A Market Transformation Strategy for Highly Efficient Steel Making

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ABSTRACT

This paper describes a highly energy-efficient technology for direct steel making, and discusses a market transformation strategy for introducing it into the U.S. steel industry. The steel industry is among the most energy-intensive manufacturing sectors, accounting for over 2% of the total energy use in the U.S. and 6.7% of total energy consumption in manufacturing. The average physical energy intensity of U.S. steel production is about 23 GJ/t. Through patented technology being supported by the U.S. Department of Energy (DOE) it may be possible to leapfrog over incremental technologies and reduce the average energy requirements of steel making by approximately 40%.

Specifically the paper proposes direct steel making by combining microwave energy, electric arc, induction, and exothermal reaction heating technologies. Large energy savings can be accomplished by elimination of pellet sintering, shipping weight and limestone requirement reductions, and elimination of the coke oven, blast furnace and basic oxygen furnace. Along with these energy savings are commensurate environmental benefits. These include substantial reductions in CO_2, conventional and toxic air pollutants, water consumption and water pollution, slag, and coke. After a brief review of the barriers to adoption of major energy-efficient technologies in the steel industry, a strategy for U.S. steel-making is described that is designed to transform its process market toward use of the highly-efficient technology. The experience of electric motors and compressed air sectors is considered, which are among the few examples of successful market transformation with industrial energy technologies.

Introduction: Structure of the Steel Industry

The iron and steel industry is one of the largest energy consumers in the U.S., accounting for 6.7% of the total manufacturing energy use and over 2% of all energy used in the nation in 1998 (EIA 2001). This industry is thus a natural target for efficiency improvements. Yet it is a tale of two sectors -- large, older, less-efficient and less profitable integrated steel mills, and smaller, younger, more-efficient and more profitable secondary steel mills ("minimills"). The 20 integrated steel mills are concentrated in the Great Lakes region near ample supplies of coal, iron ore, large port and rail facilities, and important customers such as auto-makers. The 122 minimills in contrast are often found closer to specific end-use markets, but generally near to abundant supplies of low-cost scrap metal and low electricity rates (Worrell, Martin & Price 1999). The largest number of minimills is located in Pennsylvania, Ohio, Illinois, Indiana, Texas, and Tennessee.

Integrated steel mills produce pig iron, coking coal, and steel products at over twice the overall energy intensity and emissions rates of secondary mills, and have several significant energy-using processes: the blast furnace, hot rolling mill, and the boilers (including cogeneration) (Worrell, Martin & Price 1999). The major energy sources are coal and natural gas. While the energy consumed to make steel in the basic oxygen furnace

(BOF) is only 2.7% of the total energy required to make steel in an integrated mill, it is dependent upon the molten iron production of the energy-intensive blast furnace, by far the most energy-intensive process at the mill. Secondary-steel making, while taking advantage of the large energy savings made possible through the recycling of steel scrap, requires about 34% of its total energy use in the electric arc furnace (EAF). Around 90% of the final energy consumption in the EAF is in the form of electricity, while most of the remaining energy use (40-42% of the total) takes place at the hot rolling mill (Worrell, Martin & Price 1999).

Gradual efficiency improvements at steel mills have lowered their overall energy intensity by almost 50% since 1975, as has adoption of lower energy-using processes such as cold rolling and finishing mills. Most of this reduction in energy intensity can be attributed to:

- elimination of open hearth furnace steel-making by 1992;
- shutdown of older and less efficient mills;
- near total conversion to continuous casting;
- process improvements that have increased steel-making yields;
- higher capacity utilization; and
- increased production of steel in the EAF.

Further adoption of cost-effective energy efficiency technologies and measures (assuming a 30% real discount rate) could result in an additional reduction of energy use by 18%, with up to 50% technically feasible (de Beer, Worrell & Blok 1998; Worrell, Martin & Price 1999; Stubbles 2001). Given their generally greater profitability, minimills have the greatest potential for adoption of energy-efficient technologies and measures without market intervention. In contrast, with the much larger energy-intensity of the integrated mills, these plants hold the most promise for overall efficiency gains and pollution prevention as long as they continue in use.

This paper addresses a market transformation toward highly efficient steel making. It begins by describing the two major steel manufacturing process markets, namely BOF and the EAF, and introduces a novel method that uses microwave and exothermal heating technologies. Following this the general barriers to energy-efficiency investments in industry are discussed. The paper then outlines the general elements of a market transformation strategy for promoting the early commercialization of clean and more energy-efficient technologies. This includes a clear agreement upon the goal (or goals) of the transformation, a coherent set of actions required to achieve it, and the economics of the strategy. A steel-making market transformation strategy is then described. As part of this, the potential roles of several major market players and strategic partnerships in this industry will be reviewed. The paper concludes with several recommendations for policy-makers.

