Renewable Energy in Industrial Applications

An assessment of the 2050 potential

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INDUSTRIAL DEVELOPMENT ORGANIZATION

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EXECUTIVE SUMMARY

Manufacturing industry accounts for about one third of total energy use worldwide. Roughly three quarters of industrial energy use is related to the production of energy-intensive commodities such as ferrous and non-ferrous metals, chemicals and petrochemicals, non-metallic mineral materials, and pulp and paper. In these sectors, energy costs constitute a large proportion of total production costs, so managers pay particular attention to driving them down. As a result, the scope to improve energy efficiency tends to be less in these most energy intensive sectors than in those sectors where energy costs form a smaller proportion of total costs, such as the buildings and transportation sectors. This limits the overall potential for carbon dioxide (CO_2) reductions through energy efficiency measures in industry to 15% - 30% on average.

Industrial production is projected to increase by a factor of four between now and 2050. In the absence of a strong contribution from energy efficiency improvements, renewable energy and CO_2 capture and storage (CCS) will need to make a significant impact if industry is substantially to reduce its consequent greenhouse-gas (GHG) emissions.

Although renewable energy has received a good deal of attention for power generation and for residential applications, its use in industry has attracted much less attention. Renewable energy plays only a relatively small role in industry today. Biomass currently makes by far the most significant renewable energy contribution to industry, providing around 8% of its final energy use in 2007.

The present analysis of the long-term potential for renewable energy in industrial applications suggests that up to 21% of all final energy use and feedstock in manufacturing industry in 2050 can be of renewable origin. This would constitute almost 50 exajoules a year (EJ/yr), out of a total industry sector final energy use of around 230 EJ/yr in the GEA Scenario M that is used as the baseline projection in this study. This includes 37 EJ/yr from biomass feedstock and process energy and over 10 EJ/yr of process heat from solar thermal installations and heat pumps.

The use of biomass, primarily for process heat, has the potential to increase in the pulp and paper and the wood sectors to 6.4 EJ/yr and 2.4 EJ/year respectively in 2050. This represents an almost threefold increase in the pulp and paper sector and a more than fivefold increase in the wood sector, reaching a global average share of 54% and 67% respectively of the total final energy use in each sector. Other sectors, including some of the most energy intensive such as chemicals and petrochemicals and cement, also have potential to increase their use of biomass, but they will only achieve that potential if there is a concerted effort for them to do so. For chemicals and petrochemicals, wider biomass deployment will depend mainly on investment in bio-refineries that can make profits and spread risk through the production of a range of products. In the cement sector what is most needed is a proper policy framework for the management of wastes and incentives to increase their use in cement production.

Interesting potential lies in the development of bio-based vehicle tyres and their subsequent use in cement kilns at the end of their useful life.

This analysis suggests that, by 2050, biomass could constitute 22% (9 EJ/year) of final energy use in the chemical and petrochemical sectors and that alternative fuels could constitute up to 30% (5 EJ/year) of final energy use in the cement sector.

Across all industrial sectors, biomass has the potential to contribute 37 EJ/yr. But the achievement of this potential will depend on a well-functioning market and on the development of new standards and pre-processing technologies. About one-third of the potential (12 EJ/yr) could be achieved through interregionally traded sustainable biomass feedstocks.

Solar thermal energy has the potential to contribute 5.6 EJ/yr to industry by 2050. Almost half of this is projected to be used in the food sector, with a roughly equal regional distribution between OECD countries, China and the rest of the world, mainly in Latin America (15%) and Other Asia (13%). Costs depend heavily on radiation intensity. They are expected to drop by more than 60%, mainly as a result of learning effects, from a range of USD 17 - USD 34 per gigajoule (GJ) in 2007 to USD 6 - USD 12/GJ in 2050.

Heat pumps also have a part to play in low temperature process applications and are estimated to contribute 4.9 EJ/year in 2050. Most (43%) of this will be concentrated in the food sector, mainly in OECD countries (60%), China (16%) and the Former Soviet Union (15%). Costs for useful energy supply are projected to drop by between 30% and 50%, due mainly to reduced capital costs, increased performance and more consistent, market driven, international electricity prices, from a range of USD 9 - USD 35/GJ in 2007 to USD 6 - USD 18/GJ in 2050.

The competitiveness of biofuels with fossil fuels is strongly dependent on national energy policy frameworks and energy prices. In the last decade, the ratio between the highest and lowest end-use prices for natural gas for industry in different countries has at times been as high as 60. At the end of 2009, the ratio stood at 10. For coal, the ratio between different countries has been as high as 30 and, at the end of 2009, stood at 15 (Annex 5).

Renewables are not cost competitive where fossil fuels are subsidised. They are, however, already cost competitive in many cases and many countries with unsubsidised fossil fuels. This is even more so where CO2 emissions carry a financial penalty that reflects their long-term economic and environmental impact. Where national energy policies subsidise fossil fuels, they strongly affect the competitiveness of renewable energy.

Overall, an increase in renewable energy in industry has the potential to contribute about 10% of all expected GHG emissions reductions in 2050. At nearly 2 gigatonnes (Gt) of CO2, this represents 25% of the total expected emission reductions of the industry sector. This is equivalent to the total current CO2 emissions of France, Germany, Italy and Spain, or around one-third of current emissions in the United States.

This potential can only be realised, however, if specific policies are developed to create a business environment conducive to private sector investment, particularly in the transition period. Current best practice shows the conditions under which the successful deployment of renewables can take place and this should guide future policy making. Research, development and deployment (RD&D) and cost reductions through economies of scale are the priorities. In the longer term, a price for GHG emissions of the order of USD 50/t CO2 is needed to support the development of a market for renewable energy technologies and feedstocks in industry.

I. INTRODUCTION

In recent years, renewable energy has increasingly attracted public and policy attention particularly for its potential to contribute to reductions in GHG emissions. Most interest has focused on the use of renewables in power generation and as biofuels. Although some attention has been paid to the potential for renewables, particularly biomass and solar thermal technologies, to contribute to heating and cooling in residential space heating applications, their use in industrial applications has received less interest. This report focuses on the potential of renewable energy sources for process heat in the industrial sector and for biomass feedstock substitution in industrial processes.

Renewable energy can be widely applied in industrial applications. The four options primarily discussed in this report are:

- Biomass for process heat;
- Biomass for petrochemical feedstocks;
- Solar thermal systems for process heat; and
- Heat pumps for process heat.

Several other options may also become relevant in the time horizon of this study. But these are unlikely to make anything more than a niche contribution and they are accordingly not discussed in any detail in this report. They include:

- Conventional geothermal heat. This is highly location dependent. Transporting heat over long distances is costly, leads to large losses and feasible in only a few specific conditions.[1] For industrial process heat, the industrial plant must be located very close to the geothermal reservoir. This is unlikely to be possible in any but a few highly specialised applications;
- Enhanced geothermal systems may make a contribution in the long run, subject to the resolution of technology issues;
- The use of run-of-river hydro for motive power, of the kind that has been used for centuries for grinding mills; and
- The use of wind for motive power, for example by driving air compressors enabling the storage of energy in the form of compressed air.

In combined heat and power (CHP) plants, the waste heat from biomass electricity generation can be used very effectively in industrial applications. Electricity generation is not covered in this paper, so CHP electricity and heat is not included in the analysis.

The full achievement of the potential described in this analysis will depend on the widespread adoption by industry of the Best Available Technologies (BAT). The speed of the adoption of BAT is, however, subject to a number of

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[1] Iceland has a 63 km pipeline transporting hot geothermal water, but such approaches are rarely feasible elsewhere.

significant barriers. These include:

- Lack of information on the potential contribution of renewables and ways of achieving it;
- Cheap fossil fuels;
- The absence of appropriate technology supply chains;
- Lack of technical capacity;
- The high cost of capital in many developing countries;
- A focus on upfront investment cost instead of full lifecycle cost;
- Risks associated with technology transitions and the adoption of early stage technologies;
- Restricted access to financial support to cover the extra costs of BAT; and
- The lock-in of inefficient, polluting technologies with long lifetimes.

International cooperation can help to address these barriers, especially where it is conducted in close collaboration with national governments.

The industrial sectors of many emerging economies are developing rapidly. It is important that they do so in a sustainable way. They need to be encouraged to leapfrog to climate friendly technologies if they are to avoid locking themselves into long-lasting, inefficient and polluting technologies for decades to come.

The barriers to the implementation of BAT affect firms' decision making processes in ways which undermine otherwise rational economic investment in renewable technologies. Even where supply cost curves show excellent opportunities for energy efficiency and renewable energy investments in industry, these investments are often not happening.

The successful deployment of climate friendly technologies depends heavily on firms having the financial capacity to invest in the relevant technologies. But it also depends on their having the knowledge to develop and exploit such technology and on the existence of organisational structures and cultures, including institutional settings and rules, that encourage the use of such technology.[2] Site-specific issues will also influence the most appropriate climate friendly technologies for a particular industrial application. To maximise efficiencies, the demand for process energy inputs must be minimised through the introduction of low-cost, efficient technologies and through systems optimisation before renewable energy options are applied.

This analysis looks at the long-term potential for the use of renewables in industry on a worldwide basis, with some regional disaggregation. It is clear, however, that national conditions vary widely in terms of resource availability, energy prices, industrial structures and financial sector performance. This will materially affect the speed of conversion to BAT in different countries.

Competition with fossil fuels is one of the main factors that determines the rate of transition to renewable energy sources in industry. The International Energy Agency (IEA) estimates that fossil fuels still receive subsidies of around USD 550 billion a year worldwide. Country end-use industrial energy prices can vary by several orders of magnitude (Annex 5).

This paper discusses the long term potential for selected renewable energy sources and technologies in the industrial manufacturing sector. It is part of the UNIDO contribution to the Global Energy Assessment (GEA), a forthcoming comprehensive assessment of energy issues

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[2] Work by IIASA has characterised these components as hardware, software and orgware (Arthur, 1983)

coordinated by the International Institute for Systems Analysis (IIASA). The reference scenario energy demand assumptions come from the GEA overall hypothesis on Infrastructure, Lifestyles and Policy (Table 1) and the IEA's Energy Technology Transitions in Industry (IEA, 2009b). A combination of these scenarios is used as the GEA scenarios do not contain sub-sectoral details for the industry sector.

Table 1

Global Energy Assessment scenario assumptions (IIASA, in preparation)

	GEA-L	GEA-M	GEA-H
Infrastructure	Decentralized-Renewables, Limited Nuclear, emphasis on "Intelligent grids"	Regional hetrogeneity in technological choice	Centralized, supply-orientation, eg CCS, Nuclear, large-scale renewables
Lifestyles	Major transformation in consumer choices, large uptake of demand savings measures, mass transit systems	Supply and demand side measures	Less emphasis on "dematerialization". Continued reliance on individual mobility
Policy	More re-regulation; subsidies, new business models, "feed-in" tariff equivalents in end use	Mix of policy "balanced" measures across the energy system	Centrally regulated markets, "feed-in" tariff for generation

The analysis is based on a combination of country and regional resource data, data and projections for the industrial activity of individual industry sectors, and data on the current and future technical and economic characteristics of renewable energy technologies for industrial applications. The main focus is on potential outcomes in 2050, and on the transition pathways that will best achieve those outcomes.

This study suggests that renewable energy use in industry has the potential to grow from less than 10 EJ a year in 2007 to almost 50 EJ a year in 2050 (Figure 1).[3] This equates to a growth from 8% to 21% of total final energy use.

In absolute terms, 70% of this potential growth comes from the greater use of biomass and wastes, with smaller contributions from solar thermal technologies and heat pumps. Bio-feedstocks constitute 7 EJ/yr out of the total of almost 50 EJ/yr of industrial feedstocks estimated for 2050, while biomass for process heat accounts for over 30 EJ/yr. Solar thermal is estimated to contribute up to 5.6 EJ/yr. Although not part of the scenario considered here, the application of concentrating solar power (CSP) technologies in the chemical sector could potentially increase the contribution of solar thermal to 8 EJ/yr. Heat pumps will compete with solar thermal technologies for low-temperature process heat applications, depending on electricity prices and the availability of solar radiation. The estimated potential for heat pumps in 2050 is 4.9 EJ/yr.

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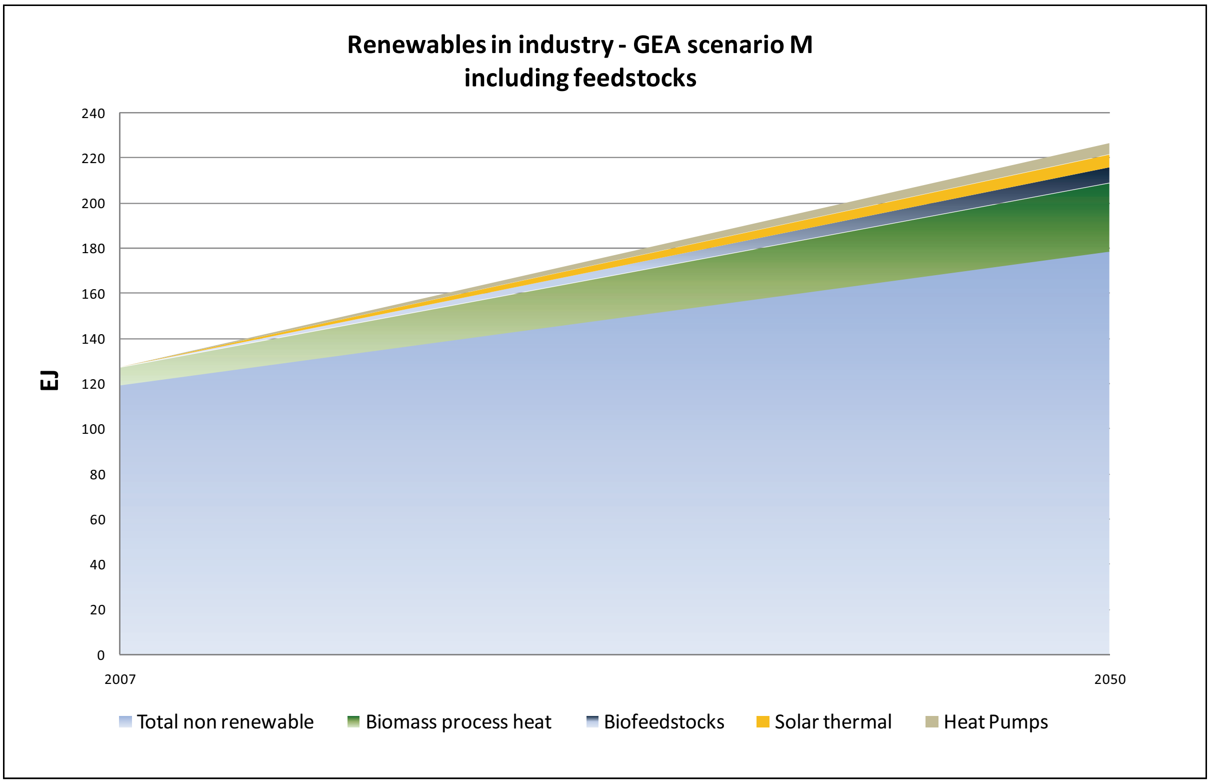
[3] The chart shows the projected average growth in the role of renewables from 2007 to 2050. It does not purport to suggest a transition pathway. Growth is represented in the style of Pacala and Socolow (2004).

Figure 1

Renewables potential in industry by 2050 - final energy and feedstocks. UNIDO analysis.



Currently around one third of the final energy consumption of the pulp and paper sector comes from biomass and waste, with a maximum of 82% achieved in Brazil. Wood and agricultural straw are an important feedstock for pulp making. Around 37% of the final energy used by the wood processing industry also comes from biomass residues, with a maximum of 81% in France. Biomass is also an important resource for synthetic organic products such as fibers, detergents, lubricants and solvents. About 10% of all feedstock for synthetic organic products is of natural organic origin. This includes cellulose from wood and natural oil for alcohols (polyols) and other chemical feedstocks.

Charcoal is still used for iron making on an industrial scale in Brazil. ArcelorMittal Bioenergetica produces charcoal from eucalyptus forestry operations. This charcoal is used to fuel iron furnaces in Juiz de Fora or exchanged for pig iron with local producers.

The cement sector has the capability to use almost any waste products with residual energy content including the combustible fraction of municipal solid wastes, discarded tyres, waste oils, plastic wastes, paper residues and other low grade biomass wastes locally available. Although interest in using such wastes is growing, these resources account for only 5% of the cement industry's fuel needs in developing countries, compared to an average of 16% in OECD countries. For this analysis, only the renewable fraction of waste is taken into account in the calculation of the renewable energy potential.

