EJ	exajoule
EU	European Union
FOB	freight on board
GJ	gigajoule
GJ_{th}	gigajoule thermal
HT	high temperature
IEA	International Energy Agency
IRENA	International Renewable Energy Agency
LT	low temperature
Mt	megatonne
MT	medium temperature
MW_{th}	megawatt thermal
OECD	Organisation for Economic Co-operation and Development
O&M	operation and maintenance
PET	polyethylene terephthalate
PJ	petajoule
PLA	polylactic acid
SE4ALL	Sustainable Energy for All
SME	small and medium enterprises

SPF	seasonal performance factor
t	tonne
thm	tonne of hot metal
TPEU	total primary energy use
UNIDO	United Nations Industrial Development Organisation
US	United States
USD	United States dollar
USGS	United States Geological Survey
yr	year

Annex

Appendix A: Technical and economic data used in the analysis

We provide detailed background data used in this analysis from Table 14 until Table 18.

Table 14: Conversion efficiency of the fossil fuel and renewable energy technologies, 2009

	OECD Americas (%)	OECD Europe (%)	OECD Pacific (%)	Other Europe (%)	China (%)	India (%)	ODA (%)	Africa (%)	Middle East (%)	Latin America (%)	References
Biomass boiler 1	90	90	90	90	80	80	80	80	80	80	IEA (2007a;2012d); Börjesson and Algrehn (2010); Laurijssen, Faaij and Worrell (2012)
Biomass boiler 2	90	90	90	90	80	80	80	80	80	80	
Biomass CHP 1 (total of electricity and heat)	83	83	83	83	75	75	75	75	75	75	Obernberger and Thek (2004); FORCE Technology (2006a;b); IEA (2007a); Börjesson and Algrehn (2010)
Biomass CHP 2 (total of electricity and heat)	83	83	83	83	75	75	75	75	75	75	
Biomass gasifier[1]	45	45	45	45	40	40	40	40	40	40	Patil *et al*. (2002); Dasappa *et al*. (2003); Ghoshh, Sagar and Kishore (2003;2006); Shivakumar, Jayaram and Rajshekar (2008); Salam, Kumar and Siriwardhana (2010)
Biogas CHP[2]	70	70	70	70	62	62	62	62	62	62	DIAFE (1999); Biogas Regions (2008)
Fossil fuel-fired boiler	90	90	90	90	90	90	90	90	90	90	Einstein, Worrell and Khrushch (2001); Fritzson and Berntsson (2006)
Fossil fuel-fired furnace	60	60	60	60	50	50	50	50	50	50	BEE (2005)
Geothermal	100	100	100	100	100	100	100	100	100	100	IEA (2007a)
Heat pump 1 (60 °C)	425	425	450	410	425	465	465	520	520	465	ITP (2003)
Heat pump 2 (100 °C)	275	275	285	270	275	290	290	310	310	290	ITP (2003)

[1] Based on the studies reviewed, biomass gasifiers use on average 30% more fuel than conventional fossil-fuel based technologies. Based on the conversion efficiency of fossil fuel-based furnaces, this relationship is used as proxy to estimate the efficiencies of biomass-fired technologies.

[2] Refers to gross conversion efficiency and excludes the total amount of heat and electricity consumed internally.

Table 15: Assumed solar collector yields (in $kWh_{th}/m^2/yr$), 2009

	OECD Americas	OECD Europe	OECD Pacific	Other Europe	China	India	ODA	Africa	Middle East	Latin America
Solar thermal for temperatures below 100 °C (flat plate)[1]	660	540	810	450	660	860	820	980	900	820
Solar thermal for temperatures below 150 °C (evacuated tube)[1]	660	540	810	450	660	860	820	980	900	820
Solar thermal for temperatures below 150 °C (concentrated solar)[2]	530	440	660	365	530	700	670	800	730	670

[1] Data for flat plate collectors is assumed based on IEA (2007a) where the authors mention annual energy yields reaching 800 $kWh/m^2/yr$ for South Europe. Data for other regions is estimated based on the relationship of global horizontal irradiation (GHI) data across different regions assuming identical conversion efficiency of collectors' worldwide.
[2] Data available from literature refers to parabolic trough systems in India (Scheffler and Arun systems) in various industry sectors with an average solar collector system area of 1000 m^2. The annual energy yield from these systems is approximately 400 $kWh/m^2/yr$ (up to applications with temperature 250 °C). International experience from US, Turkey and Australia for various process heating and cooling applications shows higher energy yields up to 800 $kWh/m^2/yr$, but for applications with temperature 175-200 °C (UNDP, 2008). This higher value for India (for lower temperature applications) is taken as a proxy and approximate the yields in other regions based on their GHI.

Table 16: Fossil fuel and renewable energy technologies and their technical and economic characteristics, 2009

Fuel type	Technology	Heat generation capacity (kW_{th})	Initial investment cost (USD/kW_{th})	O & M costs ($USD/kW_{th}/yr$)	Annual operation rate (hours)	Power-to-heat ratios (-)	References
Biomass	Boiler (small)	1,000	660	35	7,500	N/A	IEA (2007b;2012d); Börjesson and Algrehn (2010); Laurijssen, Faaij and Worrell (2012)
Biomass	Boiler (large)	5,000	580	30	7,500	N/A	
Biomass	Gasifier	1,000	215	10	7,500	N/A	Patil, Singh and Saiyed (2002); Ghosh *et al*. (2003)
Biomass	CHP (steam turbine)[1]	17,500	1,430	30	5,750	0.35	IEA (2007b); Börjesson and Algrehn (2010); Obernberger and Thek (2004)
Biomass	CHP (fluidised bed)[1]	96,000	850	20	5,750	0.33	Force Technology (2006a;b)
Biomass	CHP (biogas)[1]	1,100	2,350	70	7,000	0.89	Biogas Regions (2008); Hahn *et al.* (2010)
Fossil fuel	Steam boiler	20,000	465	12	7,500	N/A	Azar *et al*. (2003); Börjesson and Algrehn (2010); Laurijssen, Faaij and Worrell (2012)
Fossil fuel	Furnace	1,000	75	1	7, 500	N/A	Patil, Singh and Saiyed (2002); Ghosh *et al*. (2003;2006)

Solar thermal	Flat plate[2]	715	850	15	N/A	N/A	Schweiger *et al*. (2000); Kalogirou (2003); Lauterbach *et al*. (n.d.); Riffelmann, Krueger and Ritz-Paal (n.d.); Vannoni (2007); Weiss (2013); IRENA/IEA-ETSAP (2015)
Solar thermal	Evacuated tube[2]	715	1,250	25	N/A	N/A	
Solar thermal	Concentrating solar[2]	1,250	900	20	N/A	N/A	UNDP (2008)
Geothermal	Conventional direct application	3,750	900	19	4,400	N/A	IEA (2007b;2011a); IEA-ETSAP (2010); IPCC (2011)
Geothermal	Average heat plant	3,750	1,900	40	4,400	N/A	
Heat pump	Air source	500	1,300	33	7,000	N/A	Energienet (2012); IRENA/IEA-ETSAP (2013d)

Note: Initial investment costs include total of equipment and installation costs, engineering fees, contingencies, owner costs and interested during construction. All cost data is provided for OECD Americas, and costs in other regions can be estimated by using the regional cost factors.

[1] Capacity refers to total of thermal and electricity; data expressed in USD/kW_{th+e}

[2] Capacity refers to m^2. Costs are expressed in USD/m^2.

