Streamlined Life-Cycle Greenhouse Gas Emission Factors for Copper Wire

U.S. Environmental Protection Agency
Office of Solid Waste

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Executive Summary

This report provides streamlined life-cycle greenhouse gas (GHG) emission factors for copper wire. The methodology used to develop these draft factors are consistent with those employed in the WAste Reduction Model (WARM) and in the U.S. Environmental Protection Agency (EPA) report entitled *Solid Waste Management and Greenhouse Gases: A Life-Cycle Analysis of Emissions and Sinks*. The upstream energy data for copper wire was extracted from the 2002 report *Energy and Greenhouse Gas Factors for Personal Computers* produced by Franklin & Associates. Because personal computers (PCs) are a composite of several different materials, this document contains life-cycle data for several material types, including copper wire.

Emission factors for copper wire were developed for four waste management practices: source reduction, recycling, combustion, and landfilling as shown in Exhibit 1.[1] As would be expected, source reducing (e.g., reusing) copper wire has the greatest GHG benefit (expressed here in units of metric tons of carbon equivalent (MTCE) per short ton of wire). Recycling offers some GHG benefits and combustion and landfilling were estimated to result in small net GHG emissions.

When compared to existing emission factors for steel and aluminum, source reducing copper wire falls within the range established by the two other metals (e.g., -2.49 MTCE/ton for aluminum cans and -0.53 MTCE/ton for steel cans). The recycling emission factor also falls within the range of aluminum cans (-4.15 MTCE/ton) and steel cans (-0.49 MTCE/ton), and would have one of the highest GHG benefits of the existing suite of material types. Combustion and landfilling are consistent with other inert metals (except for steel, which can be recovered in the combustion process).

Exhibit 1. Copper GHG Emission Factors for Selected Waste Management Practices (MTCE/Ton)

Material	Net Source Reduction (Reuse) Emissions For Current Mix of Inputs	Net Recycling Emissions	Net Composting Emissions	Net Combustion Emissions	Net Landfilling Emissions
Copper Wire	-2.03	-1.39	NA	0.02	0.01

NA– not applicable.

Source Reduction

Copper is similar to the other metals analyzed by the EPA in that the manufacturing process begins with the extraction of ore and then proceeds through a series of industrial processes to produce copper metal. The material type modeled in Franklin's report is actually "copper wire", which means that the process energy for manufacturing both virgin and recycled copper wire would also include a winding process. The source reduction emission factor for copper wire is based on a current mix that includes some virgin and recycled material. The methodology presented below currently utilizes a value of 95 percent virgin material and 5 percent post-consumer recycled material content for copper wire (USGS, 2004a). Exhibit 2 displays the source reduction emission factor for copper wire. Please see Appendix A for details on energy consumption/fuel mix emissions data associated with virgin and recycled copper wire manufacturing.

[1] Composting is not considered because copper wire is an inert metal material that would not enter the composting wastestream.

Exhibit 2. Copper Wire Source Reduction Emission Factor (MTCE/ton)

Product	(a) Avoided Process Energy	(b) Avoided Transportation Energy	(c) Avoided Process Non-Energy	(d) Net Emissions Reduction (=a + b + c)
Copper Wire	2.02	0.01	0.00	2.03

Note: Totals may not sum due to independent rounding.

Avoided Process Emissions

In copper wire manufacturing, energy is required to obtain ore, operate ore processing equipment, and to extract and process the fuels used in the manufacturing process. The process energy to manufacture one ton of copper wire from virgin and recycled raw materials is 122.5 million Btu and 101.1 million Btu, respectively (FAL, 2002). These virgin and recycled energy values are then factored by the GHG emission values associated with their relative fuel-use mixtures to obtain emission factors of 2.04 MTCE/ton and 1.64 MTCE/ton, respectively. The two process energy values are then weighted by the current mix value of 95 percent virgin to obtain a source reduction avoided process energy value of 2.02 MTCE/ton.