New applications for industrial biomass use have emerged in the last decade. These include biomass gasification for process heat in countries such as China and India, the use of biogas from the digestion of residues in the agro-food industry, and new forms of bioplastics and biochemicals. Ethanol and methanol, which serve as a basis for a wide range of commodities, can be produced from biomass. Bulk chemicals such as ethylene are now being produced on a commercial scale from such bioethanol feedstocks. The Brazilian petrochemical firm Braskem S.A., for example, plans to have the capacity to produce 200 000 tonnes/yr of polyethylene from sugar-cane derived ethanol by October 2010. The company continues also to develop work on sugar-cane derived polypropylene and synthetic rubber.

Chemical pulp plants have become much more energy efficient to the point that they can now produce surplus electricity, heat or synfuels from production process wood residues, without additional fossil fuel use.

Solar energy is widely used for drying processes, although much of this is not accounted for in energy statistics. Solar process heating has now been applied in a few hundred enterprises in applications such as swimming pools, laundries, dairies and breweries. The temperature levels achieved are gradually increasing, as is the scale of the applications. Some of the technologies used for CSP can also be used to generate steam at a wide range of temperature and pressure levels for industrial process heat.

Solar cooling seems to have only a limited potential in industry, probably concentrated in the food sector. Demonstration plants have been successfully running under several research projects, including the IEA Solar Heating and Cooling (SHC) programme, and the Mediterranean food and agricultural industry applications of solar cooling technologies (MEDISCO).

Other renewable energy technologies for industrial process heat production include heat pumps[4]. Industry needs heat at a temperature generally significantly higher than the ambient temperature.[4] So far, heat pumps have not been able to meet this demand in many applications and they have therefore achieved only limited diffusion. Geothermal heat and the direct use of wind energy, for example for water pumping, can also play a role in niche markets.

Altogether, about 30% of the total final energy use in industry, excluding feedstocks, can be of renewable origin by 2050. This excludes the use of electricity produced from renewable resources for industrial use. In addition, up to 14% of the fossil feedstock expected to be used by industry can be substituted with biomass. Taken together, the potential exists to replace 21% of the final energy and feedstock energy expected to be used by industry in 2050 with renewables.

This analysis also suggests that renewables have the potential to play a key role in the reduction of CO_2 emissions and fossil fuel dependence in the industry sector. These benefits warrant more attention. This report identifies obstacles to the achievement of this potential and discusses the conditions for their mitigation.

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[4] For the scope of this analysis, heat produced by heat pumps is considered renewable as long as the low temperature source is renewable (such as from air, ground, surface and ground water, hot water produced by solar thermal systems or biomass boilers). Another condition is that the energy provided should be higher than the one consumed. Air heat pumps use a single unit of electricity to produce three to five units of usable heat. This means that 75% to 80% of the final energy produced is from a renewable source: ambient energy. The rest can also be renewable (electricity or heat produced from renewables) or not (electricity or heat produced from fossil fuels). Only the renewable portion of the heat produced by heat pumps is counted as being renewable. In the case of power production with efficiency of 40%, the Coefficient of Performance (COP) of a heat pump should be higher than 2.5 in order to save primary energy and be considered as providing renewable heat.

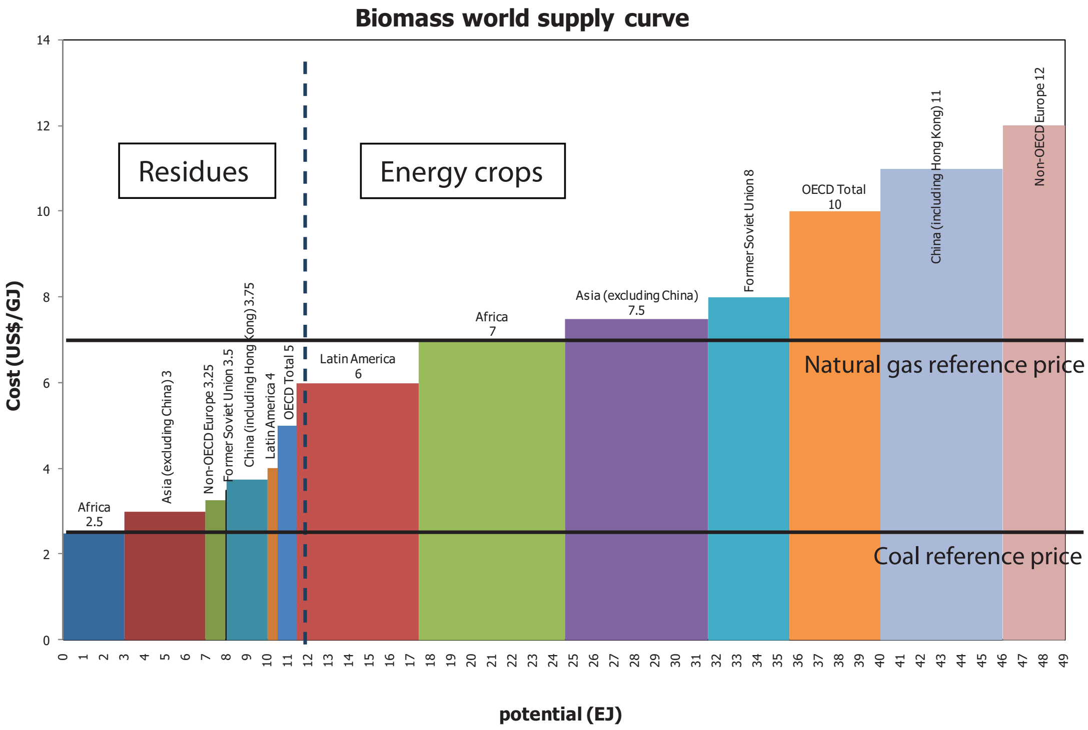
II. BIOMASS

A. BIOMASS SUPPLY POTENTIAL

The starting point for the estimation of the potential for biomass use in industry is the resource potential of biomass inputs (Figure 2). The construction of this figure is described in Box 1.

Figure 2

World biomass supply cost curve for industrial process heat production (ref. to final energy). UNIDO analysis.



Box 1: The biomass supply cost curve

The figures presented are based on the estimated potential biomass resource that can be dedicated to industry. This is derived from an estimate of 150 EJ/year of sustainable biomass supply in 2050 and the assumption that no more than one-third of this can be dedicated to industrial applications. The rest will be shared between transportation, power generation and residential sector. The upper bound of 50 EJ of biomass for industrial applications is based on a comprehensive literature review. If this biomass were grown on agricultural land it would require about 300-600 million hectares. Also significant amounts of agricultural and forestry and wood processing residues are available, in the order of 100 EJ per year.

The Y-axis shows the estimated long term supply cost for biomass from residues and from energy crops delivered at the point of use, including cost, insurance and freight. Prices may differ from supply costs given the volatility of commodity prices, the non-liquidity of many regional biomass markets and the absence of true global markets for biomass trading. These figures should be considered as a lower bound of cost for the actual price of different biomass commodities. The price will be determined by many factors that are difficult to predict, including:

- different buyers may be competing for the same commodity for different uses. In these circumstances, the price of the commodity is determined by the demand from both markets, as for example seen from the competition from biodiesel producers and food producers on the palm oil exchange in Malaysia and from ethanol producers and food producers for corn on the Chicago Board of Exchange;
- the price of biomass will be strongly linked to the price of the commodity the biomass is substituting for. So the price of other edible vegetable oils will influence the price of palm oil and the price of coal will influence the price of pellets, charcoal and bio-coal. The price of coal is especially relevant for GEA, because with high carbon prices the price of coal may be even higher than the cost of biomass substitutes, driving up the biomass price. With CO2 at USD 200/t, coal will cost USD 20/GJ, compared with USD 1 - USD 2/GJ today.
- the lock-in for some technologies such as power generation is very long. Once a plant has been designed for a specific fuel such as coconut shells, rice husks, or other specific residues, those fuels cannot be easily substituted and substitution will make no economic sense during the lifetime of the plant. This can drive up prices.

The regional break down of the resource potential accounts for the differences in sector structure and its consequences for biomass use. Looking forward to 2050, many technological breakthroughs may happen, both in the industrial sector and in the transportation sector.

This supply curve allows for increases in food production and land use for other purposes. It assumes a significant increase in productivity and a moderate change in lifestyle, notably a moderate growth in meat consumption.

Competition for biomass among different sectors

Iron and steel

Iron production requires the combustion of carbon-containing fuels to produce carbon monoxide which is reacted with ferrous oxide to produce iron and CO2. Historically, iron was produced using charcoal exclusively as fuel. At the beginning of the 18th century, charcoal started to be substituted by coke. Coke is now by far the dominant fuel in iron and steel making, with at least 10 Gt of coke being consumed per tonne of steel produced. Even so, significant amounts of pig iron are still successfully produced using charcoal.

The use of electrochemical processes to produce iron ore, known as electrowinning, is currently in an early R&D phase. Aluminum is produced entirely by electrowinning and the approach is also used in the production of lead, copper, gold, silver, zinc, chromium, cobalt, manganese, and the rare-earth and alkali metals. Electorwinning offers the possibility to produce iron without the use of carbonaceous fuels. If a technological breakthrough were to make the production of iron by electrowinning feasible, and if in future there were large quantities of low cost, low carbon electricity available, this would offer a route to the production of iron and steel with significantly reduced carbon emissions.

Petrochemical feedstocks

Carbon is also needed for the production of materials in the petrochemical sector, where it comprises around 75% of the total feedstock.

The main alternative feedstock to fossil fuels in the petrochemical sector is likely to be biomass. But waste products, such as recycled plastics, can also substitute for some fossil fuel feedstock. Alternatively, organic materials such as cellulose fibers, coconut fibers, starch plastics, fibre boards and paper foams can be produced which can directly substitute for petrochemical products in end use applications, as described in Annex 3. It is also possible to produce textile materials (mainly viscose and acetate) from wood pulp and as by-products from cotton processing.

Transportation

The transport sector is likely to be a significant competitor for any available biomass resource. If by 2050 biofuels are still the main option to displace fossil fuels from the transport sector, the availability of biomass for the industrial sector may be extremely limited. This would increase the attractiveness of other, non-biomass, renewable energy sources and of the further electrification of many industrial sectors. But at the same time, if biofuels increasingly replace petroleum fuels, this may free up large amounts of refinery-produced naphtha at low cost. In these circumstances, shifting away from naphtha as a petrochemical feedstock to alternative feedstocks or processes will be very difficult to achieve.

B. BIOMASS PROCESS HEAT

Regional and sectoral discussion

Biomass is the most widely used renewable energy source both generally and in industry. Biomass availability and use is strongly dependent on regional conditions.

Although biomass provides 8% of industry's final energy, in some regions there is almost no biomass use in any industrial sector. In regions such as Latin America and Africa, by contrast, biomass contributes around 30% of industry's final energy (IEA statistics). Wide differences in use are also observed among different industrial sectors.

Biomass is used to a significant degree for industrial heat in the food and tobacco, paper, pulp and printing and wood and wood products sectors in most regions. By contrast, almost no process heat is produced from biomass in the iron and steel and non-metallic mineral sectors, except in Brazil, or in the chemical and petrochemical, non-ferrous metals, transport equipment, machinery, mining and quarrying, construction or textile and leather sectors.

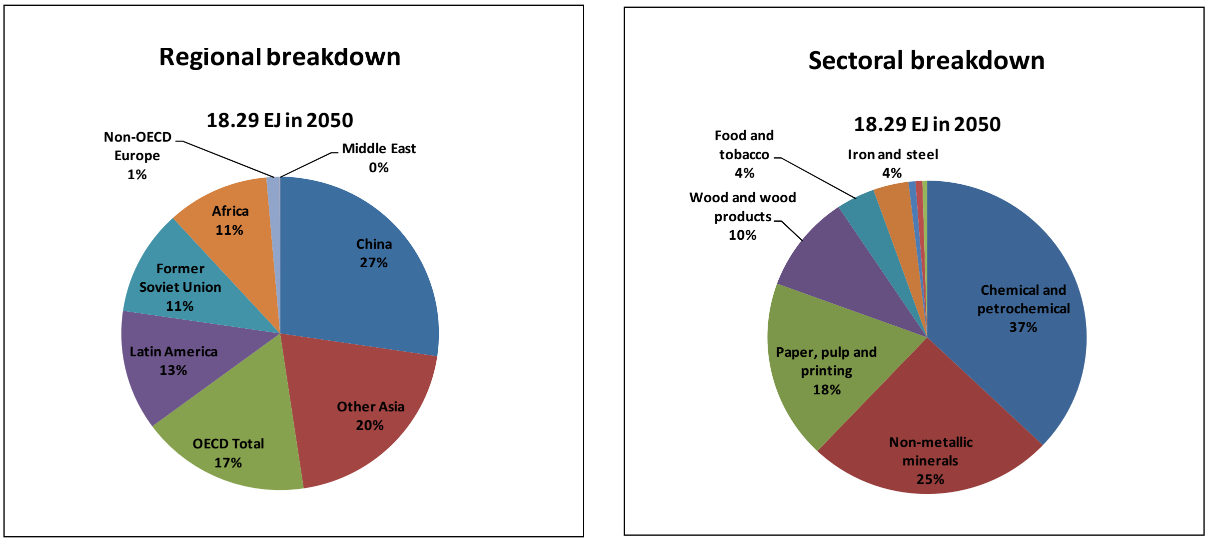
The cement and iron and steel sectors in Brazil use biomass for 34% and 40% respectively of the sectors' final energy consumption. The fact that such a high level of biomass contribution can be sustained in the two most energy intensive sectors in Brazil means that a similar level of contribution should also be technically feasible elsewhere. The limiting factors on the extension of biomass use in these two sectors are clearly therefore non-technical ones. They may include resource availability, economics and competition from other energy sources.

The estimates of the potential role of biomass in 2050 are strongly sensitive to the state of the markets for biomass trading among different regions. If there is no interregional trading of biomass, the potential contribution of biomass in industry is estimated to be 18.3 EJ/year; if there are liquid markets for interregional biomass trading this contribution is estimated to be 30.3 EJ/year (Figures 3 and 4).

Transporting biomass is unlikely to have a significant impact on overall emission reductions. A state of the art coal-fired power plant with 46% efficiency co-firing pellets shipped by a 30 kilotonne (kt) ship over 6 800 km would produce emissions of around 85 grams of CO2/kilowatt hour (kWh). Using bio-coal[5] shipped by a 80 kt ship over 11 000 km, the emissions would be reduced to 32 grams of CO2/kWh. By comparison, the same power plant using coal would emit 796 grams of CO2/kWh.

Figure 3

Regional and sectoral breakdown of biomass potential for process heat in industry in 2050, excluding interregional trade. UNIDO analysis.



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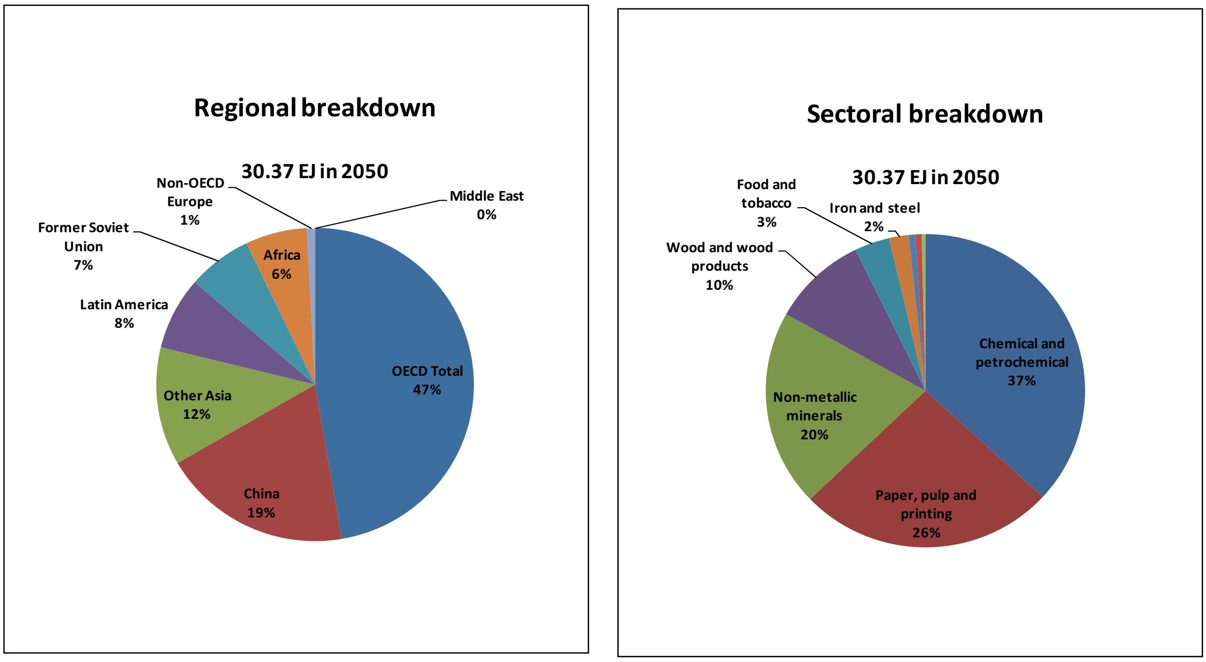
[5] Bio-coal is a solid fuel with physical characteristics (energy density, hydrophobicity, mechanical stability, etc.) comparable to coal. It is generally produced through the torrefaction of biomass feedstocks.