Process Technology Markets

For the last half century the steel industry has used largely three production processes: the open hearth furnace (OHF), EAF, and the BOF. The technology of choice for over 50 years, the OHF went from market dominance to extinction over 30 years and was phased out of U.S. mills by 1992 (though it is still used in many foreign plants). The rapid decline and disappearance of OHF production is attributable to low productivity, low energy efficiency, tighter air emissions standards, and competition from modern and foreign steel plants. Thus the other two production technologies have taken up the slack in steel production (AISI 2002).

Basic Oxygen Furnace

The Linz-Donawitz or basic oxygen furnace (BOF) was introduced in 1952, or a half century after the EAF. Its introduction had been delayed until industrial methods became available for making large amounts of oxygen. In a BOF a charge of pig iron and scrap steel (usually less than 25% of the total material input) are heated and refined with small amounts of manganese and fluxes to produce crude steel. In this process, pure oxygen is blown down through a water-cooled lance from the top of the furnace into a converter. Bottom-blowing and combined top and bottom-blowing BOFs also are used on a small scale. An improved version of the Bessemer process, the BOF moved more quickly to broader market applications than what was to become its main process competitor. The BOF has a quicker refining time and much greater energy efficiency than the OHF. Other advantages of this process include: the gas volume to be heated and compressed is much smaller, the metal does not dissolve in the presence of nitrogen, and the by-product heat from top gas recovery melts 20-30% additional scrap input (de Beer, Worrell & Blok 1998, 130).

Oster (1982) conducted a plant-specific econometric analysis of the rate of adoption of the BOF among several large firms in the U.S. steel industry in the post World War II period. She found that differences among firms in the rate of adoption are attributable to the characteristics of the adopting plants that determine the profitability of the BOF, as well as firm size. Other analysts, such as Kwasnicki and Kwasnicka (1996) have used longer-term evolutionary models to explain the evolution and adoption of steel-making technologies. While the share of U.S. steel produced by the BOF has not changed much over the past 30 years (and currently accounts for 53%), its capacity and output have significantly declined over this period as the EAF and foreign imports have gained increased market shares (AISI 2002). The BOF, however, is still the preferred technology to manufacture flat steel products (Crompton 2001).

Electric Arc Furnace

While the electric arc furnace (EAF) was first introduced in the late 19th century its application was initially limited to specialty steel-making (De Beer, Worrell & Blok 1998, 130). Temperatures of about 1600 ° C are required to melt, mold, and refine the steel scrap, resulting in high-energy requirements. The overall energy intensity of the EAF, however, is greatly dampened by its ability to be charged with almost 100% iron and steel scrap, although as production and recycling rates have increased the availability of high-quality scrap decreases. These factors slowed the growth rate of the EAF. Steel production in the U.S. by the EAF did not exceed a few million tons per year until after World War II.

Several technical changes have improved and quickened the performance of the EAF in the past several decades. In addition, a near doubling of capacity utilization has occurred since the early 1980s, lowering the heat loss per ton of furnace charge (Margolis and Sousa, 1997). As a result, the electricity intensity of the EAF fell by about 2.3% per year over 1965-95, from 650 to 350 kWh/t (Crompton 2001). The EAF can now produce a larger variety of steel products. A typical minimill will include one or two EAFs, a continuous casting machine, and a rolling mill. Since the minimills can operate on a smaller scale than integrated steel mills, use of the EAF results in lower overhead (as well as lower capital) costs. Because of these improvements the EAF has gradually increased its output and U.S. market share to its current 47%, as production by the OHF ramped down and cumulative raw steel production increased since 1965 (AISI 2002).

