Bounding and extrapolation analyses of future energy demand of China's steel sector

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Abstract

We undertake a futures analysis of the potential for plant-level efficiency improvements to reduce net energy demand in the Chinese steel sector. Two forecasting approaches are employed: extrapolation and bounding analyses. Extrapolation assumes continuation of existing trends, resulting in a forecasted average increase of energy demand of 10% annually to 2027. While an extrapolation is precise it is highly uncertain because trends generally do not continue indefinitely. To complement this perspective we undertake an analysis to bound future energy use within a robust interval. In contrast with the traditional best/worst case scenario approach, bounds aim to exclude what *will not occur* rather than characterize a range of potential expectations. The lower bound reflects slow growth and rapid adoption of an idealized technology: the result is 0.9% annual average increases in energy use to 2027. The upper bound reflects continued dramatic growth and static technology, resulting in 9.5% average growth in net energy demand. Even unrealistically rapid efficiency improvements are to a large degree cancelled by increases in energy demand driven by growth of the industry. This result suggests that plant-level efficiency should be supplemented with systems-level considerations which account for the life cycle delivery of services associated with a material.

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1. Background and motivations

Society places high expectations on technological progress to mitigate the environmental, social and economic impacts of energy use. Energy-related technologies take many forms, from low carbon alternative energy sources, improved materials, more efficient production technologies, to low carbon alternatives to deliver services (e.g. telework). Whatever form this technological progress may take, it is important to understand to the extent possible, aggregate effects on the impacts of energy.

The IPAT equation is one approach to relate technological improvements with total environmental impacts (26):

$$\text{Impact} = \text{population} \times \text{wealth (GDP/person)} \times \text{impact intensity (impact/GDP)} \quad [1]$$

Analysts considering the potential of technologies to mitigate impacts frequently focus on the third term assuming (explicitly or implicitly) that the first two are constant (1-3,26). There are limitations in this bounding of scope. One is the question of the degree to which technological change in itself induces economic and population growth. In other words, interactions between the terms in equation [1] can be non-trivial. Increased adoption of a given technology as a result of improved efficiency is studied under the term rebound effect (30). There are analysts working to understand the role of technological progress as a production factor contributing to macro-economic growth (29). Whether or not interactions between efficiency and growth are strong, weak or non-existent, efficiency must clearly improve more rapidly than growth to mitigate net impacts. For example, setting aside the potential of carbon sequestration, managing climate change will require net reductions in emissions of greenhouse gases. Technological progress must first be rapid enough to cancel increased carbon emissions driven by growth. Consideration of aggregate impacts via an IPAT-style approach is thus important to characterize targets for technological progress that would deliver net benefits.

We explore the relationship between growth and efficiency improvements via a case study of plant-level efficiency of producing a fundamental material in an increasingly important part of the world: steel-making in China. Steel is a key constituent in infrastructures and products, and the energy needed for its production is significant, roughly 5% of global energy demand. The relevance of China is clear: between 1980 and 2000, steel output from China tripled, and since 1996 it has been the world's largest steel producer, followed by the Japan and the U.S. Growth of the

Chinese steel industry since 2000 has been unusually rapid, 20-25% per annum (6). These levels of iron/steel output growth are probably the highest the world has seen since England's during the industrial revolution. The rapid and sustained growth of the Chinese iron/steel sector is important for the global environment. 2003 energy demand of the sector of 5,334 billion MJ (1 MJ = 1 megajoule = 1 million joules) represents 1.6% of global energy demand, a considerable share for a single industrial sector in a single nation (9). In addition to carbon emissions, this energy use induces a variety of other environmental impacts associated with fossil-based energy use, such as SOx and particulate emissions. Mitigating energy demand in the sector is clearly an important priority for mitigating climate change as well as other environmental impacts associated with energy use.

Our research question is: to what extent can future improvements in technical plant efficiency be expected to mitigate overall energy demand? Improving efficiency has been considered particularly promising in China given historically inefficient industries (1-2). However, as we will see, the iron/steel sector has transformed rapidly in the last decade and the gap between China and international best practice is not large. The industry also continues to grow rapidly, leading to the question of whether the adoption of efficiency can be rapid and sustained enough to mitigate growth in demand. This analysis aims to forecast future energy use of the Chinese iron/steel sector from 2007-2027 from two perspectives: extrapolation and bounding. Extrapolation assumes continuation of existing trends: the next twenty years reflect the previous twenty. A bounding analysis is an attempt to characterize an interval for future values which can be asserted with a reasonable degree of certainty.

