Iron and charcoal

The industrial fuelwood crisis in Minas Gerais

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Charcoal-based iron- and steelmaking, a technology which died out in Europe at the time of the Industrial Revolution, is still employed on a large scale in the Brazilian state of Minas Gerais. Industrial use of charcoal reflects both the area's natural resource endowment and foreign exchange constraints. However, the growing demand for charcoal, driven by Brazilian industrial development, exceeds the sustainable yields of local forests, creating a fuelwood supply crisis. The state energy planning agency is analysing alternative wood supply and demand policy options through the use of LEAP, an integrated energy planning model which emphasizes fuelwood issues.

Keywords: Fuelwood and charcoal crisis; Brazilian iron and steel industry; Energy planning

For much of the Third World, the energy crisis of the last two decades has created two principal barriers to development. First, the high economic cost of fossil fuels has slowed, if not reversed, the growth of the modern sector. Second, growing biomass fuel use has led to high environmental costs such as deforestation, soil and water degradation, or even 'desertification'. Since fossil fuels and biomass fuels are sometimes substitutes, a 'solution' to one problem may cause a worsening of the other.

These two energy problems – the high economic cost of fossil fuels and the high environmental costs of biomass fuels – appear in varying local forms, due to differing natural resources and patterns of development. One unique form of energy crisis appears in the Brazilian state of Minas Gerais. Here modern industry, particularly iron and steel, relies heavily on charcoal, which accounts for most of the state's use of fuelwood. The current consumption of wood is far above the sustainable yield, causing widespread stock cutting and threatening wood shortages in the not-too-distant future. In many areas, including other parts of Brazil, fuelwood shortages would be felt most severely by rural households; in Minas Gerais, on the other hand, the impact would be greatest on industry.

Energy resources: Brazil and Minas Gerais

Brazil in general, and Minas Gerais in particular, possess extensive biomass and hydroelectric resources, but very limited fossil fuel supplies. At the national level, Brazilian energy policy responded reasonably successfully to the oil crisis of the 1970s and early 1980s.[1] New discoveries of oil have reduced, though not eliminated, dependence on imports. Industrial use of fuel oil has been reduced through greater use of electricity, biomass, and other fuels. And thanks to government subsidies for alcohol production, more than half the cars on the road, and virtually all new cars, use alcohol rather than petrol. Though the alcohol programme remains controversial because of its high cost,[2] it is a policy which reflects Brazil's physical resource endowment – a locally produced biomass fuel, alcohol, has replaced a fossil fuel, petrol.

The industrial use of charcoal in Minas Gerais can be viewed in an analogous manner. The lack of fossil fuels (metallurgical coal, in this case) has resulted in dependence on biomass fuels (charcoal), with potentially harmful environmental effects. But due to the particular combination of natural resources available in Minas Gerais, charcoal-fired iron and steel production has long been profitable, and is likely to remain attractive as long as wood is available.

Minas Gerais is a mountanous, inland state, adjacent to Rio de Janeiro and São Paulo. It has an area

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of over 58 million hectares (ha) (greater than the area of France; or in American terms, almost as big as Texas), and a population of 16 million. Among Brazilian states, it is second only to São Paulo in the value of industrial production. In some sectors, including iron and steel, it is the country's leading producer. The iron industry is located in the state because of the abundant supply of iron ore; indeed, Minas Gerais means 'general mines' in Portuguese.

In addition to iron ore, many other minerals, including gold and precious and semi-precious stones, are mined in Minas Gerais – but not coal. Brazil's limited reserves of coal are of low quality and located far from Minas Gerais. The lack of coal leads directly to the demand for charcoal. Either charcoal or coke must be used for smelting iron ore since the fuel must provide not only heat, but also carbon for the chemical reduction of the ore. With seemingly ample supplies of trees close at hand, part of the iron industry of Minas Gerais never made the transition from charcoal to coke, a transition which first occurred roughly 200 years ago in the UK.