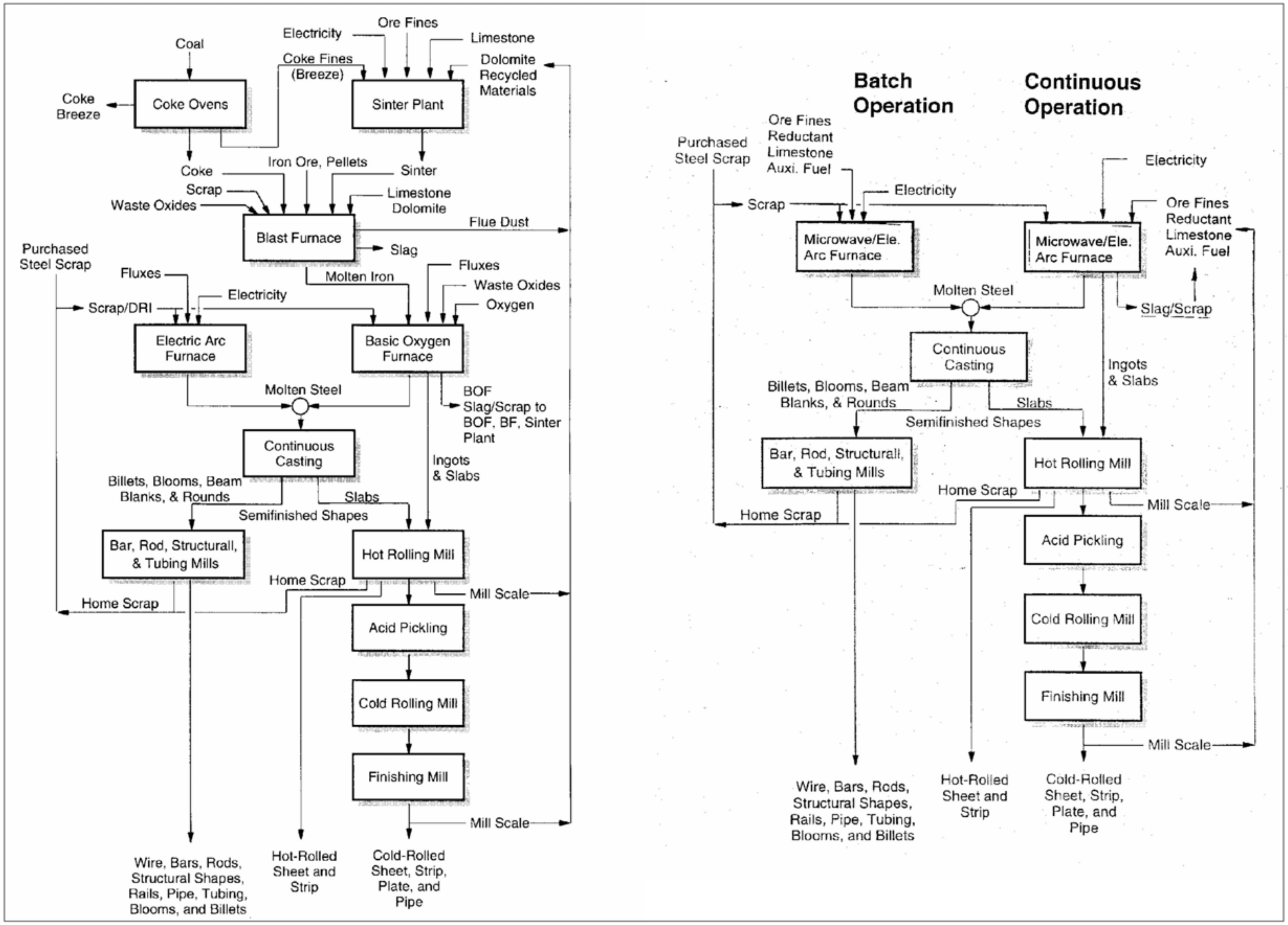
It is generally assumed that the steel market share captured by EAF production will steadily rise over the next 10-20 years. For example, Crompton (2001) forecasts that the EAF will account for 50.1% of total U.S. steel output in 2010 while Ruth and Amato (2002) forecast a 53% base case market share by 2020 and an 80% maximum. The econometric model of the latter assumes that all new capacity additions by the U.S. steel industry would be made in the EAF sector, since there are many more opportunities for future efficiency improvements with the EAF than with the BOF. This analysis found that a "cost of carbon" policy such as a carbon tax or tradable carbon permits generally would be more effective in meeting an emissions reduction goal than would a performance goal (technology-led policy) on new EAF capacity. This is because the latter policy would do little to encourage a shift in production away from the BOF. While this model does not account for the introduction of novel technologies such as microwave and exothermal heating, a cost of carbon policy would similarly encourage its more rapid introduction into the steel market.