Table 17: Regional fixed and variable cost factors and discount rates

	OECD Americas	OECD Europe	OECD Pacific	Other Europe	China	India	ODA	Africa	Middle East	Latin America	
	(-)	(-)	(-)	(-)	(-)	(-)	(-)	(-)	(-)	(-)	References
Relative investment cost	100	110	140	125	90	90	125	125	90	100	Gielen (2003)
Relative variable costs	100	95	95	85	80	80	80	90	85	85	
	(%)	(%)	(%)	(%)	(%)	(%)	(%)	(%)	(%)	(%)	
Discount rates	5	5	5	10	10	10	15	15	10	10	IRENA (2014a)

Table 18: Assumed end-user energy prices (excluding tax)

	OECD Americas (USD/GJ)	OECD Europe (USD/GJ)	OECD Pacific (USD/GJ)	Other Europe (USD/GJ)	China (USD/GJ)	India (USD/GJ)	ODA (USD/GJ)	Africa (USD/GJ)	Middle East (USD/GJ)	Latin America (USD/GJ)	References
2009											
Biomass (residues)	5	5	6	4	2	2	2	2	6	2	Eisentraut (2010); de Wit and Faaij (2010); IEA (2012d); IRENA (2014c); Taibi, Gielen and Bazilian (2012)
Biomass (energy crops)	10	12	14	12	14	10	10	10	14	8	
Coal	3	5	4	1	3	2	3	1	3	2	IEA (2011b); EIA (2010a)
Oil	13	13	13	13	13	13	13	13	13	13	IEA (2011b)
Petroleum products[1]	15	15	15	15	15	15	15	15	15	15	See footnote
Natural gas	4	11	10	8	10	5	7	9	1	5	Sharma (2008); PotashCorp (2009); EIA (2010b)
Electricity	27	36	43	19	19	19	19	7	7	25	IEA (2011b); EIA (2010c)
2030 (low energy price scenario)											
Biomass (residues)	5	5	6	4	2	2	2	2	6	2	IEA (2011b)
Biomass (energy crops)	10	13	16	13	16	10	10	10	16	9	IEA (2011b)
Coal	2	4	3	1	2	1	2	1	2	2	IEA (2011b)
Oil	19	19	19	19	19	19	19	19	19	19	IEA (2011b)
Petroleum products[1]	23	23	23	23	23	23	23	23	23	23	IEA (2011b)
Natural gas	6	15	11	10	12	7	9	11	2	7	IEA (2011b)
Electricity	32	44	52	23	23	23	23	8	8	30	IEA (2011b)
2030 (high energy price scenario)											
Biomass (residues)	7	7	9	6	3	3	3	3	9	3	IEA (2011b)
Biomass (energy crops)	14	17	21	17	21	14	14	14	21	12	IEA (2011b)
Coal	3	6	5	1	3	2	3	1	3	3	IEA (2011b)
Oil	19	19	19	19	19	19	19	19	19	19	IEA (2011b)
Petroleum products[1]	23	23	23	23	23	23	23	23	23	23	IEA (2011b)
Natural gas	8	18	13	12	16	8	11	14	2	8	IEA (2011b)
Electricity	40	54	64	29	28	28	28	10	10	37	IEA (2011b)

[1] Price of petroleum products is assumed 20% higher than the price of crude oil. Both the crude oil and petroleum products prices are assumed to be same worldwide.

Appendix B: Realisable technical potential

Iron and steel sector

Global iron and steel sector is estimated to use 21 EJ fossil fuels by 2030. More than 90% of this demand is for high temperature applications (*e.g.,* pig iron production in blast furnaces, sintering).

Primary steel making process consists of 5 major processes, namely coking in coke ovens, iron ore agglomeration by sintering or pelletising, iron ore production in blast furnaces, primary steel production in the basic oxygen furnace (BOF), and final product manufacture by casting, rolling or finishing. This route accounts for about 70% of the total steel production worldwide today and its share is estimated to remain at a similar magnitude by 2030. The remainder is secondary steel production via the electric arc furnace (EAF) route.

Approximately 80% of the iron and steel sector's fossil fuel demand is provided by coal and its products. Coke and powder coal is mainly used in blast furnaces. Blast furnaces use about 350 kg coke per tonne of hot metal (thm) produced. In addition, 125 pulverised coal is injected per thm (IEA, 2007b; Corsten, 2009). This is equivalent to 18 EJ total energy input to blast furnaces worldwide (WSA, 2012). More than half of all iron ore (2,200 Mt/yr by 2030) is converted to sinter (IEA, 2007b) which requires approximately 1.4 EJ of solid fuels (*e.g.,* coke breeze or other coal products) (IPTS/EC, 2013a). Steel rolling requires approximately 4.2 EJ of primary energy (IPTS/EC, 2013a, Corsten, 2009; WSA, 2012) and fuels used in EAF route require another 0.5 EJ of primary energy, mainly for scrap melting (IPTS/EC, 2013a; WSA, 2012). Iron casting requires also similar quantities of 0.5 EJ of primary energy (Saygin, Patel and Gielen, 2010).

Given the high temperature levels of the production processes, the only renewable energy technology alternative is biomass based options, primarily in iron making. Coke input and coal injection to blast furnaces can technically be replaced with charcoal, but charcoal lacks the physical stability to substitute coke. Therefore currently charcoal operated blast furnaces are typically smaller than coke operated blast furnaces (located in Brazil; Babich, Senk and Fernandez (2010)). Charcoal can also substitute injection coal (Gielen and Moriguchi, 2002). Current injection rates in Brazil are 100-150 kg per tonne of hot metal (thm) (Babich, Senk and Fernandez, 2010). This is possible in large blast furnaces. According to recent lab research results industrial grade bio-coke can be produced with better mechanical stability (NRCAN, 2011; Ng *et al*., 2012). According to Sampaio (2005) and Norgate *et al*. (2011;2012), charcoal substitution potential can range from as low as 20% (for cokemaking blend component in blast furnaces) to as high as 100% (coal injection). Complete substitution of fossil fuel use requires 725 kg/thm. This is by a factor 6 higher than the current rates (Ferreira, 2000). Technical potential of charcoal is estimated as **7.1 EJ** to substitute 20% of coke and 100% of coal input to blast furnaces in the AmbD scenario. The potential is lower in the AccD scenario, equivalent to **2.5 EJ** (10% coke and 25% coal input substitution).

The process heat temperature in sintering iron ore is very high (>1300 ^{o}C). The use of charcoal would be the only option to substitute solid fuel use (*i.e.,* coal, coke breeze) in sinter ovens. According to Norgate *et al*. (2012), about all solid fuels could technically be replaced by charcoal. This would require about **1.4** EJ charcoal in the AmbD scenario. In the AccD scenario, when only a quarter of the fuels are substituted, thus **0.3 EJ** charcoal would be required.

Steel rolling operates with relatively lower temperature levels between 600 and 800 °C. In India, biomass gasification is demonstrated for steel re-rolling mills. According to the current energy use of steel re-rolling mills (Banerjee *et al.*, 2012) and the steel production growth estimates in India, it is estimated that at least 0.2 EJ of fossil fuel energy will be required in such small mills. This would technically require about **0.2 EJ** of biomass (in both AmbD and AccD scenarios).

In total, a global charcoal demand between **8.5 EJ** (AmbD scenario) and **2.8 EJ** (AccD scenario) is estimated in the iron and steel sector by 2030. An additional technical potential for biomass of **0.2 EJ** is estimated. This is equivalent to a total biomass demand of **8.7 EJ** (AmbD scenario) and **3.0 EJ** (AccD scenario) compared to the sector's 21 EJ fossil fuel demand. While biomass would be primarily used in iron making, the remainder of the sector's energy use (12-18 EJ) would still be provided by fossil fuels, mainly coke for blast furnaces and fuels for EAF route and other thermal processes (see Table 19 and Table 20).

No limitations are considered related to the fact that a large share of the sector's capacity will need to be retrofitted since charcoal use and biomass gasifiers can be integrated to existing plants easily. However, as for today, resource potential could be a limiting factor to reach these potentials also in future. Currently charcoal use across the global iron and steel sector is limited due to its availability (see below). Charcoal production was about 50 Mt/yr only with two-thirds realised in Africa (Steierer, 2011) (or 1.4 EJ per year, assuming 27 GJ/t energy content; Gielen, 2001) and its total trade worldwide was less than 5% of the total production (Steierer, 2011). Its current production level is sufficient to meet only 20% of the technical substitution potential in the global iron and steel sector by 2030.

Table 19: Summary of the realisable technical potential of renewable energy technology for the iron and steel sector in the AmbD scenario (in EJ/yr)

	Low temperature	Medium temperature	High temperature	Total
Biomass	N/A	N/A	8.7	8.7

Table 20: Summary of the realisable technical potential of renewable energy technology for the iron and steel sector in the AccD scenario (in EJ/yr)

	Low temperature	Medium temperature	High temperature	Total
Biomass	N/A	N/A	3.0	3.0

Chemical and petrochemical sector

Process heat

The chemical and petrochemical industry is estimated to use 24 EJ energy for process heat generation in 2030. About half of the sector's total process heat demand will be for high-temperature applications (12 EJ). Approximately 30% (7 EJ) and 20% (6 EJ) of the sector's process heat demand will be for medium- and low-temperature applications, respectively.

In the chemical and petrochemical sector, a large share of process heat is used via steam, and the remainder via direct heat. Total demand is supplied by stand-alone steam boilers, CHP plants (up to 40% of the total demand in some countries; IEA, 2007b) and furnaces. Technically, all low temperature process heat can be provided by renewable energy technologies such as solar thermal, geothermal, heat pumps or biomass. For medium temperature heat applications, biomass and solar thermal are considered only. For high-temperature applications which are related to the production of high value chemicals, ammonia and methanol, no potential for renewable energy technologies is considered unless these chemicals are produced from bio-based feedstocks (see next sub-section).