History of charcoal in the iron industry

Charcoal-fired iron production[3] is an ancient technology and the resulting deforestation an ancient problem. Archaeologists have suggested that deforestation resulting from charcoal production may have caused the abandonment of a major ironmaking centre in central Africa around AD 500.[4]

Throughout Europe, charcoal was the predominant fuel in the iron industry before the Industrial Revolution. Complaints of deforestation around ironmaking centres, due to the demand for charcoal, were recorded in England as early as the 1540s.[5] During the late seventeenth and early eighteenth centuries, the cost and difficulty of obtaining charcoal limited the growth of the English iron industry. Demand for iron was rising, but English imports of iron from Sweden and Russia (countries with more extensive forests) grew much faster than domestic production.[6]

The first successful experiments with coke-fired ironmaking took place in the early eighteenth century; however, the practice did not become widespread until late in the century, at the time of the Industrial Revolution. Coke typically contains more mineral impurities than charcoal and therefore produces lower-quality iron. Moreover, coke-fired smelting requires higher temperatures, making it practical only in larger furnaces. The rapid growth in demand at the time of the Industrial Revolution led to larger furnaces, in which coke could more readily be used. (Ultimately, as furnaces become even larger, a size is reached at which coke is required. Above a certain size, charcoal cannot support the weight of the ore in the furnace.)

For the UK, which possessed large quantities of metallurgical-quality coal, but relatively little wood, the transition to coke rescued the iron industry from a period of stagnation. For continental Europe, where the shortage of wood was not as extreme and the Industrial Revolution arrived later, the industry's transition to coke did not occur until the mid-nineteenth century. In contrast, for Brazil, where the relative endowment of wood and coal is roughly the opposite of the English pattern, the switch to coke has never been a viable option for a large part of the industry.

This does not mean that Brazil's iron and steel industry is ancient. Despite scattered beginnings in the colonial era and small-scale production throughout the nineteenth century, Brazilian pig iron production had reached only 35 000 tonnes by 1930 – much less than 1% of current output. None of the leading firms in the industry today existed before the 1920s; most did not begin production until the second world war or even later.[7] The structure of the industry today reflects choices made in this century, long after coke-fired iron and steel technology became available.

Another question of relative resource availability also influences the choice between charcoal and coke. Coke use requires more capital, to build the coke ovens; charcoal use, on the other hand, requires more labour but relatively less capital to harvest the wood and produce the charcoal. In a well-known history of the Brazilian iron and steel industry, Werner Baer emphasizes the abundance of labour relative to capital, as well as the endowment of wood compared with coal, as factors leading to charcoal-based production.[8] However, it seems likely that the fuel endowment is the more important factor. Capital scarcity alone is not decisive – Brazil has adopted highly capital-intensive US and European technologies in many other areas; and countries with even greater relative scarcities of capital than Brazil have created entirely coke-fired steel industries.

Brazil may be the only industrializing country which possesses iron ore and extensive wood resources, but little coal. Hence it is one of the few places where a charcoal-based iron and steel industry could develop in the twentieth century. As the twenty-first century approaches, however, that industry may be undermining the basis for its own existence. Steadily growing charcoal use has chopped down much of the once-abundant forests of Minas Gerais, thereby placing future charcoal supplies in jeopardy. The threat of wood shortages is high on the list of problems facing the state's energy planners.

Planning methodology

The energy planning agency for Minas Gerais is the state-owned energy company, CEMIG (Companhia Energética de Minas Gerais). CEMIG's primary function is to supply electricity for Minas Gerais. However, CEMIG's Department of Energy Planning, created in 1984, is responsible for the state's long-term energy planning and for the identification of problems and potential solutions in the areas of biomass and other fuels. The goal of the planning process is to forecast energy demand and to ensure the availability of energy required to maintain growth of the state's output and employment.

One of the key decisions made by the Department of Energy Planning was the selection of a methodology for analysing long-term energy trends. As explained in a technical paper,[9] the department rejected exclusive reliance on econometric modelling techniques and on estimated price elasticities or income elasticities. Such techniques inevitably incorporate the assumption that past social, economic and political relationships will continue into the future. This assumption is not appropriate in the context of rapid structural change, as in Brazil today. Instead, the department opted for 'technical-economic' modelling techniques, allowing simulation of multiple scenarios embodying alternative assumptions about economic trends and energy policies. After evaluating a variety of energy planning models, CEMIG selected LEAP (Long-range Energy Alternatives Planning System).