Direct Steel-Making With Microwave Heating

Direct steel making through the use of microwaves, EAF, and exothermal heating has been patented and proven in the laboratories of Michigan Technological University. The technology can produce molten steel directly from a shippable agglomerate consisting of iron ore concentrate, pulverized coal powder, and limestone as a fluxing agent. The coal serves as a reducing agent for iron oxides and as an auxiliary heat source via exothermal reaction in the presence of oxygen. This process will eliminate many current intermediate steps such as coking, sintering, blast furnace iron-making, and BOF steel-making. The proposed technology is based on the unique ability of microwaves to rapidly heat steel-making raw materials to elevated temperatures and then rapidly reduce iron ore to metal by volumetric heating, which based on laboratory analysis can cut production time by over 50%. The technology is viable because iron ore and carbon are excellent microwave absorbers. This heating method, augmented with EAF and exothermal heating reactions, can produce molten steel for either batch or continuous operations (Figure 1).

In the first application an auxiliary microwave heating device is added to an existing EAF so it can use iron ore directly as the feed material, instead of being dependent on steel scrap and direct reduced iron. A port is created in the cover of a conventional EAF to introduce microwaves into the furnace chamber through a wave-guide. A charge of iron ore-coal-limestone (ICL) agglomerate is then loaded into the chamber. Microwave energy is introduced through the wave-guide, where the agglomerates absorb microwave energy and their temperature rises to the point of coal ignition. Exothermal heat from the carbon-oxygen

Figure 1. Comparison of conventional steel-making with proposed direct steel-making technology



reaction will be generated to further increase temperature. The iron ore will then react with the reductant to become directly-reduced iron. The EAF electrodes will then descend to provide electric arcing energy to the material, producing molten steel and slag. The molten slag and steel will be removed by conventional methods utilizing the tilting of the furnace chamber. Thus, the furnace can use feed ranging from 100% scrap to 100% ICL agglomerates. In the second application a stationary microwave EAF will be developed, in which iron ore, coal, and limestone agglomerates will be continuously charged in the furnace through a feed chute. The resulting molten steel and slag will be continuously discharged through respective tap holes.

Microwave steel-making has many important advantages. It has the potential to save roughly 40% of the energy used by conventional steel-making; dramatically reduce or eliminate emissions of CO_2, SO_2, NO_x, VOCs, dust and fine particles, air toxics, and coke; substantially cut water use, pollution, slag and emission control costs; and lower production costs by 35%.

While the proposed microwave steel-making technology has not been commercially demonstrated, significant progress has been made in related applications. For example, in 1997 EMR Microwave Technology Corp. built a pilot microwave metallurgy system with two reactors and 75 kW generators in Fredericton, New Brunswick, Canada to calcine pyrite and refractory gold ores and concentrates. This plant can process 5-20 tons of concentrate per day. A larger plant capable of processing 1000 tones of concentrate per day is in the design stage, and 100 MW(e) and 10GW(e) high energy microwave systems are under development.

Barriers to Energy-Efficient Investments in Industry

It is well known that many potentially profitable investments in energy efficiency with rates of return in excess of 30% are not made immediately, if ever, by firms and individuals. Many economists have attributed this behavior to hidden transaction costs and other hidden costs, and urge restraint from market intervention. Another plausible explanation for the lack of investment may be imperfect access to capital markets, often the case for expensive technology.

DeCanio (1998), Brown (2001), and Geller (2003, 33-45), among others, have provided broad perspectives on why firms do not always invest in theoretically attractive energy-efficient measures. This research has expanded the theoretical framework for this problem beyond simple economic explanations. These studies are highly applicable to the U.S. steel industry. The authors reviewed numerous reasons why profit-maximizing firms may not undertake profitable investments in energy-efficiency technologies, including: limited supply infrastructure, at least initially; product quality problems; firms do not behave like individuals; failures of complete profit maximization or inadequate purchasing procedures; asymmetric information and misplaced incentives between shareholders and management; problems of focus, training, and attention on seemingly small energy savings; selection bias in estimating potential investment returns; lack of money or financing; pricing or tax barriers; regulatory or utility barriers; and political obstacles.

DeCanio (1998) conducted extensive multiple regression analysis of lighting upgrade investments undertaken by over 3,600 projects in the U.S. Environmental Protection Agency (EPA) Green Light's program. He found that organizational and institutional factors (type and size of organization, method of lighting survey and analysis, type of equipment provider and facility, financing method, etc.) were at least as important as economic ones (lighting hours, payback period, electricity prices, etc.) in explaining the investment behavior of the firms, although 76% of the total variation was not explained by his analysis. The study concluded that major impediments to energy-efficient investments exist, which were internal to private and public-sector organizations. Indeed, much organizational adaptation may be required to realize the full benefits of innovative energy saving technology (DeCanio, Dibble & Amir-Atefi 2000).