Avoided Transport Emissions

The transportation energy to manufacture one ton of copper wire from virgin and recycled raw materials is 0.46 million Btu and 2.17 million Btu, respectively (FAL, 2002). These virgin and recycled energy values are then factored by the GHG emission values associated with their relative fuel-use mixtures to obtain emission factors of 0.01 MTCE/ton and 0.04 MTCE/ton, respectively. The transport energy values are then weighted by the current mix value of 95 percent virgin to obtain a source reduction avoided process energy value of 0.01 MTCE/ton.

Avoided Process Non-energy Emissions

The process non-energy emissions associated with the manufacture of virgin and recycled copper wire are both reported as being 0.000001 MTCE/ton (FAL, 2002). This process non-energy emission source may be attributed to the very small amounts of fossil-based materials used directly in the copper wire manufacturing process as a reactant rather than a fuel (heat) source. The small size of this emission factor translates into a negligible impact on the overall source reduction emission factor for copper wire.

Recycling

Copper wire is a highly recyclable material that has the potential to be nearly completely recovered after its useful life in most applications. There are two basic classifications of recycled copper wire, No.1 and No. 2. No. 1 copper wire is typically high quality unburned copper that is free of contaminants. No. 2 copper wire is slightly lower in quality with minimal amounts of impurities. Given the very high virgin content of copper wire (due to purity standards), it is likely that recovered copper wire would in most cases go into lower grade copper alloys (CDA, 2003). Therefore, the most accurate representation of this LCA would be to determine the energy/emissions associated with the production of smelted copper, rather than finished copper wire.[2]

The emission factor for copper wire recycling is calculated as the difference between emissions associated with producing copper from recycled materials (No. 1 and 2 scrap) and from virgin raw materials, adjusted to reflect the portion of copper that is lost during the recovery process (19 percent) (FAL, 2002). In addition, the recycled material component is assumed to be a weighted average of the energy/emissions associated with No.1 and 2 scrap which is estimated to be 93 and 7 percent, respectively (USGS, 2004b).

[2] The recycling of copper wire can be considered a quasi-open loop in that the material is not typically used to produce new copper wire, but is utilized in other copper products and alloys.

This calculation is completed for all three components of the recycling emission factor – process energy, transportation energy, and process non-energy emissions – and the sum reflects the net emission reduction associated with recycling copper wire as shown in Exhibit 3. Please see Appendices B and C for details on energy consumption/fuel mix emissions data associated with virgin and recycled copper manufacturing.

Exhibit 3. Copper Wire Recycling Emission Factor (MTCE/Ton)

Product	(a) Avoided Process Energy	(b) Avoided Transportation Energy	(c) Avoided Process Non-Energy	(d) Net Emissions Reduction (=a + b + c)
Copper Wire	1.37	0.02	0.00	1.39

Note: Total may not sum due to independent rounding.

Avoided Process Emissions

As with copper wire manufacturing, energy is required to obtain ore, operate ore processing equipment, and to extract and process the fuels used in the smelting process. The process energy to manufacture one ton of copper from virgin raw materials is 109.23 million Btu (Battell, 1975). The recovery and processing of copper wire scrap typically requires chopping, sorting and cleaning steps prior to smelting. The process energy to manufacture one ton of copper from No. 1 and 2 scrap is 7.21 and 20.75 million Btu, respectively (Kusik and Kenahan, 1978). These virgin and recycled energy values are then factored by the GHG emission values associated with their relative fuel-use mixtures to obtain emission factors of 1.81 MTCE/ton, and 0.11 and 0.37 MTCE/ton, respectively. The two recycled process energy values are then weighted by the recovery mix value of 93 percent No. 1 and 7 percent No. 2 to obtain a composite scrap wire recycling emission factor of 0.13 MTCE/ton. The differential between the process emissions for recycled and virgin copper production is 1.68 MTCE/ton. The recycling differential is then weighted by the scrap retention rate of 81 percent to obtain a recycling avoided process energy value of 1.39 MTCE/ton.