To place the scope of this analysis in the context of existing literature, note that there is an existing body of work analyzing energy use and carbon emissions of the Chinese iron/steel sector. For example, after adjustments of Chinese official energy statistics, Price and collaborators characterize the gap between report energy use in 1995 and what it would be under international best practices (1). Kim and Worrel undertook a decomposition analysis of historical CO_2 emissions from the iron/steel sector in seven countries, including China (2). One result was that improvements to processes were the main contributor to reductions in CO_2 intensity, as compared to shifts in industry structure, fuel mix, or utility sector. Looking at the future, de Beers and collaborators consider the long-term potential for improvements in energy efficiency of the global industry (3). We draw on the results and knowledge gained from this previous work to take the analysis in a different direction: to explore if future growth and efficiency trends can bounded with sufficient certainty to yield relevant lessons.

2. Scope of analysis and indicator – primary energy

Our analysis focuses on characterizing primary energy consumed in megajoules (MJ) per mass output (kg) of crude steel produced, assuming a constant share of primary versus recycled product. In this section we elaborate on this definition of scope and some of its limitations.

Primary energy use is defined as the cumulative heating value of fuels used in a process including coal, oil, gas and electricity. Electricity requires special treatment because the types of fuel required to generate it depend on the grid to which the facility is drawing from. As with previous analysts (1-2) we assume a global average electricity grid with a net primary energy conversion factor of electricity to energy of 3, regardless of the local grid. While it is clear that the electricity mix varies from nation to nation and facility to facility, a constant factor is chosen because: 1. it reflects general trends in the energy overhead to make electricity and 2. our purpose is to track the consumption efficiency of energy not the production types. The measure of primary energy we use is net consumption by a facility, implying that any outputs in the form of electricity, gas or other fuels are subtracted from inputs. Also, if a national steel industry is making steel from imported iron we add the primary energy to produce this iron to its inputs.

Measuring energy efficiency involves normalizing energy use by an appropriate unit of consumption. As in standard in analyses of the steel sector we normalize by the total output of crude steel of a national industry. Note however that the final product of steel industries takes a variety of forms such as ingots, sheets, and tubing of different specifications and grades. While most of the energy associated with producing steel products is in making iron and converting to crude steel, the final processing to different products takes varying amounts of energy. Differences over time and place in the profile of final products can affect comparisons of energy use. We do not consider this here.

A third simplification we make is to assume a constant share of steel made from ore versus recycled scrap. There are two main paths to make steel in today's industry: 1. reducing iron ore using a carbon course (coal/coke) in a blast furnace and then converting it to steel in a Basic Oxygen Furnace (BOF) or 2. melting steel scrap recovered from recycling in an Electric Arc Furnace (EAF). Not surprisingly, it takes far less energy to make steel from scrap (e.g. 9 MJ/kg) as compared to ore (e.g. 19 MJ / kg). National statistics describing energy use in steel making generally aggregate both types BOF and EAF production. Producing relatively more steel from scrap will reduce the primary energy needed. It is the purpose of this analysis to consider how potential improvements in plant efficiency affect energy use, not the effect of increased or decreased recycling. Thus in forecasting we fix the share of ore versus recycle based steel fixed to its historical constant. Considering the effect of increased recycling is an important issue for the net environmental efficiency of steel production/use. Given the increasing globalization of scrap flows and their complexity this task is left for future work.

3. Forecasting Methodologies – contingent bounding analyses and extrapolation

The time evolution of net energy use can be represented by the equation:

$$N(t) = P(t)\, e(t), \qquad [2]$$

where N is net energy demand, P is production output of the industry, and e is the energy intensity associated with one unit of production (e.g. megajoules (MJ) needed to produce one kilogram of steel), which are all functions of the year t .

The task posed in this analysis is characterization the future evolution of N(t) from 2007-2027 in order to address the question of whether plant-level efficiency improvements can make a significant contribution to mitigating future net energy demand. Various futures approaches, including scenario analysis and expert panel opinion, have been applied to forecasting energy demand (32). Futures perspectives face dual challenges of uncertainty and subjectivity (31). As previous energy demand forecasts have proved notoriously unreliable (22) this subset of futures analysis is no exception to this rule. In particular, energy forecasting has tended to rely on analyst-constructed scenarios which in retrospect were overly pessimistic regarding the potential for energy efficiency to mitigate demand. Traditional scenario analysis does not address the likelihood of different futures.

Our goal is to work towards more robust futures analysis through characterizing parameter intervals as opposed to “best-guess” scalar values. The presumption is that it is possible to characterize lower and upper limits of an interval with greater certainty than a scalar. In working with intervals however there will be tradeoffs between certainty and precision of the forecast which in turn relate to utility. At one end of the spectrum, for example, one can assert with almost complete certainty that future net energy demand N(t) will lie in the interval between 0 and total world energy demand. While certain, this interval is not specific enough to usefully constrain the future. At the other end of the spectrum, if the forecast is a scalar number reflecting the subjective opinion of an analyst, the forecast is uncertain but precise. Past experience suggests this is also of limited utility. It is our objective to explore the degree to which intervals can be constrained to be reasonably certain but also specific enough to constrain the future in a useful way.