Elements of the Market Transformation Strategy

Market transformation programs (MTPs) are called for in order to increase the demand for and promote early commercialization of clean and energy-efficient technologies that exhibit substantial "learning-by-doing". While considerable experience has been gained with market transformation strategies for popular consumer technologies and products in residential and commercial markets (refrigerators, multiple-glazed windows, computers, office equipment, electronic ballasts, compact fluorescent lamps, etc.), little such experience exists in the industrial sectors. This is because industrial firms have more direct incentive to adopt energy-efficient technologies, and operate in a highly competitive environment. Most of the industrial experience with market transformation is with electric motors and compressed air systems.

A successful steel-making MTP will require a more active and effective network of stakeholders, including steel mills, scrap haulers and brokers, equipment vendors, trade associations, government officials, research specialists, and perhaps others. While a collaborative partnership already exists, it could be strengthened and energized. The U.S. Department of Energy (DOE), its national laboratories, and trade associations such as the American Iron and Steel Institute (AISI) will need to be heavily involved during the period of market transformation in order to keep the key players active in the network.

Friedman et al. (1996) categorized the elements of a market transformation strategy into two broad groups: 1) direct market actions, which influence behavior and lead directly to enhanced technology or system performance and a reduction in energy consumption, and: 2) infrastructure/enabling actions, which lay the foundation for follow-up actions with direct market results. These latter actions usually address knowledge, information or awareness deficiencies in a specific market. Many of the actions may need to be implemented together, either on the supply-side (market-pull actions) or demand-side (market-push actions). Several possible actions that may be applicable to the steel-manufacturing market will be discussed.

Direct Market Actions

- <u>Voluntary Commitment and Recognition Activities</u> - Voluntary energy-efficiency programs such as Green Lights and Energy Star are well known for their high levels of adoption and the public relations value of official recognition for being a green corporate citizen (Brown, Webber & Koomey 2000). While the pace of adoption of highly efficient steel-making is likely to be slow given the level of capital commitment required, the value of a steel challenge and recognition program for energy and environmental accomplishments should be considered.

- Financial Incentives - Financial assistance offered by electric utilities to industrial end users to buy energy-efficient technologies, while rarer in the current era of utility deregulation and restructuring, is still attractive in jurisdictions with limited power reserves or sharp load peaks and valleys, such as parts of the Northeast and California. Utilities may benefit from providing time of use rates or lower demand charges, e.g., to smooth out their load profile through adoption of more energy-efficient technologies by large end users. In addition, state agencies may find that tax incentives to encourage the adoption of highly energy-efficient technologies can be an important component of policies to control air pollution or greenhouse gas emissions.
- Encourage Early Equipment Retirement - Steel-making equipment is usually used for several decades. With many U.S. steel facilities finding it difficult to compete in the global marketplace, it has become much more difficult to justify early equipment replacement, leading to a "Catch 22" situation. Consequently, it may be desirable to provide government financing support, rebates, or tax credits for early retirement of existing steel-making equipment, perhaps of a specified vintage (e.g., not so old that it would be cost-effective to phase out a furnace without additional incentives) or range of operating efficiency.
- Voluntary Certification - New product vendors will probably emerge in the market to offer highly efficient steel-making technology and products. The potential buyers of the technology would benefit from an independent, third-party assessment of the competence of these vendors, especially in the early stages of a market transformation. A voluntary product certification system can provide a convenient means of identification of vendor proficiency or product quality. Several organizations could provide this service, such as trade associations, manufacturing extension agents, a non-profit organization, among others. The DOE or EPA may not want to provide this service because of potential liability associated with such assurances. While such product certification would be in line with the Energy Star Program, the much larger technology cost raises new risks if the product fails.

Infrastructure/Enabling Actions

- Research and Development - While microwave heating is commonplace it is not yet commercial in the steel industry. Thus, a minimum level of research support, probably from the DOE, will need to be continued in order to refine the technology during the market transformation period.
- Demonstrations - Demonstrations of new steel-making technology, either through additional showcase events at individual steel mills or trade shows, will allow potential users a first-hand look at process innovations. The demonstrations would initially be made at pilot plants before the new technology is more widely adopted by the industry.
- Training, Education and Technical Assistance - Since it uses a common consumer technology the application of microwave heating in the steel industry is unlikely to be complex. Nevertheless, because of its relative novelty in industrial settings training

manuals, short courses, or government or industry-sponsored technical assistance programs may still be helpful to consider.