Figure 4

Regional and sectoral breakdown of biomass potential for process heat in industry in 2050, including interregional trade. UNIDO analysis.



In the absence of interregional markets, the estimated marginal cost of biomass would be around USD 7/GJ of primary energy, mostly in the form of locally consumed residues and energy crops in Latin America, with a smaller level of local consumption in Africa. With liquid interregional markets, large volumes of biomass will be moved around the world, mostly into OECD countries (11 EJ) and some into the Chinese market (less than 1 EJ). Despite much higher levels of demand, the marginal cost would be around USD 7.5/GJ, assuming the exploitation of Africa's very large potential for energy crops, and significant use also of Asia's potential.It is clear from this analysis that creating tradable biomass commodities and allowing free trade from developing countries to industrialised ones will have a potentially positive impact on GHG emission reductions in industry. It will also, importantly, provide an opportunity significantly to increase development. Supporting sustainable biomass production, deploying technologies that will enable the conversion of biomass into tradable commodities and allowing those commodities to reach OECD markets will provide Africa with a potential cash flow of up to USD 50 billion a year for the industrial sector alone. It will be important that these markets are developed in a sustainable manner.

In addition, the demand for biomass for industrial applications may present an opportunity for biomass resource-rich countries to secure a larger share of industrial production. This could become a source of economic growth and provide a basis for new industries and jobs in developing countries. In a development context, biomass resources may help developing countries to increase their industrial value added, moving progressively up the value chain from being exporters of their resources to using their resources to manufacture exportable finished products.

Bioenergy Technologies

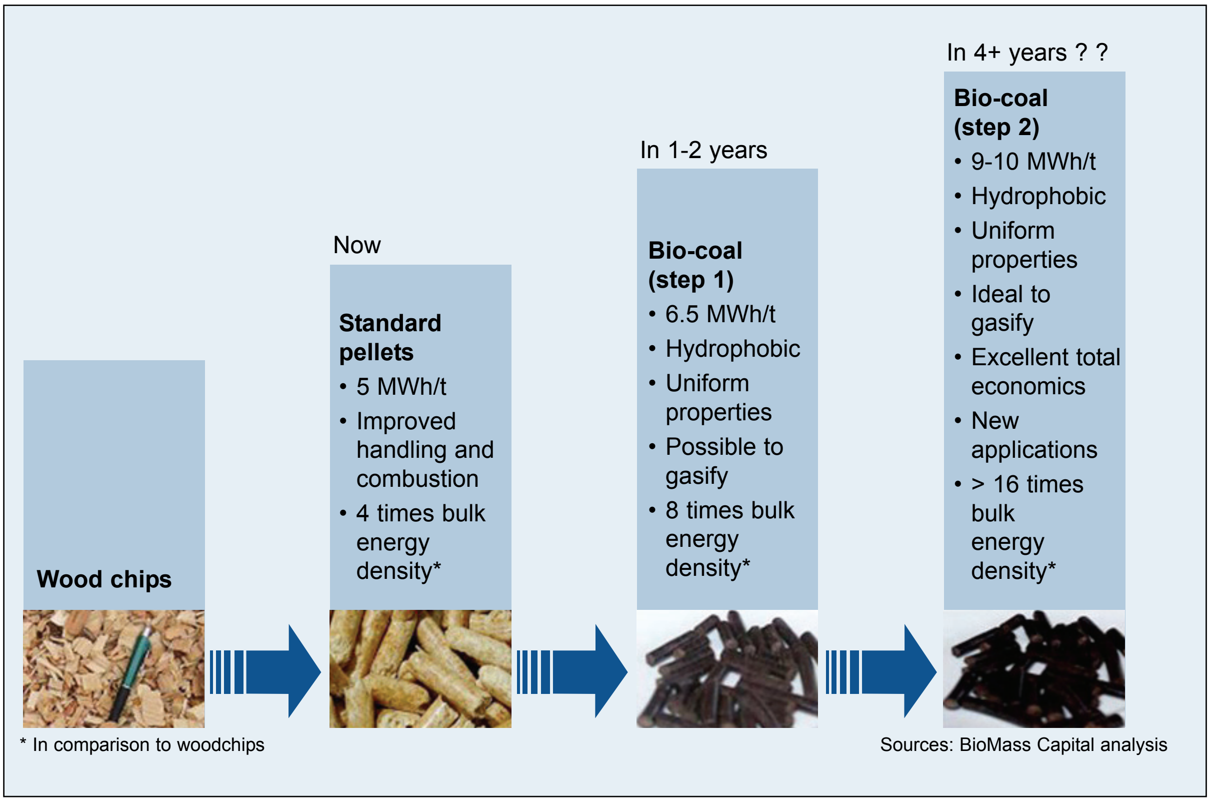
A range of bioenergy technologies for industrial process heat production are already commercialised. Others are at earlier points on the RD&D spectrum. Biomass derived fuels, like fossil fuels, come in solid, liquid and gaseous forms.

Liquid biofuels include ethanol from the fermentation of sugars and biodiesel from the transesterification of vegetable oils. Second generation biofuels are currently the subject of intensive RD&D. About 57 kilotonnes (kt) of production capacity is in operation, and about ten plants each with a capacity of between 50 kt and 300 kt per year are planned to start operation in the coming two years.

Solid bioenergy products are likely to be the most effective substitute for coal. Several options are already on the market. Charcoal, for example, was well established as a coal substitute thousands of years ago. Other products such as pellets, described in more detail in Annex 2, have been developed more recently.

Significant quantities of biomass are already co-fired with coal in conventional coal power plants. For example, the Amer 9 CHP power plant in the Netherlands, which produces 600MW of electricity and 350 MW of heat, currently co-fires 35% of biomass mostly in the form of wood pellets with 65% coal. The technological development of solid biomass fuels is likely to be directed at a scaling up in the energy density of the reprocessed biomass until it can be used without any modification on its own in coal-burning power plants, furnaces and industrial processes (Figure 5).

Figure 5
Biomass solid fuel roadmap



* In comparison to woodchips

Sources: BioMass Capital analysis

The two main current forms of gaseous biofuels are biogas from anaerobic fermentation and producer gas or synthetic gas (syngas) from biomass gasification.

Anaerobic fermentation yields a biogas product which is very similar to natural gas. Once cleaned, it can be fed directly into existing natural gas distribution pipelines or used in stationary power generation in gas engines. Its use for gas turbines is still limited, mostly due to the relatively small scale of existing biodigesters relative to the gas demand and to the need to improve the quality of gas purification.

Biomass gasification, although still only in an early commercial phase, offers good prospects for the use of biomass for process heat and power generation. Gasifiers produce a synthetic gas (syngas) that can be adjusted for direct use in combined cycle gas turbine plant for power generation, or fed into existing distribution networks, or used for the production of liquid fuels through the Fischer-Tropsch process, or even be used for hydrogen production through the use of special catalysts in the gasification bed. Most of these routes are currently in pilot demonstration phase in the CDFB gasifier in Güssing, Austria.

It is not clear yet whether the most effective technology will be a highly flexible gasifier capable of transforming many different qualities of low cost biomass into a standardised, good quality syngas, or whether it will be based on a highly optimised gasifier that is fine tuned to use pre-processed solid or liquid biomass commodities in the form of, for example, pellets or black liquor.

Three current examples of the use of biomass in industry are discussed in more detail below.

Charcoal use in blast furnaces

Charcoal is widely used today as a fuel. World average charcoal production from 2001 to 2005 was around 43 Mt per year (equivalent to approximately 1.3 EJ/yr). It has been expanding by around 2% a year in recent years.

Most of this charcoal is used for cooking in developing countries. Around 37 million cubic metres (m^3) a year (2004 figures, equivalent to approximately 7.7 Mt), however, are used for iron making particularly in small scale blast furnaces in Brazil. Charcoal does not have the mechanical stability of coke, but it has similar chemical properties. A processed type of charcoal with better mechanical stability is under development. This "biocoal" could substitute for coke. Assuming the complete replacement of fossil fuels on a thermally equivalent basis, the production of 1 t of hot metal requires 0.725 t of charcoal produced from 3.6 t of wet wood. Charcoal produced in Minas Gerais costs about USD 200/t (Santos Sampaio, 2005). This is comparable with current coking coal industrial prices in non-subsidised markets. So the economic impact on iron prices would be neutral.

Alternatively, the use of renewables could be increased in iron and steel making by using renewable power for electrowinning. At the current stage of technological development, electrowinning it is not feasible for iron and steel production. Significant further technology development would be needed, together with economies of scale, if this were to become a realistic option. Some industry R&D is in train to develop such technology, but its long-term success is uncertain.

Biomass co-combustion in cement kilns

The use of alternative fuels in the cement industry is a long established practice in many countries. It offers the opportunity to reduce production costs, to dispose of waste, and in some cases to reduce CO2 emissions and fossil fuel use.

Cement kilns are well-suited for waste combustion because of their high process temperature and because the clinker product and limestone feedstock act as gas-cleaning agents. Used tyres, wood, plastics, chemicals, treated municipal solid waste and other types of waste are co-combusted in cement kilns in large quantities. Where fossil fuels are replaced with alternative fuels that would otherwise have been incinerated or land filled, this can contribute to lower overall CO2 emissions. In a survey conducted by the World Business Council on Sustainable Development in 2006, participants reported 10% average use of alternative fuels, of which 30% was biomass (WBCSD, 2006).

European cement manufacturers derived 3% of their energy needs from waste fuels in 1990 and 17% in 2005 (IEA, 2009b). Cement producers in Belgium, France, Germany, the Netherlands and Switzerland have reached substitution rates ranging from 35% to more than 80% of the total energy used (Figure 6). Some individual plants have achieved 100% substitution of fossil fuels with waste materials. Waste combustion in cement kilns also needs an advanced collection infrastructure and logistics (collection, separation, quality monitoring, etc.).

If waste materials are more generally to achieve widespread use in cement kilns at high substitution rates, tailored pre-treatment and surveillance systems will be needed. Municipal solid waste, for example, needs to be screened and processed to obtain consistent calorific values and feed characteristics. In Europe, the burning of alternative fuels in cement kilns is regulated by European Directive 2000/76/EC. In some non-European countries the use of alternative fuels is controversial, because cement kilns may not be subject to sufficiently stringent emission controls and regulations. Clear guidelines and public information campaigns could help reduce misconceptions and facilitate the increased use of waste in cement kilns. A well-designed regulatory framework for waste management is an important factor in facilitating the use of waste.

Figure 6

Share of alternative fuel use in clinker production by country (IEA, 2008a)

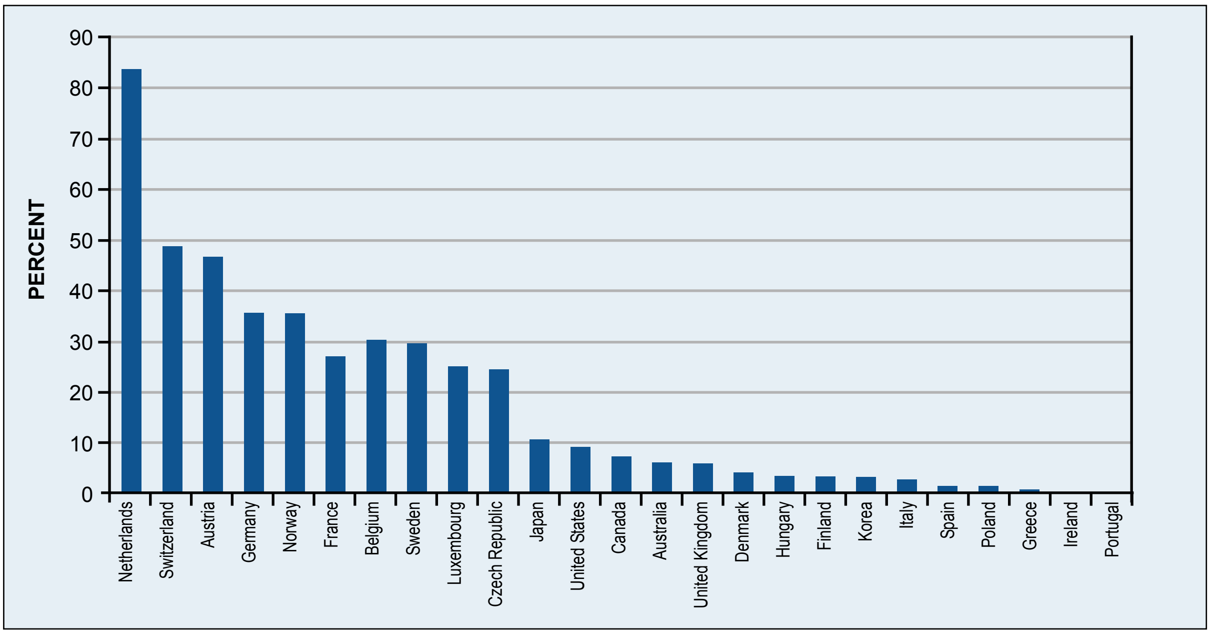
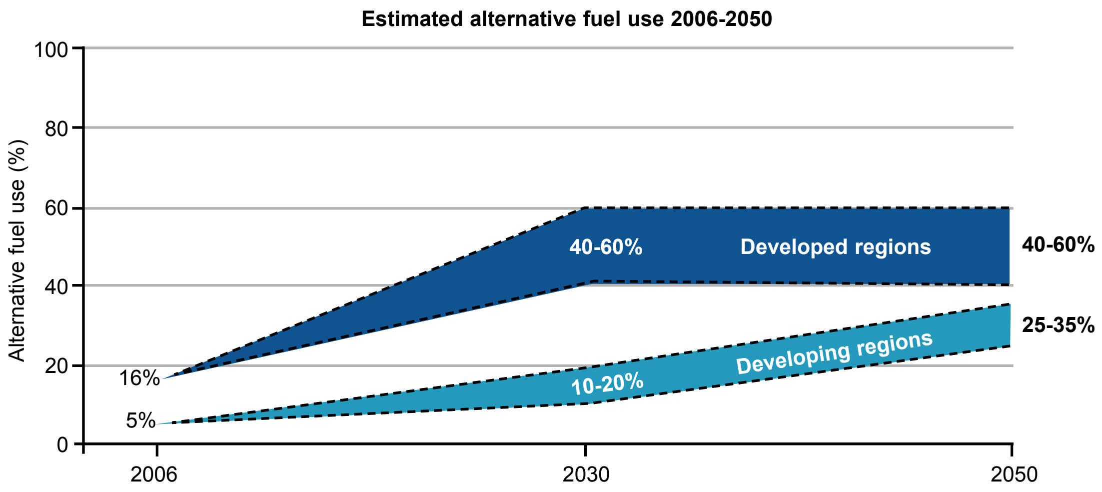


Figure 7
Alternative fuels roadmap for cement production (IEA and WBCSD, 2009)



Source: ECRA Technology Papers (2009), Getting the Numbers Right data 2006 (WBCSD), IEA (2009)
Note: the maximum levels in each region depend on competition from other industries for alternative fuels

Outside the OECD countries, the use of alternative fuels is not widespread. In developing countries, although interest is growing, alternative fuel use constitutes only 5% of cement industry fuel needs, compared to an average of 16% in the OECD. This suggests that there is considerable scope to increase alternative fuel use globally with benefits both for profits and for the environment.

Table 2
Economics of thermal applications of biomass gasifiers in SMEs

	Gasifier unit size (30 kW)	Gasifier unit size (100 kW)
Unit capital costs for gasifiers (USD/kW)	200	146
Total gasifier capital costs (USD)	3750	12,500
For SME units with existing liquid fuel consumption		
Substitution of liquid fuel by biomass (litres/h)	9.4	31.3
Net savings (USD/h)	3	9
Payback (months)	6	6
For SME units with existing solid biomass burning		
Reduction in biomass consumption (kg/h)	30	100
Net savings (USD/h)	0.8	2.7
Payback (years)	2	2

Note: *An average 8 hours of daily operation is assumed for a firm in the SME category. All cost figures in the study are in 2003 USD.*

Source: Gosh *et al.*, 2006

Biomass gasifiers for kilns and furnaces

In India, the use of gasifiers for thermal applications in SMEs offers favourable economic and financial outcomes across a wide range of different unit capacities and for different feedstocks such as rice husk and other agricultural residues. Where gasifiers replace liquid-fuel use, small (~30 kW) or medium (~100 kW) sized gasifiers have payback periods of the order of only 6 months, assuming a biomass supply price of less than 2 USD/GJ (USD 27/t biomass) (Table 2). However biomass gasification is still in a stage of variation and there has been no dominant design yet (Kirkels and Verbong, 2010). In most markets it is unable to compete with other technologies, and technology standardization is needed to ensure proper operation.