LEAP is a microcomputer-based planning tool, designed for use in long-term integrated energy planning, with a special emphasis on fuelwood problems.[10] Before its adoption by CEMIG, LEAP had been used primarily in Africa; however, it has proved well suited to the Brazilian context. The remainder of this paper discusses the results of CEMIG's preliminary LEAP analysis of the fuelwood problem in Minas Gerais.

One aspect of LEAP terminology may be unfamiliar to may readers. LEAP users develop 'base case' projections of energy supply and demand. However (in contrast to the use of the term in some models), the LEAP base case is *not* usually a scenario which is considered likely to occur. Rather, it consists of a projection into the future of current trends and policies, taking into account expected macroeconomic and demographic changes, and any other anticipated events. It may be thought of as a 'business as usual' scenario, assuming no changes in energy policies.

Often the LEAP base case turns out to be an implausible scenario for the future. In Minas Gerais, it projects a growing gap between fuelwood supply and demand. This shows that current trends and policies cannot continue unchanged, a result which provides the starting point for energy policy analysis. LEAP also allows simulation of policy scenarios, in which the user tests the expected effects of alternative future policies aimed at solving the problems identified in the base case. Indeed, policies such as energy conservation, fuel-switching, reforestation, and new end-use technologies, can be modelled and compared to the LEAP base case. The tables and quantitative projections presented in this paper are taken from the LEAP base case for Minas Gerais.[11] That is, they do not represent what we expect will happen; instead, they show what might happen in the absence of changes in energy policies and/or technologies.

Projections of fuelwood shortages, such as those developed in the LEAP analysis of Minas Gerais, have been criticized by some authors. For example, Gerald Leach and Robin Mearns argue that the extent of the impending fuelwood shortage in Africa has been overstated in many recent studies.[12] Their most important arguments are that most deforestation in Africa is caused by land clearance for agriculture, not by the demand for fuel, and that rising fuelwood prices will cause substitution by other fuels even in the absence of new policies.

However, these points are not directly applicable to our analysis. It is true that land clearance for agriculture is still an important source of wood in Minas Gerais. However, the state's charcoal-using industries are projected to grow much faster than population or agricultural land clearance. This provides a different, industrial dynamic to fuelwood demand, which is generally absent in the African context discussed by Leach and Mearns. And as we will explain, the industrial consumers of fuelwood in Minas Gerais have only limited opportunities for substitution.

The wood crisis in brief

The demand for wood, like the demand for energy in general, is calculated in LEAP by a disaggregated end-use model. Growth in demand in different sectors may be 'driven' by different economic or demographic variables, at the user's discretion. For example, the household energy consumption estimates in the Minas Gerais base case are based on a recent household energy survey and on demographic modelling of the nine subregions of the state.

To project industrial energy consumption, CEMIG has developed separate estimates for 13 major sectors, based in many cases on in-depth studies of individual industries. The sectoral estimates, in turn, are driven by a macroeconomic scenario for Brazil, under which real gross domestic product (GDP) grows at 5.4–5.5% annually from 1990 to 2005. While rapid in comparison with the experience of the 1980s, such growth rates are slow in comparison with earlier Brazilian experience. This macroeconomic scenario, in fact, was the most pessimistic of the three options initially considered by CEMIG.

For each industrial sector, estimates are made of the relationship between GDP and sectoral output, and of the likely share of Minas Gerais in national output. The iron and steel studies will be discussed in more detail below. Once the state output has been projected, the base case energy requirements are calculated by assuming that the specific consumption (energy–output ratio) of each fuel in each industrial process will remain constant. The result of this analysis, in brief, is that Minas Gerais faces a severe wood crisis. The magnitude of the projected crisis is outlined in Tables 1–3. These show, in particular, the predominance of charcoal in the state's pattern of fuelwood use.

As an end-use fuel (Table 1), charcoal provided somewhat more energy than fuelwood in 1985, and is projected to grow faster as well. When the energy losses in kilns are included (Table 2), the role of charcoal demand looms even larger. It rises from 69% of wood requirements in 1985 to 73% in 2005. The quantity of wood required for charcoal production increases at an annual average rate of 2.6% over than 20 year period.

