Steel Industry Marginal Opportunity Study

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for the
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Introduction

The objective of this study is to generate a marginal opportunity curve for the ITP steel subprogram showing the location of the current portfolio compared against all opportunities for steel manufacturing. A companion study ("Investment Sizing") will determine the optimal R&D investment size considering different scenarios and other significant energy-saving targets of greatest impact. It is anticipated that the results of these studies will enable more informed portfolio decision-making and provide decision input for reallocating funds if needed due to incremental increases/decreases in funding.

The major activities in the study include:

- Identifying broad process-related best practices opportunities for steel manufacturing
- Identifying broad R&D opportunities for steel manufacturing
- Examining the steel industry energy bandwidth and determining:
    - how much of the gap between practical minimum energy requirements and today's energy use can be addressed through best practices and how much can be addressed by R&D (the "R&D opportunity")
    - how much of the R&D opportunity is being addressed by current projects
- Creating an initial marginal opportunity curve plotting energy savings versus R&D investment for the current portfolio
- Estimating the potential energy savings associated with each R&D opportunity based on assumed markets
- Estimating the total Federal R&D investment that would be required for each opportunity
    - assume 50% Federal cost-share for small to medium-sized projects
    - assume 10% Federal cost-share for large projects
- Evaluating the opportunities on a benefit-to-cost basis (accounting for overlaps to ensure that the total potential energy savings gap on the bandwidth is not exceeded) and add them to the marginal opportunity curve

The subsequent Investment Sizing study will interpret these results in light of total investment required, anticipated length of R&D efforts, steel industry financial health, predicted structural and market trends, and the industry's history of R&D investment and adopting new technologies. An estimate of the typical investment sizes related to potential impact in the steel industry will be made, and boundary curves for optimal investments in the industry will be constructed.

Three main areas of steel manufacturing – corresponding to the areas examined in the bandwidth analysis – have been analyzed:

- Ore-based steelmaking
- EAF steelmaking
- Casting/rolling (including reheating)

In the ITP steel energy bandwidth report ("Steel Industry Energy Bandwidth Study," October 2004), hot metal production and BOF steelmaking were considered separately. In this analysis, these two processes have been combined and entitled "ore-based steelmaking" because the existing energy bandwidth values for BOF steelmaking already included the ironmaking process. Combining these two processes also made it easier to gauge the effect of direct smelting (where steel is produced directly from coal and iron ore) on overall energy use in the production of steel from iron ore.

The broad R&D opportunities identified for the three main areas of steelmaking generally fall into the categories defined by Kawasaki Steel for future developments in manufacturing processes:

- Development of processes for raw materials flexibility
- Improvements in purity, cleanliness, and homogeneity by refining and solidification processes
- Synchronization, continuation, and integration of processing steps
- Unification and simplification of processing steps
- System integration by automation, adopting more robots, and AI control
- Improvements in technologies for energy savings, environmental protection, and waste recycling.

Ore-Based Steelmaking: Bandwidth and Opportunities

Table 1 shows the energy bandwidth data for the production of hot metal during ore-based steelmaking. In order to include the steelmaking step in the analysis, a BOF steelmaking energy intensity of 0.3 MBtu/ton (Fruehan 2000) was added to the industry average of 16.2 MBtu/ton for hot metal production. The total combined average energy intensity for hot metal production and steelmaking is therefore 16.5 MBtu/ton. On the other hand, the theoretical and practical minimum energy requirements for BOF steelmaking are assumed to be zero since this is an autogenous process.

Table 1. Energy Bandwidth Data for Ore-Based Steelmaking

Energy Bandwidth Data for Ore-Based Steelmaking (10^6 Btu/ton)			
Process	**Theoretical Minimum**	**Practical Minimum**	**Industry Average**
Hot Metal (pellets and coke)	10.9	11.4	16.5

Sources: *Steel Industry Energy Bandwidth Study*, Energetics, Inc. for DOE/ITP, October 2004.
Theoretical Minimum Energies to Produce Steel, R.J. Fruehan for DOE/OIT, September 2000.

The data in Table 1 have been used to create the energy bandwidth for ore-based steelmaking (hot metal production plus steelmaking) illustrated in Figure 1. The total opportunity for energy savings -- 5.1 MBtu/ton of steel -- was taken as the difference between today's actual energy use (16.5 MBtu/ton) and the practical minimum energy requirement (11.4 MBtu/ton). That opportunity consists of two elements:

- best practices (state-of-the-art technologies, processes, and practices that are available today)
- R&D opportunities (new technologies, processes, and practices that are under development or have been developed but require more effort in order to become commercially viable)

Tables 2 and 3 present best practice and R&D opportunities for ore-based steelmaking. Most of the best practice opportunities in Table 2 were taken from a 1999 report by Lawrence Berkeley National Laboratory (LBNL) based on 1994 energy consumption data. Because a significant percentage of these opportunities have likely already been achieved by the steel industry between 1994 and today, both the original estimate and a conservative 50% estimate of the opportunities are shown in Table 2. The conservative estimates were used in determining the size of the best practices area of opportunity in Figure 1. Throughout this report, any potential energy savings listed as "unknown" are considered to be zero when total potential energy savings for that process are determined.

It should be noted that the focus of this study is *R&D opportunities* in ironmaking and steelmaking. The best practices opportunity is approximated only to help quantify the magnitude of the R&D opportunity that would remain after steel mills adopt state-of-the-art technologies and practices.

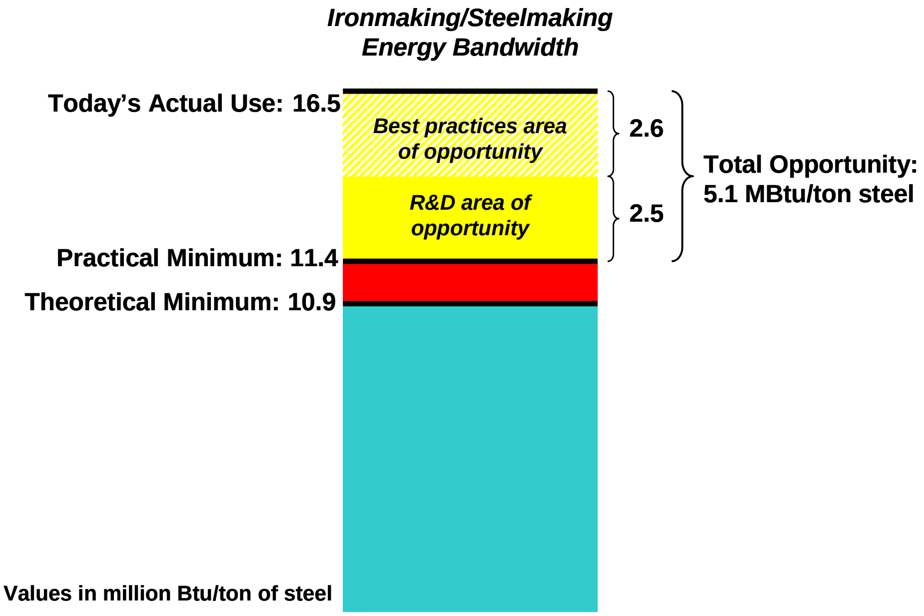


Figure 1. Energy Bandwidth for Ore-Based Steelmaking

Table 2. Ore-Based Steelmaking Best Practice Opportunities

Action/Opportunity	Assumptions/Examples	Potential Primary Energy Savings: Total and [50% of Total]	
		GJ/tonne crude steel	MBtu/ton steel
General			
1. Energy monitoring and management systems	• On-site energy mgmt systems for energy recovery and distribution between processes	0.14 [0.07]	0.12 [0.06]
2. Cogeneration	• Ready access to COG • Repowering of 55% of current systems with off-gas turbine/steam turbine systems	1.1 [0.06]	0.95 [0.48]
3. Variable speed drives for pumps and fans	• Electricity savings of 42% • Applicable to 5% of electricity use	0.06 [0.03]	0.05 [0.03]
4. Preventive maintenance	• Savings of 2% of total energy use	0.49 [0.25]	0.42 [0.21]
GENERAL SUBTOTAL (#s 1,2,3,4)		**1.79**	**1.54**