C. BIOMASS AS PETROCHEMICAL FEEDSTOCK

Carbon is also needed for the production of materials in the petrochemical sector, where it comprises around 75% of the total feedstock. Olefins (mainly ethylene, propylene and butadiene) are typically produced through the steam cracking of various petrochemical feedstocks such as ethane, liquid petroleum gas, naphtha and gas oil. Naphtha is the main feedstock for the production of aromatics such as benzene, toluene and xylenes through reforming.

The main alternative feedstock to fossil fuels is likely to be biomass. But waste products, such as recycled plastics, can also substitute for some fossil fuel feedstock. Alternatively, organic materials such as cellulose fibers, coconut fibers, starch plastics, fibre boards and paper foams can be produced which can directly substitute for petrochemical products in end use applications, as described in Annex 3. It is also possible to produce textile materials (mainly viscose and acetate) from wood pulp and as by-products from cotton processing.

The production of ethylene from bioethanol is technically relatively straightforward and some companies are already doing it on a large scale. For example, Braskem is currently producing 200 000 t of bio ethylene from sugar cane ethanol, to be polymerised into high density polyethylene (HDPE) and linear low density polyethylene (LLDPE). The current production of other petrochemical products from bio feedstocks is set out in Table 3.

Table 3

Production capacity for bio-based plastics in 2009

	[kt/yr]
Cellulose plastics (of which at least 1/3 fully bio-based)	4 000
Partially bio-based thermosets	1 000
Partially bio-based starch plastics	323
Polylactic acid (PLA)	229
Ethylene from bio-based ethanol	200
Polyhydroxyalkanoates (PHA)	80
PUR from bio-based polyol	13
Partially bio-based PTT	10
Bio-based monomers	10
Bio-based Polyamide (PA)	5
Total	**5 870**

* fully bio-based unless otherwise stated

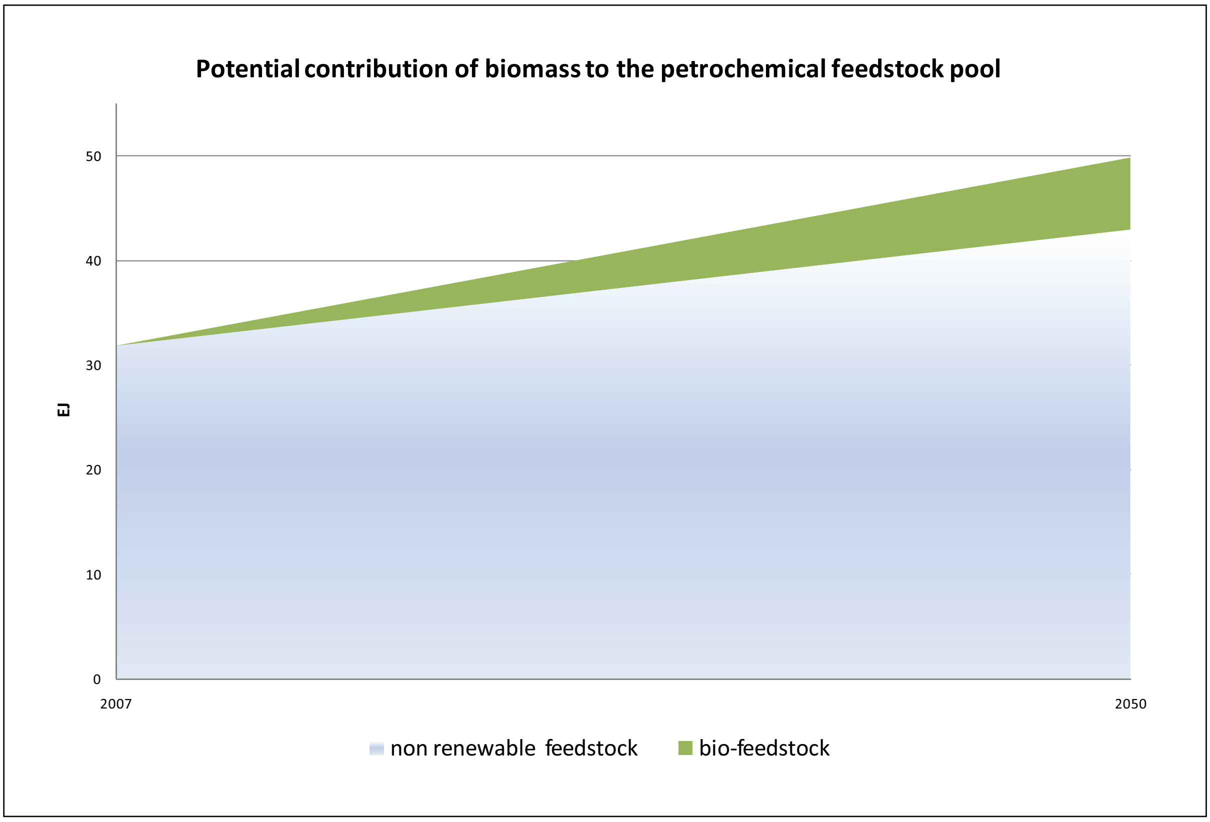
Source: Shen et al, 2009

Bio feedstocks are estimated to have the potential, based on the assumptions in GEA Scenario M, to supply 6.9 EJ/yr of the petrochemical sector's energy needs in 2050 (Figure 8). The achievement of this potential is likely, however, to be dependent on a number of factors, including the cost and availability of petrochemical feedstocks which will themselves be dependent on limitations in the refinery product mix and refinery product demand.[6]

The achievement of this potential will require the use of bio feedstocks in the production of a number of materials and products and through the substitution of bio-based products for conventional ones. For example bio-based polyethylene can be used as a substitute for polypropylene. Aromatics can also be produced from biomass feedstocks, particularly from lignin which is an important constituent of wood that may be produced in substantial amounts as a by-

Figure 8

Potential contribution of biomass to the petrochemical feedstock pool (UNIDO analysis)



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[6] Since 2005, motor gasoline demand has been stagnating worldwide. It is declining in OECD countries. This has led to refinery overcapacity in certain areas. As a result, naphtha has been increasingly available as a low cost petrochemical feedstock. In these circumstances, it will be increasingly difficult for bio-feedstocks to compete on availability and cost with surplus naphta. If the use of naptha for gasoline is constrained, the potential for biomass as petrochemical feedstock is assumed to be as low as 4% by 2050. But if there were to be an increase in demand for naptha, or a widespread conversion of cat-cracking capacity to hydrocracking, then the potential demand for bio feedstocks may be as high as 23% in 2050. In a mid-case scenario, bio feedstocks are estimated to meet 14% of the petrochemical sector's demand, equivalent to around 7 EJ/yr, in 2050.

product if second generation ethanol production takes off. This would offer new opportunities for the development of biorefineries.

The most promising petrochemical bio-feedstocks other than bio-ethylene, are polylactic acid (PLA) as a substitute for polyethylene terephthalate (PET) and polystyrene (PS), poly hydroxy alkaonates (PHA) as a substitute for high density polyethylene (HDPE), and bio poly trimethylene terephtalate (PTT), as a substitute for fossil-based PTT or nylon 6 (Dornburg *et al*, 2008).

Traditional fossil feedstocks can be substituted with bio-derived ones at a number of points in the petrochemical products production chain:

- fossil feedstock can be substituted with a bio-based one (e.g. natural gas can be substituted with synthetic natural gas from biomass gasification and subsequent methanisation);
- petrochemical building blocks can be substituted (e.g. ethylene can be substituted with bio-ethylene);
- traditional plastics can be substituted with a bio-based substitute (e.g. PET can be substituted with PLA); or
- a petrochemically produced material can be substituted with a bio-based material with similar functional characteristics (e.g. plastic can be substituted with wood or nylon with silk).

Several substitution processes are discussed in more detail in Annex 3.

Worldwide plastics consumption amounts to approximately 245 Mt/yr. Olefins (ethylene and propylene) are the most important feedstock. The steam cracking of naphtha, ethane and gas oil is the dominant production technology. Large amounts of aromatics are also produced from refinery streams. World-wide, steam cracking accounts for approximately 3 EJ of final energy use and approximately 200 million tonnes of CO2 emissions. This represents around 20% of the total final energy use and about 17% of the total CO2 emissions from the chemical and petrochemical sector. A number of new technologies are being developed to manufacture olefins from natural gas, coal and biomass. Only those based on biomass offer the potential to eliminate fossil fuel use and GHG emissions.

The first chemicals and man-made plastics, commercialised in the 19th century, were made of bio-based polymers. Most of these materials were gradually displaced by synthetic polymers as the petrochemical industry grew after the 1930s, although some, such as man-made cellulose fibers, maintained a market niche. In the last twenty years, bio-based chemicals and plastics have been receiving increased attention as a means of responding to problems with waste management (limited capacities and littering), high prices for fossil fuels and feedstocks, questions about the medium- to long-term supply security of these feedstocks, technological progress, and policy goals including climate policy.

Bio-based polymers are produced in three main ways:

- by using natural polymers such as starch and cellulose which can be modified;
- producing bio-based monomers by fermentation or conventional chemistry and polymerising them, for example to produce PLA; or
- producing bio-based polymers directly in microorganisms or in genetically modified crops.

The first of these three production methods is currently by far the most important, being involved for example in the use of starch in paper making, in man-made cellulose fibers, and in the development of starch polymers. Much is expected of the future development of the second option, with the first large-scale plants currently coming into operation. No meaningful quantities are yet produced by the third production method, although a good deal of research is being devoted to it.

In addition to ethanol, a number of basic chemicals required for advanced manufacturing can be generated from biological sources (Spath and Dayton, 2003; Werpy et al. 2004). Most chemical co-products can be created from the basic chemical building blocks of sugars and alcohols. For example:

- Polyols, used in a variety of products including antifreeze, plastic bottles, brake fluid, synthetic fibers, resins, auto bodies, and sweeteners, can be derived from xylose and arabinose;
- Using genetically modified (GM) micro-organisms, glucose can be converted into 3G (1,3-propanediol), which can then be used to manufacture the polymer 3GT in existing facilities. 3GT has excellent stretch recovery, resilience and toughness, and it can be dyed easily;
- Using GM bacteria, succinic acid can be produced from sugars. This chemical can be used as a precursor in many industrial processes, and can be used in the manufacture of butanediol, tetrahydrofuran, and other chemicals used in the manufacture of plastics, paints, inks, and food and as a possible replacement for the benzene class of commodity petrochemicals (Crawford 2001).

Ten years ago the primary advantage of bio-based chemicals and polymers lay in their biodegradability. Now non-degradable bio-based polymers are increasingly being commercialised such as bio-based polyethylene, bio-based polypropylene, blends of petrochemical polypropylene with starch, and bio-based epoxy resin. It is estimated that bio-based plastics could replace around 80% of petrochemical-based plastics (Shen *et al.,* forthcoming).

The non-renewable energy used in the production of most bio-based chemicals and polymers is clearly significantly less than that used in the production of their petrochemical equivalents. The savings are even larger if R&D manages to succeed in making woody biomass (lignocellulosics) available as feedstock for biotechnological routes. Even larger savings can be obtained by using tropical crops (e.g. sugar cane) and tropical wood types due to the higher yields and larger amounts of byproduct which can be converted into heat, power or products (Patel *et al.,* 2006). In the long term, the potential exists to save around two-thirds of the non-renewable energy that would be consumed by petrochemical bulk products, and similar advantages can be expected for GHG emissions. Total energy use (including non-renewable and renewable energy) is in some cases higher for bio-based chemicals and polymers than for comparable petrochemical products, given the higher efficiency of the traditional conversion processes.

Box 2: Green tyres

Several leading tyre manufacturers are looking to identify alternative, non-fossil based synthetic rubber for vehicle tyres. Bio-isoprene has been successfully produced by the Danish company Genencor, one of the leaders in the production of enzymes for second generation biofuels. The company is preparing to build a pilot plant in 2011 to brew more bio-isoprene, which it plans to sell to Goodyear and other tyre manufacturers. Goodyear says it expects to have tyres suitable for road testing in mid-2011.

Other major manufacturers are looking to substitute black carbon filler with silica, fossil process oil with vegetable oil, and poly-isoprene with chemically modified natural rubber. Through such substitutions, the Sumitomo Rubber Industries for Dunlop have managed to reduce the fossil content in the Enasave tyre to only 3%. The Yokohama dB Super E-spec tyre uses chemically modified natural rubber and processing oil derived from orange peels shipped from orange juice factories, reducing fossil content of the tyre to 20%. Michelin uses sunflower oil in its Primacy MXM4 all-weather tyre.

All these tyres, by reducing their fossil fuel content, reduce the demand for oil in the petrochemical sector. They also save further CO2 emissions from the large share of the billion tyres discarded every year that end up being burned in cement kilns.

III. SOLAR THERMAL SYSTEMS

A. SOLAR PROCESS HEAT

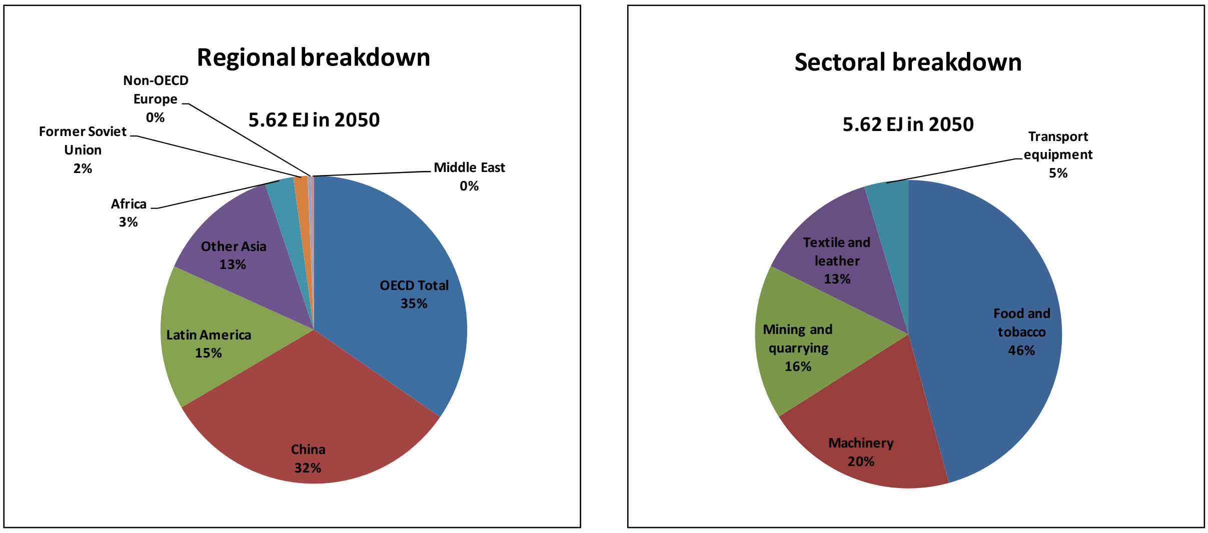
The analysis underpinning this paper has identified the potential for solar thermal sources to produce 63 EJ of process heat for industry in 2050. This potential is shown, by region and by sector, in Figure 9.

From the regional breakdown, it is clear that most regions have the potential for the significant application of solar thermal systems for process heat production. Regional potentials are mainly dependent on the overall consumption of the selected sectors, on their demand for low temperature process heat and, importantly, on the amount of solar irradiation available. OECD countries have a large potential due to their large industrial energy demand. Niches exist in several sectors in which part of the low-temperature energy demand can be economically supplied by solar thermal systems.

In terms of the sectoral breakdown, the food and tobacco sector has almost half of the potential, with the balance well spread among other

Figure 9

Regional and sectoral breakdown of solar thermal potential for process heat in industry in 2050. UNIDO analysis[7]



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[7] Figures are in useful energy terms, after accounting for efficiency losses in solar panels and distribution systems

sectors. This is particularly important for developing and least developed countries, where the development and modernisation of the food industry has a critical role to play in terms of food security. Solar thermal systems can help developing countries to stabilise food prices by reducing their connection to the volatile prices of oil and other energy commodities.

Unlike biomass, where resource availability may limit the potential and raise sustainability concerns, solar has an almost unlimited resource potential. Estimates of the theoretical potential of solar energy are in the range of millions of EJ/yr (e.g. 3.9 million EJ/yr). This is hundreds of thousands of times larger than the current world total primary energy supply of 503 EJ in 2007 (IEA statistics). The quality of the resource, i.e. the insolation rate, however, depends on latitude and climatological conditions.

An analysis of several sources suggests the current generation and investment costs for different configuration and radiation levels shown in Table 4[8].