Available supplies of wood are inadequate to meet this demand. The growth of demand is pressing against a declining wood resource base and the LEAP base case projections show wood shortfalls emerging in most regions of the state. By 2005 the statewide shortfall is projected to reach 23 million tonnes of wood, or 40% of wood requirements (Table 3).[13]

In short, continuation of current trends and expected growth rates could lead to widespread deforestation and collapse of the state's charcoal-using industries in less than 20 years. To prevent such a catastrophe, Minas Gerais will need vigorous, creative changes in energy policies. Reduction of the projected wood shortfall can be achieved through changes in technology which lower the demand for fuelwood, through improvements in the efficiency of charcoal kilns, and/or through increases in the supply of wood.

The structure of wood demand

Fuelwood, used primarily for cooking, accounts for a declining fraction of total wood requirements – 28% in 1985, falling to 23% in 2005 (see Table 2). In absolute terms, it is projected to grow at an average of 1.2% annually. The rural sector, where fuelwood use is most important, is expected to have only slow population growth to the year 2005; this demographic projection is the principal factor limiting fuelwood growth. Both rural and urban households are assumed to be substituting other fuels for fuelwood throughout the forecast period.

Charcoal use is essentially all industrial, with the bulk of demand coming from iron, steel, ferroalloys and cement producers (Table 4). The cement indus-

Table 1. Consumption of charcoal and fuelwood (million toe).[a]

	1985	1995	2005
Charcoal	3.44	4.79	6.16
Fuelwood			
Urban households	0.91	0.75	0.69
Rural households	1.52	1.46	1.56
Industry	0.51	0.91	1.48
Other	0.15	0.21	0.28
Total	3.09	3.33	4.01

[a] toe = tonnes of oil equivalent.

Table 2. Total wood requirements (including kiln losses) (million tonnes).

	1985	1995	2005
Wood for charcoal	25.3	34.3	41.9
Fuelwood	10.1	10.6	12.9
Pulp/paper industry	1.0	2.3	2.4
Total	36.4	47.2	57.2

Table 3. Wood supply and shortfall (million tonnes).

	1985	1995	2005
Sustainable yields	31.0	30.9	25.8
Stock cutting	5.4	8.4	8.1
Wood supply	36.4	39.3	33.9
Total requirements	36.4	47.2	57.2
Wood shortfall	0.0	7.9	23.3

Table 4. Charcoal use (million toe).[a]

	1985	1995	2005
Integrated steel mills	1.09	1.55	2.06
Non-integrated iron producers	1.80	2.38	2.67
Ferroalloys	0.23	0.35	0.45
Cement	0.17	0.32	0.51
Other industries	0.14	0.28	0.45
Households	0.01	0.01	0.02
Total	3.44	4.79	6.16

[a] toe = tonnes of oil equivalent

ty mainly uses small particles, or 'fines', of charcoal, while the iron and related industries mainly use the larger pieces.[14] The fines are produced both in the kilns and during the transportation of charcoal; in general there is a surplus of fines, while larger sizes of charcoal are in greater demand. So the cement industry, or any other industry which can use fines, is not the primary cause of the demand for charcoal.

In the iron, steel, and ferroalloy industries, the production processes involve chemical reduction of iron ores. Charcoal fines cannot be used in the reduction process because they do not allow the circulation of the reduction gas. To support the ore and allow gas circulation, larger pieces of either charcoal or coke are required. Thus the demand for charcoal is created almost entirely by the iron-related industries.

Heavy metals – the demand for charcoal

The iron and steel industry in Minas Gerais includes two major sectors – there are eight integrated steel producers, six of which use charcoal, and dozens of small, non-integrated pig iron producers (Table 5).[15] The economics of charcoal use are influenced by very different factors in these two sectors.

Most of the integrated steel mills are large enough to use coke, if it were available – although substantial new investments would be needed to adapt their plants. Indeed, two of the largest steel mills, accounting for over half of steel output, do use coke at present. However, most of the coking coal used in these two mills is imported. The obstacles to expansion of coke use include not only the high cost of coke and the investment required to install coke furnaces, but also foreign exchange limitations.