Action/Opportunity	**Assumptions/Examples**	**Potential Primary Energy Savings: Total and [50% of Total]**	
		GJ/tonne crude steel	**MBtu/ton steel**
		[0.90]	**[0.77]**
Ironmaking			
5. Sinter plant measures	• Heat recovery • Use of waste fuels	0.20 [0.10]	0.17 [0.09]
6. Cokemaking measures	• Coal moisture control • Dry quenching	0.51 [0.26]	0.44 [0.22]
7. Ironmaking	• Pulverized coal and natural gas injection • Top pressure recovery turbines • Hot blast stove automation • Improved blast furnace control	3.12 [1.56]	2.68 [1.34]
IRONMAKING SUBTOTAL (#s 5,6,7)		**3.83** **[1.92]**	**3.29** **[1.65]**
Steelmaking			
8. Steelmaking (BOF)	• Sensible heat recovery	0.93 [0.47]	0.80 [0.40]
STEELMAKING SUBTOTAL (#8)		**0.93** **[0.47]**	**0.80** **[0.40]**

Note: All data from Worrell et al 1999 unless otherwise noted.
1 GJ/tonne = 0.86 10^6 Btu/ton

The estimated best practices energy savings opportunity shown in Figure 1 (2.6 MBtu/ton) consists of the following elements from Table 2:

- 0.58 MBtu/ton from general practices around the plant
- 1.65 MBtu/ton from ironmaking improvements, and
- 0.40 MBtu/ton from steelmaking improvements.

The first figure was calculated by taking the total estimated savings from improved general practices around an integrated steel plant in Table 2 (0.77 MBtu/ton) and assuming that 75% of this could be attributed to the coke ovens, blast furnace, and BOF.

The energy savings that could be achieved through R&D are shown in Figure 1 to be 2.5 MBtu/ton of steel. This value was determined by subtracting the estimated best practices opportunity (2.6 MBtu/ton) from the total savings opportunity (5.1 MBtu/ton); it is very close to the savings potential of 2.6 MBtu/ton shown in Table 3 for direct smelting. It is assumed that if direct smelting were adopted as the main ore-based steelmaking route, then none of the other R&D opportunities shown in Table 3 would be needed (and would in fact represent double-counting).

Table 3. Ore-Based Steelmaking R&D Opportunities

R&D Opportunity*	Assumptions/Source	Potential Primary Energy Savings	
		GJ/tonne crude steel	MBtu/ton steel
Blast Furnace Ironmaking			
1. Increased direct carbon injection	• Injection of 220 kg of C/ tonne of crude steel by 2020 • Source: Icarus-4/Michels	0.81	0.70
2. BF slag heat recovery	• Technical and economic issues • Implementation 2020 • Savings may accrue to other industries • Source: Icarus-4/Michels	0.32	0.28
3. Effective utilization of dust and sludge	• *Steel Technology Roadmap*	Unknown	Unknown
4. Other technological advances	• Not yet identified	Unknown	Unknown
BLAST FURNACE SUBTOTAL (#s 1,2)		**1.13**	**0.98**
Steelmaking			
5. Increased scrap input to BOF	• Potential of 213 kg scrap/ tonne of crude steel in 2020 • Source: Icarus-4/Michels	3.6	3.1
6. BOF slag heat recovery	• Same as BF slag case	0.14	0.12
7. Direct smelting of iron ore using coal	• *Icarus-4/Michels estimate* - More advanced than current (e.g., cyclone converter furnace) - Implementation by 2010	3.0	2.58
	• *ATLAS estimate* - Expected intensity of 11 GJ/tonne pig iron (equiv to 9.8 GJ/tcs)	~4.45	~3.83
	• *DOE study* - Direct steelmaking producing molten steel directly from shippable agglomerate - Savings up to 25% over current route	Unknown	Unknown
STEELMAKING SUBTOTAL (#s 5,6)		**3.74**	**3.22**
STEELMAKING SUBTOTAL (#7)		**3.0**	**2.58**

1 GJ/tonne = 0.86 10^6 Btu/ton; 1 GJ/tonne pig iron = 0.89 GJ/tonne steel

* Some opportunities are mutually exclusive

EAF Steelmaking: Bandwidth and Opportunities

Table 4 shows the energy bandwidth data for the production of hot metal in an EAF furnace. Although separate data for both EAF long products and EAF flat products were available, they were almost identical in magnitude and therefore the data for long products have been used to represent both types of products.

Two sets of data are shown in Table 4, reflecting two different sets of calculations:

- the original data from the Fruehan theoretical minimum energy report (which exclude electrical transmission and distribution losses)
- the data from the DOE steel energy bandwidth report, which include electrical losses but have been revised from the report to more accurately reflect the distribution between chemical and electrical energy inputs; for theoretical and practical minimum, 45% chemical input is assumed based on data from the Nucor-Yamato mill, while the industry average is Stubbles "good practice" EAF value minus energy required for the LMF

Table 4. Energy Bandwidth Data for EAF Steelmaking

Energy Bandwidth Data for EAF Steelmaking (10^6 Btu/ton)			
Process	**Theoretical Minimum**	**Practical Minimum**	**Industry Average**
Liquid Steel (long products) *Electrical losses not included*	1.1	1.4	2.0
Liquid Steel (long products) *For first two columns, assumes 45% chemical input and 55% electrical (losses included); industry average value is from Table 6 of the Stubbles report, excluding LMF*	2.4	3.0	5.7

Sources: *Steel Industry Energy Bandwidth Study*, Energetics, Inc. for DOE/ITP, October 2004.
Theoretical Minimum Energies to Produce Steel, R.J. Fruehan for DOE/OIT, September 2000.
Energy Use in the U.S. Steel Industry, A Historical Perspective and Future Opportunities, J. Stubbles for DOE/OIT, September 2000.
"EAF Energy Optimization at Nucor-Yamato Steel," *Iron & Steel Technology*, July 2004.

The data in Table 4 have been used to create the energy bandwidth for EAF steelmaking illustrated in Figure 2. The total opportunity for energy savings – 2.7 MBtu/ton of steel – was taken as the difference between today's actual energy use (5.7 MBtu/ton) and the practical minimum energy requirement (3.0 MBtu/ton). As with the ore-based steelmaking analysis, the total opportunity is made of two components – best practices and R&D opportunities.

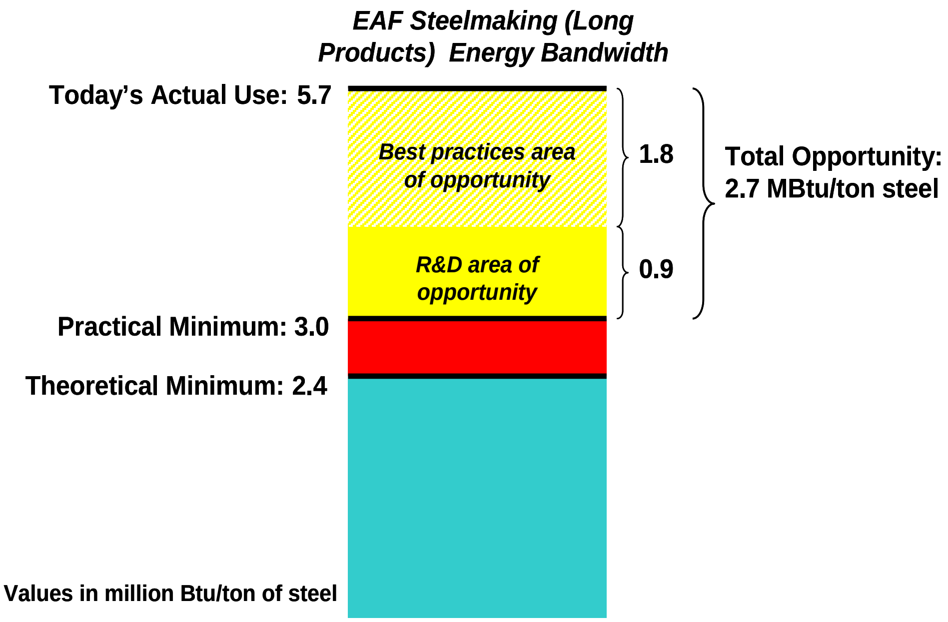


Figure 2. Energy Bandwidth for EAF Steelmaking

Figure 2 shows that 1.8 MBtu/ton, or two-thirds of the total potential reduction in energy intensity available to EAF steelmakers, can be achieved through adoption of existing state-of-the-art technologies and best practices. An additional savings of about 0.9 MBtu/ton of steel are believed to be achievable through R&D on advanced technologies. These values were derived from the data in Tables 5 and 6.