Avoided Transport Emissions

The transportation energy to manufacture one ton of copper from virgin raw materials is 3.06 million Btu (Battell, 1975). The transportation energy to manufacture one ton of copper from No. 1 and 2 scrap is 1.56 and 2.04 million Btu, respectively (Kusik and Kenahan, 1978). These virgin and recycled energy values are then factored by the GHG emission values associated with their relative fuel-use mixtures to obtain emission factors of 0.06 MTCE/ton, and 0.03 and 0.04 MTCE/ton, respectively. The two recycled process energy values are then weighted by the recovery mix value of 93 percent No. 1 and 7 percent No. 2 to obtain a composite scrap wire recycling emission factor of 0.03 MTCE/ton. The differential between the process emissions for recycled and virgin copper production is 0.03 MTCE/ton. The recycling differential is then weighted by the scrap retention rate of 81 percent to obtain a recycling avoided process energy value of 0.02 MTCE/ton.

Avoided Process Non-energy Emissions

The process non-energy emissions associated with the manufacture of virgin and recycled copper is assumed to be consistent as those for copper wire – where both are reported as being 0.000001 MTCE/ton. As a result the differential between manufacturing copper wire using virgin or recycled materials is zero.

Combustion

We were unable to find information on the combustion of copper wire. For the sake of developing a rough estimate, we applied the average of the existing combustion emission factors for aluminum and steel cans (without the steel recovery energy benefit). This value is 0.02 MTCE/ton combusted.

Landfilling

Copper wire is an inorganic material that produces no emissions in the landfill environment. As a result, the landfilling emission factor is the standard disposal emission factor of 0.01 MTCE/ton.

References

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Kusik and Kenahan, 1978. *Energy Use Patterns for Metal Recycling*. U.S. Bureau of Mines. 1978

USGS, 2004a. Personal communication between Daniel Edelstein of the United States Geological Survey and Jeremy Scharfenberg of ICF Consulting. September 2004.

USGS, 2004b. *Mineral Industry Surveys – Copper*, United States Geological Survey. May 2004.

Appendix A: Copper Wire Energy/Fuel Mix GHG Emission Tables

Exhibit A-1. Process Energy Emissions for Virgin Copper Wire

Fuel Type	(a) Percent of Total Btu[a]	(b) Million Btu used for Clay Brick Production (=122.52 x a)	(c) Fuel-specific Carbon Coefficient (MTCE/ Million Btu)[b]	(d) Fugitive CH_4 Emissions (MTCE/Million Btu)	(e) Process Energy CO_2 Emissions (MTCE/Ton) (=b x c)	(f) Process Energy CH_4 Emissions (MTCE/Ton) (=b x d)	(g) Total Process Energy Emissions (MTCE/Ton) (=e + f)
Gasoline	0.29%	0.3500	0.0192	0.0001	0.0067	0.0000	0.0068
LPG	0.02%	0.0200	0.0169	0.0001	0.0003	0.0000	0.0003
Distillate Fuel	0.77%	0.9400	0.0199	0.0001	0.0187	0.0001	0.0188
Residual Fuel	6.14%	7.5200	0.0214	0.0001	0.1610	0.0007	0.1617
Biomass/Hydro	0.05%	0.0600	0.0000	0.0000	0.0000	0.0000	0.0000
Diesel	10.82%	13.2600	0.0199	0.0001	0.2635	0.0013	0.2648
National Average Fuel Mix for Electricity	49.95%	61.2000	0.0158	0.0006	0.9666	0.0359	1.0025
Coal	2.25%	2.7600	0.0251	0.0009	0.0693	0.0025	0.0718
Natural Gas	29.38%	36.0000	0.0138	0.0007	0.4961	0.0253	0.5214
Nuclear	0.29%	0.3600	0.0000	0.0000	0.0000	0.0000	0.0000
Other	0.04%	0.0520	0.0000	0.0000	0.0000	0.0000	0.0000
Total	**100.00**	**122.5220**	**n/a**	**n/a**	**1.9822**	**0.0658**	**2.0481**

n/a – not applicable. Note: Totals may not sum due to independent rounding
Sources: [a]FAL 2002; [b]EIA 2001 (the electricity EF was calculated from a weighted average of fuels used in the US).