It may not be coincidence that the two coke-fired steel mills are public enterprises, while most of the charcoal-fired mills are private firms. The two coke-fired mills are owned by SIDERBRAS, the federal holding company which is now the world's fifth-largest steel company.[16] Public enterprises in Brazil are able to raise the large amounts of capital required (over US$4 billion in each of the two mills) and may be able to deal with the government bureaucracies involved in import regulation more successfully than private firms.

Although the episode is rather dated by now, it is interesting to note that an American investor, Percival Farquhar, tried to start a coke-fired steel mill in Brazil after the first world war. His plan included coordination of iron ore exports with steel production – ships were to leave Brazil with ore exports and return with coal. After years of difficulty, both in obtaining US financing and in obtaining the necessary Brazilian government approvals for transportation and foreign exchange, he gave up and instead became one of the founders of a major charcoal-fired steel company in Minas Gerais.[17]

Bureaucractic obstacles to imports, however, may be viewed as an awkward but effective reflection of Brazil's long-standing high shadow price for foreign exchange. The current debt crisis has only made the shadow price higher. As long as the economy remains tightly constrained by the lack of foreign exchange, there is no possibility of large-scale conversion to coke. (Nor, on the other hand, is there enough wood for the coke-fired steel mills to switch to charcoal.)

While small in comparison to SIDERBRAS, the charcoal steel mills of Minas Gerais are by no means marginal enterprises. Three of the six currently produce more than 500 000 tonnes of steel annually. On average, they consume 2.8 m^3 of charcoal to produce a tonne of steel. The six plants vary widely in fuel efficiency and some charcoal savings could be achieved simply by bringing new investment in all of the mills up to the level of the most efficient current production. Further research is definitely needed on ways to reduce the consumption of charcoal per tonne of steel produced in these mills.

Of equally great importance to charcoal demand is the expected growth of steel production. CEMIG's projections examine five separate categories of steel output, in most cases using growth rates close to the GDP growth rate, and assuming 20–25% of national

Table 5. Projected output of iron, steel and ferroalloys (thousand tonnes).

	1985	1995	2005
Integrated steel mills: coke	3 330	6 869	8 820
Integrated steel mills: charcoal	2 852	4 074	5 405
Semi-integrated steel mills	485	1 228	1 442
Non-integrated iron producers	3 665	4 654	5 444
Ferroalloys	355	500	657

production will be exported.[18] After projecting national production, CEMIG calculates the amount supplied by existing and planned capacity in other states, and by the planned massive expansion of the two coke-fired plants in Minas Gerais. The residual – the amount of national production which is not supplied either by other states or by the two coke-fired plants – is the required level of charcoal-fired steel production.

As seen in Table 5, Minas Gerais steel output (sum of the first three lines in the table) is projected to grow at an average of 6.0% annually from 1985 to 1995, and 2.6% in the following decade. The earlier growth reflects the scheduled jump in the state's coke-fired capacity, while the later slowdown reflects the planned rapid expansion of capacity elsewhere in Brazil after 1995. The required charcoal steel production grows at an average of 3.6% annually in the first decade and 2.9% in the second decade.

The situation is quite different in the other major charcoal-using sector, the non-integrated iron industry. Brazil has 73 ironmaking firms with 146 blast furnaces, of which 69 firms and 139 furnaces are located in Minas Gerais.[19] Many of these enterprises began in the late 1950s and early 1960s, a time when rapid Brazilian industrialization created a demand for steel that could not be satisifed by the country's integrated steel mills. Smaller, semi-integrated steel mills sprang up to process the pig iron from the non-integrated iron producers.