We suggest that the notion of lower and upper bounds as used in mathematics can aid this goal. To briefly recap the mathematical definition, upper and lower bounds are values that an equation or variable cannot exceed/be lower than. The process of proof by finding converging bounds is a standard approach in real analysis (33). How to apply the idea of bounds in a futures context? First note that bounds do exist for elements of equation (1), in particular e(t). To whit, the energy requirements of smelting steel from iron ore will never improve beyond the enthalpy of the basic chemical reaction ($2Fe_2O_3 + 3\ C \rightarrow 4\ Fe + 3CO_2$) plus the heat capacity of the melt, around 8.6 MJ per kg (4). The energy to make steel from recycled scrap will never be less than the heat needed to melt scrap steel, about 1.3 MJ per kg (4). Under the condition that steel making requires heating to the melting point, these lower bounds are absolutely certain. One can also argue that barring a dramatic shift in the world economy and society that technology will get not get worse such that the industry needs increasing energy to produce a kilogram of steel. The assertion is that e(t) will not increase *above* its current value, thus e at it current value can be considered as an *upper bound* on e(t). Note however that the argument for the upper bound is not fundamentally rigorous as was for the lower bound. It required an assumption, or contingency, that technology will not worsen in the near future. In general, to make the bounding concept useful in practice it will often be necessary to relax the mathematical constraint of an absolute bound and work with *contingent* bounds.

We emphasize that contingent bounds are qualitatively different from best and worst case scenarios from scenario analysis. Best and worst case scenarios reflect the range of possibility which the analyst believes could actually occur. Contingent bounds on the other hand are intended to exclude what could *not* occur. *It is irrelevant whether an upper or lower bound is actually possible to achieve in practice.* In fact, a lower or upper bound which is impossible to realize yet still usefully constrains the future is in fact the most desirable situation, because such a bound requires no contingency. Another way to express this idea is that best/worst scenarios satisfy the relation worst

$\leq$parameter $\leq$ best while bounds satisfy lower < parameter < upper. While the notational difference may seem trivial, conceptually these two relations describe the difference between finding the range a parameter *can* take while the latter describes values it *cannot*.

The bounding approach is intended to constrain the future with relative certainty, but this certainty will come at the cost of ignoring the momentum of existing trends. To provide a complementary perspective, we will also forecast by extrapolation of existing trends. While a completely objective extrapolation is not possible, we work to reach as close as possible to this goal. One important issue is selection of time scale on which base the extrapolation. In the interest of objectivity we assume time symmetry, meaning that the next 20 years will be based on the previous 20 years. Sector level growth goes through business cycles month to several year scale. Previous analysis of long-term growth patterns of several global sectors suggests that for time scales greater than seven-ten years that aggregate growth rates are surprisingly constant (34). Thus a twenty year average should be a sufficient to average out business cycle fluctuations. This being said, we do not assert that the extrapolation is a likely future, simply that it is a reflection of what would happen should existing trends continue. A summary of best-guess, best/worst case scenarios, extrapolation and bounding approaches is shown in Table 1.

4. Extrapolation Analysis

This section undertakes the extrapolation of historical trends in production output (P(t)) and energy efficiency (e(t)) to characterize possible future energy consumption (N(t)) over the next twenty years. Our approach is to separately consider now P(t) and e(t) have evolved in the past twenty years and assume the same trends hold for the next 20. Note that this extrapolation assumes that industry growth and energy efficiency are independent. There is compelling evidence that this would not be a reasonable extrapolation for an entire economy (29) and that indeed efficiency improvements are a major enabler of economic growth. Note however that we are considering a single economic sector whose output is a fundamental requirement of many other sectors. For the purposes of extrapolation we thus argue that it is reasonable to assume that steel demand as an exogenous factor.

Extrapolation of production trends (P(t))

World crude steel production in 2007 was 1.34 billion metric tons, of which Chinese production accounted for 36% of the global total (6). Over the last twenty year period from 1987-2007 the average annual output growth of the industry was 10.8%. Questions regarding the accuracy of Chinese growth statistics aside, official real GDP in Yuan grew an average of 8.9% over the same period. Thus steel output grew faster than GDP by around 2% over longer time scales. Our extrapolation of production trends assumes constant growth at a rage of 10.8% from 2007-2027. Note that this is an extrapolation of the aggregate 20-year trend and that year-to-year variations are to be expected.

Energy intensity: e(t)

The first step is to construct a retrospective of energy intensity of the Chinese steel sector, the result of which appears in Figure 1. Data for this comes from Ministry of Metallurgical Industries (9) and has been adjusted to match international reporting practices following the work of Price and collaborators (1). Details of construction of this data set are in the Appendix. The main trend to note is rapid and sustained reductions in energy intensity over the last 20 years. This has been driven by modernization of the industry, intensified recently with the entry of China in 2000 to the World Trade Organization. Newly built steel facilities are in line with international best practice.