Exhibit A-2 Process Energy Emissions Recycled Copper Wire

Fuel Type	(a) Percent of Total Btu[a]	(b) Million Btu used for Clay Brick Production (=101.05 x a)	(c) Fuel-specific Carbon Coefficient (MTCE/ Million Btu)[b]	(d) Fugitive CH_4 Emissions (MTCE/Million Btu)	(e) Process Energy CO_2 Emissions (MTCE/Ton) (=b x c)	(f) Process Energy CH_4 Emissions (MTCE/Ton) (=b x d)	(g) Total Process Energy Emissions (MTCE/Ton) (=e + f)
Gasoline	0.33%	0.3300	0.0192	0.0001	0.0064	0.0000	0.0064
LPG	0.01%	0.0084	0.0169	0.0001	0.0001	0.0000	0.0001
Distillate Fuel	0.81%	0.8200	0.0199	0.0001	0.0163	0.0001	0.0164
Residual Fuel	6.87%	6.9400	0.0214	0.0001	0.1486	0.0007	0.1493
Biomass/Hydro	0.05%	0.0480	0.0000	0.0000	0.0000	0.0000	0.0000
Diesel	0.00%	0.0000	0.0199	0.0001	0.0000	0.0000	0.0000
National Average Fuel Mix for Electricity	52.65%	53.2000	0.0158	0.0006	0.8402	0.0312	0.8714
Coal	2.53%	2.5600	0.0251	0.0009	0.0643	0.0024	0.0666
Natural Gas	36.42%	36.8000	0.0138	0.0007	0.5071	0.0258	0.5330
Nuclear	0.30%	0.3000	0.0000	0.0000	0.0000	0.0000	0.0000
Other	0.04%	0.0420	0.0000	0.0000	0.0000	0.0000	0.0000
Total	**100.00**	**101.0484**	**n/a**	**n/a**	**1.5830**	**0.0602**	**1.6432**

n/a – not applicable. Note: Totals may not sum due to independent rounding
Sources: [a]FAL 2002; [b]EIA 2001 (the electricity EF was calculated from a weighted average of fuels used in the US)

Exhibit A-3 Virgin and Recycled Copper Wire Process Non-energy Emissions

Type of Product	Non-Energy Carbon Emissions (MTCE/ton)	CO_2 Emissions (MT/Ton)
Copper wire	0.000001	0.000003

Source: FAL 2002

Exhibit A-4. Transportation Emissions Virgin Copper Wire

Fuel Type	(a) Percent of Total Btu[a]	(b) Million Btu used for Clay Brick Production (=0.4644 x a)	(c) Fuel-specific Carbon Coefficient (MTCE/ Million Btu)[b]	(d) Fugitive CH_4 Emissions (MTCE/Million Btu)	(e) Process Energy CO_2 Emissions (MTCE/Ton) (=b x c)	(f) Process Energy CH_4 Emissions (MTCE/Ton) (=b x d)	(g) Total Process Energy Emissions (MTCE/Ton) (=e + f)
Gasoline	0.09%	0.0004	0.0192	0.0001	0.0000	0.0000	0.0000
LPG	0.08%	0.0004	0.0169	0.0001	0.0000	0.0000	0.0000
Distillate Fuel	0.39%	0.0018	0.0199	0.0001	0.0000	0.0000	0.0000
Residual Fuel	4.16%	0.0193	0.0214	0.0001	0.0004	0.0000	0.0004
Biomass/Hydro	0.06%	0.0003	0.0000	0.0000	0.0000	0.0000	0.0000
Diesel	87.04%	0.4042	0.0199	0.0001	0.0080	0.0000	0.0081
National Average Fuel Mix for Electricity	0.02%	0.0001	0.0158	0.0006	0.0000	0.0000	0.0000
Coal	0.86%	0.0040	0.0251	0.0009	0.0001	0.0000	0.0001
Natural Gas	6.92%	0.0322	0.0138	0.0007	0.0004	0.0000	0.0005
Nuclear	0.34%	0.0016	0.0000	0.0000	0.0000	0.0000	0.0000
Other	0.05%	0.0002	0.0000	0.0000	0.0000	0.0000	0.0000
Total	**100.00**	**0.4644**	**n/a**	**n/a**	**0.0090**	**0.0001**	**0.0091**

n/a – not applicable. Note: Totals may not sum due to independent rounding.
Sources: [a]FAL 2002; [b]EIA 2001 (the electricity EF was calculated from a weighted average of fuels used in the US)