Table 5 presents best practice opportunities for EAF steelmaking, while Table 6 shows R&D opportunities. Some of the best practice opportunities in Table 5 (those from the LBNL report) were derived from 1994 data; it is assumed that a significant percentage of them have already been achieved by the industry. Therefore, a more conservative estimate of 50% of the opportunities has been added to Table 5. These lower estimates were used in estimating the size of the best practices area of opportunity in Figure 2, where applicable. As noted previously, the focus of this study is *R&D opportunities*; the best practices opportunity is approximated only to help quantify the magnitude of the R&D opportunity.

Using the data in Table 5, the total estimated savings potential from best practices opportunities would be1.8 MBtu/ton. This represents the difference between the industry average energy consumption (5.7 MBtu/ton) and the energy consumption of a very efficient mill, EAF #1 at Nucor-Yamato Steel in Blytheville, AK (3.9 MBtu/ton, shown in row 3 of Table 5). Although this mill makes a particular product that may requires less furnace energy than mills making other products, its energy intensity is used to represent a lower bound of EAF energy consumption using best practices. By comparison, the sum of the LBNL EAF steelmaking best practices opportunity (1.82 MBtu/ton) and the energy monitoring and management opportunity (0.03 MBtu/ton) is 1.85 MBtu/ton.

Table 5. EAF Steelmaking Best Practice Opportunities

Action/Opportunity	Assumptions	Potential Primary Energy Savings: Total and [50% of Total]	
		GJ/tonne crude steel	MBtu/ton steel
General			
1. Energy monitoring and management systems	• On-site energy mgmt systems for energy recovery and distribution between processes	0.06 [0.03]	0.05 [0.03]
2. Preventive maintenance	• Savings of 2% of total energy use	0.24 [0.12]	0.21 [0.11]
GENERAL SUBTOTAL (#s 1,2)		**0.30 [0.15]**	**0.26 [0.13]**
Steelmaking			
3. EAF Steelmaking	• *LBNL Estimate* - Improved process control - Oxy-fuel burners - DC-arc furnace - Scrap preheating - Post combustion	4.22 [2.11]	3.63 [1.82]
	• *State-of-the-art Mill Estimate* Calculations based on state-of-the-art EAF at Nucor-Yamato Steel (AK) with per-ton energy inputs of: - 287 kWh/ton - 1430 scf oxygen - 300 scf natural gas - 0.14 tons injected carbon Total use = 3.9 MBtu/ton steel	2.1	1.8
STEELMAKING SUBTOTAL (#3)		**2.1**	**1.8**

Note: All data from Worrell et al 1999 except for 3b, which is based on data in "EAF Energy Optimization at Nucor-Yamato Steel," *Iron & Steel Technology*, July 2004.
1 GJ/tonne = 0.86 10^6 Btu/ton
Fuel conversion factors: 10,500Btu/kWh, 175 Btu/scf oxygen, 1,000 Btu/scf natural gas, 12,500 Btu/lb of carbon

The energy monitoring and management figure was calculated from the total estimated savings from improved general practices in Table 5 (0.13 MBtu/ton) and assuming that 60% of it could be attributed to the steelmaking step alone.

The potential energy savings from R&D activities (0.9 MBtu/ton) is calculated by subtracting the value of the best practices opportunities (1.8 MBtu/ton) from the total opportunity of 2.7 MBtu/ton. The R&D savings value is relatively close to the steelmaking R&D opportunity subtotals (1.01 MBtu/ton for long products and 0.76 MBtu/ton for flat products) calculated in Table 6.

Table 6. EAF Steelmaking R&D Opportunities

R&D Opportunity	Assumptions/Source	Potential Primary Energy Savings	
		GJ/tonne crude steel	**MBtu/ton steel**
Steelmaking			
1. Melting	• Long products • Flat products • Both estimates from Stubbles report	0.47 0.17	0.4 0.15
2. EAF reduction in tap temperature	• 100F reduction worth 10 kWh/ton • *Steel Technology Roadmap* and Stubbles	Unknown	Unknown
3. Integration of refining functions/reduction of heat losses prior to casting	• Saves energy currently supplied to LMF process • Kawasaki Steel and Peter et al	0.41	0.35
4. Economical capture of heat from EAF waste gas	• *Steel Technology Roadmap*	0.30	0.26
STEELMAKING SUBTOTAL (#s 1,3,4) (Note: represents long products)		**1.18**	**1.01**
Feedstocks			
5. Purification/upgrading of scrap	• Kawasaki Steel	Unknown	Unknown
6. Effective utilization of slag and dust	• ~40% of EAF dust landfilled (>100,000 tons of iron units) • *Steel Technology Roadmap*	Unknown	Unknown
FEEDSTOCKS SUBTOTAL (#s 5,6)		**Unknown**	**Unknown**

1 GJ/tonne = 0.86 10^6 Btu/ton

Casting/Rolling: Bandwidth and Opportunities

Table 7 shows the energy bandwidth data for casting and hot rolling combined, and also for cold rolling. Separate data are shown for ore-based steelmaking and EAF steelmaking. The energy requirements for reheating the steel are included as part of the casting/rolling process data in Table 7.

Table 7. Energy Bandwidth Data for Casting/Rolling

Energy Bandwidth Data for Casting/Rolling (10^6 Btu/ton)			
Process	**Theoretical Minimum**	**Practical Minimum)**	**Industry Average[a]**
Hot Rolling (Ore-Based Steelmaking)	0.01	0.8	2.6
Hot Rolling (EAF Steelmaking)	0.01	0.8	2.7
Cold Rolling (Ore-Based Steelmaking)	0.02	0.02	4.5
Cold Rolling (EAF Steelmaking)	0.02	0.02	3.8

a Includes 0.3 MBtu/ton as the industry average value for continuous casting

Sources: *Steel Industry Energy Bandwidth Study*, Energetics, Inc. for DOE/ITP, October 2004.
Theoretical Minimum Energies to Produce Steel, R.J. Fruehan for DOE/OIT, September 2000.
Energy and Environmental Profile of the U.S. Steel Industry, Energetics, Inc. for DOE/ITP, August 2000.
Energy Use in the U.S. Steel Industry, A Historical Perspective and Future Opportunities, John Stubbles and Energetics for DOE/ITP, September 2000.

The data in Table 7 have been used to create the energy bandwidth for casting and rolling, illustrated in Figures 3 and 4 for ore-based and EAF steelmaking, respectively. The total opportunity for energy savings in hot rolling – 1.8 MBtu/ton of steel for ore-based plants and 1.9 MBtu/ton for EAF plants – was taken as the difference between today's actual energy use and the practical minimum energy requirement. For cold rolling, the total opportunity was 4.5 MBtu/ton for ore-based steelmaking plants and 3.8 MBtu/ton for EAF plants. The total potential energy savings consists of both best practice opportunities as well as R&D opportunities.

The data used to determine the magnitudes of the best practices opportunities are shown in Tables 8 and 9 for ore-based and EAF steelmaking, respectively. Table 10 shows the data used to determine the R&D opportunity for the two types of steelmaking. As before, the best practice data from Worrell at LBNL were based on the state of the industry in 1994; it is assumed that the industry has closed much of this gap between 1994 and today. Therefore, a conservative estimate of 50% of the potential savings for these opportunities (from the LBNL report only) has been included in Tables 8 and 9. These lower estimates were used in determining the magnitude of the best practices area of opportunity in Figure 3.