By the end of the 1960s, integrated steel capacity had caught up with demand and the small iron producers were left with excess capacity of up to 50%. During the 1970s, and especially the 1980s, the iron producers therefore exported a growing part of their output. Since 1983, exports have accounted for over half of Brazil's non-integrated pig iron production. By 1985 Brazil was the second-largest exporter of pig iron (after the USSR), accounting for 24% of world exports.[20]

The cost of charcoal is more than half the final value of the non-integrated ironmakers' product; in effect, the addition of iron ore allows these firms to turn charcoal into foreign exchange. Their furnaces are too small for coke use. Moreover, they generally lack the capital for expensive investment in new technologies. That is, Baer's argument that capital scarcity favours charcoal use may be particularly relevant for the smaller, non-integrated ironmakers. Without charcoal supplies, these firms would simply go out of business.[21]

CEMIG's projections for the non-integrated iron sector show a substantial growth of Brazilian output to 2005, with most of the growth for domestic rather than export demand. However, it is also assumed that the price of charcoal will increase in Minas Gerais, making it more economic to expand pig iron production in the north of Brazil (particularly around Carajas, in the eastern Amazon region), where wood is more abundant and charcoal is cheaper. The Minas Gerais share of national production is projected to fall from 91% in 1987 to 72% in 2005. As seen in Table 5, the state's output is projected to grow at an annual average of 2.4% from 1985 to 1995, and only 1.6% after 1995.

Perhaps because the current technological level in this sector is relatively low, it is easy to identify technical changes which would lower fuelwood requirements. For example, waste gas from a blast furnace can be used to pre-heat the ore and the air in the combustion chamber, reducing charcoal consumption per tonne of iron.

Critics of LEAP-type models and 'fuelwood gap' analyses often claim that such approaches ignore the role of prices and the possibility of automatic market adjustments in response to price changes. But it should be noted that CEMIG's base case projections already incorporate the assumption that rising charcoal prices in Minas Gerais will slow the growth of the state's charcoal-using industries, leading to faster increases in iron and steel production in other markets. In the case of the non-integrated iron industry, the 'automatic' market adjustments may increase the problems of over-exploitation of forests in the Amazon (a topic which is beyond the scope of this paper). In any case, CEMIG's LEAP analysis projects a serious wood gap for Minas Gerais, even with substantial market response to higher charcoal prices.

Charcoal production

Much of the wood requirements shown in Tables 2 and 3 will be consumed in charcoal kilns. Two types of kilns are in widespread use – the traditional Brazilian 'hot tail' (*rabo quente*) kiln, used mainly for charring wood from native forests; and the newer, 'surface' (*superficie*) kiln, used on wood from commercial reforestation projects. The traditional kiln has an energy efficiency of 49% (ratio of energy content of charcoal output to energy content of wood input) and accounts for about 80% of Minas Gerais production; the newer style of kiln has an energy efficiency of 53% and accounts for 20% of production.

Brazilian kiln efficiencies are already quite high by international standards.[22] However, wood requirements could be reduced still further by increasing the use of advanced kilns, particularly if the wood supply from reforestation projects also increases (see next section).

A much more dramatic potential change in charcoal production is still in the experimental stage. Researchers at a number of local companies are trying to create more advanced continuous kilns which would capture commercially useful quantities of tar and other chemical byproducts, as well as producing charcoal. The tar, for instance, is a usable substitute for fuel oil. Successful commercialization of these techniques could lead to greatly increased investment, both in improved kilns and in reforestation projects to ensure a fuel supply for the new production processes. However, these newest kilns have not yet been proved successful on a large scale.

Reforestation projects

To date, one of the most widespread responses to the impending fuelwood shortage has been the development of commercial reforestation projects. Those projects have generally planted eucalyptus trees, which have been found to grow considerably faster than any native varieties. Tax credits for industries which invest in reforestation, and legal requirements that companies using fuelwood must develop reforestation areas, have resulted in extensive planting; more than 1.9 million ha of forest have been replanted over the last 20 years. That is, about 3% of the state's total area, or 9% of the area with significant wood growth, is now covered with recently planted eucalyptus trees – often arranged in rows, looking strangely like armies of telephone poles. The integrated steel firms already draw much of their charcoal, in some cases as much as 50%, from reforestation projects rather than natural forests.

The newest eucalyptus projects will produce as much as 15–30 tonnes/ha/year; the wood can be harvested economically after seven years' growth. Better forest management may lead to even higher yields in the future. However, many older projects, initiated by industries solely in order to gain tax benefits or to comply with reforestation laws, have been managed carelessly and have annual yields much lower than 15 tonnes/ha.