Exhibit A-5. Transportation Emissions for Recycled Copper Wire

Fuel Type	(a) Percent of Total Btu[a]	(b) Million Btu used for Clay Brick Production (=2.1741 x a)	(c) Fuel-specific Carbon Coefficient (MTCE/ Million Btu)[b]	(d) Fugitive CH_4 Emissions (MTCE/Million Btu)	(e) Process Energy CO_2 Emissions (MTCE/Ton) (=b x c)	(f) Process Energy CH_4 Emissions (MTCE/Ton) (=b x d)	(g) Total Process Energy Emissions (MTCE/Ton) (=e + f)
Gasoline	0.10%	0.0022	0.0192	0.0001	0.0000	0.0000	0.0000
LPG	0.08%	0.0017	0.0169	0.0001	0.0000	0.0000	0.0000
Distillate Fuel	0.39%	0.0084	0.0199	0.0001	0.0002	0.0000	0.0002
Residual Fuel	3.84%	0.0835	0.0214	0.0001	0.0018	0.0000	0.0018
Biomass/Hydro	0.05%	0.0012	0.0000	0.0000	0.0000	0.0000	0.0000
Diesel	87.67%	1.9062	0.0199	0.0001	0.0379	0.0002	0.0381
National Average Fuel Mix for Electricity	0.00%	0.0001	0.0158	0.0006	0.0000	0.0000	0.0000
Coal	0.86%	0.0186	0.0251	0.0009	0.0005	0.0000	0.0005
Natural Gas	6.63%	0.1442	0.0138	0.0007	0.0020	0.0001	0.0021
Nuclear	0.33%	0.0072	0.0000	0.0000	0.0000	0.0000	0.0000
Other	0.05%	0.0010	0.0000	0.0000	0.0000	0.0000	0.0000
Total	**100.00**	**2.1742**	**n/a**	**n/a**	**0.0424**	**0.0003**	**0.0427**

n/a – not applicable. Note: Totals may not sum due to independent rounding.
Sources: [a]FAL 2002; [b]EIA 2001 (the electricity EF was calculated from a weighted average of fuels used in the US)

Appendix B: Virgin Copper Energy/Fuel Mix GHG Emission Tables

Exhibit B-1. Process Emissions for Virgin Copper

Fuel Type	(a) Percent of Total Btu[a]	(b) Million Btu used for Clay Brick Production (=109.23 x a)	(c) Fuel-specific Carbon Coefficient (MTCE/ Million Btu)[b]	(d) Fugitive CH_4 Emissions (MTCE/Million Btu)	(e) Process Energy CO_2 Emissions (MTCE/Ton) (=b x c)	(f) Process Energy CH_4 Emissions (MTCE/Ton) (=b x d)	(g) Total Process Energy Emissions (MTCE/Ton) (=e + f)
Gasoline	0.00%	0.0000	0.0192	0.0001	0.0000	0.0000	0.0000
LPG	0.00%	0.0000	0.0169	0.0001	0.0000	0.0000	0.0000
Distillate Fuel	0.00%	0.0000	0.0199	0.0001	0.0000	0.0000	0.0000
Residual Fuel	0.00%	0.0000	0.0214	0.0001	0.0000	0.0000	0.0000
Biomass/Hydro	0.00%	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
Diesel	21.36%	23.3317	0.0199	0.0001	0.4636	0.0023	0.4659
National Average Fuel Mix for Electricity	51.24%	55.9700	0.0158	0.0006	0.8840	0.0328	0.9168
Coal	0.0036%	0.0039	0.0251	0.0009	0.0001	0.0000	0.0001
Natural Gas	27.04%	29.5361	0.0138	0.0007	0.4070	0.0207	0.4278
Nuclear	0.00%	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
Other	0.00%	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
Total	**100.00**	**109.2300**	**n/a**	**n/a**	**1.7547**	**0.0558**	**1.8105**