Naïvely approaching an extrapolation analysis would involve picking a representative curve (e.g. linear) and projecting efficiency out for the next 20 years. We argue that this would not be appropriate given China's industry is nearing current international best practice and that international best practice has not changed much the last 20 years. A more sensible extrapolation would involve China evolving first to best practice and then following global trends thereafter. To clarify trends in international best practice we gather and present data on trends in energy intensity of steel making in the U.S., Germany and Japan, also shown in Figure 1. Data sources are (10-15) and we explain the details of constructing this graph in Appendix. At first glance Figure 1 suggests that the U.S. industry has made the most improvements and currently has the lowest energy intensity among the three nations. We clarify that this is not the case. The essential difference is that is that the U.S. steel industry has undergone comparatively large structural change towards increased production of scrap-based EAF steel compared to ore-based BOF steel. This can been seen from Figure 2, which shows historical trends in the share of steel made from scrap using EAF in the U.S., Germany, Japan and China (6, 12-15). The U.S. industry has moved from a 15% EAF share in 1970 to 57% in 2006, versus a relatively constant share for Germany and Japan. In general it takes more energy to make steel from ore is than scrap, a good practice integrated BOF steel mill uses around 19 MJ/kg and an EAF plant uses 9 MJ per kg (19). Thus a steel industry relying more on recycling scrap will, with other factors constant, use less energy.

The American Iron and Steel Institute releases period reports detailing relative energy use of BOF versus EAF plants, this data was used to produce Figure 3 (15). First note the rate of efficiency improvement is significantly slower after factoring out the structural shift towards more recycled steel. Secondly, the absolute energy intensity of U.S. BOF plants is apparently higher than Germany and Japan. This suggests that the U.S. is only recently catching up in terms of efficiency and that the experience of Germany and Japan are more suitable for benchmarking trends in international best practice. Thus an extrapolation analysis implies that the next twenty years mirrors that last twenty: little to no change in the net energy intensity of steel-making. For our extrapolation we thus project recent improvements in Chinese steelmaking, which yields that international best practice is attained in 2010. From 2010-2027 we assume the energy intensity is 17 MJ/kg, which is best available practice for a steel sector producing 18% EAF steel.

Overall result: extrapolation analysis

To obtain an extrapolation for future net energy use we simply multiply respective extrapolations of P(t) and E(t). The result is shown in Figure 4. To provide context, historical behaviour from 1987-2007 are shown on the same graph. Two main factors underlie the dramatic growth in energy use shown the extrapolation. One is that recent steel sector growth has been particularly rapid, pushing up the 20 year average to the 11 percent range. The second is a plateau in energy intensity signifies no mitigating force of technological improvement on total energy use.

5. Bounding analysis

Bounds on future production of steel: P(t)

In this section we develop contingent lower and upper bounds for future steel production (P(t)) to 2027. As we will see, the bounding approach is less robust for economic growth related quantities as compared to energy intensity. This is because economic growth interfaces with larger social and technological systems and is also not constrained by thermodynamics as energy intensity is.

Contingent lower power on steel output: 6% annual growth

One could consider a lower bound contingent on a major failure in the global economy leading to stagnation or even falling GDP and steel production. In this analysis we are interested in energy futures assuming a functional world economy and set this as a contingency for the lower bound. We base a lower bound based on pessimistic forecasts of Chinese future economic growth and the steel production associated with this growth. Macroeconomists tend to believe that GDP growth will slow substantially in the next two decades. A state economist in China suggests that growth will slow to 7.8% in 2005-2010 to 6.2% in 2015-2020 (24). The forecasts of the US Department of Energy are similar, suggesting an average annual GDP growth of 7.2% from 2005-2015 and 6.4% from 2016-2025 (25). We assume a low-end figure of average 5% annual GDP for 2008-2027.

How does this translate into growth in steel output? Over time scales of 2-3 decades, steel growth has tended to exceed GDP growth by about 2% (e.g. see Section 4). For a lower bound, we add in a safety factor and assume that steel growth exceeds GDP by only 1%. This yields an lower bound of average 6% growth for steel production P(t) from 2008-2027.

Contingent upper bound on steel output: 20% average annual growth until cap reached, afterwards following cap

How to conceptualize an upper bound for steel production? Our approach is to first assume that dramatic growth of this decade continues. Growth rates since 2000 are in the 20% range are unprecedented in a basic commodity sector in modern experience and twice already rapid growth rates in GDP. It is difficult to believe such growth will be sustained over decades. Based on this we posit that annual steel production growing at 20% annually is a plausible upper bound. Again we reiterate the meaning of an upper bound means that exceeding this level is highly unlikely and does not suggest reaching this level is probable or even possible.

We think it possible however to constrain growth below 20% in the future while still maintaining a plausible upper bound. If 20% growth were to continue over a decade, China would not only have per capita domestic consumption higher than any nation in history but also supply the entire world demand for steel. We thus propose to cap Chinese steel production according to the formula

Cap (t) = Chinese population (t) max consumption per capita + Rest of World steel demand (t) [3].