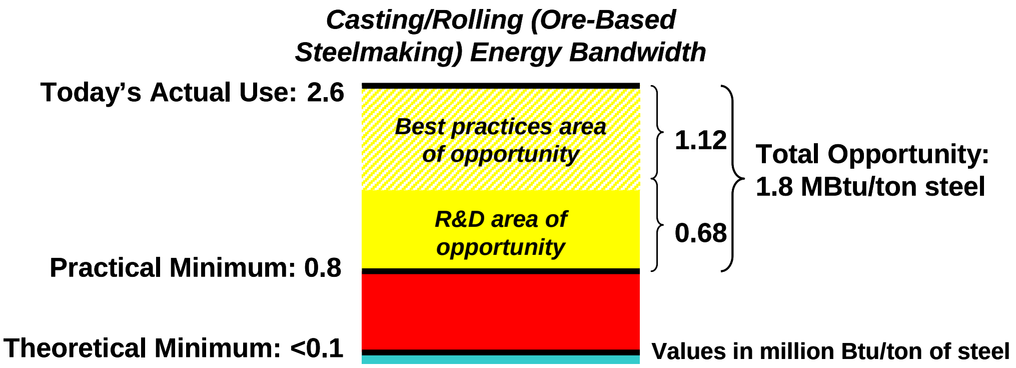


Figure 3. Energy Bandwidth for Casting/Rolling (Ore-Based Steelmaking)

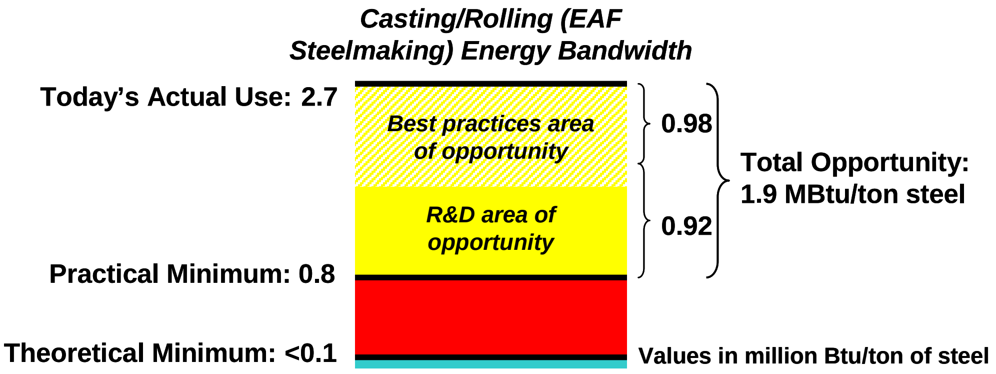


Figure 4. Energy Bandwidth for Casting/Rolling (EAF Steelmaking)

For ore-based steelmaking, the 1.12 MBtu/ton potential savings from the adoption of existing state-of-the-art technologies and practices comprise 0.93 MBtu/ton savings from the adoption of thin slab casting used with a tunnel furnace plus 0.19 MBtu/ton from general practices around an integrated plant. This latter figure was calculated by taking the total estimated savings from improved general practices in Table 2 (0.77 MBtu/ton) and assuming that 25% could be attributed to casting, rolling, and finishing processes.

The best practices opportunity for EAF steelmaking, which totals 0.98 MBtu/ton, includes 0.93 MBtu/ton from the adoption of thin slab casting and a tunnel furnace plus 0.05 MBtu/ton from improved general practices. This latter figure was calculated by taking the total estimated savings from improved general practices in Table 5 (0.13 MBtu/ton) and assuming that 40% could be attributed to casting, rolling, and finishing processes. As noted previously, the focus of this study is *R&D opportunities*; the best practices opportunity is approximated only to help quantify the magnitude of the R&D opportunity.

Table 8. Casting/Rolling Best Practice Opportunities (Ore-Based Steelmaking)

Action/Opportunity	Assumptions/Examples	Potential Primary Energy Savings: Total and [50% of Total]	
		GJ/tonne crude steel	MBtu/ton steel
General			
1. Energy monitoring, preventive maintenance, etc.	• Based on 1.54 MBtu/ton [0.77 MBtu/ton conservative] from Table 2, #1 and assuming 25% attributed to casting, rolling, and finishing	0.44 [0.22]	0.38 [0.19]
GENERAL SUBTOTAL (#1)		**0.44** **[0.22]**	**0.38** **[0.19]**
Casting/Hot Rolling			
2. Thin Slab Casting/ Tunnel Furnace	• Savings of 0.6 MBtu for use of tunnel furnace rather than billet reheat furnace (Stubbles 2001) • Savings of 0.33 MBtu/ton because of reduced rolling needs (Forbes 2001) • No 50% conservative required	1.08	0.93
3. Endless rolling	• 1% yield increase and 20% productivity increase • Danieli, Kawasaki Steel	Unknown	Unknown
CASTING/HOT ROLLING SUBTOTAL (#2)		**1.08**	**0.93**
Cold Rolling Increment			
4. Cold Rolling/ Finishing	• Heat recovery (annealing) • Automation and control systems	0.68 [0.68]	0.58 [0.29]
COLD ROLLING INCREMENT SUBTOTAL (#4)		**0.68** **[0.34]**	**0.58** **[0.29]**

Note: All data from Worrell et al 1999 unless otherwise noted.
1 GJ/tonne = 0.86 10^6 Btu/ton

The magnitudes of the R&D opportunities for the two types of steelmaking were calculated by subtracting the best practices opportunity from the total opportunity shown in Figures 3 and 4. These values were compared for reasonableness to the data in Table 10. The combined potential savings shown in Table 10 for reduction of heat losses and near net shape casting was estimated at 1.35 MBtu/ton (obtained by summing subtotal 1 and 2 in Table 10). This value likely includes some overlap because near net shape casting technology also reduces heat losses. Therefore, the 0.68 MBtu/ton and 0.92 MBtu/ton R&D opportunities shown in Figures 3 and 4 appear reasonable.

Table 9. Casting/Rolling Best Practice Opportunities (EAF Steelmaking)

Action/Opportunity	Assumptions	Potential Primary Energy Savings: Total and [50% of Total]	
		GJ/tonne crude steel	MBtu/ton steel
General			
1. Energy monitoring, preventive maintenance, etc	• Based on 0.26 MBtu/ton [0.13 MBtu/ton conservative] from Table 5, #1 and assuming 40% attributed to casting/rolling/finishing	0.12 [0.06]	0.10 [0.05]
GENERAL SUBTOTAL (#1)		**0.12** **[0.06]**	**0.10** **[0.05]**
Casting/Hot Rolling			
2. Thin slab casting/ tunnel furnace	• Savings of 0.6 MBtu for use of tunnel furnace rather than billet reheat furnace (Stubbles 2001) • Savings of 0.33 MBtu/ton because of reduced rolling needs (Forbes 2001) • No 50% conservative required	1.08	0.93
3. Endless rolling	• 1% yield increase and 20% productivity increase • Danieli, Kawasaki Steel	Unknown	Unknown
CASTING/HOT ROLLING SUBTOTAL (#2)		**1.08**	**0.93**
Cold Rolling Increment			
4. Cold Rolling/ Finishing	• Heat recovery (annealing) • Automation and control systems	0.68 [0.68]	0.58 [0.29]
COLD ROLLING INCREMENT SUBTOTAL (#4)		**0.68** **[0.34]**	**0.58** **[0.29]**

Note: All data from Worrell et al 1999 unless otherwise noted.
1 GJ/tonne = 0.86 10^6 Btu/ton

Table 10. Casting/Rolling R&D Opportunities (Ore-Based and EAF Steelmaking)

R&D Opportunity	Assumptions/Source	Potential Primary Energy Savings	
		GJ/tonne crude steel	MBtu/ton steel
Casting/Rolling			
1. Reduction of heat losses from cast products prior to rolling (reheating)	- Stubbles	0.87	0.75
2. Thin strip casting/near net shape casting	- Icarus-4/Michels - Stubbles - Forbes	0.6 0.7 0.8	0.5 0.6 0.7
3. Semi-solid state forming	- Kawasaki Steel	Unknown	Unknown
4. Other technological innovations	- Not yet identified	Unknown	Unknown
SUBTOTAL (#1)		**0.87**	**0.75**
SUBTOTAL (#2) (Note: #1 overlaps with #2)		**0.7**	**0.6**

Note: ATLAS (2005) reports primary energy savings of 1.8 GJ/tonne steel (1.55 MBtu/ton) for R&D Opportunity #2 (Thin strip casting/near net shape casting). This value was not included in the table since it is an outlier compared to the values reported by three other sources as shown.