n/a – not applicable. Note: Totals may not sum due to independent rounding
Sources: [a]Battell 1975; [b]EIA 2001 (the electricity EF was calculated from a weighted average of fuels used in the US)

Exhibit B-2. Transportation Emissions for Virgin Copper

Fuel Type	(a) Percent of Total Btu[a]	(b) Million Btu used for Clay Brick Production (=3.059 x a)	(c) Fuel-specific Carbon Coefficient (MTCE/ Million Btu)[b]	(d) Fugitive CH_4 Emissions (MTCE/Million Btu)	(e) Process Energy CO_2 Emissions (MTCE/Ton) (=b x c)	(f) Process Energy CH_4 Emissions (MTCE/Ton) (=b x d)	(g) Total Process Energy Emissions (MTCE/Ton) (=e + f)
Gasoline	0.00%	0.0000	0.0192	0.0001	0.0000	0.0000	0.0000
LPG	0.00%	0.0000	0.0169	0.0001	0.0000	0.0000	0.0000
Distillate Fuel	0.00%	0.0000	0.0199	0.0001	0.0000	0.0000	0.0000
Residual Fuel	0.00%	0.0000	0.0214	0.0001	0.0000	0.0000	0.0000
Biomass/Hydro	0.00%	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
Diesel	72.25%	2.2101	0.0199	0.0001	0.0439	0.0002	0.0441
National Average Fuel Mix for Electricity	27.75%	0.8489	0.0158	0.0006	0.0134	0.0005	0.0139
Coal	0.00%	0.0000	0.0251	0.0009	0.0000	0.0000	0.0000
Natural Gas	0.00%	0.0000	0.0138	0.0007	0.0000	0.0000	0.0000
Nuclear	0.00%	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
Other	0.00%	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
Total	**100.00**	**3.0590**	**n/a**	**n/a**	**0.0573**	**0.0007**	**0.0580**

n/a – not applicable. Note: Totals may not sum due to independent rounding
Sources: [a]Battell 1975; [b]EIA 2001 (the electricity EF was calculated from a weighted average of fuels used in the US)

Appendix C: Recycled Copper Energy/Fuel Mix GHG Emission Tables

Exhibit C-1. Process Emissions for Recycling No.1 Wire Scrap

Fuel Type	(a) Percent of Total Btu[a]	(b) Million Btu used for Clay Brick Production (=7.2100 x a)	(c) Fuel-specific Carbon Coefficient (MTCE/ Million Btu)[b]	(d) Fugitive CH_4 Emissions (MTCE/Million Btu)	(e) Process Energy CO_2 Emissions (MTCE/Ton) (=b x c)	(f) Process Energy CH_4 Emissions (MTCE/Ton) (=b x d)	(g) Total Process Energy Emissions (MTCE/Ton) (=e + f)
Gasoline	0.00%	0.0000	0.0192	0.0001	0.0000	0.0000	0.0000
LPG	0.00%	0.0000	0.0169	0.0001	0.0000	0.0000	0.0000
Distillate Fuel	15.81%	1.1400	0.0199	0.0001	0.0227	0.0001	0.0228
Residual Fuel	0.00%	0.0000	0.0214	0.0001	0.0000	0.0000	0.0000
Biomass/Hydro	0.00%	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
Diesel	0.00%	0.0000	0.0199	0.0001	0.0000	0.0000	0.0000
National Average Fuel Mix for Electricity	28.43%	2.0500	0.0158	0.0006	0.0324	0.0012	0.0336
Coal	0.00%	0.0000	0.0251	0.0009	0.0000	0.0000	0.0000
Natural Gas	53.40%	3.8500	0.0138	0.0007	0.0531	0.0027	0.0558
Nuclear	0.00%	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
Other	2.36%	0.1700	0.0000	0.0000	0.0000	0.0000	0.0000
Total	**100.00**	**7.2100**	**n/a**	**n/a**	**0.1081**	**0.0040**	**0.1121**

n/a – not applicable. Note: Totals may not sum due to independent rounding
Sources: [a] Kusik and Kenahan, 1978; [b]EIA 2001 (the electricity EF was calculated from a weighted average of fuels used in the US)