When the 20% growth assumption reaches this time-dependent cap, we assume that the upper bound on Chinese steel production will follow the cap. To determine the maximum consumption per capita we assume that China will not exceed historian experience. Figure 5 shows trends in steel consumption per capita over time in different nations (6,21). The peak was attained by Korea and Taiwan of one ton per capita per year which we assume will be the maximum consumption per capita for China. To determine the steel demand of the world excepting China, note that historically this grew 1.1% annually over the interval 1987-2007 and 2.0% annually from 1997-2007 (6). We assume a growth rate for demand of the rest of the world for steel of 2% annually. For example, applying these assumption in formula [3] for t = 2015, the cap on domestic consumption is 1,400 million tons and steel for export 1,060 tons, for an upper bound production of the Chinese steel sector of 2,460 million tons (6, 23).

Bound on future energy intensity: e(t)

We proceed to develop quasi-bounds on future energy use in steel making in China. Constraints based on physical laws ultimately limit the attainable efficiency of steelmaking. The fundamental chemical reaction for producing iron from iron ore is

$2Fe_2O_3 + 3C \rightarrow 4Fe + 3CO_2$. [4]

The absolute minimum energy to carry out this reaction is given by the sum of the enthalpy of reducing the ore at room temperature (298K) and then heating the ore to its melting point (1813 K). The total of these two steps is 8.6 MJ/kg (4). In the same analysis, Fruehan and collaborators also estimated that the “practical” minimum to produce a hot rolled steel product is 9.1 MJ/kg. For an EAF using recycling scrap, the absolute minimum is 1.3 MJ/kg, while the practical minimum for a hot rolled product is 2.5 MJ/kg (Ibid).

Lower Contingent bound for e(t): rapid adoption of idealized technology

Our concept to develop a lower contingent bound for e(t) is to first assume that a technology is invented which realizes the theoretical minimum energy needed to make steel assuming an 80%/20% split of ore (BOF) and recycled (EAF) steel: 7.2 MJ/kg. Even if such a technology was available today, given sunken investments in existing plants it would take years for the industry to transform to the new technology. We thus postulate a lower bound for e(t) based on the contingency that the new technology is adopted to meet all new production requirements and to replace plants more than 20 years old. Achieving the theoretical minimum for the energy required for steel-making in the next 20 years is highly unlikely. This suggests we have a robust lower bound in this case.

Note that the adoption rate of the new technology depends on the growth rate of the industry. Since it is the product of lower bounds for production and energy intensity which yields the lower bound for net energy use, we construct e(t) based on the lower bound for P(t). This results an energy intensity which evolves from a value of 20 MJ/kg in 2007 to 7.3 MJ/kg in 2027.

Upper contingent bound for energy intensity (e(t)): static technology

What is an appropriate upper bound for energy intensity? We assume static technology: e(t) remains at it 2007 value of 20 MJ/kg. The contingency assumption here is that there are no major shifts in technologies or supply quality which would make efficiency worse than it is now. Note that this upper bound is not significantly different from the extrapolation of e(t). This is because there has not been significant improvement in international best practice for the last several decades.

6. Bounds on future energy demand of China's iron/steel sector 2007-2027

Combining the growth and energy intensity bounds from the last section, Figure 4 shows results for projections of lower and upper bounds on net energy demand from 2007-2027, along with the extrapolation results from Section 4. The upper bound shows dramatic growth in energy: averaging each year for the period yields a figure of 9.4% annual growth. Note that the extrapolation has an even higher final energy demand: this is because no cap on steel production was built into the extrapolation and growth of 108% per year yields total production on 3,800 million tons in 2027, well above the cap. For the lower bound, rapid adoption of the idealized technology was effective at mitigating net demand for part the early phase but net demand begins to grow again in 2015 as the theoretical minimum energy for steel making is neared. The steel sector in 2027 still uses about 20% more energy than it did in 2007 and will continue to rise unless demand is mitigated.

Our interpretation of these results is that while plant-level efficiency can be expected to mitigate a degree of energy use, this strategy by itself is unlikely to result in net reductions or even stabilization of carbon emissions from the sector. The lower bound which achieves temporary stabilization requires rapid adoption of a technology which has yet to be realized in the laboratory, much less at an industrial level.

7. Discussion: systems efficiency

The results suggest that plant-level efficiency improvements alone do not look promising as a dominant strategy to mitigate carbons emissions and other impacts of energy use in the sector. It is possible that the situation is similar in other energy intensive heavy industries, such as cement making and aluminium smelting. Given this situation, what is an appropriate portfolio of strategies to manage impacts? One obvious possibility and indeed the focus of much the energy community, is shifting towards more renewable, low-impact sources of energy. Restructuring the energy supply in China and elsewhere is discussed elsewhere and we do not here offer any addition to this debate.