The large amount of existing reforestation is still far from adequate to solve the fuelwood problem of Minas Gerais. The base case projections of wood shortages, reported above, include the yields from existing eucalyptus projects. To close the wood supply gap, much more would be needed. For instance, one set of scenarios analysed by CEMIG includes introduction of pre-heating throughout the pig iron industry, some residential adoption of more-efficient wood stoves, and a doubling of the use of more efficient *superficie* kilns. In combination with these initiatives, it would be necessary to roughly double the area of eucalyptus projects over the next ten years, and to bring the old projects up to the yields of the newer ones, in order to eliminate wood shortages.

'Prisoners of the eucalyptus'

Some reforestation is certainly essential; the huge and growing demand for charcoal could not possibly be satisfied by the much lower yields of natural forests. However, *exclusive* reliance on reforestation is not a viable answer to the problem. That approach would involve massive increases in reforestation area, to an extent which may not be economically feasible – or socially desirable.

A few rural villages have already been described as 'prisoners of the eucalyptus' – hemmed in on all sides by commercial reforestation areas, the villagers have trouble obtaining land to grow their food. Moreover, replacement of diverse native forests by a eucalyptus monoculture has environmental drawbacks (just as with sugar cane, coffee, or other monocultures), including potential extinction of some indigenous wildlife species. It is therefore desirable to develop a fuelwood strategy which involves other approaches in combination with appropriate amounts of reforestation.

Any solution to the wood problem must consist of some combination of demand reduction, kiln efficiency improvements, and wood supply increases. Little more can be done to improve the kilns, given existing technology. As a result, there is a tradeoff between changes in charcoal demand and changes in wood supply. In any scenario which closes the wood gap, less reforestation requires more changes in the structure of demand.

Thus the analysis of the wood crisis in Minas Gerais leads back, in the end, to the iron and steel industry, the principal consumer of fuelwood. If it is not feasible or desirable to solve the problem through reforestation *alone*, then it is necessary to lower charcoal consumption in iron- and steelmaking.

Of course, there is one other alternative. If the economic crisis of the late 1980s continues, iron and steel output may be stagnant, and the fuelwood problem will be postponed. This is certainly a possible, indeed all too believable, 'solution' to the problem. The question for the state's energy planners is – are there any other solutions? Is there a resource plan that would permit a resumption of economic growth? Such a plan must involve reduction in the charcoal requirements of iron and steel production.

Pig iron production is a relatively small branch of the state's economy, representing only 3% of the gross industrial product of Minas Gerais. Charcoal accounts for more than 50% of the cost of pig iron, so producers will need dramatic improvements in energy efficiency to remain economically viable as charcoal prices increase. CEMIG projects slower growth in the state, and faster growth elsewhere in Brazil, for this industry, as a result of rising charcoal prices. Since the industry is comparatively small and much of its product is exported, slow growth or even decline in this sector would not cripple the state's economy.

The steel industry is a more important sector of the state's economy, making a product used by many other industries. Moreover, charcoal makes up a smaller part of total costs in steel than in pig iron, easing the process of adjustment to higher prices. While projected to grow more slowly than coke-fired mills, the charcoal-fired steel mills remain essential to the industrial growth of Minas Gerais and of Brazil. A shortage of charcoal for this sector would have a devastating economic impact. So the challenge for the industry and for the state is to develop and implement new technologies which reduce charcoal requirements in the process of steel production.

[1]See, for instance, João Lizardo de Araujo and Andre Ghirardi, 'Substitution of petroleum products in Brazil', *Energy Policy*, Vol 15, No 1, February 1987, pp 22–39; Andre Ghirardi, 'Trends of energy use in Brazil: is self-sufficiency in sight?', *Journal of Energy and Development*, Spring 1985.

[2]There is an ongoing debate about the proper role for the alcohol programme in the light of the low oil prices of the late 1980s. It is possible that Brazil will return to producing some petrol-burning cars in the future. The debates about the alcohol programme are beyond the scope of this paper.