Table 4

Investment and generation costs for solar thermal for industrial process heat - 2007[9]

			General Cost US$/MWh	Investment Cost thousands US$/MW
Case 1:	2000kWh/m^2/year storage	current break even	57 50	450 350
Case 2:	1200kWh/m^2/year daily storage	current break even	94 50	450 238
Case 3:	1200kWh/m^2 year seasonal storage	current break even	90 60	765 508
Case 4:	2000 kWh/m^2/year including cooling	current break even	137 80	1,450 847

This shows that, where good solar radiation is available, solar thermal technologies for industrial process heat are very close to break even. The Table shows average figures. In many specific cases where the cost of the reference energy unit is higher or where locally manufactured solar thermal systems are cheaper, solar thermal technologies are already cost effective without any need for subsidies. In areas with lower solar radiation, such as in central Europe, solar thermal technologies need substantial cost reductions to become competitive. In some specific markets, taxes on fossil fuels or subsidies for renewable energy make solar thermal competitive already today even in areas of low solar radiation. Although solar cooling is still in an early demonstration stage, in countries with stable solar radiation and unstable, expensive electricity, solar cooling may become a viable alternative to electric chillers in the next ten years.

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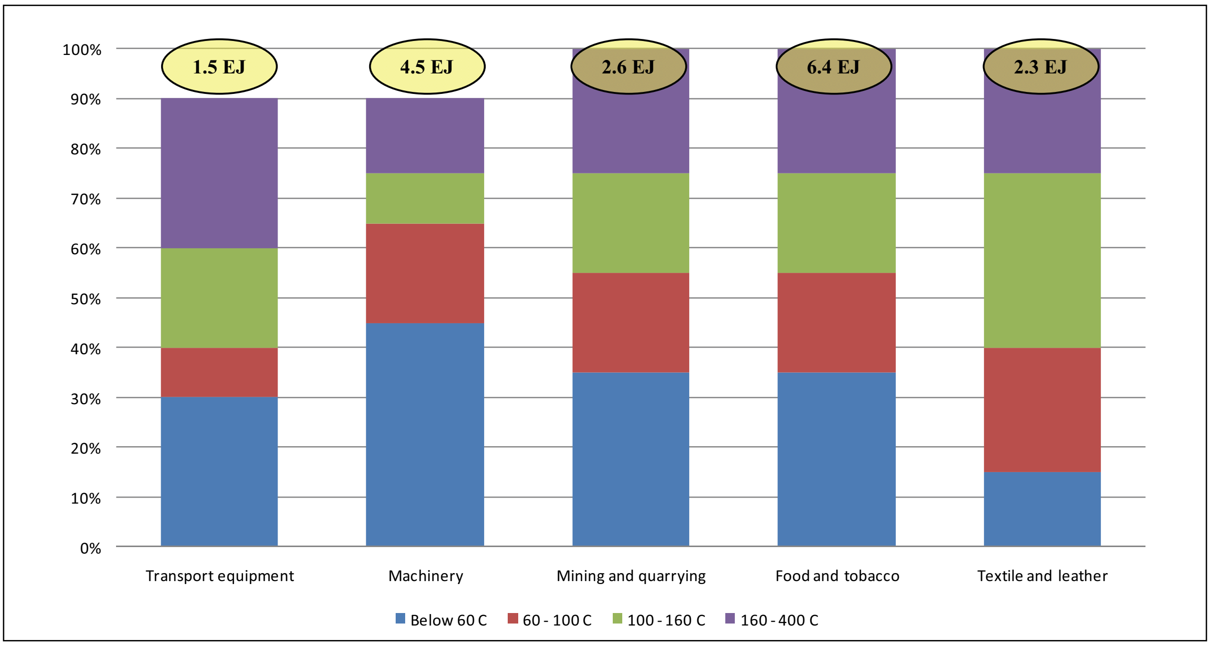
[8] The most comprehensive and recent survey is the IEA's Solar Heating and Cooling brochure (2009) at http://www.iea.org/papers/2009/Solar_heating_cooling.pdf

[9] Assuming, based on IEA data on capacity and production, a world average load factor for 2007 of 605 full load hours/yr, a 7% interest rate, and a capital recovery factor of 9%. O&M costs, in USD/MWh/year, are 2.5% of the ratio between investment costs and full load hours.

In industry, five sectors use a significant proportion of their process heat at temperatures lower than 400°C, and are therefore likely to have a strong potential for solar thermal to meet their process heat needs. These are transport equipment, machinery, mining and quarrying, food and tobacco, and textiles and leather (Figure 10). Many processes and activities that are common to these sectors can benefit from the implementation of solar thermal systems. These include: washing, pre-heating of boilers feed water and space heating in industrial buildings.

Figure 10

Low and medium temperature process heat demand by sector (Taibi 2010)



The chemical sector has also a high potential for solar thermal, but generally on a very large scale. Cost reductions in CSP technologies, combined with the growth in the production of chemicals in Africa and Middle East, suggest growing scope for the development of solar thermal applications in the chemical sector. The main barriers to the greater use of solar thermal in this sector are the scale of the area needed for solar collectors, solar radiation conditions and achieving sufficiently high temperature levels needed for the most likely applications, boiling and distilling. So far there is only very limited experience with solar thermal energy in this sector or at this scale. This makes an accurate estimate of the potential difficult at this stage.

In 2006, 7 of the identified 85 potential applications for solar thermal in industry were in the chemical sector (ESTIF, 2006). In 2007, heat demand in the chemical industry was around 11 EJ/yr. Around half of this (5.7 EJ/yr) is estimated as being below 4000C and 20% (2.3 EJ/yr) below 1000C. If half of this process heat demand were to be met in areas where direct natural insolation is sufficient to justify the use of CSP technologies, the potential for the use of solar thermal technologies in the chemical sector in 2050 would be around 2.4 EJ/yr. This would increase the total estimated potential for solar thermal in industrial applications in 2050 from 5.6 EJ/yr to around 8 EJ/yr.

Figure 11
Parabolic trough field, El NASR Pharmaceutical Chemicals, Egypt (Weiss and Mauthner, 2010)

Different solar technologies have different investment costs per unit of capacity, and different levels of capability in terms of thermal output. Flat plate collectors are the cheapest technology, but they can only be used to heat loads to around 700C. Vacuum tubes or parabolic mirrors in combination with a suitable heat energy carrier can reach 1200C to 4000C. Successful tests have been carried out using solar energy to achieve temperatures sufficient to produce pure metals from ore. But the cost and technical challenges involved in upscaling these tests make the widespread application of solar heat at temperature levels above 4000C unlikely before 2050.

Given the profile of temperature needs in industry (Figure 12), most process heat demand can be met using relatively low cost flat plate and vacuum tube collectors. Only 8% (0.5 EJ/yr) of the estimated 5.6 EJ/yr of solar thermal energy in 2050 will require the use of CSP technologies; the rest can be achieved using flat pane collectors and evacuated tube collectors.

The economic competitiveness of solar thermal energy in industry will be very positively affected by high carbon prices. Among renewable technologies, solar has an advantage over bioenergy as it is not exposed to feedstock price volatility. To increase competitiveness, the capital cost of solar technologies needs to be reduced through learning, starting with the deployment of solar thermal systems in selected sectors in regions where solar radiation is abundant and as constant as possible throughout the year, such as for example in the dairy sector in India (discussed further in Annex 4). The deployment of solar thermal systems where they are already competitive today will facilitate the diffusion of economically attractive, reliable, industrial-scale solar thermal systems to other regions and sectors, as learning effects and economies of scale come into play.

The main competitors for solar thermal systems will be heat pumps. Heat pumps operate in similar low-temperature ranges. Like solar technologies, the lower the temperature increase they have to provide, the more efficient they are. In general, the relative competitiveness of these two technologies in any specific situation will depend on a balance between the main factors underpinning each technology, i.e. on the balance between available solar radiation and local electricity costs. By 2050, the competitiveness of the two technologies is expected to be determined by regional considerations as much as by sectoral ones.

Solar thermal technologies will need to be implemented widely if they are to become competitive with conventional process heat production (Table 5). The cases describe different levels of insolation and different storage approaches. As with other technologies, there are clearly advantages in deploying early systems where they are most effective, i.e. initially on simple systems in areas with abundant solar radiation. Such deployment is already cost effective today. As further such investments are made, the cost of solar thermal systems should reduce, making them progressively more economically viable in other less favourable conditions.

Table 5

Break even analysis and learning investments for solar thermal in industry[10]

	Break even cumulative capacity *GW*	Total cost of reaching Break even *Billion US$*	Learning investment *Billion US$*
Case 1: 2000kWh/m^2/year daily storage	252	34	2
Case 2: 2000kWh/m^2/year daily storage	1,235	320	67
Case 3: 2000kWh/m^2/year seasonal storage	609	264	41
Case 4: 2000kWh/m^2/year including cooling	908	769	144

To achieve the projected 5.6 EJ/yr in 2050, the solar capacity needed by the industrial sector would be over 2 500 gigawatt hours (GWth), assuming current levels of full load at 605 hr/year and that learning effects are achieved only in the industrial sector. Depending on the lifetime of the systems and on the rate of their diffusion, the total cumulative capacity that will need to be installed by 2050 would be in the range of 3 500 GWth. At the current learning rate of 20%, solar thermal would be expected to break even in most potential applications, even in temperate climates using seasonal storage for solar cooling. (Table 6). Given that, in 2008, the total capacity of solar thermal installations was only 171 GWth, this will require a major investment programme.

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[10] Table 5 is based on the same assumptions and calculation methodology as Table 4. The full load hours (in hours/yr) for the four cases are: 750, 450, 800 (with the benefit of seasonal storage) and 1000 (benefiting from a good match between the load curve for cooling and peak production from solar thermal systems).

Table 6

Investment and generation costs for solar thermal for industrial process heat - 2050

			General Cost US$/MWh	Investment Cost thousands US$/MW
Case 1:	2000kWh/m²/year	2050	21	170
	storage	break even	50	397
Case 2:	1200kWh/m²/year	2050	36	170
	daily storage	break even	50	238
Case 3:	1200kWh/m² year	2050	34	289
	seasonal storage	break even	60	508
Case 4:	2000 kWh/m²/year	2050	52	549
	including cooling	break even	80	847

For the calculation of 2050 supply cost curves (Figure 12), the feasible temperature limit for solar thermal is set at 1000C. This is a conservative assumption. There are already pilot systems, such as the ARUN solar concentrator dish in India, that produce solar thermal process heat at temperatures up to 2500C (as described in Annex 4). The cost per unit of energy produced is calculated on a regional basis. The potential is based on the proportion of the process heat demand of each industrial sector that is less than 600C for 2007 and less than 1000C for 2050.

Similar cost curves have also been developed for the other four industrial sectors in this analysis. Each of them illustrates how the potential for solar thermal technologies in industrial applications is distributed among regions and temperature levels, showing the cost of useful energy for each of them. This cost can be compared with the local energy market conditions for currently used fuels to evaluate the economical feasibility of investing in solar thermal systems in specific industrial sectors and processes.

B. SOLAR COOLING

The chemical and petrochemical and food and tobacco sectors are the largest industrial users of process cooling. Most of the cooling in both sectors is currently done with electric chillers. The main alternative, especially in the chemical and petrochemical sector, is natural gas powered absorption chillers.

Data from the United States Energy Information Agency's Manufacturing Energy Consumption Survey (MECS) indicates that process cooling accounts for 8.5% of the total power demand of the global chemical industry and for 12.5% of the global demand of the petrochemical industry[11]. It is unlikely, however, that much of this demand can be met by solar cooling, given the very low temperatures required by chemical processes and the relatively high energy demands of individual facilities. These characteristics are difficult to meet with solar thermal systems, given the large areas of solar panel that would be needed to deliver them.

This leaves only one sector with a good potential for solar process cooling, the food and tobacco sector. According to the MECS, process cooling in the food and tobacco sector accounts for 27% of the sector's electricity demand, equivalent to 6% of the sector's total final energy demand. On this basis, the total process cooling demand for the food and tobacco sector is estimated in 2007 to

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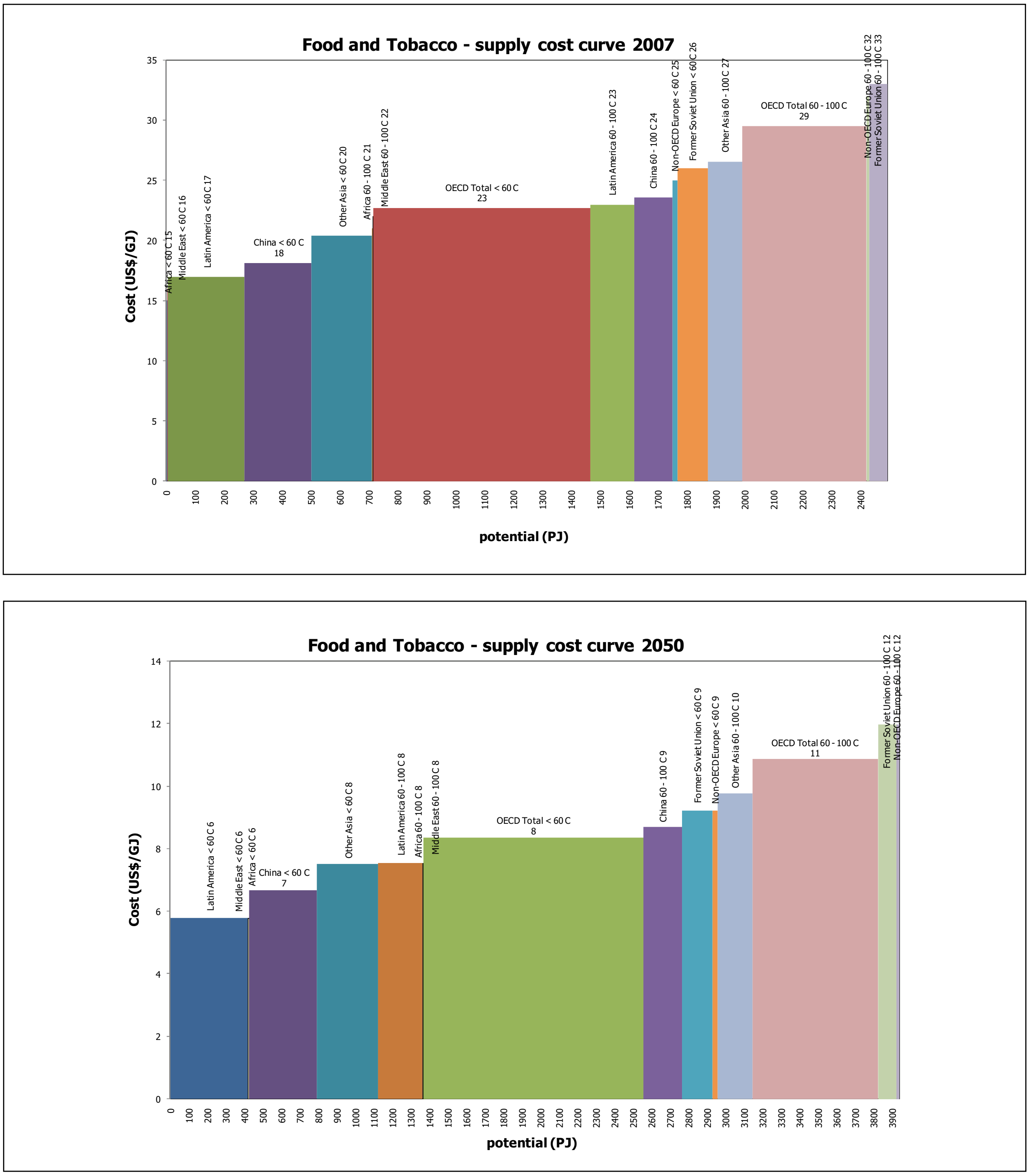
[11] http://www.eia.doe.gov/emeu/mecs/mecs2006/2006tables.html

have been less than 0.4 EJ/year worldwide. Although solar cooling can play an important part in niche applications in the industry, for example in cooling greenhouses, it is unlikely to offer the potential to achieve significant savings in fossil fuel use or GHG emissions. Further details on the technologies and their potential can be found in Annex 4.

Figure 12

Supply cost curve for solar thermal in the food and tobacco sector. UNDIO analysis.