The average size of individual plants in the sector is large and/or many chemical plants are located in large industrial parks benefiting from material and energy integration. For this reason, solar thermal which require large site area or heat pumps which have limited heat capacity may see only limited potential, although they technically qualify. For the same reason of high process integration, retrofitting old plants with non-fossil fuel based alternatives will be technically challenging; the potential in new capacity, therefore, is primarily considered. For new capacity, technical potential of **1.5 EJ** and **0.8 EJ** is estimated for solar thermal and geothermal for low temperature, respectively (assuming no biomass for low temperature heat) and **3.8 EJ** solar thermal for medium-temperature applications (both AmdD and AccD scenarios) (see Table 21 and Table 22). The biomass potential for medium-temperature and high-temperature heat (excluding the production of the aforementioned basic chemicals) are estimated at **8.6 EJ** and **4.3 EJ** according to the AmbD and AccD scenarios, respectively. Up to another **1.7 EJ** solar thermal potential for low temperature applications could be reached in the existing capacity.

Table 21: Summary of the realisable technical potential of renewable energy technology for the chemical and petrochemical sector in the AmbD Scenario (in EJ/yr)

	Low temperature	Medium temperature	High temperature	Total
Biomass	N/A	4.0	4.6	8.6
Solar thermal	3.2	3.8	N/A	6.9
Geothermal	0.8	N/A	N/A	0.8

Table 22: Summary of the realisable technical potential of renewable energy technology for the chemical and petrochemical sector in the AccD Scenario (in EJ/yr)

	Low temperature	Medium temperature	High temperature	Total
Biomass	N/A	2.0	2.3	4.3
Solar thermal	3.2	3.8	N/A	6.9
Geothermal	0.8	N/A	N/A	0.8

Feedstock

In 2030, materials production is estimated to use 27 EJ fossil fuels. Basic chemicals can be produced from biomass feedstocks which offer the advantage of keeping the downstream production infrastructure of the sector unchanged. Alternatively, end-products of the sector (*i.e.,* polymers) could be directly produced from biomass without the need to produce high value chemicals. The technical substitution potential for the production of chemicals and polymers is estimated to range between 32 EJ and 36 EJ of biomass per year (Saygin *et al*., 2014). The technical potential is assumed to apply to new plants and estimated as **19.2 EJ** and **9.6 EJ** per year according to the AmbD and the AccD scenarios, respectively. Quantities of methanol (~20%) and ammonia (~90%) which are utilised outside the boundaries of the organic chemical sector can be produced from biomass feedstocks via the gasification route. This is equivalent to additional realisable biomass potentials of **5.9 EJ** and **2.9 EJ** per year according to the AmbD and the AccD scenarios, respectively (see Table 23 and Table 24). The quantities of biomass includes the process energy required to produce these chemicals as well, therefore they offer the potential to substitute fossil fuels used for high-temperature process heat applications.

Table 23: Summary of the realisable technical potential of renewable energy technology for feedstock use in the AmdD scenario (and high-temperature heat applications) (in EJ/yr)

	Total
Biomass	25.1

Table 24: Summary of the realisable technical potential of renewable energy technology for feedstock use in the AccD scenario (and high-temperature heat applications) (in EJ/yr)

	Total
Biomass	12.6

Non-ferrous metals sector

Non-ferrous metals are aluminium, copper, zinc, lead and a few others such as cadmium or nickel. In 2030, sector's energy use is estimated to reach 5.8 EJ (including electricity, process heat use in alumina production). A large share of the sector's total final energy use is electricity for primary aluminium smelting (3.6 EJ). Alumina production dominates the sector's fossil fuel based process heat use (0.6 EJ). Copper and zinc production used another 0.8 EJ as fuels (*e.g.,* to re-melt copper) and electricity. More than a third of the sector's heat use is for medium-temperature applications (0.8 EJ).

Renewable heat generation technologies offer potential for digestion of aluminium compounds in the production of alumina since the temperature of the process ranges between 140-280 °C (IPTS/EC, 2014). Solar thermal and biomass heating technologies have estimated potentials of **0.6 EJ** and **0.8 EJ**, respectively according to the AmbD scenario. The potential of biomass according to the AccD scenario is lower, estimated at **0.3 EJ**. In both retrofits and new investments, low temperature process heat can be provided by solar thermal and biomass with less than **0.1 EJ** potential each, according to both the AmbD and AccD scenarios. New primary aluminium smelters can benefit from re-location to sites where hydropower plants exist. Up to **1.0 EJ** potential exists for renewable electricity in the non-ferrous metals sector, according to the AmbD scenario (see Table 25 and Table 26). In the AccD scenario, the potential for renewable electricity is estimated at **0.6 EJ**.

Table 25: Summary of the realisable technical potential of renewable energy technology for the non-ferrous metals sector in the AmdD scenario (in EJ/yr)

	Low temperature	Medium temperature	High temperature	Total
Biomass	<0.1	0.8	N/A	0.8
Solar thermal	<0.1	0.6	N/A	0.6
Electricity	N/A	N/A	1.0	1.0

Table 26: Summary of the realisable technical potential of renewable energy technology for the non-ferrous metals sector in the AccD scenario (in EJ/yr)

	Low temperature	Medium temperature	High temperature	Total
Biomass	<0.0	0.3	N/A	0.3
Solar thermal	<0.0	0.6	N/A	0.6
Electricity	N/A	N/A	0.6	0.6

Non-metallic minerals sector

Production of non-metallic minerals includes cement and ceramic products (*e.g.,* tiles, bricks), glass and lime. Based on data reported for 2010 in IEA energy balances (IEA, 2012a;b), fossil fuel-based heat demand of the non-metallic minerals sector is estimated at 10 EJ for 2030. A large share of the sector's heat demand is via direct heat at high-temperature applications (>90%).

Cement production dominates in terms of energy use and volume (9.9 EJ fossil fuel based heat per year). Brick making is estimated to use another 6 EJ process heat (1000 ^{o}C process heat temperature) in 2030 (IPTS/EC, 2007; Saygin, Patel and Gielen, 2010; Banerjee *et al*., 2012). Lime production (excluding captive production which accounts for about half of the global production) is estimated to use another 0.5 EJ by 2030 (900-1200 ^{o}C process heat temperature) (Saygin *et al*., 2010; Banerjee *et al*., 2012; IPTS/EC, 2012). Melting energy (mostly provided by fuels) for glass production requires about 0.6 EJ (1500 ^{o}C process heat temperature) (Saygin, Patel and Gielen, 2010; IPTS/EC, 2013b). The total energy use of these four products is equivalent to about 17.7 EJ. This is 70% higher than what is estimated based on IEA energy balances. This difference is explained by the fact that a share of the sector's total energy use is most likely allocated to the non-specific industry sector in the IEA energy balances. This difference of about 8 EJ is allocated to the non-metallic minerals sector as additional fuel demand.

Cement kilns are very well suited for the use of renewable energy. Part of the fuel is added in the precalciner (60%) and part is added at the end of the rotary kiln (40%) (ECRA/CSI, 2009). Direct combustion of biomass at the precalciner is easier because the temperatures are lower. Biomass gasification is another alternative where syngas can be combusted at the precalciner, but experience with this technology in the cement industry is limited to few plants in Europe only (Seboka, Getahun and Haile-Meskel, 2009). Today, typically waste wood, waste tyres or even municipal waste are used (about 0.2 EJ according to IEA energy balances; IEA, 2012a;b). In Europe high levels of waste fuel use have been reached and the technology is widely accepted. Realisable technical potential for biomass of **7.1 EJ** is estimated, given fuel switching is possible in most types of existing kilns as well (accounting for the differences in efficiency between fossil fuels and biomass). Similarly, realisable technical potential of **4 EJ** exists in the existing and new brick and lime kilns when assuming a 50% technical potential for fuel switching since the quality of the end products depend on fuel type (IPTS/EC, 2007; 2012). Compared to total estimated biomass potential of **11.1 EJ** according to the AmbD scenario for high-temperature applications, **7.2 EJ** potential is estimated according to the AccD scenario. For the small quantities of low- and medium-temperature heat demand, it is assumed that solar thermal and geothermal sources can provide alternatives, with realisable potentials of **0.4** and **0.1 EJ,** respectively (according to both AmbD and AccD scenarios) (see Table 27 and Table 28).