- Information Systems and Databases - New users of novel direct steel-making technology will need to compare the equipment's performance to an industry standard. This type of data need will be especially critical early in the market transformation process, and could be addressed along with other technical assistance needs. Especially important would be a database on the energy requirements of the new manufacturing system, along with expected quality specifications of the various steel products.
- Decision Support Tools - While the adoption of novel direct steel-making technology is expected to lead to large cost-savings and reduction in pollution and energy use, many mills have difficulty attracting investment capital and will need to carefully evaluate major purchase decisions. For these firms a decision support software package that considers company or plant specific investment criteria and discount rates will be invaluable in providing guidance on optimal plant performance. The EPA and the DOE have provided decision support tools to businesses for over a decade in environmentally beneficial programs such as Green Lights, Energy Star, and Motor Challenge. A similar program could be easily developed for steel making, perhaps called Energy Star Steel, Steel Challenge, Green Steel, etc.

Goal of a Steel-Making Market Transformation

The goal of the proposed steel making MTP is to cost-effectively achieve a 50% reduction in energy use. To achieve this result, the shift toward increased production with the EAF needs to be accelerated, thereby lessening the need for iron making in the blast furnace. With conventional steel-making technology, however, it is not possible to totally eliminate the need for iron making. By combining use of the EAF with microwave and exothermal heating technologies such an advance in direct steel making may indeed be possible (Figure 1). The components of the market transformation are based on elements of a successful generic MTP, and the steel-making process in particular.

While transformation of a market to greater energy efficiency can be complex, much of the groundwork has already been laid by the DOE through its Steel Industry of the Future Program (though the DOE has not adopted the 50% reduction goal). The DOE's Office of Industrial Programs (OIP) in the Office of Energy Efficiency and Renewable Energy and its national laboratories have worked closely with the steel industry, academia and others to achieve common goals such as increased process efficiency, production efficiency, and recycling. The industry's broad goals contained in the 1995 vision report "Steel: A National Resource for the Future" led to an R&D compact with the DOE to create a voluntary collaborative research partnership. The key industry partners are the AISI and the Steel Manufacturers Association (SMA). The DOE signed a cooperative agreement with the AISI in 1997 to provide joint industry-federal funding to support this vision. Such cooperation is important because less than half of the steel companies that have identified a given technology as critical have significant R&D programs addressing the technology (Fruehan 1997). In addition, a tactical long-term research, development & demonstration (RD&D) agenda with key milestones and performance targets was released in 1998 and updated in 2001 (AISI 2001).

The Technology Roadmap has guided the OIP in funding R&D projects since 1998, including the Steel Industry Research Challenge initiated in 2000, which is sponsoring the novel direct steel-making project that combines microwave heating with the EAF. Over $70 million in total R&D support has been committed since 1997, with the OIP providing about two-thirds of this total. Several showcase events have been held at steel mills since 1998 to allow the industry to gain a close look at advanced, energy-efficient technologies and practices.

Economics

Despite an impressive track record in supporting clean energy technologies (DOE 2000), the federal government has occasionally been criticized for inappropriately picking technology or market winners and losers. Many new energy technologies in fact fail to find a market niche, though clean energy technologies can justify government support. Such debate calls for caution and analytical rigor in selecting energy technologies for market transformation and an important role for economic analysis. Duke and Kammen (1999) provide a general economic framework for assessment of MTPs, while conducting a benefit-cost analysis for three such energy programs in particular (electronic ballasts in EPA's Green Lights, the World Bank's photovoltaic market initiative, and the U.S. Federal grain ethanol subsidy). They argue for government support for priority clean technologies that meet five criteria (p. 17):

1. Excellent prospects for long-term market penetration once "subsidies" end;
2. Potential for relatively fast cost reductions as indicated by a favorable "progress ratio" and relatively low cumulative production to date;
3. Elastic market demand;
4. Public access to high-quality data about 1-3; and
5. Ability to displace substantial negative externalities (e.g. environmental or military security).

While microwave steel-making only meets the first and fifth (and perhaps the second) criteria at present, the prospects for meeting the others are good once the market develops.