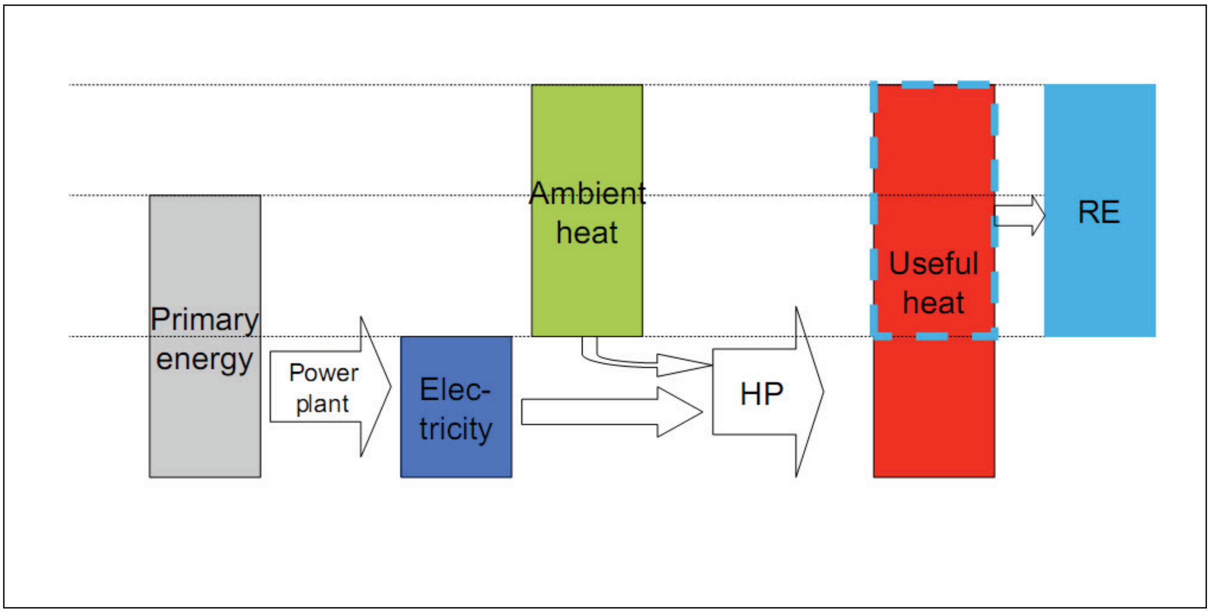
IV. HEAT PUMPS

A. HEAT PUMPS FOR PROCESS HEAT

Heat pumps can take heat from the environment or from waste heat streams and supply it to industrial applications without the need to burn any fuel. In applications where the pumping energy input is in the form of electricity produced from renewable energy sources, heat pumps are a fully renewable energy technology. Where the electricity is generated from fossil fuels, only part of the energy output of heat pumps can be regarded as renewable (Figure 13). So, for example, if the electricity comes from fossil fuel generation with an efficiency of 40%, the coefficient of performance[12] of the heat pump needs to be higher than 2.5 if the pump is to save primary energy and be considered as providing renewable heat. The amount of useful heat provided must be higher than the primary energy consumed.

Figure 13

Calculation of the renewable energy contribution of a heat pump, according to the European Renewable Energy Directive



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[12] The coefficient of performance is the ratio of useful output energy and useful input energy under standardized testing conditions

Box 3: Advantages and disadvantages of using heat pumps in industrial applications

Current disadvantages of industrial heat pumps

- Lack of refrigerants in the relevant temperature range;
- Lack of experimental and demonstration plants;
- User uncertainty about the reliability of heat pumps;
- Lack of necessary knowledge among designers and consulting engineers about heat pump technologies and their application.

Current advantages of industrial heat pumps

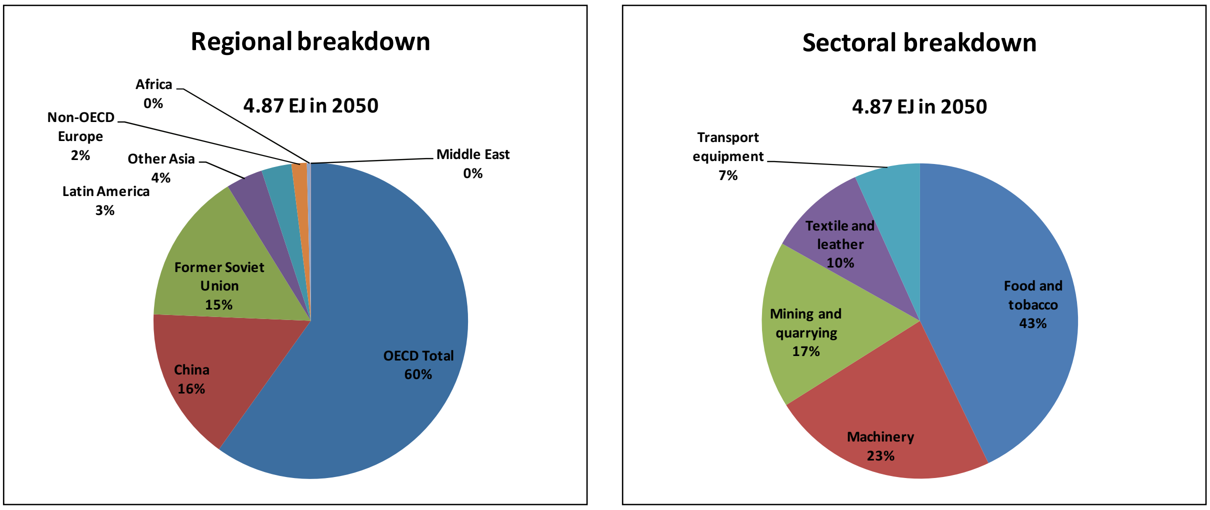
- High coefficients of performance (COP) in applications requiring a low temperature lift and/or operating in high ambient temperatures;
- Long annual operating time;
- Relatively low investment cost, due to large units and small distances between the heat source and heat sink;
- Waste heat production and heat demand occur at the same time.

Source: Jakobs, 2010

The analysis underpinning this paper has identified the potential for heat pumps to meet 4.87 EJ/yr of industry's process heat demands in 2050, as shown in Figure 14 by region and by sector.

Figure 14

Regional and sectoral breakdown of the heat pump potential for process heat in industry in 2050. UNIDO analysis.



OECD countries have an important role to play in the potential deployment of heat pumps for industrial process heat. This reflects the fact that most OECD countries already have reliable electricity grids which deliver electricity at competitive prices. The high efficiency of electric industrial heat pumps makes this technology competitive with solar thermal technologies where electricity prices are low and solar radiation is less than optimum, conditions which describe many of the regions where OECD industrial production is located.

Two other factors, the capital cost of the equipment and its performance, are also important in determining the competitiveness of heat pumps. Performance is expressed in terms of the number of units of energy the heat pump can move from the lower temperature of the source to the higher temperature needed, using one unit of electricity. In most normal operating conditions, the amount of electricity required is considerably less than the amount of heat provided, particularly in applications demanding relatively low temperature process heat. The main thermodynamically limiting factor in the use of heat pumps for high temperature process heat, however, is that their performance decreases the greater the difference in temperature between the input source and the output demanded. So heat pumps are more efficient in delivering low temperature process heat demands. And air heat pumps are more efficient in warmer climates. This factor has been taken into account in analysing the cost of the process heat in individual regions.

Supply cost curves have been calculated for 2007 and 2050 for the same temperature range categories as in the supply cost curve for solar thermal, using the cost per unit of useful energy based on the cost of electricity, an indicative capital cost of the heat pump and its performance coefficient. The performance coefficient of pumps decreases as the temperature lift increases. It is much lower for the 600 - 1000C range than for temperature lifts less than 600C. Electricity costs are taken from the IEA Energy Prices and Taxes database, using the data for the final price of electricity for the industrial sector. For those regions not in the database, the data of a representative country have been used as a proxy, notwithstanding the very significant differences in electricity prices among different countries in the same region. For those countries for which historical data are missing, a 2007 figure has been calculated using the OECD price in 1996 as base and rescaling as a proportion of the OECD 2007 figure. The resulting cost curve for the food and tobacco sector, as an example, is shown in Figure 15.

The curve for 2050 has been created using reduced capital costs, increased performances and more homogeneous electricity prices, ranging from USD 12 to USD 24/GJ (real terms 2007 prices).

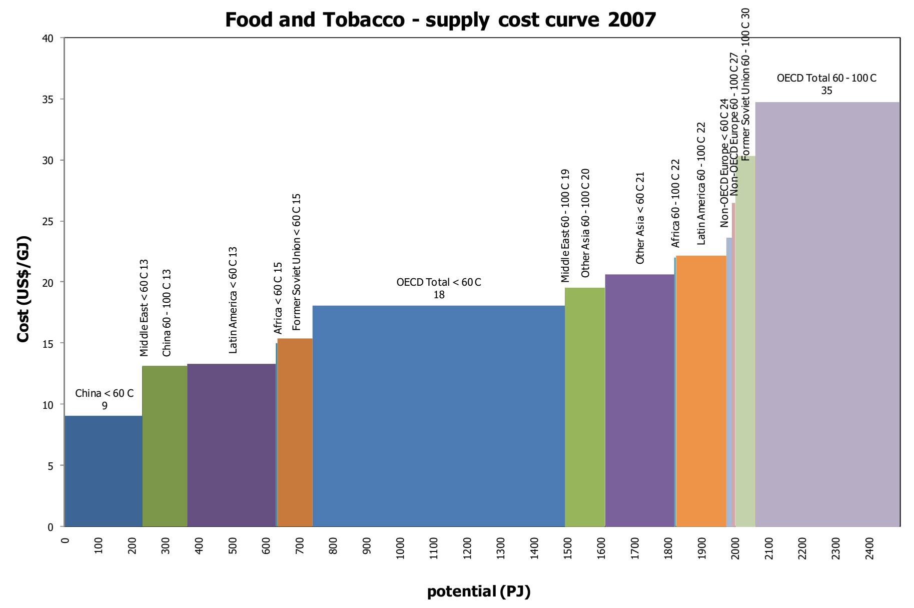
Heat pumps can already provide a competitive alternative to fossil fuels for low temperature process heat in several regions. One of the driving factors, for example in China, is the availability of cheap electricity. But where this electricity is generated by low-efficiency or coal-fired power plant, this can completely offset the potential CO2 emission reductions associated with the use of heat pumps.

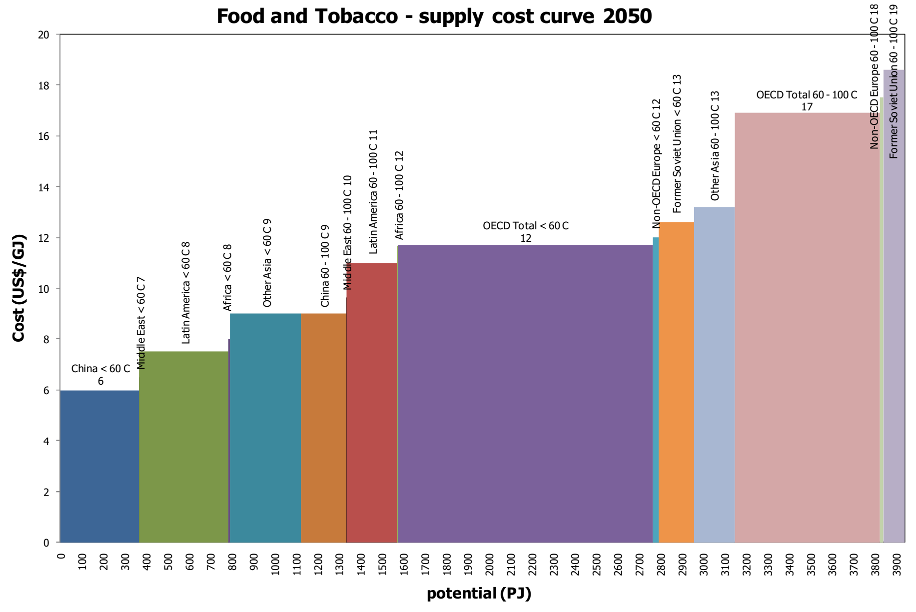
The competition for low-temperature renewable process heat production between heat pumps and solar thermal will be heavily dependent on regional and local conditions. This analysis shows how the relative competitiveness of the two technologies is likely to be both regionally and sectorally polarised. Both technologies have substantial improvement potentials between 2007 and 2050. But the cost of the electricity that drives the cost of process heat from heat pumps is unlikely to reduce significantly in future. Indeed, the progressive introduction of a carbon price on non-renewable power generation, already in place today in the EU and other OECD countries, will probably increase prices.

Conversely, solar thermal technologies still have a large potential for cost reduction. They may as a result become the dominant renewable energy technology for low temperature process heat by 2050 in many regions.

Figure 15

Supply cost curves for heat pumps in the food and tobacco sector. UNIDO analysis.





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VI. ANNEXES

ANNEX 1

Modelling energy transitions: the Logistic Substitution Model for biomass in industry

The Logistic Substitution Model is used in the wider analysis in this paper to assess the way in which fossil fuels will be replaced by renewables as carbon emissions progressively attract a price that reflects their economic and social cost.

The model builds on a time series of the contribution of different energy sources in a specific sector in a specific region to project the development of new energy sources as percentage of the relevant sector's total energy consumption. For this analysis, the three main sources competing with each other are taken to be bioenergy, fossil fuels and electricity.

The resulting demand for bioenergy is then aggregated by region and checked against the regional availability of sustainable biomass resources. In some regions, the potential demand for biomass is far below its availability. But in others, particularly the OECD, demand exceeds supply in every scenario. This demand can only be met by the trading of resources internationally from regions with excess supply to those with excess demand.

The development of a liquid international market for bioenergy will be fundamental both to economically effective international trading and to maximising the exploitation of the world's biomass resources in industrial applications. Such a market will be essential to the transformation of the use of bioenergy in the industrial sector and to the achievement of the sector's full potential for biomass use. The modelling shows that, if liquid international bioenergy markets are in place by 2050, there will be enough sustainable biomass to provide more than 18 EJ of heat and almost 7 EJ of petrochemical feedstocks. In the absence of such bioenergy markets, these figures are scaled down by almost 50%, with most of the reduction in achieved potential occurring in the OECD countries.

The development of an international biomass market is likely to depend initially on the emergence of large volume biomass traders who are active in the power generation market. Current subsidies for renewable energy are mainly in the form of feed-in tariffs or tradable green certificates for power generation. This attracts large volumes of biomass to the power sector for co-firing with coal or burning in dedicated biomass power plants. Biomass is used for heat still mainly in residential space heating.

As the biomass quality becomes more consistent and as the supply quantities become more reliable, intercontinental trading of biomass for energy purposes is already happening. Most of this trading is by sea. The higher the energy density of the biomass commodity, the cheaper, the more environmentally friendly and the easier its long distance shipping will be. A fully hydrophobic bio-coal could make direct use of the existing overseas shipping and delivery infrastructure for coal. The shipping of similarly large volumes of wood chips, however, would require the adaptation of existing energy transport facilities and would be considerably more expensive in terms of the amount of useful energy moved.

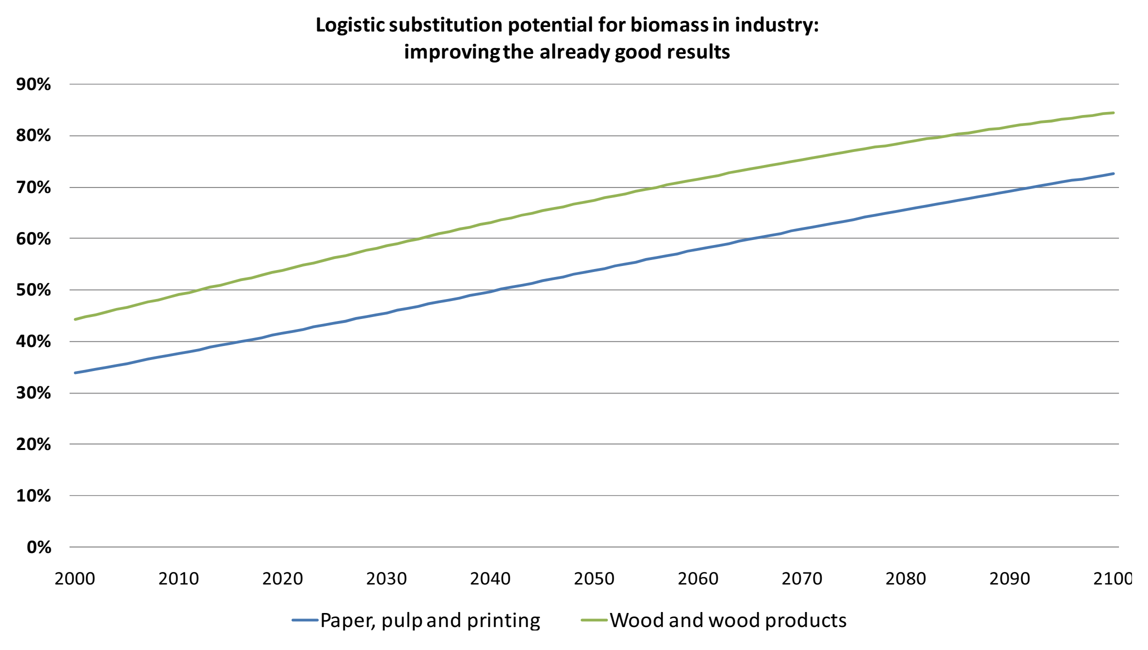
The pulp and paper and wood sectors, the feedstocks and final products of which are woody commodities, already make significant use of bioenergy in their final consumption. The logistic substitution modelling indicates that this already high proportion of final energy use can be further increased, from around 33% in 2007 to 55% in 2050 in the paper and pulp sector and from 45% to almost 70% in 2050 in the wood sector (Figure 16).