Table 27: Summary of the realisable technical potential of renewable energy technology for the non-metallic minerals sector in the AmbD scenario (in EJ/yr). Data *corrected* for allocation in IEA energy balances for the non-metallic minerals sector

	Low temperature	Medium temperature	High temperature	Total
Biomass	N/A	N/A	11.11	11.4
Solar thermal	0.2	0.2	N/A	0.4
Geothermal	<0.1	N/A	N/A	<0.1

Table 28: Summary of the realisable technical potential of renewable energy technology for the non-metallic minerals sector in the AccD scenario (in EJ/yr). Data *corrected* for allocation in IEA energy balances for the non-metallic minerals sector

	Low temperature	Medium temperature	High temperature	Total
Biomass	N/A	N/A	7.2	7.2
Solar thermal	0.2	0.2	N/A	0.4
Geothermal	<0.1	N/A	N/A	<0.1

Food and tobacco sector

The food and tobacco sector's fossil fuel demand in 2030 is estimated to be 4.2 EJ. In addition, combustible renewable and waste will contribute another 1.3 EJ. With the exception of pulp and paper and wood products sectors (>40%), food and tobacco sector has the highest share of renewable energy use in its fuel mix. No high-temperature heat applications exist in the sector. 60% of the heat demand based on fossil fuels is low temperature applications (2.5 EJ) and therefore renewable energy is well suited for this sector. A few hundred demonstration projects exist in the dairy industry, bakeries, meat processing, distilleries, fish processing and others, notably using solar thermal for heating/cooling and biomass, in particular residues and biogas.

Among the sectors where a breakdown is provided for, dairy, meat, refined sugar and alcoholic beverage sectors are the most energy intensive. Starch, tea and vegetable oil production and the processing of cocoa beans, coffee (including post harvesting) and fish products account for a large share of the sector's energy use as well. It is technically possible to apply biomass (including biogas) and solar thermal based heating systems for these sectors as well as for other processes of the sector. Technical potentials of **4.8 EJ** and **2.9 EJ** are estimated for biomass to cover all low- and medium-temperature heat according to the AmbD and AccD scenarios, respectively.

Solar thermal for heating and drying operations is suitable to substitute fossil fuel-based processes. However, its potential largely depend on area availability at site and the possibility for process integration, and a realisable potential of **1.4 EJ** is estimated. For low temperature heat applications, there is realisable potential for heat pumps of **0.4 EJ**. Realisable geothermal heat potential of **0.2 EJ** is estimated for low temperature heat. All these potentials refer to both AmbD and AccD scenarios.

In industrialised countries, up to a quarter of the sector's total electricity demand is currently due to process cooling and refrigeration for meat, dairy products as well as vegetables and fruits (MECS, 2010). In the past two decades, the demand for cooling has increased due to stricter hygiene regulations in industrialised countries (Ramirez, 2005). Along with the developments in the developing countries and economies in transition related to the food and hygiene policies in the sector, the share of electricity demand is expected to increase. The total electricity demand for food sector's process cooling and refrigeration of 0.3 EJ is estimated by 2030. New capacity investments can benefit from solar cooling systems instead of electric chillers which creates a realisable technical potential of **0.1 EJ**. This adds up to a total realisable potential of **1.5 EJ** for solar thermal technology in the food sector (see Table 29 and Table 30) according to both AmbD and AccD scenarios.

Table 29: Summary of the realisable technical potential of renewable energy technology for the food and tobacco sector in the AmbD scenario (in EJ/yr)

	Low temperature	Medium temperature	High temperature	Total
Biomass	2.8	1.9	N/A	4.8
Solar thermal	0.9	0.6	N/A	1.4
Solar cooling	0.1	N/A	N/A	0.1
Geothermal	0.2	N/A	N/A	0.2
Heat pump	0.4	N/A	N/A	0.4

Table 30: Summary of the realisable technical potential of renewable energy technology for the food and tobacco sector in the AccD scenario (in EJ/yr)

	Low temperature	Medium temperature	High temperature	Total
Biomass	1.7	1.1	N/A	2.8
Solar thermal	0.9	0.6	N/A	1.4
Solar cooling	0.1	N/A	N/A	0.1
Geothermal	0.2	N/A	N/A	0.2
Heat pump	0.4	N/A	N/A	0.4

Pulp and paper sector

The pulp and paper sector is estimated to use 2.8 EJ fossil fuels for process heat generation in 2030. Being the largest renewable energy user, the sector will use in addition about 1.9 EJ of renewable energy. Printing represents a relatively small share of the sector's total final energy use and all of its processes are electricity-based (5%; IEA, 2007b). Integrated pulp and paper mills are typically more efficiency than stand-alone mills though not entirely self-reliant. They may still require about 10-30% of their total fuel need from external sources. Stand-alone mills could be as much efficient if excess biomass by-products and steam can be sold to third parties. Papermaking is the largest user of heat in such integrated plants (50-60%), followed by bleaching and mechanical pulping (IEA, 2007b). Stand-alone paper and recycling mills use fossil fuels. Fuels are used to a large extent for steam generation and for drying pulp, and to some extent for lime production. In China, India and Africa, the majority of the production capacity consists of small mills (IEA, 2007b; Gielen and Taylor, 2009; IRENA, 2014d). Switching to integrated mills offers a large potential for energy integration by using biomass to meet all energy demand. More than 80% of the sector's process heat is used in low and medium temperature applications which are equivalent to a realisable technical potential of **1.6 EJ** according to the AmbD scenario (see Table 31). However, it is hard to justify the extent whether all mills could be integrated in the next decades given there will always be stand-alone mills processing recovered paper only. Thus, half of the realisable technical potential in the AccD scenario is assumed (**0.8 EJ**) (Table 32).

Table 31: Summary of the realisable technical potential of renewable energy technology for the pulp and paper sector in the AmbD scenario (in EJ/yr)

	Low temperature	Medium temperature	High temperature	Total
Biomass	1.1	0.5	N/A	1.6

Table 32: Summary of the realisable technical potential of renewable energy technology for the pulp and paper sector in the AccD scenario (in EJ/yr)

	Low temperature	Medium temperature	High temperature	Total
Biomass	0.5	0.3	N/A	0.8

Textile and leather sector

The textile and leather production is estimated to use a total of 1.1 EJ of fossil fuels in 2030 to generate process heat. About 30% of this demand is low temperature and the remainder 70% is medium-temperature heat applications. Data for the US and Japan show that about all fossil fuel demand of the sector is for process heat generation, for direct firing, steam generation and drying (Hasanbeigi and Price, 2012).

All renewable energy technologies have realisable technical potential for low temperature applications: biomass (**0.4 EJ** and **0.2 EJ** according to both AmbD and AccD scenarios, respectively), solar thermal (**0.1 EJ** for both scenarios), geothermal **(<0.1 EJ** for both scenarios) and heat pumps (**0.1 EJ** for both scenarios). Biomass is suitable for medium-temperature applications with realisable technical potentials of **0.9 EJ** and **0.4 EJ** according to the AmbD and AccD scenarios, respectively as well as solar thermal with potential of **0.3 EJ** (see Table 33 and Table 34).

Table 33: Summary of the realisable technical potential of renewable energy technology for the textile and leather sector in the AmbD scenario (in EJ/yr)

	Low temperature	Medium temperature	High temperature	Total
Biomass	0.4	0.9	N/A	1.3
Solar thermal	0.1	0.3	N/A	0.4
Geothermal	<0.1	N/A	N/A	<0.1
Heat pump	0.1	N/A	N/A	0.1

Table 34: Summary of the realisable technical potential of renewable energy technology for the textile and leather sector in the AccD scenario (in EJ/yr)

	Low temperature	Medium temperature	High temperature	Total
Biomass	0.2	0.4	N/A	0.6
Solar thermal	0.1	0.3	N/A	0.4
Geothermal	<0.1	N/A	N/A	<0.1
Heat pump	0.1	N/A	N/A	0.1

Non-specific industry and other sectors

The seven sectors which are described above are estimated to use in total 62 EJ fossil fuels by 2030. The remainder of industrial fossil fuel use is 23 EJ and will be used by various small sectors, namely transport equipment manufacture, machinery, mining and quarrying, construction and non-specific industry sectors. A share of the energy use of the seven sectors which are described earlier is aggregated under non-specific industry in the IEA energy balances. The most important one is the energy use of the products of the non-metallic minerals sector where the energy use of some cement kilns and brick and tiles making are most likely covered here or their energy use are only to some extent reported (at least 8 EJ). A large share of the total heat demand in these sectors is for low temperature (55%) and medium-temperature applications (25%). In addition, 40% of the sector's total energy use in 2030 will be from new investments. Realisable potential for low- and medium-temperature heat applications for biomass, in both existing and new installations, is equivalent to **18.7 EJ** and **9.3 EJ** according to the AmbD and AccD scenarios, respectively. In new installations, low temperature heat can be provided by solar thermal or geothermal with realisable potential of **3.4 EJ** and **0.8 EJ** respectively. Solar thermal also has potential to provide medium-temperature applications with a total demand of **1.8 EJ**. Heat pumps have similar realisable technical potential to supply low temperature process heat (see Table 35 and Table 36). It should, however, be noted that the potential for this sector are highly uncertain as it is unclear which sectors energy uses are reported here.