Production cost-reductions result from the interplay of several factors: 1) Technological progress; 2) Input price changes; 3) Internal efficiency improvements; 4) Learning-by-doing that spills over among firms; and 5) Economies of scale. While cumulative production experience with the energy technology in question facilitates improvement in worker skills and reduction in unit input costs (though at a diminishing rate), these gains would not be appropriable with proprietary learning and thus not without the MTP. This learning improvement is often measured as the:

$$\text{Progress Ratio} = [a(2\bullet q(t)/q(0))^{-b}] \,/\, [a(q(t)/q(0))^{-b}] = PR = 2^{-b} \quad (1)$$

where a = unit cost at t = 0, q(0) = cumulative production by the firm at t = 0, b = the rate of innovation, or the learning parameter; thus for each doubling of cumulative production the cost per unit decreases by (1 - PR) percent.

Duke and Kammen (1999) capture this learning with a benefit-cost analysis framework that accounts for indirect effects of the MTP, and assumes a fixed 20-year time horizon and a 5% social discount rate. They assume that a price reduction will be induced via the "experience curve", or the rate at which manufacturers are able to reduce costs over time with additional production, which will result in a market demand response that further lowers the technology price. To account for indirect effects in estimating marginal program costs a price elasticity of demand formula is used:

$$Ep = [(Q_1 - Q_0)/(Q_1 + Q_0)/2]/[(P_1 - P_0)/(P_1 + P_0)/2], \quad \text{where:} \tag{2}$$

$$(Q_1 - Q_0) = Ep \bullet [(P_1 - P_0)/(P_1 + P_0)/2] \bullet (Q_1 + Q_0)/2, \text{ thus:} \tag{3}$$

$$\text{indirect effect} = Ep \bullet [(P_{MTP} - P_{BAU})/(P_{MTP} + P_{BAU})/2] \bullet (Q_{MTP} + Q_{BAU})/2 \tag{4}$$

where Ep is exogenous and the subscripts MTP and BAU refer to Market Transformation Program and Business as Usual scenarios, respectively. The cumulative industry production for each period Q(t) equals the sum of Q(t - 1), current sales directly attributable to the MTP, and the indirect effects. Current price, accounting for indirect effects from equation 4, is derived by substituting the cumulative production (Q (t)) into marginal cost equation 5 and using the parameter b from equation 1 based on practical experience (e.g., the PR has been estimated at 0.68-0.82 for the photovoltaic cell industry and 0.89 for electronic ballasts):

$$\ln(MC(q(t))) = \ln(a) - b \bullet \ln(q(t)/q(0)) \tag{5}$$

To estimate marginal program benefits the authors add a carbon tax to account for the un-internalized negative externalities of global climate change to the change in consumer surplus. The primary MTP benefit equals the price reduction times the production level at the BAU price that would have been expected without the MTP plus the indirect demand effect. The indirect demand effect will continue until the product market saturates, or unit costs reach a hypothetical minimum.

The Proposed MTP

While there are many possible actions that can be taken to promote the early commercialization of highly efficient steel making using microwaves, five categories of priority actions have been identified (Table 1). Actions were selected that can offer the greatest potential leverage and yield the largest technical opportunities (cf. Friedman et al. 1996). While this action set should be refined and updated over time, it provides a framework for initial discussions between the DOE, steel companies, AISI and other stakeholders. Ideally, the DOE would adopt this proposal as part of its Technology Roadmap for the steel industry.

Table 1. Proposed Market Transformation Actions for Efficient Steel-Making

Action Category	*Leading Actions*
Research, Development & Demonstration	• continue research & development • commission a pilot plant • showcase the new technology
Training & Education	• work with industry to understand and meet training and technical assistance needs • promote the strategic advantage of microwave manufacturing technology
Information Systems & Databases	• equipment performance and cost database • estimation of environmental benefits • estimation of steel product quality
Decision Support Tools	• life-cycle costing software • equipment selection software
Voluntary Recognition Activities	• develop a Green Steel Challenge program

Research, development and demonstration. The initial stage of research and development of the proposed microwave steel-making technology ends in fall, 2003. Depending on the results from this research phase, another one to two years of follow-up work may be required. Nevertheless, development of a pilot plant to field test the technology should be undertaken in the next two years; preliminary discussions that may lead to such a plant are already underway with the project's industrial advisory committee. It is important that this pilot plant be developed by a highly regarded company, and that the facility be available for showcasing by the DOE and AISI. A private company such as WorkSmart Energy Enterprises, Inc. may be approached to facilitate these developments.