Instead we pose the question of the implications of this result for demand-side strategies. In particular, if indeed plant-level efficiency can only make a modest contribution, does this suggest that efficiency overall is less important a strategy? One important point is that there are many other industrial sectors and products (such as automobiles) for which we can expect much more dramatic improvements in efficiency. Our focus here, however, is on the potential to broaden the concept of efficiency to incorporate a systems perspective. In fields such as Industrial Ecology and Life Cycle Assessment, methods and tools are being developed to assess and manage the life cycle environmental impacts of systems delivering products and services, rather than focusing on the plant or product level (26, 27). For example, the Materials Input per unit Service (MIPS) is a perspective which cast the challenge of product design in terms of focusing on what materials are really needed to realize the service delivered by a product (e.g. washing clothes) as opposed to the product itself (e.g. a washing machine) (28).

Considering the current context, much of the demand for steel in China is driven by the demand for building buildings and transport infrastructure and steel-intensive durable goods such as automobiles. There are different levels at which the efficiency of delivering the services from steel may be considered. One is the question of what alternative materials and combination of materials might yield the same service for lower impact. At another level, while there may be no obvious alternative to standard steel in many cases, such as in building frames, efforts can certainly be made in design and deconstruction practice to ensure this steel is recycled at demolition. At a broader level, steel demand is driven by macro-level decisions such as investments in transport systems. The personal automobile based transport system is probably much more steel intensive than public transit. The point here is than in addition to obvious direct impacts such as fuel used during transport, the life cycle impacts of different choices are non-trivial.

It could thus be fruitful to consider the systems level efficiency of steel use in its major applications in society. One can envision, for example, assessing transport system alternatives in terms of person-kilometer delivered per demand of steel and other major materials. Plant-level efficiency improvements would become part of a larger portfolio of efficiency options, and alternatives assessed in terms of what delivers the most improvements with least effort.

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Appendix: Details on estimation of time series energy intensities for China, U.S., Germany and Japan

Given that national governments and industry associations gather statistics on consumption of different fuels in steel making as well as output of the sector, characterizing trends ought to be a simple matter. There are differences in statistical definitions and sources which complicate the situation. The most inclusive database, *Energy Balances of OECD Countries*, developed and maintained by the International Energy Agency (IEA), differs greatly from other sources (10, 11). While it has the virtue of including data on energy use for steel industries in the four nations of interest from 1970 to the present, figures can differ from other sources by around a factor of two. For example, Japanese national data reports the net electricity consumption of the Japanese steel sector in 1994 to be 35 billion kWh while the IEA database reports 64 billion kWh (10, 12). While the source of this and other discrepancies between data sources is not clear, part of the explanation surely lies in differences in definition of what industrial activities are included the definition of the steel sector. We will thus base on approach on other databases.

Researchers have shown that the standard Chinese database, developed by the Ministry of Metallurgical Industries (MMI), is based on definitions of energy use substantially different from many other nations (1). One aspect is that additional activities, such as energy use by workers in co-located housing, are also included in sector energy demand. Another issue is that the statistics double count coal and some forms of co-products produced and in the mill, such as waste gases and heat [Ibid]. Price and collaborators develops corrections to match the MMI statistics to international standards, which yielded adjustments ranging from 20-28% over the period 1985-1996. For our analysis, we take these figures as the base for this period, and then extend them using more recent MMI statistics to 2003, assuming that the correction factor of a 20% reduction remains constant from 1996-2003.

To characterize energy intensity trends in the U.S., Germany and Japan our approach to dealing with this issue is to first take the international database developed by the International Iron and Steel Institute (IISI) as standard [13, 14]. It includes data on energy use of steel industries in the U.S., Germany and Japan (but not China) from 1980-1994 for Japan and Germany and from 1980-1991 for the U.S. Along the lines of previous analysts (2), we argue that an international industry organization is well positioned to rationalize the different national data sources into a common framework.

For this report, however, we should have a longer range of available data than is available in this database. We extend the coverage by drawing on U.S. (15) and Japanese (12) national databases, using this data to generate *relative* shifts in intensity beyond the range of the IISI database. Results of these analyses are shown in Figure 1.

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Table 1: Comparison of traditional scenario, extrapolation and bounding approaches

Approach	**Summary**
Best-guess forecast	Analyst guess of most likely future
Best/worst case scenarios	Analyst guess of possible range (worst ≤parameter ≤ best)
Extrapolation	Forecast based on continuation of existing trends
Bounding	Find upper and lower limits on values the parameter *cannot* (or very unlikely to) take (lower < parameter < upper)