Table 35: Summary of the realisable technical potential of renewable energy technology for non-specific industry and other sectors in the AmbD scenario (in EJ/yr)

	Low temperature	Medium temperature	High temperature	Total
Biomass	12.1	6.6	N/A	18.7
Solar thermal	3.4	1.8	N/A	5.3
Geothermal	0.9	N/A	N/A	0.9
Heat pump	1.8	N/A	N/A	1.8

Table 36: Summary of the realisable technical potential of renewable energy technology for non-specific industry and other sectors in the AccD scenario (in EJ/yr)

	Low temperature	Medium temperature	High temperature	Total
Biomass	6.1	3.3	N/A	9.3
Solar thermal	3.4	1.8	N/A	5.3
Geothermal	0.9	N/A	N/A	0.9
Heat pump	1.8	N/A	N/A	1.8

Table 37: Summary of the realisable technical potential of renewable energy technologies in the global industry sector with a breakdown by sector, temperature level and new/existing capacity, 2030 in the AmbD scenario (in EJ/yr)

	Process heat temperature			Existing capacity	New capacity	Total	Substitution potential
	Low	Medium	High				
Biomass							
Iron and steel			8.7	6.3	2.4	8.7	43%
Chemical and petrochemical		4.0	4.6	1.7	6.9	8.6	42%
Feedstock	N/A	N/A	N/A		25.1	25.1	53%
Non-ferrous metals	0.0	0.8		0.6	0.2	0.8	32%
Non-metallic minerals			11.1	4.5	6.7	11.1	52%
Food and tobacco	2.9	1.9		2.9	1.9	4.8	100%
Pulp and paper	1.1	0.5			1.6	1.6	40%
Textile and leather	0.4	0.9		0.8	0.5	1.3	102%
Other	12.1	6.6		11.1	7.6	18.7	84%
Total industry	**16.5**	**14.6**	**24.4**	**27.8**	**52.9**	**80.6**	57%
Solar thermal							
Iron and steel						0.0	0%
Chemical and petrochemical	3.2	3.8		1.7	5.2	6.9	46%
Non-ferrous metals	0.02	0.6		0.4	0.2	0.6	31%
Non-metallic minerals	0.2	0.2			0.4	0.4	2%
Food and tobacco	0.9	0.6			1.4	1.4	40%
Pulp and paper						0.0	0%
Textile and leather	0.1	0.3		0.2	0.1	0.4	40%
Other	3.4	1.8			5.3	5.3	31%
Total industry	**7.8**	**7.2**	**0.0**	**2.3**	**12.6**	**14.9**	20%
Geothermal							
Iron and steel						0.00	0%
Chemical and petrochemical	0.8			0.4	0.4	0.79	5%
Non-ferrous metals						0.00	0%
Non-metallic minerals	0.0				0.0	0.04	0%
Food and tobacco	0.2				0.2	0.22	6%
Pulp and paper						0.00	0%
Textile and leather	0.0				0.0	0.03	3%
Other	0.9				0.9	0.86	5%
Total industry	**1.9**	**0.0**	**0.0**	**0.4**	**1.5**	**1.9**	3%
Heat pumps							
Iron and steel						0.0	0%
Chemical and petrochemical						0.0	0%
Non-ferrous metals						0.0	0%
Non-metallic minerals						0.0	0%
Food and tobacco	0.4			0.3	0.2	0.4	12%

Pulp and paper						0.0	0%
Textile and leather	0.1			0.0	0.0	0.1	6%
Other	1.8			1.1	0.7	1.8	11%
Total industry	**2.3**	**0.0**	**0.0**	**1.4**	**0.9**	**2.3**	3%
Electricity							
Non-ferrous metals	N/A	N/A	N/A		1.0	1.0	28%
Food and tobacco	N/A	N/A	N/A		0.1	0.1	9%
Total of non-ferrous metals and food and tobacco sectors	N/A	N/A	N/A		**1.1**	**1.1**	23%

Note: Potentials provided in the table refer to individual technologies and competition of technologies for the same heat application for a specific sector is not taken into account. Each technology should therefore be treated separately and the potentials of all technologies should not be added on top of each other to estimate the total renewable energy technology potential for the industry sector.

Values refer to the potentials of technologies, and not to the substituted fossil fuel

Table 38: Summary of the realisable technical potential of renewable energy technologies in the global industry sector with a breakdown by sector, temperature level and new/existing capacity, 2030 in the AccD scenario (in EJ/yr)

	Process heat temperature			Existing capacity	New capacity	Total	Substitution potential
	Low	Medium	High				
Biomass							
Iron and steel			3.0	2.2	0.8	3.0	15%
Chemical and petrochemical		2.0	2.3	0.8	3.5	4.3	21%
Feedstock	N/A	N/A	N/A		12.6	12.6	53%
Non-ferrous metals	0.0	0.3		0.2	0.1	0.3	13%
Non-metallic minerals			7.2	2.8	4.4	7.2	34%
Food and tobacco	1.7	1.1		1.7	1.1	2.9	60%
Pulp and paper	0.5	0.3			0.8	0.8	20%
Textile and leather	0.2	0.4		0.4	0.3	0.6	51%
Other	6.1	3.3		5.6	3.8	9.3	42%
Total industry	**8.5**	**7.4**	**12.5**	**13.7**	**27.3**	**41.0**	29%
Electricity							
Non-ferrous metals	N/A	N/A	N/A		0.6	0.6	18%
Total of non-ferrous metals and food and tobacco sectors	N/A	N/A	N/A		**0.8**	**0.8**	16%

Note: Potentials provided in the table refer to individual technologies and competition of technologies for the same heat application for a specific sector is not taken into account. Each technology should therefore be treated separately and the potentials of all technologies should not be added on top of each other to estimate the total renewable energy technology potential for the industry sector.

Values refer to the potential of technologies, and not to the substituted fossil fuel