1 GJ/tonne = 0.86 10^6 Btu/ton

1 GJ/tonne pig iron = 0.89 GJ/tonne steel

Analysis of Current ITP Portfolio

The first step toward constructing a marginal opportunity curve for steel industry R&D was to examine the current projects funded by the ITP steel subprogram. For each project, the cumulative federal spending and the estimated energy savings projected for the technology were determined (Table 11). The year when a commercialized technology will reach its maximum savings potential (specifically, savings that can be attributed to DOE) depends on its year of commercialization, its market risk, and the number of years that its commercialization was accelerated because of DOE involvement. Therefore, Table 11 shows both the estimated technology energy savings for the year 2020 and also the year when the technology will achieve its maximum energy savings (those savings for which DOE can take credit). ITP calculates these savings annually in compliance with the Government Performance and Reporting Act (GPRA).

Table 11. Costs/Benefits of Projects in FY05 ITP Steel Subprogram Portfolio

Project (Active in FY05)	**Cumulative DOE Funding ($)**	**GPRA Energy Savings (10^{12} Btu/yr)**		**10^6 Btu/ $ of Investment**
		2020	**Max Savings/ Year**	
Novel Direct Steelmaking	301,970	3.83	18.9/2030	62.5 (6.3 at 10%)[1]
Process to Continuously Melt and Refine Steel	395,097	2.62	14.6/2030	36.9 (3.7 at 10%)[1]
ASCAT	1,027,302	1.56	3.11/2014	3.0
Flame Impingement Heating	1,250,000	1.78	4.79/2030	3.8
AISI Tech Roadmap (only projects still active in FY05)	7,766,359		n/a	
• Enhanced Inclusion Removal from Steel in the Tundish	860,880			
• Constitutive Behavior High Strength Multiphase Steel	1,034,060	1.94	1.97/2021	1.9
• Enrichment of By-products from Pickling Acid Regeneration	1,934,930	Unk	0.8[2]/2013	0.4
• Validate Hot Strip Mill Model	2,594,476		2.2[3]/2020	0.8
• Inclusion Optimization of Next-Generation Steel Products	448,210	5.05	5.42/2022	12.1
• SENs Plant Trial	893,803	12.98	12.98/2020	14.5

1 Project is to establish feasibility only but GPRA savings estimates assumed technology development and commercialization. Assumed that this feasibility phase represents only 10% of total DOE investment required, and therefore savings shown are 10% of the GPRA savings for this technology.

2 Estimated savings of 0.54 trillion Btu/yr from developer plus 0.25 trillion Btu/yr estimated savings from reduced transportation requirements and elimination of dual raw material handling.

3 No GPRA results; uses higher of two energy savings estimates from the developer.

DOE has commissioned a study that is currently underway to reconcile the steel subprogram's GPRA energy savings metrics with the steel energy bandwidth and the ITP goal of 20% energy savings by 2020. The results from the metric reconciliation study, once available, will show how much energy savings can be expected from the current steel portfolio under various market growth scenarios. In comparison, this study uses the energy savings projected in GPRA to determine the fraction of total R&D opportunity that is addressed in the current portfolio, which is then used to estimate the marginal opportunity curve.

Figure 5 presents a curve of the energy savings (only those attributable to DOE, not total expected from that technology) versus cumulative federal investment for the projects listed in Table 11. The analysis has accounted for the fact that some technologies address the same market; no double-counting takes place in the energy savings shown in Figure 5. It should be noted that several of the projects shown in Figure 5 have significant non-energy benefits that are not represented in the energy savings shown on the curve.

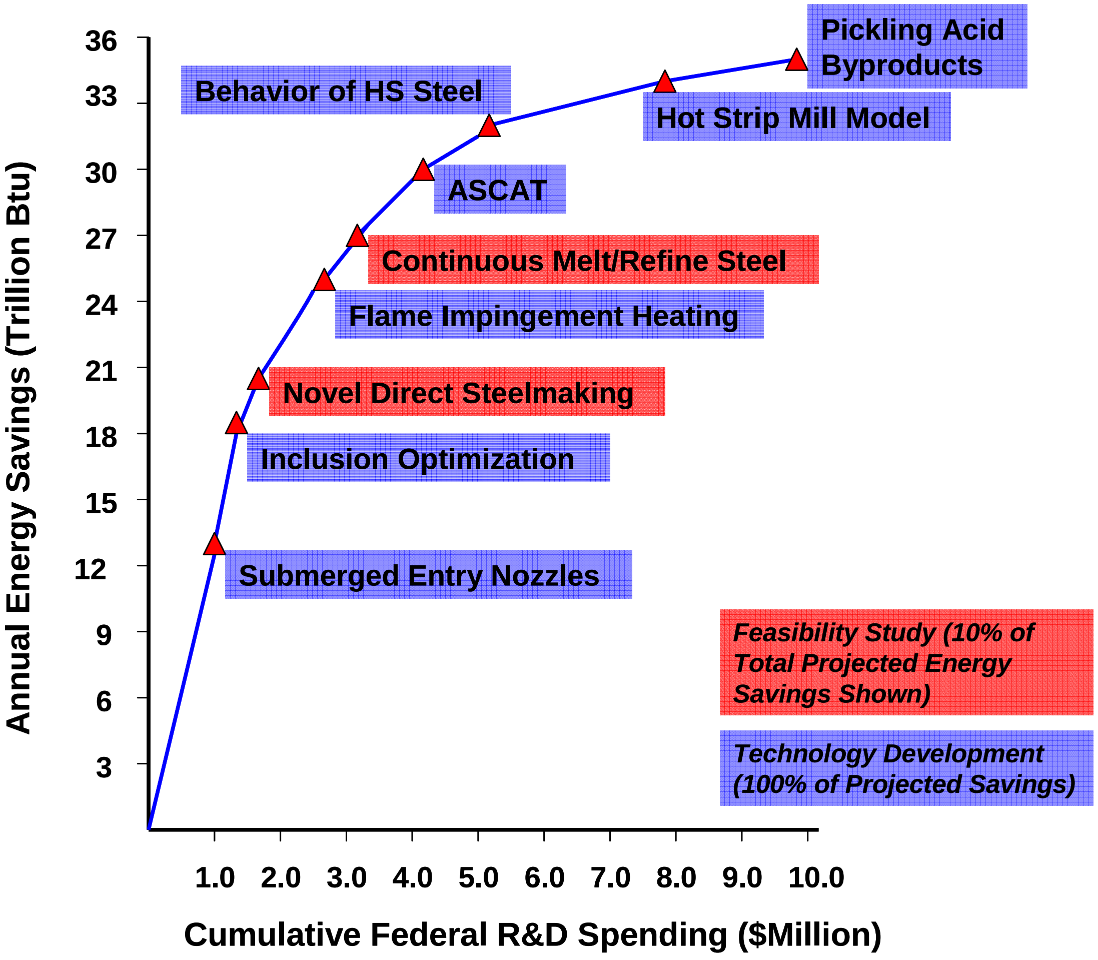


Figure 5. Energy Savings Attributable to DOE versus Cost for FY05 Steel Subprogram Portfolio

Because DOE cost-shares the projects to varying degrees, it cannot take full credit for future energy savings from the new technologies. Therefore, in order to present a more complete picture, the total energy savings that should be realized by adoption of the DOE projects shown in Table 11 are shown in Figure 6.