Exhibit C-2. Process Emissions for Recycling No.2 Wire Scrap

Fuel Type	(a) Percent of Total Btu[a]	(b) Million Btu used for Clay Brick Production (=20.750 x a)	(c) Fuel-specific Carbon Coefficient (MTCE/ Million Btu)[b]	(d) Fugitive CH_4 Emissions (MTCE/Million Btu)	(e) Process Energy CO_2 Emissions (MTCE/Ton) (=b x c)	(f) Process Energy CH_4 Emissions (MTCE/Ton) (=b x d)	(g) Total Process Energy Emissions (MTCE/Ton) (=e + f)
Gasoline	0.00%	0.0000	0.0192	0.0001	0.0000	0.0000	0.0000
LPG	0.00%	0.0000	0.0169	0.0001	0.0000	0.0000	0.0000
Distillate Fuel	39.71%	8.2400	0.0199	0.0001	0.1637	0.0008	0.1645
Residual Fuel	0.00%	0.0000	0.0214	0.0001	0.0000	0.0000	0.0000
Biomass/Hydro	0.00%	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
Diesel	0.00%	0.0000	0.0199	0.0001	0.0000	0.0000	0.0000
National Average Fuel Mix for Electricity	54.31%	11.2700	0.0158	0.0006	0.1780	0.0066	0.1846
Coal	1.35%	0.2800	0.0251	0.0009	0.0070	0.0003	0.0073
Natural Gas	4.63%	0.9600	0.0138	0.0007	0.0132	0.0007	0.0139
Nuclear	0.00%	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
Other	0.00%	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
Total	**100.00**	**20.7500**	**n/a**	**n/a**	**0.3620**	**0.0083**	**0.3703**

n/a – not applicable. Note: Totals may not sum due to independent rounding
Sources: [a] Kusik and Kenahan, 1978; [b]EIA 2001 (the electricity EF was calculated from a weighted average of fuels used in the US)

Exhibit C-3. Process Emissions for Recycling Low Grade Copper Scrap

Fuel Type	(a) Percent of Total Btu[a]	(b) Million Btu used for Clay Brick Production (=44.310 x a)	(c) Fuel-specific Carbon Coefficient (MTCE/ Million Btu)[b]	(d) Fugitive CH_4 Emissions (MTCE/Million Btu)	(e) Process Energy CO_2 Emissions (MTCE/Ton) (=b x c)	(f) Process Energy CH_4 Emissions (MTCE/Ton) (=b x d)	(g) Total Process Energy Emissions (MTCE/Ton) (=e + f)
Gasoline	0.00%	0.0000	0.0192	0.0001	0.0000	0.0000	0.0000
LPG	0.00%	0.0000	0.0169	0.0001	0.0000	0.0000	0.0000
Distillate Fuel	16.10%	7.1400	0.0199	0.0001	0.1419	0.0007	0.1426
Residual Fuel	0.00%	0.0000	0.0214	0.0001	0.0000	0.0000	0.0000
Biomass/Hydro	0.00%	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
Diesel	0.00%	0.0000	0.0199	0.0001	0.0000	0.0000	0.0000
National Average Fuel Mix for Electricity	36.53%	16.2000	0.0158	0.0006	0.2559	0.0095	0.2654
Coal	46.09%	20.4400	0.0251	0.0009	0.5131	0.0188	0.5319
Natural Gas	1.20%	0.5300	0.0138	0.0007	0.0073	0.0004	0.0077
Nuclear	0.00%	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
Other	0.00%	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
Total	**100.00**	**44.3100**	**n/a**	**n/a**	**0.9181**	**0.0294**	**0.9475**

n/a – not applicable. Note: Totals may not sum due to independent rounding
Sources: [a] Kusik and Kenahan, 1978; [b]EIA 2001 (the electricity EF was calculated from a weighted average of fuels used in the US)