Training and education. While most steel companies have a fairly advanced understanding of energy consumption issues at their facilities, the industry has been hard pressed to keep up with the latest technical advances. This has especially been the case with larger firms beset with profitability and competitiveness challenges. Consequently, the DOE should expand its collaboration with the steel industry as part of the Allied Partner program. In this manner, the OIT can work with key equipment suppliers, manufacturers, consultants and other stakeholders to better understand and meet the training and technical assistance needs of steel-makers. In particular, the strategic advantage of the cost and environmental benefits from microwave technology can be stressed to steel firms that are struggling to survive in the global marketplace.

Information systems and databases. These actions include the compilation of databases on microwave equipment performance, costs, and the environmental benefits. The latter of course will translate into lower compliance costs and simpler permitting requirements. This information should be developed based on the research as well as pilot plant operating experiences. Since a range of operating scales and product lines will need to be accounted for, it may be necessary to review similar data for microwave applications in other metals industries. Finally, data on steel product quality characteristics should also be collected, as this will be an important determinant of the ultimate adoption of the proposed technology.

Decision support tools. Since large capital investments are difficult to make in the current economic climate facing the steel industry, the ready availability of life-cycle costing software is essential. While many such tools already exist, they need to be calibrated to account for current conditions in the industry, typical discount rates, and allow for sensitivity analysis of assumptions about operation and maintenance schedules and early retirement of existing manufacturing equipment. Such tools can be valuable in assisting a firm in making equipment selection decisions as opportunities for increased energy and cost savings are explored.

Voluntary recognition activities. A voluntary recognition program should be developed to encourage the use of highly efficient steel-making technologies, including the application of microwaves and exothermal heating. This could be called Energy Star Steel, Steel Challenge, Green Steel or a similar name, and should be included as part of the DOE's BestPractices Program activities. It may also be desirable to co-sponsor this program with the EPA. Modeled after Green Lights, Energy Star, the Motor and Compressed Air Challenges (Brown, Webber & Koomey 2000; McKane, Tutterow & Cockrill 2001), the goal of the Green Steel Challenge program would be the adoption of highly efficient steel-making technology to reduce energy use by 50%. Secondary goals would be to support the actions of the proposed MTP.

Collaborative Intervention: Market Players and Strategic Partnerships

Following the work of McKane, Tutterow & Cockrill (2001) with the compressed air systems market, a collaborative intervention can be developed for highly efficient steel making. While this is a market under extreme competitive pressures, a business opportunity exists to greatly increase energy efficiency and reduce pollution while transforming the steel-making market. The DOE should play the role of facilitator, and build upon its existing network of stakeholders with the BestPractices and Allied Partner programs. Program champions will need to be identified. While microwave manufacturers and early adopters are logical candidates, to be most effective the collaborative intervention should not be restricted to a single technology or a single stakeholder. The potential roles and motivations for the various stakeholders that should comprise a collaborative intervention are summarized in Table 2.

Conclusions

A 50% reduction in the energy required for producing steel in U.S. mills appears to be technically feasible through the application of microwaves, the EAF and exothermal heating. This should be confirmed by the development of a pilot plant within the next two years. Yet due to the intense competitiveness of this sector and widespread concern with fairness in international trade, this industry will not transform itself without outside assistance. Consequently it would be timely and advantageous on economic and environmental grounds for the steel industry to adopt the market transformation strategy outlined herein, probably as part of the DOE's BestPractices and Allied Partner programs. Even so, success will require an active partnership among a range of stakeholders, including equipment manufacturers and distributors, iron and steel companies, trade associations such as the AISI and SMA, metal recyclers, government, energy efficiency associations and electric utilities.

Table 2. Steel-Making Market Analysis of Interests and Motivations

Stakeholder	Potential Contribution	Initial Motivation	Primary Drivers
• Equipment Manufacturers and Distributors	• Detailed technical and market information • Identify barriers to equipment design • Customer influence	• Market growth • Brand enhancement	• Sales and profits • Increased brand recognition • Customer retention
• Iron and Steel-Producers • Trade Associations	• Determine criteria for adopting new technology	• Increase productivity and cut costs • Increase green image	• Economic survival • Reliability and best value
• Metal Recyclers	• Assess future scrap metal supply/demand • Determine criteria for furnace design, O & M	• Market growth	• Avoid shortages • of scrap metal
• Influencers: • Government, Utilities & Energy Efficiency Groups	• Technology credibility • Outreach mechanisms • Perceived neutrality	• Meets mission • Politically beneficial	• Energy and pollution control savings • Customer education, retention, recognition

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