Small and medium enterprises and small-scale clusters of the industry

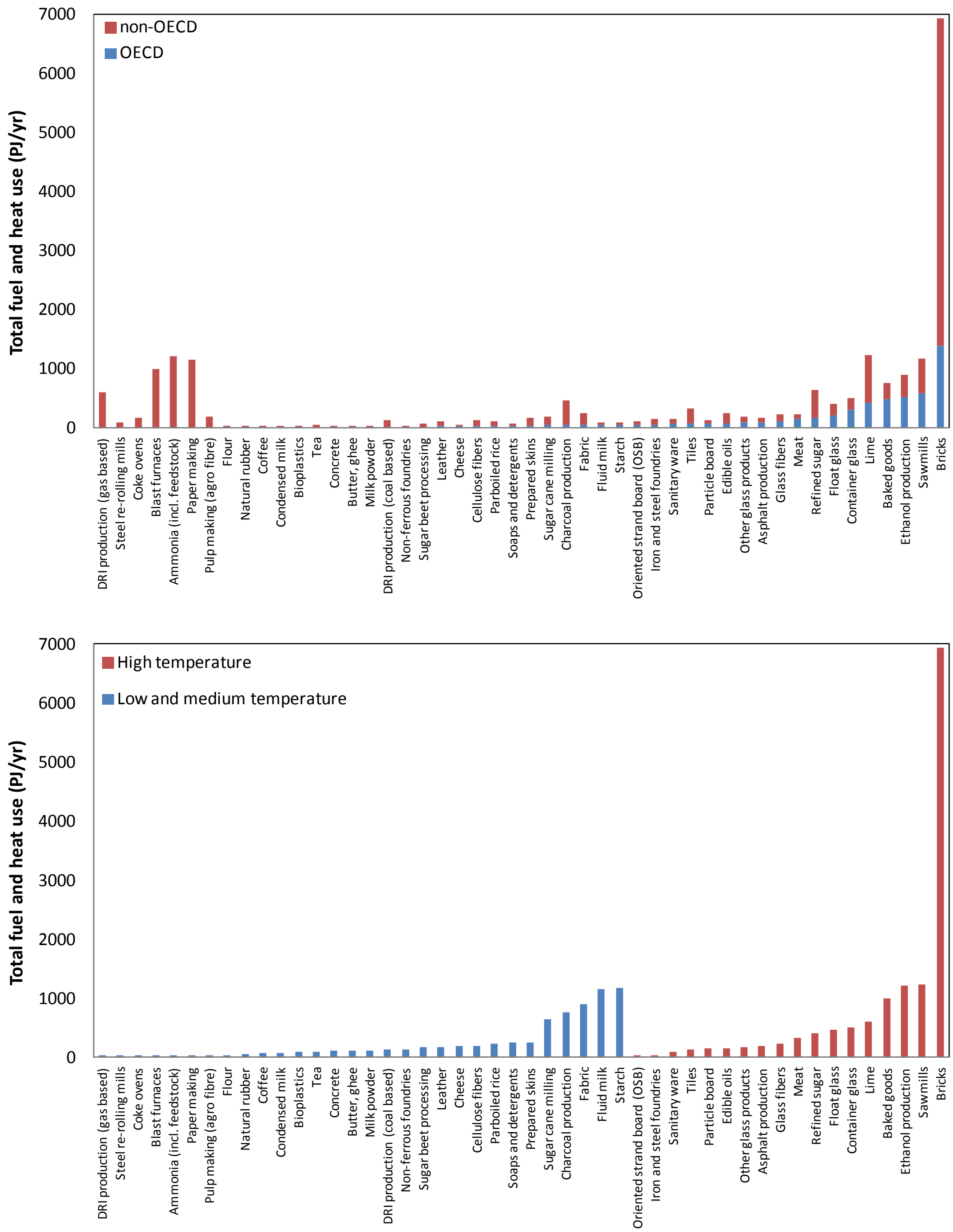
According to Banerjee *et al*. (2012), 19-35 EJ of total industrial energy use was from small and medium enterprises (SMEs) in 2007. This is about 20-35% of the total final industrial energy use worldwide (excluding feedstock use). More than 80% of the SMEs total energy use is fuel and heat use (~21 EJ). SMEs are mostly located in the non-OECD countries which account for about three-quarters of the global SME energy use (see Figure 13). Most SMEs consist of the production processes of the non-metallic minerals (brick, lime), food (dairy, meat) and the textile sectors. Small-scale plants of the energy-intensive sectors (direct reduced iron or ammonia production) in non-OECD countries also account for a large share of the energy use. Most SMEs rely on fossil fuels, but some production processes, such as brick making or various processes of the food sector, already benefit from energy provided by renewable sources. While some of these sectors are already analysed in detail in the previous sections, the energy use of SMEs are mostly covered by the non-specific industry sector according to IEA energy balances.

Among the SMEs and small-scale clusters shown in Figure 13, about one third of the process heat demand is low- and medium-temperature for the production of various food, textile and wood products. As mentioned in previous sections, all four renewable energy technologies have potential to substitute fossil fuel use in these sectors. The remainder two-thirds of process heat demand is high-temperature direct heat applications in small plants of the energy-intensive sectors. Biomass gasification and firing is the alternative to some of these sectors such as brick making, small blast furnaces or the steel re-rolling mills.

Energy intensive industries which account for a large share of the total industrial energy use have a small number of plants operating worldwide of about 200 integrated steel plants, 200 steam crackers, 200 primary aluminium smelters, 400 ammonia plants and 2000 large cement kilns (Saygin, Patel and Gielen, 2010). In comparison, only in EU-27 countries, the number of SMEs is more than 2 million in the industry sector (Ecorys, 2012). The number of SMEs in India for example is by a factor 6-7 higher than in EU-27 and it reaches 13 million (Kumar, 2012). These SMEs contribute to about half of the industry sector's total output (measured in economic terms). In other non-OECD countries, the importance of SMEs is equally high. In India alone, today 1.9 EJ is used in SMEs (or 27% compared to total final industrial energy use). A lot of demonstration examples on biomass gasifiers exist in India industry (modern biomass technologies) (Kumar, 2012), for example in non-metallic minerals sector. Similar examples of concentrated solar plants exists for pharmaceutical, food processing, paints/resins, metal treatment sectors in India (UNDP, 2008).

Given SMEs substantial contribution to industrial output as well as the considerable share of industrial energy use they account for, they deserve special attention to deploy renewable energy technologies. On a plant basis the energy use is small and with small scale investments in renewable energy capacity, most plants can increase the share of renewable energy in their fuel mix rather easily. However, economic, organisational and knowledge barriers limit often the deployment. These barriers needs to be addressed first to exploit the large potential quantified in this study.

Figure 13: Breakdown of SMEs fuel and heat use by regions and temperature level, 2007



Appendix C: Regional potential

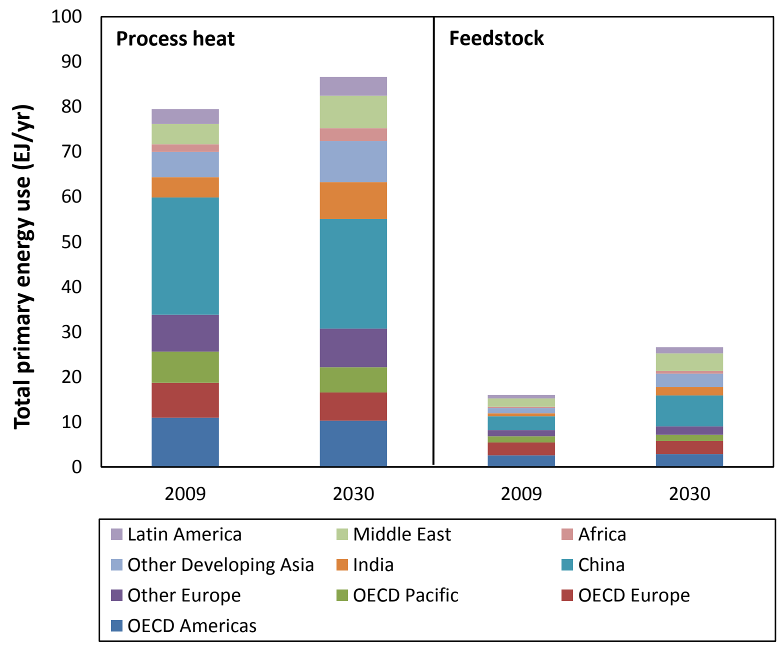
Energy use growth and structure of the industry

Figure 14 presents the developments in industrial fossil fuel use at region level:

- The fossil fuel use share of OECD countries is estimated to decrease from 32% (26 EJ) to 26% (22 EJ) between 2009 and 2030. This is partly explained by the decrease in production growth in these countries as well as the improvements in energy efficiency (new BPT investments replacing ageing capacity in OECD countries). With the exception of iron and steel sector's energy use and feedstock demand for materials production which is projected grow by approximately 10% in OECD Americas, the total energy use of all other sectors in the OECD countries decreases by between 5% and 10%.
- The total fossil fuel use of the non-OECD countries is estimated to increase from 54 EJ to 65 EJ between 2009 and 2030. While in all non-OECD countries energy use of the industry sectors increase by between 20-100%, in Other Europe demand is estimated to remain identical to 2009 or only slightly increase, in China it is estimated that it will decrease by about 5%[8]. Developments in China are explained by the limited production growth projections in iron and steel, non-ferrous metals and cement sectors. In addition, the industry sector has large potential for energy efficiency improvements which reduce the demand further. The share of China in the global fossil fuel demand decreases from 33% to 28% in the same period. Largest growth in industrial fossil fuel use is estimated in India and Africa, from 5 EJ and 2 EJ to 8 EJ and 3 EJ between 2009 and 2030, respectively. As a consequence, these two regions would account for 13% of the total energy use worldwide by 2030. The feedstock use in most non-OECD countries is estimated to increase by 2-3 times between 2009 and 2030.

[8] This is explained by the fact that trade is excluded from the analysis and therefore it is assumed that demand growth according to the IEA (2012e) is identical to the production growth. In reality, despite decreasing demand growth, China can continue to increase its production capacity for exports to other regions.