[3]This brief account of the European experience is based on H.R. Schubert, *History of the British Iron and Steel Industry from c. 450 BC to AD 1775*, Routledge & Kegan Paul, London, UK, 1957; David S. Landes, *The Unbound Prometheus: Technological Change and Industrial Development in Western Europe from 1750 to the Present*, Cambridge University Press, New York, USA, 1969; and Paul Mantoux, *The Industrial Revolution in the Eighteenth Century*, Harper & Row, New York, USA, 1961.

[4]Francis Van Noten and Jan Raymaekers, 'Early iron smelting in Central Africa', *Scientific American*, June 1988, p 107.

[5]Schubert, *op cit*, Ref 3, pp 219–220.

[6]Landes, *op cit*, Ref 3, p 94.

[7]Ronaldo Lamounier Locatelli, *Siderurgia e Desenvolvimento Economica Regional: Um Estudo de Caso*, Economics Department, University of Brasilia, Brasilia, Brazil, 1977; Fundação Centro Tecnológico de Minas Gerais (CETEC), *Uso de Energia no Setor Independente de Ferro Gusa*, CETEC, Belo Horizonte, Brazil, November 1987.

[8]Werner Baer, *The Development of the Brazilian Steel Industry*, Vanderbilt University Press, Nashville, TN, USA, 1969, especially Ch 2.

[9]Pedro Antonio Ursine Kettli and Paulo Cesar Teodoro Bechtlufft, 'Considerações metodologicas para a previsão de demanda de energia', paper presented at the Seminario Nacional de Produção e Transmissão de Energia Eletrica, Belo Horizonte, Brazil, October 1987.

[10]See Paul D. Raskin, 'Integrated energy planning in developing countries: the role of computer systems', *Ambio*, Vol 14, No 4–5, 1985; Raskin, *LEAP: a Description of the LDC Energy Alternatives Planning System*, Scandinavian Institute of African Studies, Uppsala, Sweden, 1985; or contact the Tellus Institute, 89 Broad St, Boston, MA 02110 USA, for more information.

[11]The base case results for Minas Gerais have been published in Companhia Energética de Minas Gerais (CEMIG), *Projeção do Consumo Final de Energia: Minas Gerais*, CEMIG, Belo Horizonte, Brazil, 1989.

[12]Gerald Leach and Robin Mearns, *Beyond the Woodfuel Crisis: People, Land and Trees in Africa*, Earthscan, London, UK, 1988, especially pp 5–19.

[13]Note that LEAP calculates and reports the wood shortfall implied by user-specified assumptions; it does not make any automatic adjustments or fuel substitutions to reflect what would happen if such a shortfall occurred. The report of a shortfall indicates that the specified supply and demand scenarios are inconsistent, signalling the need for alternative policies to reduce demand and/or increase supply.

[14]There are small exceptions to this pattern in both directions. One cement plant is located far from the region where charcoal fines are available; this plant buys regular-sized charcoal and mills it before use. On the other hand, a few steel plants have recently begun to inject charcoal fines into their blast furnaces, but this use is small compared with the volume of charcoal required in steelmaking.

[15]The much smaller semi-integrated steel sector, which does not use charcoal, and the ferroalloy industry, will be omitted from the discussion for the sake of simplicity.

[16]SIDERBRAS also has steel mills in other states of Brazil. CEMIG and INDI (Instituto de Desenvolvimento Industrial de Minas Gerais), *Minas Gerais: Cenarios da Economia 1987/2005 – No 7 Siderurgia*, CEMIG and INDI, Belo Horizonte, Brazil, 1988, p 17.

[17]CETEC, *op cit*, Ref 7; Baer, *op cit*, Ref 8, Ch 3.

[18]CEMIG and INDI, *op cit*, Ref 16.

[19]CEMIG and INDI, *Minas Gerais: Cenarios da Economia 1987/2005 – No 9 Ferro-Gusa Não-Integrado,* CEMIG and INDI, Belo Horizonte, Brazil, preliminary version, October 1988.

[20]*Ibid*, Tables 4 and 7.

[21]Baer, *op cit*, Ref 8.

[22]L.A. Kristofferson and V. Bokalders, *Renewable Energy Technologies: Their Applications in Developing Countries*, Pergamon Press, Oxford, UK, 1986, Ch 6.