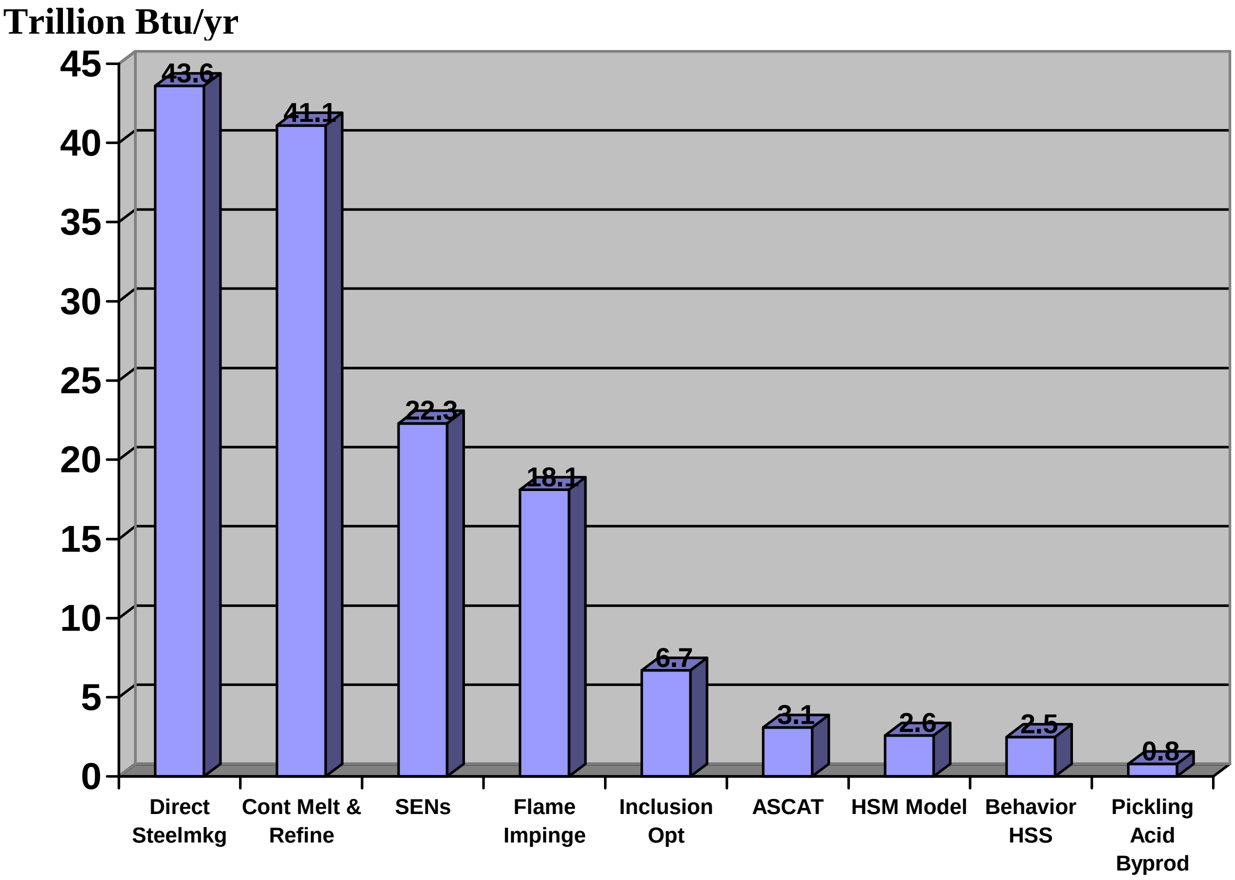


Figure 6. Total Energy Savings for Technologies in the FY05 Steel Subprogram Portfolio

Estimated Costs of R&D Opportunities

In order to compare the additional R&D opportunities in steel manufacturing to the current ITP steel portfolio, an estimate must be made of the investment that would be required to develop the new technologies. For a completely new technology, it is assumed that development would begin at the concept definition stage and continue through field testing. For other technologies that are farther along in their development cycle, the required investment is adjusted to reflect only the remaining stages of work. Estimates are derived from one or more of the following sources:

- Data in the literature
- Comparison with current and past ITP projects
- Knowledge of industry experts

The Federal share of the total investment is determined using the following guidelines:

- Small/medium-sized project (evolutionary technology) – 50% federal cost share
- Large project (transformational technology) – 10% federal cost share

Tables 12, 13, and 14 estimate the costs of R&D efforts in ore-based steelmaking, EAF steelmaking, and casting/rolling, respectively. These tables also show the estimated maximum energy savings that the technology could be expected to achieve in the year 2030. This year was chosen to allow comparison of these opportunities with the current projects shown in Table 11; 2030 is the last year for which the GPRA model estimates savings. It is assumed that any new technologies resulting from R&D on the opportunities in Tables 12 through 14 would not reach their maximum market penetration prior to that year. The calculations also assume no growth in the production of ore-based steel and 2% per year growth in the production of EAF steel.

Table 12. Investments for Ore-Based Steelmaking R&D Opportunities

R&D Opportunity	**End State for Federal Investment**	**Estimated Federal R&D Investment and Assumptions**	**Estimated 2030 Energy Savings and Assumptions**
Blast Furnace Ironmaking			
Increased direct carbon injection	Validation of results from models/studies of: - Tuyere zone combustion - Bed permeability - Optimized coal selection	*$3.6 million:* Studies and models will cost ~$750,00 each; validation in a blast furnace for a six-month period will cost on the order of $1.5M each; assume 50% cost share of $2.25M for 3 studies and $5M for validation testing	*10 trillion Btu attributable to DOE:* Assumes hot metal production of 45 million tons, ultimate potential accessible market of 90%, likely technology market share of 70%, savings of 0.7 MBtu/ton of hot metal
BF slag heat recovery	Completion of feasibility study and lab-scale demonstration	*$0.5 million:* New environmentally friendly process needed for recovering both heat and material of the slag in a closed system (Akiyama et al); assume 50% cost-share of a $1.0M effort	*2 trillion Btu attributable to DOE:* Assumes hot metal production of 45 million tons, ultimate potential accessible market of 80%, likely technology market share of 40%, savings of 0.28 MBtu/ton of hot metal
Effective utilization of BF dust and sludge	Demonstration of economical recovery and reuse method	*$4.0 million:* Two methods -- cold briquetting for return to the BF; rotary hearth furnace reduction – show potential (*Steel Technology Roadmap*); assume 50% cost-share of modeling and feasibility studies costing $2M and 10% cost-share of a demonstration costing $30M	Unknown energy savings potential
Other technological innovations	Unknown	*N/A:* Innovations yet to be determined	Unknown energy savings potential
Steelmaking			
Increased scrap input to BOF	Unknown	*N/A:* Not likely with current scrap prices	Unknown energy savings potential
Effective utilization of BOF dust and	Demonstration of economical recovery method	*$4.0 million:* Several pyrometallurgical	Unknown energy savings potential

R&D Opportunity	End State for Federal Investment	Estimated Federal R&D Investment and Assumptions	Estimated 2030 Energy Savings and Assumptions
sludge		processes show potential for recovering iron units in BOF dust and sludge (*Steel Technology Roadmap*); assume 50% cost-share of additional studies costing $2M and 10% cost-share of a demonstration costing $30M	
BOF slag heat recovery	See BF slag heat recovery above	See BF slag heat recovery above	See BF slag heat recovery above
Direct smelting of iron ore	Demonstration of continuous pilot plant operation (min 350,000 tons/yr of iron product) for at least 1 year	*$35.0 million:* Commercial-scale HIsmelt plant has been built in Australia in 2004 as Nucor joint venture for US$208M (MiningAustralia.com and Petry); assume 10% cost-share of a U.S. demonstration costing $350M	*24 trillion Btu attributable to DOE:* Assumes hot metal production of 45 million tons, ultimate potential accessible market of 90%, likely technology market share of 40%, savings of 2.58 MBtu/ton of hot metal