Figure 14: Total final energy use of the global industry with a breakdown by regions, 2009-2030

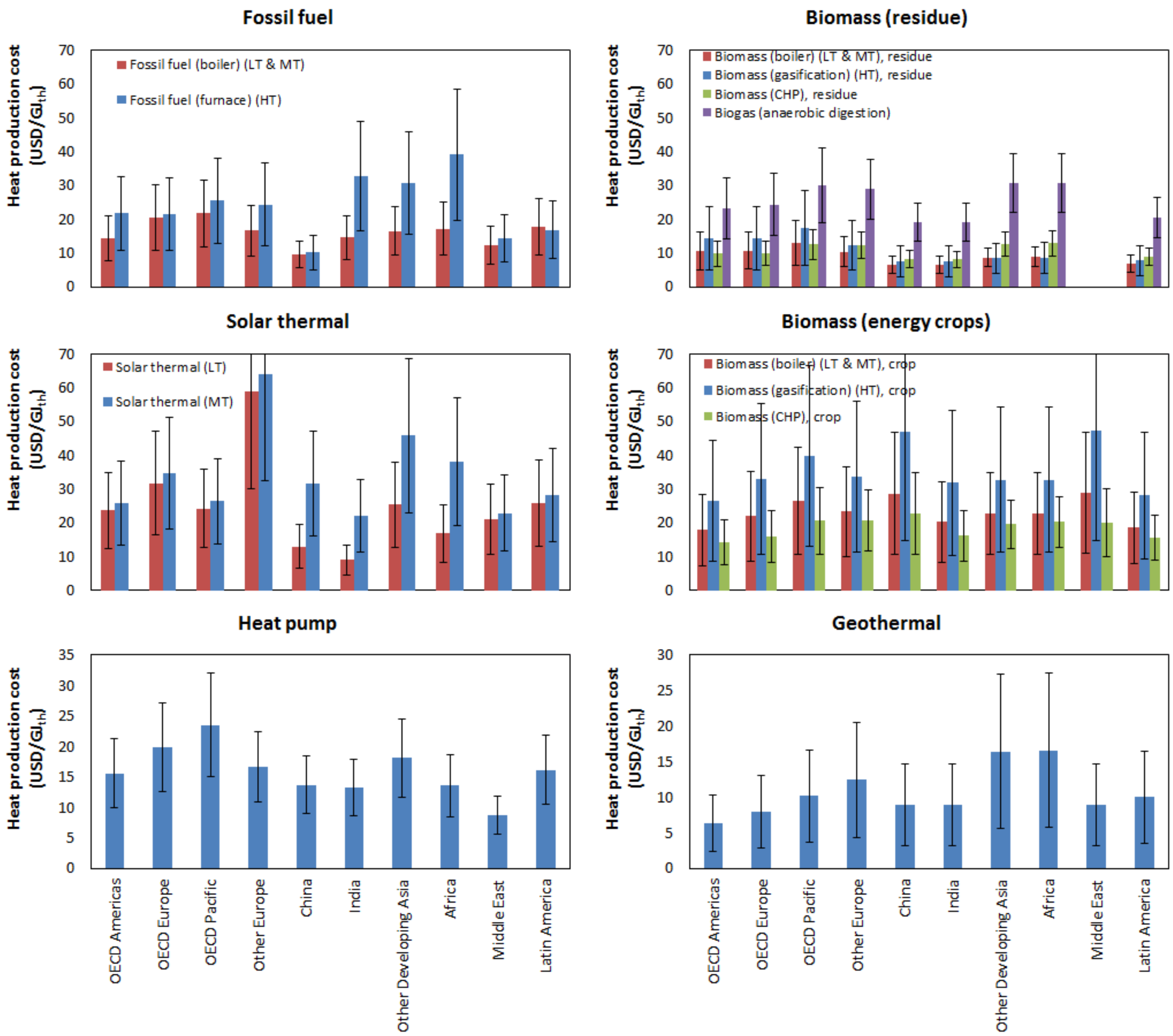


Note: Excluding electricity use and combustible renewables and waste

Costs of renewable energy technologies

In Figure 15, heat production cost estimates of process heat generation from fossil fuels and renewable technologies for the 10 regions in 2030 are provided (excluding the additional costs from CO_2 prices).

Figure 15: Heat generation costs of fossil fuel based and renewable technologies (average of low and high price scenarios), 2030



Note: Bars refer to the average of high and low price scenarios. Costs of fossil fuel technologies exclude the additional costs from CO_2 prices. Error bars refer to the estimated uncertainty margins of the mean values for the global situation.

Potential of renewable energy technologies

Realisable technical potential

The realisable technical potential of each renewable heat generation technology, with a breakdown by sectors and regions, is provided in Figure 16 and Figure 17.

Figure 16: Breakdown of realisable technical potential of renewable energy technologies in the industry sectors of the 10 regions analysed according to the AmbD scenario, 2030

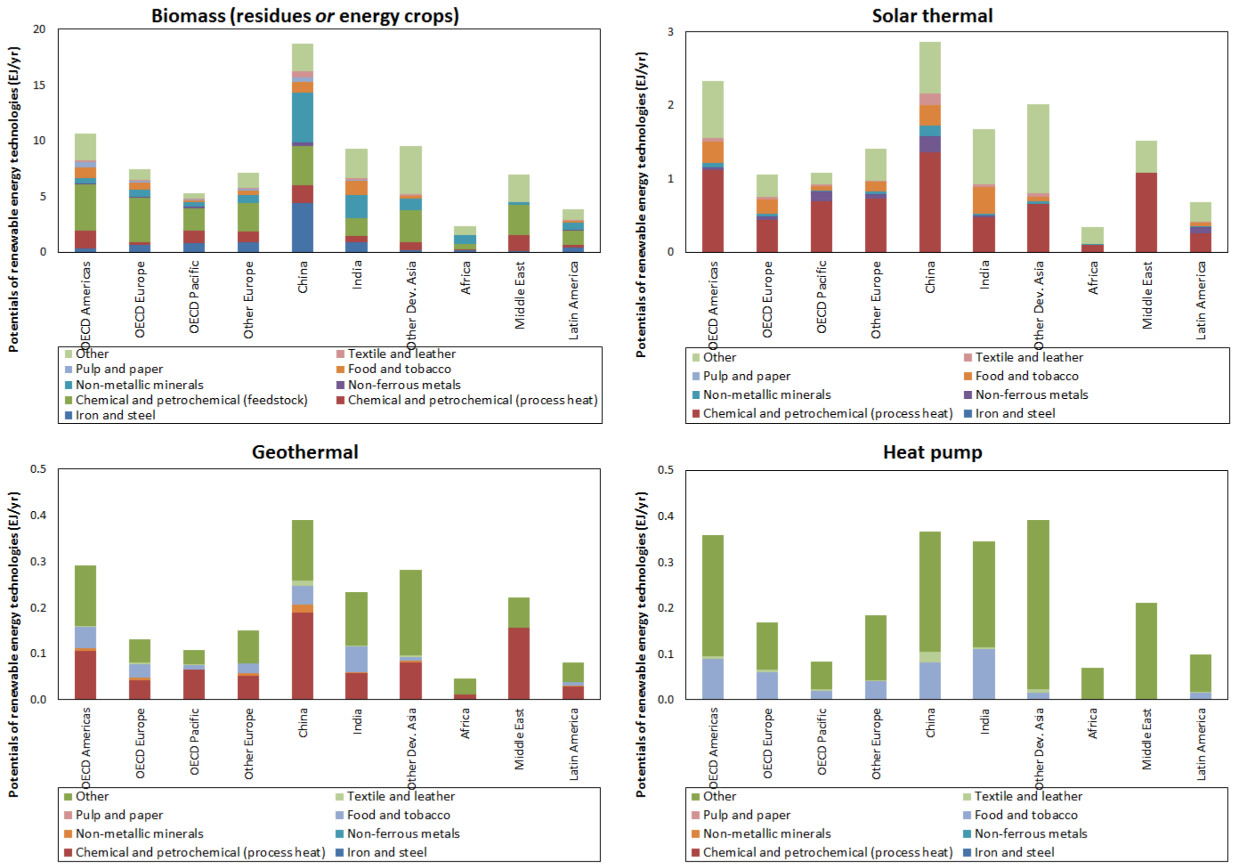
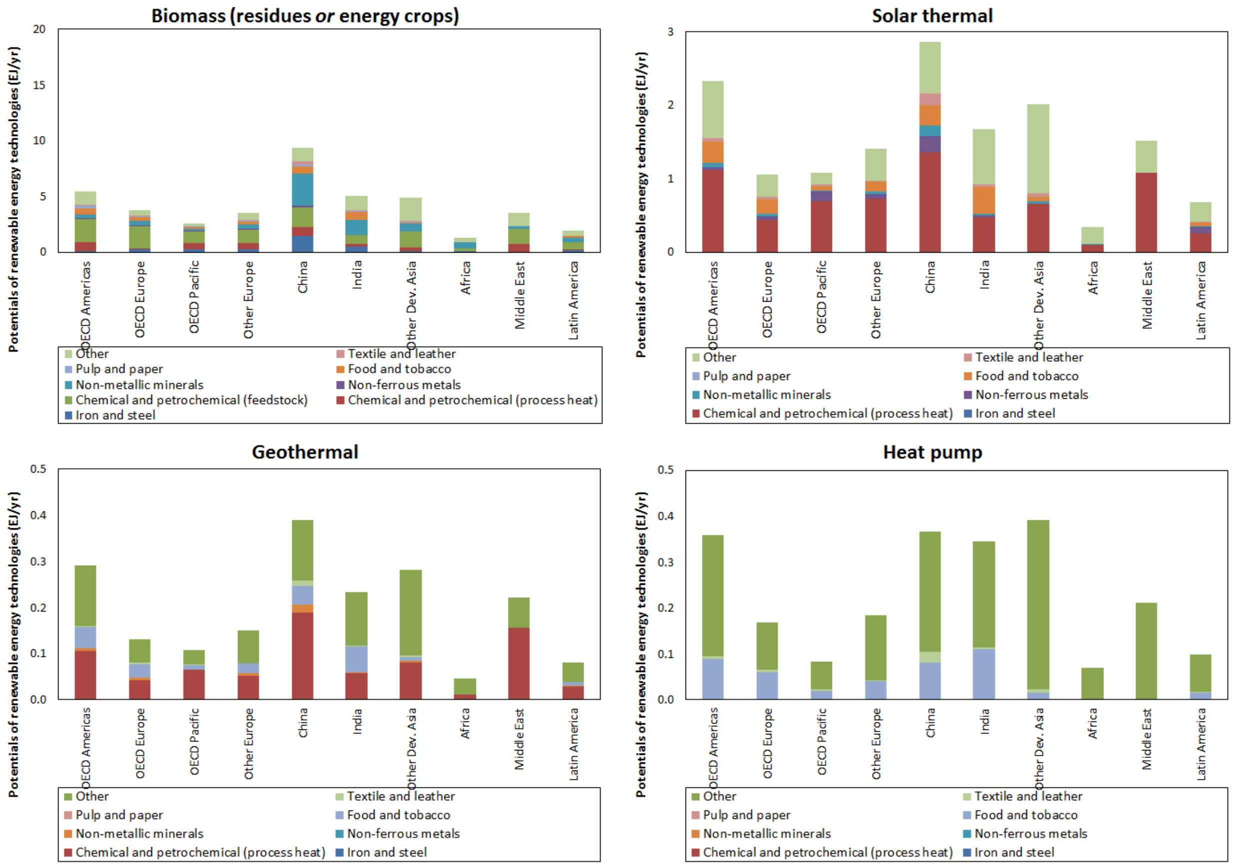