These numbers suggest a very high proportion of biomass use in these sectors. They may seem at first glance to be unrealistically high and to assume implausibly large technological transitions. But in Latin America (especially in Brazil) the pulp and paper sector already achieves higher proportions, at 63% in 2007. And in France, biomass constitutes 81% of the wood sector's final energy consumption, with a number of other countries, most of them OECD countries, also performing very strongly. Emerging economies have a very high substitution potential for the use of biomass in these sectors which remains currently very far from being fully exploited.

In the cement sector, around 3% of final energy consumption comes from biomass (IEA,WBCSD, 2009), although the situation varies widely by region. In Brazil, 35% of the final energy in the non-metallic minerals sector comes from biomass. But in China, where more than 50% of the world's cement is currently produced, more biomass would be needed to meet 35% of the

Figure 16

Logistic substitution of biomass in the chemical and petrochemical and cement industries. UNIDO analysis.



total final energy demand of the sector than could be produced sustainably at a national level.

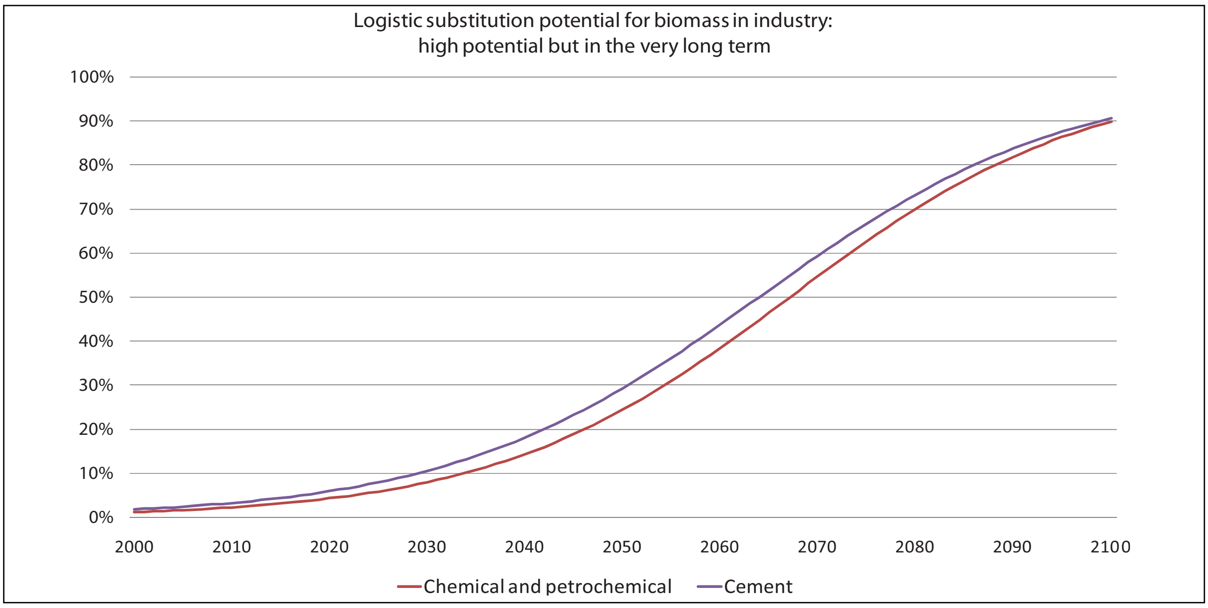
In addition to conventional biomass, the cement sector makes significant use of alternative fuels, including municipal solid waste and other discarded organic materials that are often accounted for in the renewables and waste category in international statistics. These alternative fuels are expected to meet a large part of the biomass substitution potential, thereby reducing the demand on conventional biomass resources.

No countries yet use biomass significantly in the chemicals and petrochemicals sector. Worldwide, biomass contributed 0.6% of the final energy use in the sector in 2007. Integrated biorefineries may offer the prospect of the wider use of biomass for the co-production of plastics, fuels and energy. Depending on the catalysts used, synthetic natural gas (SNG), hydrogen and liquids can be produced from biomass which, through methanisation, de-hydration and Fischer-Tropsch processes can be turned into fossil-substitute products. For example, ammonia and methanol can both be produced from SNG in much the same way as they are currently produced from fossil natural gas. Such developments offer the potential in the longer term for biomass to play a much stronger role in the chemicals and petrochemicals sector (Figure 17).

The main limits to the further penetration of biomass penetration in the chemicals and petrochemicals industry are the availability of sustainable biomass resource and its economic competitiveness. Local availability has so far been the most critical constraint. The overcoming of this barrier through the development of international biomass energy markets will be heavily dependent on the emergence of an effective transformation sector that can turn biomass from a geographically constrained fuel into a modern energy commodity. This is discussed in more detail in Annex 2.

Figure 17

Logistic substitution of biomass in the chemical and petrochemical and cement industries. UNIDO analysis.



ANNEX 2

Biomass preparation technologies

If biomass is to be more widely traded as a commodity on international markets, it will need to be available in very large volumes and in a form which enables easy handling and cost-effective transportation. Fundamental to the production of such commodities on an economic scale is the large scale provision of feedstocks to the transformation industry. The biofuel processing plants that will be needed to underpin that transformation industry will require the harvesting, treatment, transportation, storage, and delivery of large volumes of biomass feedstock, to a desired quality, all-year-round. Supplies need to be guaranteed in advance for a prolonged period to reduce the investment risks. These factors will be critical to the success of investments in biomass commodity production for the future.

Pelletising

In 2008, around 9 mt of wood pellets were produced worldwide. These replaced around 6.3 mt of coal. Wood pellets contain about 17 GJ of energy per tonne. The total primary energy obtained from wood pellets was accordingly around 0.15 EJ/yr.

It is estimated that pellet production will double over the next 4 - 5 years. Some industry experts forecast an annual growth of 25% - 30% globally over the next ten years. Europe is currently the major market for pellets, but the demand for non-fossil fuels in North America is growing. As a result, European pellet consumers will have to search for alternative supply sources in Asia, Latin America, Africa and Russia.

If the trade in wood biomass for power generation is to increase significantly, it will require the development of a standard around which transportation logistics and technology requirements can be established. Wood pellets can provide such a standard.

The wood pellet production process is relatively simple: wood material is dried and turned into a dough-like mass by being passed through a hammer mill and this mass is then squeezed through a high-pressure die with holes of the size required for the specific pellets being produced. The pressure causes a rise in temperature which plastifies the lignin in the wood and holds the pellet together.

The raw materials primarily used for pellet manufacturing have traditionally been sawdust and shavings from the sawmilling industry. As this supply source has started to be fully exploited, the search for alternative sources has widened. European pellet manufacturers are expected increasingly to use forest residues, urban wood waste and fast-growing tree species. They will also begin to compete more aggressively with pulpmills and wood-panel mills for sawmill chips and pulp logs. Some pellet plants may look to import wood chips from overseas.

A surprisingly large share of the global pellet production is already shipped to markets outside the producing country, not only between countries but also intercontinentally. An estimated 25% of world production was exported in 2008. Most of this was shipped from British Columbia in Canada to Belgium, the Netherlands and Sweden. Despite the seemingly prohibitively expensive 15 000 kilometre journey, this market is driven by the currently very low cost of shavings and sawdust in Canada and the high prices for wood pellets in Europe.

The Andritz Group currently has about a 50% share of the global market for wood pellet production equipment. Andritz is an Austrian firm that provides equipment and services for the global hydro power, pulp and paper, steel, animal feed and biofuels and other industries.

The largest pelleting machine produced to date, for a Russian paper company, produces over 900 kt of pellets a year. It cost around USD 60/t capacity. The demand for such very large machines is limited by the availability of feedstock. A plant producing 125 kt/yr costs approximately USD 20 million, i.e. around USD 160/t capacity. The capital costs of the plant depend on the type of feedstock material used. Material with moisture content greater than 12% will need drying. A dryer can cost up to 40% of the entire capital costs. Significant working capital is also needed to bridge the time it takes a plant to achieve profitability: many pellet plants take 6 to 18 months to refine the process before becoming profitable.

Agricultural products and residues such as straw, hay, miscanthus or other energy crops which are used to form so-called agri-pellets have attracted additional attention as feedstocks in recent years. Unfortunately, all of these products are harder to burn cleanly than wood. To meet existing emissions legislation in many countries, significant product development will be required before the widespread use of agri-pellets will be possible.

Fast pyrolysis

Pyrolysis is thermal decomposition that occurs in the absence of air. The pyrolysis of carboniferous material generates gases, liquids and char. Where biomass is pretreated by pyrolysis, the resulting higher energy density liquid can be transported, handled and gasified more easily than solid biomass. Although costs are higher, pretreatment would enable larger scale plants and char-free gasification processes, with economies of scale and a reduced need for residues treatment in the gasifier.

However the practical application of such Biomass to Liquid (BtL) approaches raises some important questions of scale. BtL plants need to be very large to be economic. With a minimum economic production capacity of 25 000 barrels (bbls) a day, a plant would require between 5 million and 7 million tonnes of dry biomass feedstock a year. The economic and logistical challenges involved in financing, building and operating such a biomass based plant are very considerable. To address these concerns, a number of alternative approaches are being considered. These including downscaling, less demanding process conditions that lower equipment requirements, using higher energy density gasification feedstocks, and integrating the BtL process into conventional refineries.

Bio-coal

Bio-coal can already be produced from biomass. Several new companies are entering the market with proprietary torrefaction[13] technologies. These are able to produce an energy commodity which has characteristics similar to coal from biomass of variable qualities and grades. The product has the capability to be certified as renewable coal.

These technologies offer the prospect of creating a standardised energy commodity that can be handled and managed with the existing fossil fuel coal infrastructure and which can, in due course, be traded on the same market. On this basis, the main additional cost is entailed in investment in the torrefaction equipment, rather than in any downstream process.

Several processes are currently used for the production of biocoal. These include TIES, a microwave-based process developed by Rotawave Ltd. and the TORBED reactor from Mortimer Technology Holdings Ltd which is used for torrefied pellet production by Topell Enerby BV.

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[13] Torrefaction is a form of heat treatment.

ANNEX 3

The production of synthetic organic materials from biomass feedstocks

Ethylene Production from Bioethanol

In June 2007, Braskem announced the successful production of the first internationally certified plastics made from sugarcane ethanol. One month later, Dow entered into a joint venture with Crystalsev, the leading Brazilian ethanol producer, to produce bioplastics. Both companies have moved quickly to achieve commercial production. Braskem is now building a USD 300 million plant at its existing Triunfo complex with the capacity to produce 200 000 tonnes of green plastics a year. The plant came online in September 2010, the first facility of its kind to enter commercial operation (Biopol, 2010).

In parallel, Dow and Crystalsev are developing the first facility to integrate a sugar cane plantation with an ethanol mill and a plastics manufacturing plant to produce bioplastics. This facility will produce 350 000 tonnes of plastics a year and is expected to start production in 2011, becoming a key part of Dow's growth strategy in Brazil. Although the integrated facility will take longer to become operational than the Braskem plant, it will allow Dow and Crystalsev to take advantage of important synergies in the production process, such as using the water that results from the conversion of ethanol into ethane and co-generating electricity using the by products of the sugar cane production.

Braskem's second bioplastics plant, scheduled to start production between 2012 and 2014, will also be a totally integrated facility in order to exploit production synergies.

i. Methanol to Olefins

Olefins (ethylene and propylene) can be produced from methanol. Bio-methanol can be produced from biomass.

The BioMCN process for bio-methanol production uses feedstock from non-food sources such as organic waste materials and non-food crops. BioMCN, the world's first industrial scale bio-methanol producer, has received an investment of EUR 36 million from the private equity firm Waterland to go towards the continued construction of its bio-methanol plant in Delfzijl, Holland. BioMCN opened in June 2010 the largest second generation biofuel plant in the world. With a production capacity of 250 million litres, BioMCN can immediately fulfill the entire Dutch biofuel obligation - a minimum of 4% blended into gasoline (BioMCN, 2010).

Bio-methanol is produced through an innovative process, patented by BioMCN, and is made from crude glycerin, a sustainable biomass which is a residue from the industrial processing of vegetable oils and animal fats.. The facility is scheduled to expand again in future to 800 000 mt.

Two relatively new technologies have been developed to produce olefins from methanol. These processes could as readily use bio-methanol as fossil fuel-based methanol.

Lummus Technology and Shaanxi Xin Xing Coal Chemical Science & Technology Development have signed a cooperative marketing agreement globally to license dimethyl ether/methanol-to-olefin (DMTO) technology. This breakthrough technology not only enables the production of olefins from methanol, but also produces enhanced yields that will enable producers cost-effectively to expand existing capacity-restricted olefins plants. The first application of this technology will be at the Shenhua Baotou Coal Chemicals plant in Baotou, China. The first DMTO commercial unit in the world, with a production capacity of 600 000 tonnes of lower olefins from methanol per year, was proved to be successful in its first commissioning operation.

The DMTO process (DICP Methanol to Olefins) was a proprietary technology developed by Dalian Institute of Chemical Physics, Chinese Academy of Sciences (DICP). The commercialisation of the DMTO process signified a new milestone in the production of olefins via a non-petrochemical route. It was a significant R&D achievement, after the efforts of DICP researchers over more than 20 years.

Viva Methanol Limited, a subsidiary of Eurochem, has selected an olefin cracking process technology to produce light olefins, the basic building blocks for plastics, from natural gas-derived methanol at a new facility in Nigeria. The new facility will produce 1.3 mt of ethylene and propylene annually for the production of polyethylene and polypropylene. The new plant is expected to come online in 2012.

ii. Bioplastics

Bioplastics are plastics that are up to 100% bio-based. They may also be biodegradable. The percentage of bio-based ingredients and the conditions under which the product biodegrades, if it does it at all, vary widely. The production of bioplastics has expanded rapidly in recent years. From an international capacity of 150 kt in 2006, production is expected to rise to 2 Mt in 2011. This represents about 1% of the total global plastics market.

Bioplastics are made from a variety of natural feedstocks including corn, potatoes, rice, tapioca, palm fibre, wood cellulose, wheat fibre and bagasse. Products are available for a wide range of applications such as cups, bottles, cutlery, plates, bags, bedding, furnishings, carpets, film, textiles and packaging materials. In the United States, the percentage of bio-based ingredients required for a product to be classified as being bio-based is defined by the U.S. Department of Agriculture (USDA) on a product-by-product basis. The Institute for Local Self-Reliance (ILSR) has recommended that the USDA set a minimum threshold of 50 percent bio-based content for products to be considered bio-plastics.

Performance and usage

Many bioplastics lack the performance and ease of processing of traditional materials. PLA is being used by a handful of small companies for water bottles. But shelf life is limited: the plastic is permeable to water so the bottles lose their contents and slowly deform. Bioplastics are seeing some use in Europe, where they account for 60% of the biodegradable materials market. The most common end-use market is for packaging materials. Japan has also been a pioneer in bioplastics, incorporating them into electronics and automobiles.

Starch based plastics

Constituting about 50% of the bioplastics market, thermoplastic starch such as Plastarch currently represents the most important and widely used bioplastic. Pure starch possesses the characteristic of being able to absorb humidity and is thus being used for the production of drug capsules in the pharmaceutical sector. Additives such as sorbitol and glycerine are used to enable the starch to be processed thermo-plastically. By varying the amounts of these additives, the characteristic of the material can be tailored to specific needs.

Polylactic acid plastics

PLA is a transparent plastic produced from cane sugar or glucose. It not only resembles conventional petrochemical mass plastics such as polyethylene or polypropylene in its characteristics, but it can also be processed easily on standard equipment that already exists for the production of conventional plastics. PLA and PLA-blends generally come in the form of granulates. They are used in the plastic processing industry for the production of foil, moulds, tins, cups, bottles and other packaging.

Poly-3-hydroxybutyrate

The biopolymer poly-3-hydroxybutyrate (PHB) is a polyester produced by certain bacteria as they process glucose or starch. Its characteristics are similar to those of petroplastic polypropylene. The South American sugar industry has decided to expand PHB production to an industrial scale. PHB can be used for production of transparent film that is biodegradable without residue.