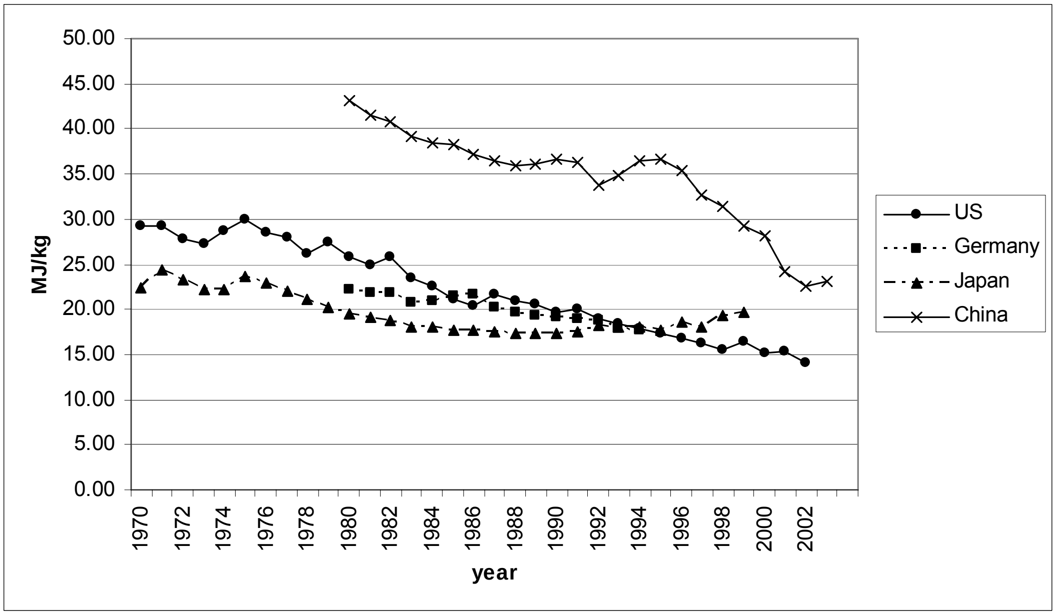
Figure 1: International trends in the energy intensity of steel making: 1970-2005

Figure 2: International trends in shares of scrap-based Electric Arc Furnace (EAF) steel production: 1970-2005

Figure 3: Energy intensities of U.S. steel-making: ore-based Basic Oxygen Furnace (BOF) and scrap-based Electric Arc Furnace (EAF) technologies

Figure 4: Extrapolation and bounding analyses of future net energy demand of the Chinese steel sector (data from 1987-2007 is historical, 2008-2027 are projections described in Sections 4 and 5).

Figure 5: Steel consumption per capita from 1974-2004 for seven nations



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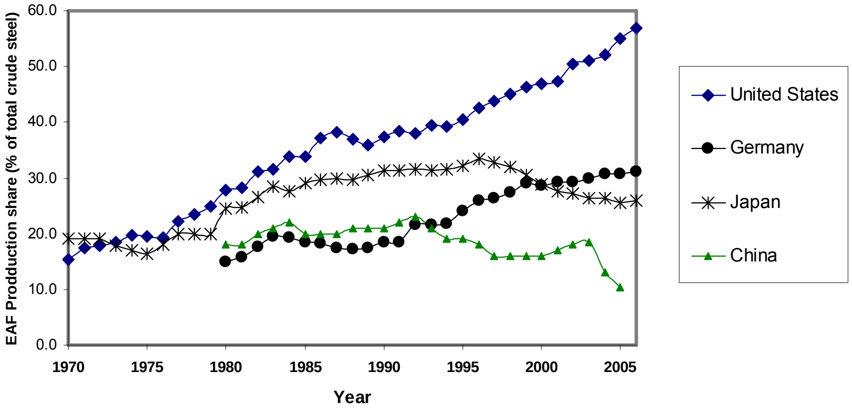


Figure 2: International trends in shares of scrap-based Electric Arc Furnace (EAF) steel production: 1970-2005