Table 13. Investments for EAF Steelmaking R&D Opportunities

R&D Opportunity	End State for Federal Investment	Estimated Federal R&D Investment and Assumptions	Estimated 2030 Energy Savings and Assumptions
EAF Steelmaking			
Melting advances	Demonstration of new practices	*$0.25 – 1.5 million per advance:* Continued improvements to furnace design, scrap preheating, oxygen and/or fossil fuel injection, and charging practices; assume 50% cost-share of R&D efforts from $0.5M to $3.0M	*8 trillion Btu attributable to DOE:* Assumes 2005 EAF steel production of 57 million tons and 2%/yr market growth, ultimate potential accessible market of 100%, likely technology market share of 90%, savings of 0.1 MBtu/ton of steel
Integration of refining functions	Pilot-scale demonstration of new process	*$3.0 million:* Similar to portions of DOE continuous steelmaking project at	*11 trillion Btu attributable to DOE:* Assumes 2005 EAF steel

R&D Opportunity	**End State for Federal Investment**	**Estimated Federal R&D Investment and Assumptions**	**Estimated 2030 Energy Savings and Assumptions**
		Univ of Missouri-Rolla; assume 10% cost-share of $30M RD&D effort (commercial plant construction would be on the order of $300M)	production of 57 million tons and 2%/yr market growth, ultimate potential accessible market of 90%, likely technology market share of 55%, savings of 0.35 MBtu/ton of steel
Economical capture and use of heat from EAF waste gas	Development of economical methods to use the heat from the fourth hole	*$2.5 million* Consteel process is commercial; other methods to use the heat could be developed; assume 50% cost-share of a $5M R&D effort	*8 trillion Btu attributable to DOE:* Assumes 2005 EAF steel production of 57 million tons and 2%/yr market growth, ultimate potential accessible market of 80%, likely technology market share of 40%, savings of 0.26 MBtu/ton of steel
Feedstocks			
Purification of scrap	a. Pilot test of low-cost dezincing process *and* b. Development of theory on heavy metals and demonstration of viable removal process	*a. $2.0 million:* Commercial electrochemical dezincing plant (DOE cost-shared $1.9M of $3.2M) now in operation by Meretec in Indiana (Taylor); lower-cost process (e.g., chlorine-based) is needed (*Steel Technology Roadmap*); assume 50% cost-share of $4M effort *b. $4.0 million:* Removal process will involve removing heavy metals from slag; assume 50% cost-share of $8M RD&D effort	Unknown energy savings potential
Upgrading of scrap	Development and demonstration of an upgrading process	*$5.0 million:* Theory is already fairly well understood; technology being developed in Japan by NIMS (Osawa); demonstration will need to handle large volumes; assume 50% cost-share of $10M development and demonstration effort	Unknown energy savings potential

R&D Opportunity	**End State for Federal Investment**	**Estimated Federal R&D Investment and Assumptions**	**Estimated 2030 Energy Savings and Assumptions**
Effective utilization of slag and dust	Proven technical and economic viability of emerging EAF dust recycling technologies	*$3.0 million:* Many emerging hydrometallurgical, pyrometallurgical, and thermal processes in various stages of development, demonstration, or use (*Steel Roadmap*); assume 10% cost-share of $30M demonstration	Unknown energy savings potential

Table 14. Investments for Casting/Rolling R&D Opportunities

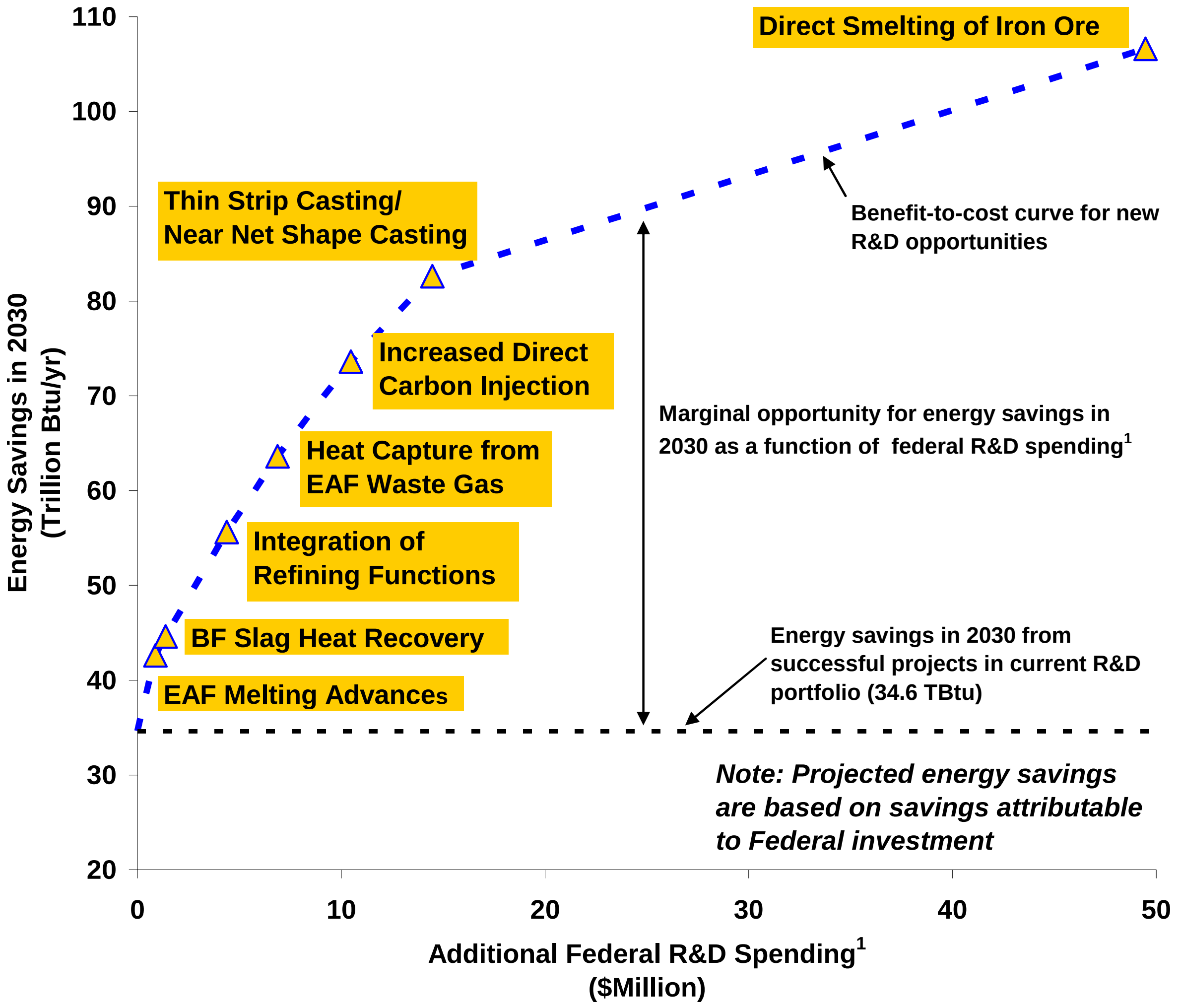
R&D Opportunity	End State for Federal Investment	Estimated Federal R&D Investment and Assumptions	Estimated 2030 Energy Savings and Assumptions
Casting/Rolling			
Thin strip casting/ near net shape casting	Proven commercial viability of existing technology (product has acceptable microstructure); extension of technology to very large mills	*$4.0 million:* Some materials research still required; commercial-scale plant has been built at Nucor Crawfordsville in 2002 at a cost of ~$300M, but commercial potential has not yet been proven (Buecher), plus application to large mills has not been shown feasible; assume 50% cost-share of $3M R&D plus 10% cost-share of a $25M demonstration/validation (excluding construction) effort	*9 trillion Btu attributable to DOE:* Assumes total steel production of 110 million tons and 1.5%/yr market growth, ultimate potential accessible market of 66%, likely technology market share of 40%, savings of 0.6 MBtu/ton of steel
Semi-solid state forming	Pilot-scale demonstration of a new process	*$5.0 million:* DOE cost-shared $5.9M of an $8.1M steel spray forming project (pre-FY94); assume 10% cost-share of a $50M RD&D effort	Unknown energy savings potential
Other ways to reduce heat losses before rolling	N/A	*N/A:* Overlaps with thin strip casting/near net shape casting; not enough information to suggest options	Unknown energy savings potential
Other technological innovations	Unknown	*N/A:* Innovations yet to be determined	Unknown energy savings potential