Polyamide 11

Polyamide 11 (PA 11) is a biopolymer derived from natural oil. It is also known by the trade name Rilsan B, commercialised by Arkema. PA 11 belongs to the technical polymers family and is not biodegradable. PA 11 is used in high performance applications such as automotive fuel lines, pneumatic airbrake tubing, electrical anti-termite cable sheathing, oil and gas flexible pipes, sports shoes, electronic device components and catheters.

Genetically modified bioplastics

Looking further ahead, some of the second generation bioplastics manufacturing technologies under development adopt a "plant factory" model in which they use genetically modified (GM) crops or genetically modified bacteria to optimise efficiency. A change in the consumer perception of GM technology in Europe will be required for these to be widely accepted.

iii. Bio Building Blocks

Hydrolysis plants, based on a range of processes, are already operating commercially.The Biofine process, is a commercialised technology that uses two-step dilute mineral acid hydrolysis to break down biomass containing lignocellulose into intermediate chemicals that can be further transformed into 2-Methyltetrahydrofuran (MeTHF) and other chemical products. The Biofine process was developed by BioMetics Inc with funding from the United States Department of Energy.

A pilot plant producing 1 t/day of intermediate chemicals has been operating in South Glens Falls, New York since 1998. The first commercial-scale biomass-based plant, which produces 10 t/day of levulinic acid from local tobacco bagasse and paper mill sludge, has been built in Caserta, Italy, by Le Calorie. This started operation in 2006.

Levulinic acid can be produced in yields of up to 70%, or about 0.5 kg per kg of cellulose, along with formic acid and furfural as valuable by products. Used for years in food, fragrance, and specialty chemical applications, levulinic acid is a precursor for methyltetrahydrofuran, v-valerolactone, and ethyl levulinate, which can all be blended with diesel or gasoline to create cleaner-burning fuels. Another derivative, diphenolic acid, is a potential replacement for bisphenol which is suspected to be an endocrine disrupter.

iv. Wood Board and Engineered Wood Materials

Wood board materials are made from thin sheets (plywood), particles (particle board) and oriented strand board or fibers (fibreboard). Engineered wood includes a range of derivative wood products which are manufactured by using adhesives to bind together the strands, particles, fibers, or veneers of wood to form composite materials. These products are engineered to precise design specifications which are tested to meet national or international standards.

Typically, engineered wood products are made from the same hardwoods and softwoods that are used to manufacture lumber. Sawmill scraps and other wood waste can be used for engineered wood composed of wood particles or fibers, but whole logs are usually used for veneers, such as plywood. It is also possible to manufacture similar engineered cellulosic products from other lignin-containing materials such as bamboo, straw, or sugar cane residue.

Engineered wood products are beneficial from an energy and CO2 perspective because:

- They can be made from fast growing crops or residues;
- Their properties are superior to those of natural wood;
- They open up new markets where wood could not compete;
- They reduce the demand for tropical hardwoods.

The standing wood stock is about 422 Gt worldwide. The total global production of wood-based panels, including plywood, particle board, fibre board and oriented strand board, reached 266 million m^3 in 2007, about 175 Mt). Production of saw logs and veneer logs amounted to1 007 million m^3 in the same year, and of industrial roundwood to around 1 705 million m^3. This is around half of the total roundwood production of 3 591 million m^3 in the same year, the other half of which was used in energy production.

Engineered wood products accounted for only 600 000 m^3 in 2007, about 0.3 Mt. Engineered wood product markets are very small today compared to conventional wood markets.

New products such as pressed bamboo can achieve considerable strengths, comparable to that of tropical hardwoods. This market is growing rapidly. Total global bamboo production is of the order of 100 Mt per year. China is by far the largest producer, producing 60 Mt 80 Mt/yr), followed by India. Bamboo production is rapidly expanding worldwide.

ANNEX 4

Solar thermal heating and cooling systems for industry

Solar heating is a well established and commercial technology for residential hot water and heating applications. So far, solar heating in industry has been limited to a small number of demonstration projects. Solar thermal is not particularly well suited to the high temperatures that are generally needed for industrial applications other than in the food sector. Solar thermal technologies could be attractive in the food sector, especially in developing countries with abundant solar irradiation. Solar cooling is an emerging technology, still at an earlier stage of development than solar heating.

This Annex provides a brief overview of current solar thermal technologies and illustrates these with a selection of examples of industrial applications of solar heating and cooling.

Operating Solar Thermal Plants for Industrial Applications:

Statistics as of October 2006

More than 80 solar thermal plants with a total collection area of about 34 000 m2 were in operation in industrial applications in October 2006. Most of these were in the food industry, particularly in dairies, in car washing facilities, or in metal treatment and textile and chemical plants. The textile sector accounts for the highest share, at about 40%, of the capacity installed.

Solar heat is used at 20° - 90°C for washing, the space heating of production halls and the preheating of boiler feed-water. In the dairy sector, for example in Greece, solar is used to produce hot water for the washing of equipment and to preheat boiler feed-water at temperature levels up to 80°C. In Austria, the space heating of production halls is the most common application. Car, lorry and container washing facilities account for 11 plants in Austria, Germany and Spain. Wineries account for 4 of the 6 plants reported within the beverage sector, where there remains a large potential for future applications.

The main solar thermal technologies are described briefly below. About 80% of the plants supply heat below 100°C. These are mostly flat plate collectors or evacuated tube collector systems working at 60° - 100°C. Only evacuated tube collectors are used in the range 100° - 160°C. Above 160°C, parabolic trough collectors are used mainly for steam production or cooling with double effect absorption chillers.

Solar thermal for process heat: Collector Overview[14]

New designs for concentrating solar collectors are appearing on the market, dedicated to specific niches or needs. Some of these can be integrated into roof structures, producing more than 200°C of temperature increase at 60% efficiency, such as the Chromasun design. Others enable the combined production of electricity, heat, desalination and air conditioning at a household level.

In the field of solar concentrators, all the technologies use one of a limited range of available optical designs. Cassegrain designs (Schmidt-Cassegrain, Maksutov-Cassegrain) that intensely concentrate the light have not yet penetrated the solar thermal market, although they are very common in astronomical optics. A similar design has been recently implemented in Canada and has been patented as the Kinley Dual Mirror System. In its initial tests, this design reached 1755°C before melting the platinum thermocouples that were measuring the temperature reached by the system. In niche applications, this could provide an interesting

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[14] Overview from http://www.iea-shc.org/publications/downloads/task33-Process_Heat_Collectors.pdf
Source: IEA Task 33

solution for the melting or even the vaporisation of small quantities of metals.

A similar device is installed in the Paul Scherrer Institut (PSI) in Switzerland and known as High-Flux Solar Furnace. The furnace consists of a 120m² sun-tracking flat heliostat on-axis with an 8.5 m-diameter paraboloidal concentrator. It delivers up to 40 kW at peak concentration ratios exceeding 5000 suns (1 sun = 1 kW/m²). The solar flux intensity can be further augmented to up to 10 000 suns by using CPC secondary concentrators. A venetian blind-type shutter located between the heliostat and the concentrator controls the power input to the reactor.

Examples of solar thermal systems applied to the Greek dairy industry

Two applications of solar thermal systems in the dairy industry in Greece are described in the box below (Karagiorgas *et al.,* 2001).

Mandrekas S.A.

Mandrekas S.A. is a small dairy situated on the outskirts of the city of Korinthos. Its main industrial activity is the production of dairy products such as yoghurt, milk and cream. Steam is required by a range of plant processes, including pasteurisation, sterilisation, evaporation and drying, and hot water is required to maintain the yoghurt at 45°C during its maturing process. Steam is provided by a steam boiler running on liquid propane gas (LPG), the cold water being supplied by the water supply grid, and hot water is provided by the solar system. The factory uses 15m³ of hot water a day.

The solar system was installed in 1993. It consists of 170m² of tube-?n, flat plate collectors coated with black paint located on the roof of the factory, an open loop circuit and two parallel, horizontal, 1000 l closed storage tanks located in the boiler room of the dairy. The water from the water supply grid enters the solar storage tanks and from there is fed to the solar collectors where it is heated and returned to the solar storage tanks. The hot water leaving the solar storage tanks is either fed directly to the factory's washrooms or is fed to the yoghurt maturing process and then returned to the tanks. Any auxiliary heating required by the yoghurt maturing process is provided via a heat exchanger, which receives steam from the steam boiler.

The system is still operational and in very good working order. The hot water requirements of the yoghurt maturing process are much smaller than the amount of hot water produced by the solar system which is oversized for the need. In addition, given the low hot water requirement of the yoghurt maturing process, the steam heat exchanger is heating the solar storage tanks thereby reducing the efficiency of the solar system.

Mevgal S.A.

Mevgal S.A. is a dairy situated on the outskirts of the city of Thessaloniki. Its main industrial activity is the production of dairy products such as butter, cheese and buttermilk. Steam is required for pasteurisation, sterilisation, evaporation and drying and hot water is required for the cleaning and disinfecting of utensils and machinery. Originally, steam was provided by steam boilers running on heavy oil which fed cold water exchangers. Today the hot water produced by a solar system is used to pre-heat the water; electric resistance heaters provide any auxiliary heating required. The system is operational and in excellent working order.

Solar cooling technologies for industrial applications

Solar cooling technologies have so far been used primarily for space cooling. Applications for process cold, especially below zero degrees, have been typically powered with fossil fuel burners or electric chillers. For solar systems without traditional burners, adsorption technologies are the most promising. They range from 5 kW to 600 kW capacity, with minimum water temperatures between 50° and 60°C.

For systems with auxiliary burners available, deep freezing down to -50°C is possible using ammonia-water absorption chillers. Other options may be to use high temperature solar collectors, such as parabolic trough collectors (PTC) or linear fresnel collectors (LFC). Well established companies with experience in high-temperature solar thermal systems and solar cooling such as Solitem are already deploying PTC systems successfully. The problem in deep freezing with concentration solar technologies is that where direct solar radiation is strong enough to ensure the production of high temperature process heat for driving the absorption ammonia-water chiller, the outside temperature is also very high. The higher the outside temperature, the less cold the temperature that can be reached, given a maximum temperature decrease of 55° Kelvin (K) (Table 7).

DY Refrigeration from China (now acquired by the Canadian company Thermalfrost) is in the process of implementing solar cooling applications down to -30°C in a dairy industry demonstration plant.

Table 7

Main characteristics of thermally driven chillers

	Single effect $H_2O/LiBr$	Double effect $H_2O/LiBr$	Triple effect $H_2O/LiBr$	Single effect NH_3/H_2O
Temperature drop (max)	25° K	250 K	25° K	55° K
Temperature of Cold	5° to 20°C	5° to 20°C	5° to 20°C	-20° to 20°C
Driving temperature	70° to 90°C	140° to 180°C	230° to 270°C	160° to 180°C
Max. COP	0.7 - 0.8	1.1 - 1.4	1.6 - 1.8	0.6 - 0.7

One of the largest solar cooling systems is installed in Sudan. It provides cooling to a hospital, the Salam Centre for Cardiac Surgery, run by the NGO Emergency under critical operating conditions as described in the Box below.

Every hour, the Salam Centre requires 28 000 m^3 of cold air.

This has been achieved by a system employing 288 vacuum-sealed solar collectors with a total surface of 900 m^2. These produce 3 600 kWh with zero CO_2 emissions, an amount of energy that would otherwise require the burning 335 kg of gasoline per hour. Each solar collector houses copper tubing lodged inside vacuum-chambered glass tubes through which water circulates, allowing the sun to heat the water by irradiation without heat dispersion. The water running through the pipes constitutes the vector fluid transferring heat to a 50 m^3 reservoir, where water is stored at a temperature around 90°C. The transformation of heat into cooling power takes place in two absorption chillers, where the circulating hot water heats up a solution of Lithium bromide. By reaching the gaseous state, Lithium bromide removes heat and water cools down to 7°C. This cold water is then circulated in the Air Treatment Units (ATU), cooling air to the desired temperatures. From the 8 ATU installed in the Centre, air is then further filtered by F7, F9 or absolute filters, according to the needs of the different areas of the Centre. When solar energy is insufficient to meet the Centre's cooling requirements, two gasoline boilers switch on automatically, re-adjusting the water temperature in the reservoir, ensuring an optimal functioning of the chillers.

Another example is the use of solar heat for the dairy industry. Various designs have been demonstrated. One of them is the so-called ARUN concentrator (Kedare et al., 2008).

ANNEX 5

Cost-effectiveness of renewables for industrial use

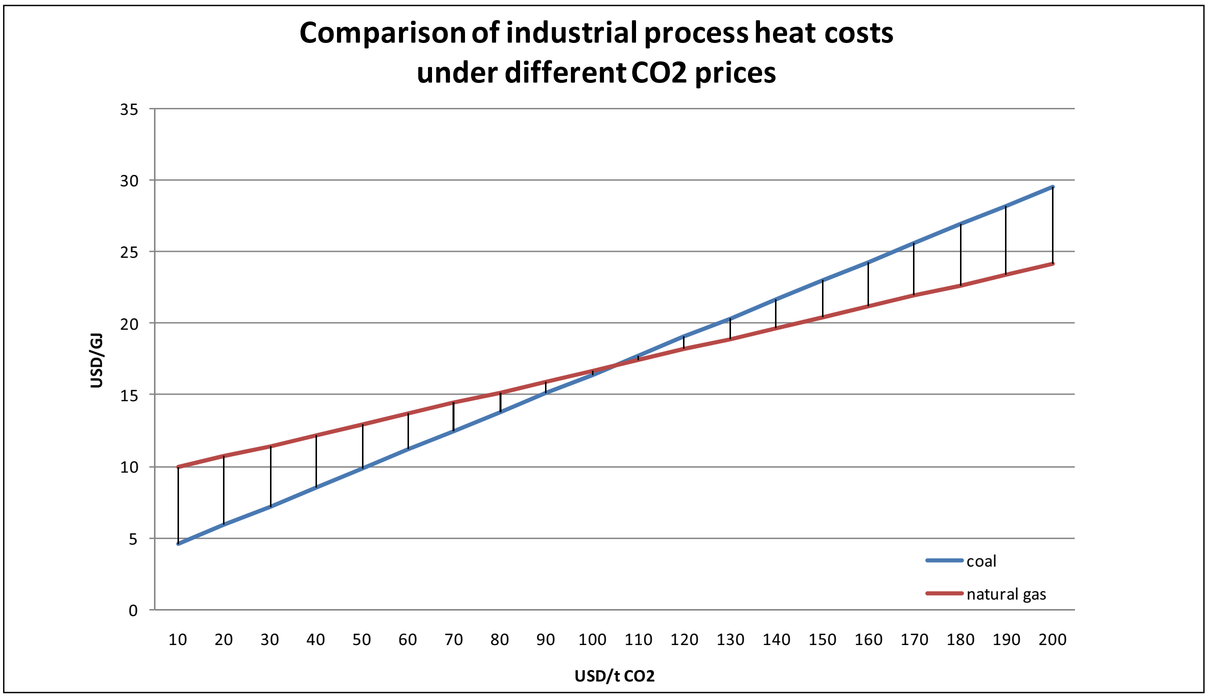
The competitiveness of renewables with fossil fuels is strongly dependent on national conditions and on fluctuations of energy prices in international markets. According to the IEA Energy Prices and Taxes database, between 1998 and 2009 natural gas end-use prices for industry were at a minimum in 2000 of USD 16/tonne of oil equivalent (toe) in the Russian Federation and at a maximum in 2008 of USD 953/toe in Hungary, varying by a factor of almost 60. At the end of 2009, the lowest and highest industrial end-use natural gas prices varied by a factor of around 10, from USD 90/toe in Kazakhstan to USD 870/toe in Denmark.

Similarly, coal prices varied by a factor of 30 from a minimum of USD 13/toe in Kazakhstan in 2003 and a maximum of USD 422/toe in 2008 in Switzerland. At the end of 2009, prices differed by a factor of almost 15, between USD 26/toe in Kazakhstan and USD 373/toe in Austria.

If a liquid, effective and efficient carbon market was be in place, the price of CO_2 would be one of the main factors in determining the success of renewable energy and the mix of fossil fuels (Figure 18). In the short term, the existing plant infrastructure is a significant barrier to price-driven fuel switching. But in the longer term, if prices stabilise on the carbon market and major energy consumers become more directly involved, more carbon intensive fuels such as coal will see their role reduced in favour of less carbon-intensive fuels such as natural gas and renewables. Biomass, through pre-processing technologies, will offer the only short term option for coal substitution without any replacement of the existing equipment, especially in sectors where the carbon content of the fuel is fundamental to the industrial process such as in the iron steel and chemical and petrochemical sectors.

Figure 18

Cost of useful process heat produced by main fossil fuels, under different CO2 prices



UNITED NATIONS INDUSTRIAL DEVELOPMENT ORGANIZATION
Vienna International Centre, P.O. Box 300, 1400 Vienna, Austria
Telephone: (+43-1) 26026-0, Fax: (+43-1) 26926-69
E-mail: unido@unido.org, Internet: www.unido.org