Figure 17: Breakdown of realisable technical potential of renewable energy technologies in the industry sectors of the 10 regions analysed according to the AccD scenario, 2030



Economic and realisable economic potential

The economic potential of the renewable energy technologies across regions depend on the energy prices, depreciation costs (relative investment costs, discount rates), conversion efficiency of technologies and the level of CO_2 prices. The findings for the economic potential at sector and region level are discussed below:

- In the low price scenario, assuming no CO_2 emission pricing policy exists, the economic potential for expensive biomass sources exist in all regions except for China and Middle East (however, there are sectors within regions that do not represent a business case), 13 and 25 EJ according to the AccD and AmbD scenarios, respectively. For cheap sources of biomass, potential exists in all regions (23-40 EJ).
  On average, largest users of biomass residues and energy crops for process heat generation could be located in India, Other Developing Asia, Africa, Latin America and some OECD countries. Due to low fossil fuel prices in the Middle East and parts of Other Europe, the economic potential for biomass is relatively lower.
  We estimate economic potential of biomass use as feedstock in regions where biomass is cost-competitive regardless of the price scenario, namely India, Other Developing Asia, Africa and Latin America, with a total of 3 and 6 EJ in 2030 according to the AccD and AmbD scenarios, respectively.

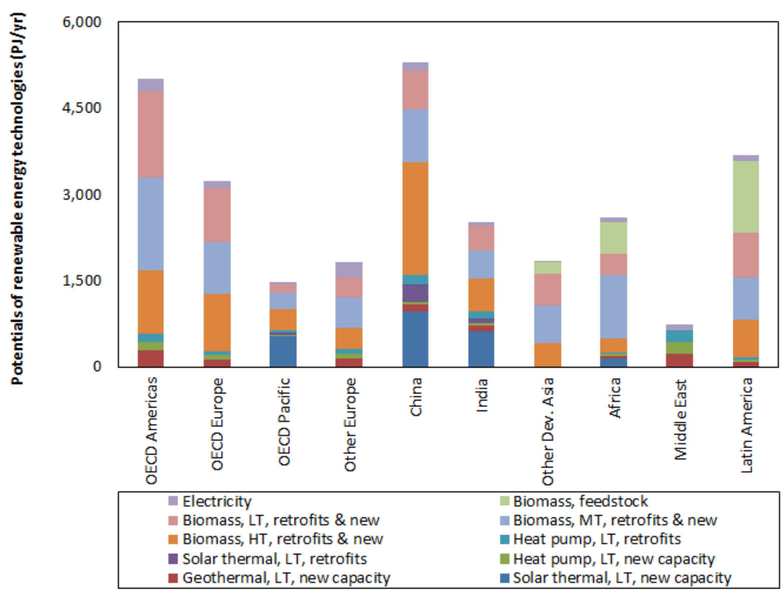
- In the absence of CO_2 pricing, economic potential exists for low temperature process heat from solar thermal technology in India (0.9 EJ) and Africa (0.1 EJ). When regional CO_2 prices are considered, the economic potential could increase to 3.8 EJ worldwide due to the additional potential in OECD countries, China and Latin America.
- For low temperature heat applications, economic potential of geothermal technology and heat pumps are equivalent to their realisable technical potential. According to the high price scenario, heat pumps may see rather limited economic viability in parts of China and OECD Americas.

For all 10 regions analysed, realisable economic potential for the low price scenario is equal to the economic potential for solar thermal, geothermal and heat pump technologies. For biomass, there are large differences across regions given the fact that domestic biomass supply is limited to meet the demand.

Allocation of realisable economic potential

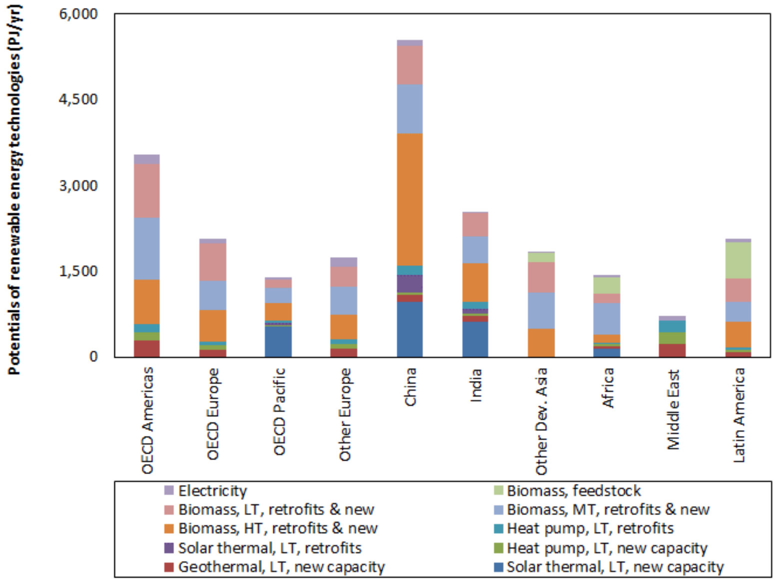
As for the global industry, the realisable economic potential of renewable energy technologies is allocated to their most optimal and effective use across different applications in each of the 10 regions. In Figure 18 (AmbD scenario) and Figure 19 (AccD scenario), the results for the low price scenario are presented.

Figure 18: Realisable economic potential of renewable energy technologies in the total industry sectors of the 10 regions with a breakdown by technology according to the low price scenario (according to the AmbD scenario), 2030



LT: low temperature, MT: medium temperature, HT: high temperature

Figure 19: Realisable economic potential of renewable energy technologies in the total industry sectors of the 10 regions with a breakdown by technology according to the low price scenario (according to the AccD scenario), 2030


Potentials of renewable energy technologies (PJ/yr)
6,000
4,500
3,000
1,500
0
OECD Americas
OECD Europe
OECD Pacific
Other Europe
China
India
Other Dev. Asia
Africa
Middle East
Latin America
Electricity
Biomass, feedstock
Biomass, LT, retrofits & new
Biomass, MT, retrofits & new
Biomass, HT, retrofits & new
Heat pump, LT, retrofits
Solar thermal, LT, retrofits
Heat pump, LT, new capacity
Geothermal, LT, new capacity
Solar thermal, LT, new capacity

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