A reasonable estimate could be made regarding both the estimate cost and energy savings in 2030 for seven of the opportunities listed in Tables 12 – 14. These seven opportunities are summarized in Table 15 with an estimated federal investment and energy savings in 2030. To remain consistent with the analysis of the current ITP portfolio, the R&D opportunities with an unknown investment and/or unknown energy savings are excluded from the cost-benefit curve.

Table 15. Summary of Costs/Benefits of R&D Opportunities in ITP Steel Subprogram

R&D Opportunity	Estimated Federal R&D Investment ($Million)	Estimated 2030 Energy Savings attributable to DOE (TBtu)	10^6 Btu/$ of Investment
Increased direct carbon injection	3.6	10	2.8
BF slag heat recovery	0.5	2	4
Direct smelting of iron ore	35.0	24	0.7
EAF Melting advances	0.25 – 1.5	8	9.1 (avg)
Integration of EAF refining functions	3.0	11	3.7
Economical capture and use of heat from EAF waste gas	2.5	8	3.2
Thin strip casting/ near net shape casting	4.0	9	2.3

A graphical illustration of Table 15 is provided in Figure 7, which presents the marginal opportunity curve for additional energy savings in 2030 as a function of cumulative federal funding. The distance between the R&D opportunity curve and the current R&D portfolio represents the marginal opportunity for additional energy savings from the ITP steel subprogram. The R&D opportunity curve is plotted on a benefit-to-cost basis from data summarized in Table 15 (projects are not adjusted for risk). Note that only those energy savings directly attributable to each opportunity are considered; spillovers from R&D are not included. As before, projects with unknown energy savings potential are excluded from Figure 7.



1 Federal R&D Opportunities Spending is in addition to the financing of projects in the current R&D portfolio, which totals about $10 million (see Figure 5).

Figure 7. Energy Savings versus Cost for R&D Opportunities in ITP Steel Subprogram

Figure 8 provides a combination of Figure 5 and Figure 7, showing the R&D opportunity curve together with the current R&D portfolio curve.

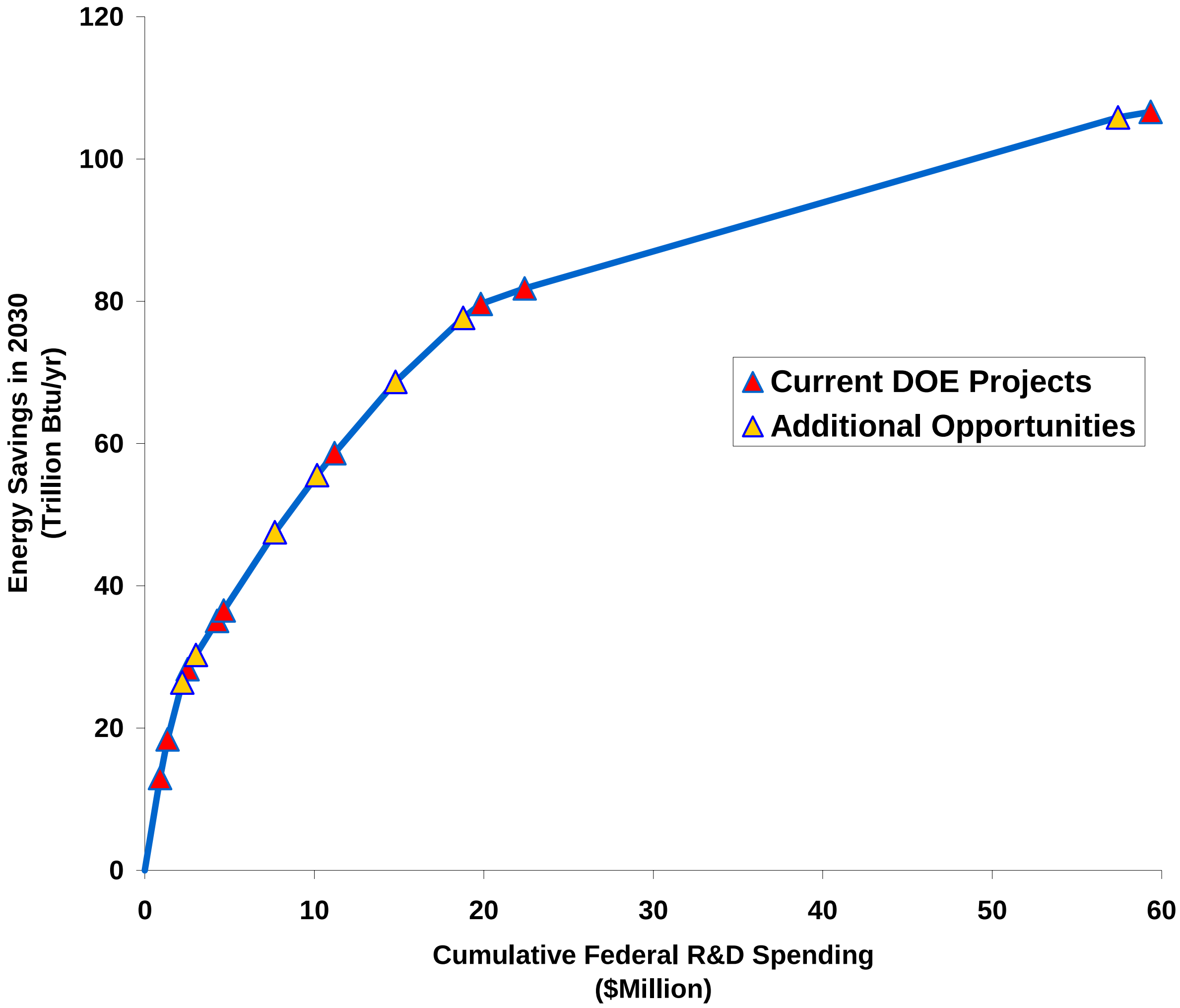


Figure 8. Energy Savings versus Cost for current R&D projects and new R&D Opportunities in ITP Steel Subprogram

Summary of Results

The marginal opportunity curve presented in Figures 7 and 8 show the energy savings in 2030 for the current portfolio compared against energy savings for potential R&D opportunities. In order to make a fair comparison between the R&D opportunities and the current portfolio, only those projects (or potential projects) where a reasonable estimate of federal investment and energy savings could be made were included in these figures. A comprehensive look at the current portfolio and R&D opportunities are included in Table 11 and Tables 13 – 15, which contain descriptions of estimated energy savings and federal investment.

In determining the energy savings potential from R&D opportunities, currently-available best practices were considered, as illustrated in Figures 1-4. The best practices opportunities were subtracted from the total opportunity to more accurately quantify the magnitude of R&D opportunities.

As shown in the resulting marginal opportunity curve (Figure 7), federal investment in R&D opportunities for steel manufacturing can reduce energy consumption by 72 TBtu/yr in 2030. Combine this with the 35 TBtu/yr savings from the current portfolio, and there is the potential for over 105 TBtu/yr of energy savings in 2030 attributable to the ITP steel subprogram, if all R&D opportunities identified in Table 15 are funded and successful.

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