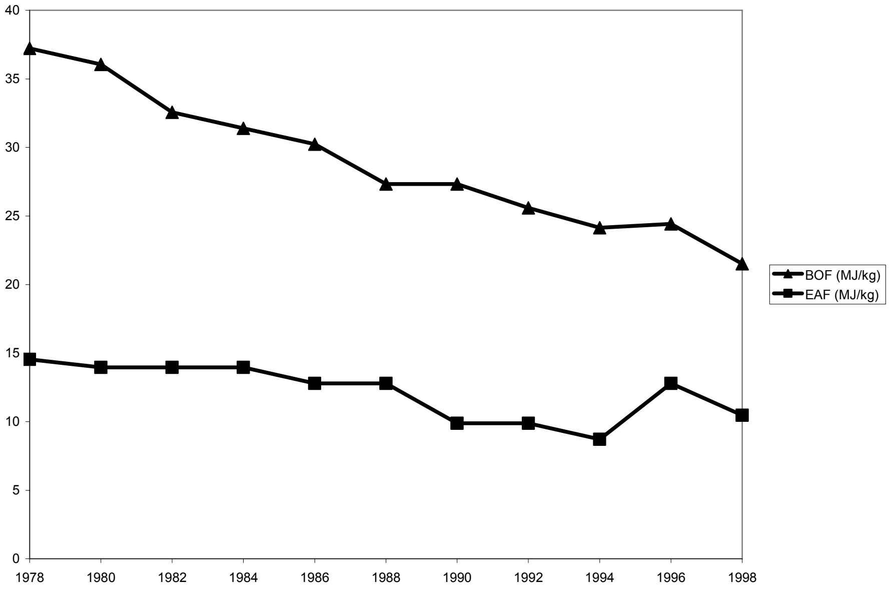
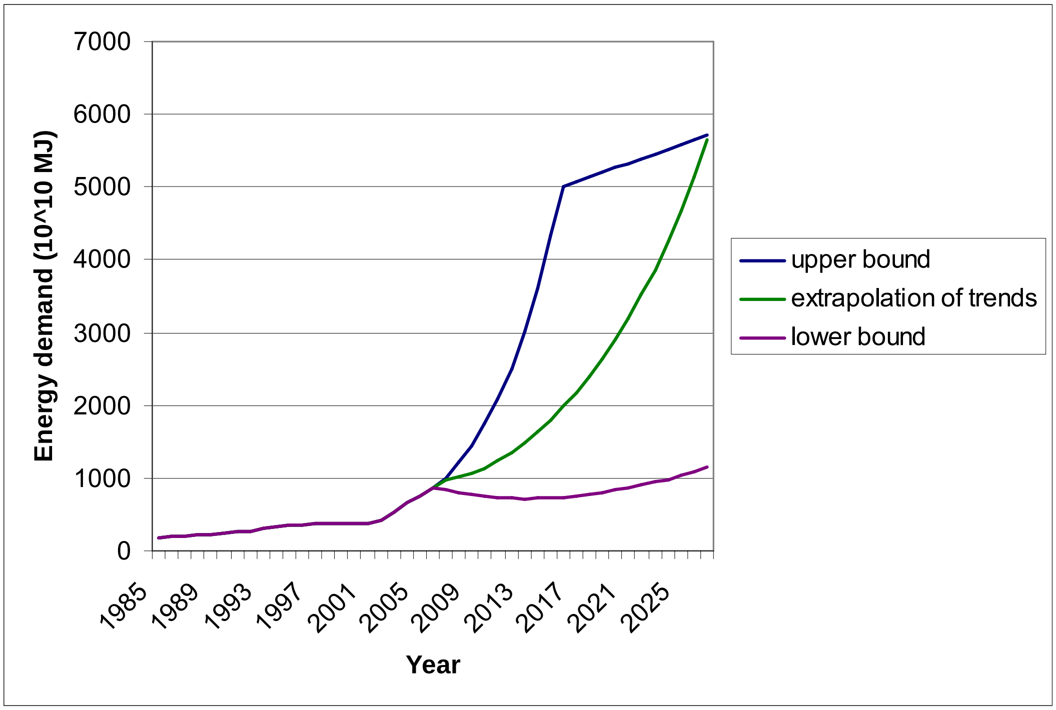


Figure 3: Energy intensities of U.S. steel-making: ore-based Basic Oxygen Furnace (BOF) and scrap-based Electric Arc Furnace (EAF) technologies



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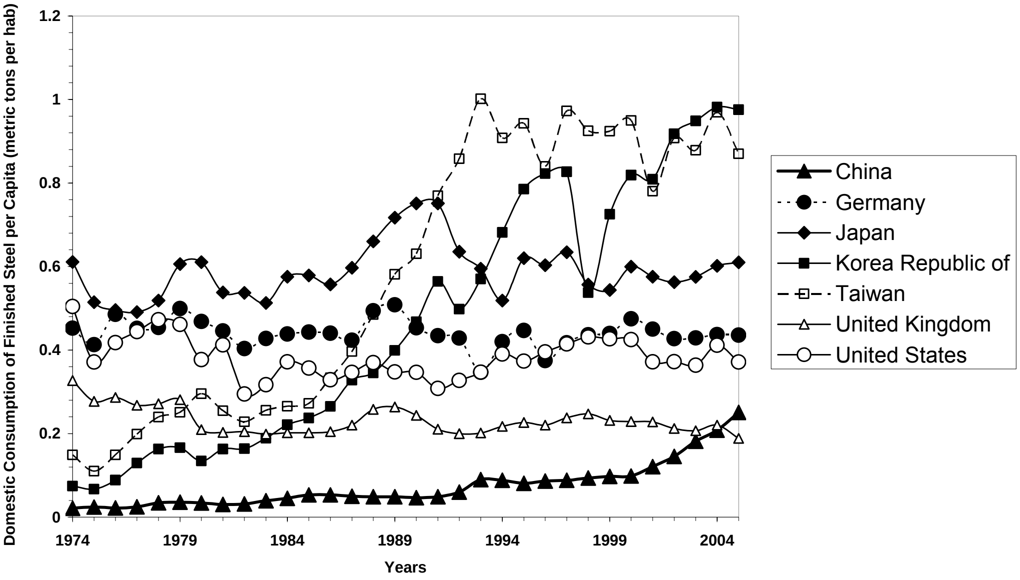

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