Exhibit C-4. Process Emissions for Recycling Brass and Bronze Scrap

Fuel Type	(a) Percent of Total Btu[a]	(b) Million Btu used for Clay Brick Production (=9.5700 x a)	(c) Fuel-specific Carbon Coefficient (MTCE/ Million Btu)[b]	(d) Fugitive CH_4 Emissions (MTCE/Million Btu)	(e) Process Energy CO_2 Emissions (MTCE/Ton) (=b x c)	(f) Process Energy CH_4 Emissions (MTCE/Ton) (=b x d)	(g) Total Process Energy Emissions (MTCE/Ton) (=e + f)
Gasoline	0.00%	0.0000	0.0192	0.0001	0.0000	0.0000	0.0000
LPG	0.00%	0.0000	0.0169	0.0001	0.0000	0.0000	0.0000
Distillate Fuel	15.78%	1.5100	0.0199	0.0001	0.0300	0.0001	0.0302
Residual Fuel	0.00%	0.0000	0.0214	0.0001	0.0000	0.0000	0.0000
Biomass/Hydro	0.00%	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
Diesel	0.00%	0.0000	0.0199	0.0001	0.0000	0.0000	0.0000
National Average Fuel Mix for Electricity	29.68%	2.8400	0.0158	0.0006	0.0449	0.0017	0.0465
Coal	2.30%	0.2200	0.0251	0.0009	0.0055	0.0002	0.0057
Natural Gas	48.07%	4.6000	0.0138	0.0007	0.0634	0.0032	0.0666
Nuclear	0.00%	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
Other	4.18%	0.4000	0.0000	0.0000	0.0000	0.0000	0.0000
Total	**100.00**	**9.5700**	**n/a**	**n/a**	**0.1438**	**0.0052**	**0.1490**

n/a – not applicable. Note: Totals may not sum due to independent rounding
Sources: [a] Kusik and Kenahan, 1978; [b]EIA 2001 (the electricity EF was calculated from a weighted average of fuels used in the US)

Exhibit C-5. Transport Emissions for Recycling No.1 Wire Scrap

Fuel Type	(a) Percent of Total Btu[a]	(b) Million Btu used for Clay Brick Production (=1.5600 x a)	(c) Fuel-specific Carbon Coefficient (MTCE/ Million Btu)[b]	(d) Fugitive CH_4 Emissions (MTCE/Million Btu)	(e) Process Energy CO_2 Emissions (MTCE/Ton) (=b x c)	(f) Process Energy CH_4 Emissions (MTCE/Ton) (=b x d)	(g) Total Process Energy Emissions (MTCE/Ton) (=e + f)
Gasoline	0.00%	0.0000	0.0192	0.0001	0.0000	0.0000	0.0000
LPG	0.00%	0.0000	0.0169	0.0001	0.0000	0.0000	0.0000
Distillate Fuel	0.00%	0.0000	0.0199	0.0001	0.0000	0.0000	0.0000
Residual Fuel	0.00%	0.0000	0.0214	0.0001	0.0000	0.0000	0.0000
Biomass/Hydro	0.00%	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
Diesel	100.00%	1.5600	0.0199	0.0001	0.0310	0.0002	0.0311
National Average Fuel Mix for Electricity	0.00%	0.0000	0.0158	0.0006	0.0000	0.0000	0.0000
Coal	0.00%	0.0000	0.0251	0.0009	0.0000	0.0000	0.0000
Natural Gas	0.00%	0.0000	0.0138	0.0007	0.0000	0.0000	0.0000
Nuclear	0.00%	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
Other	0.00%	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
Total	**100.00**	**1.5600**	**n/a**	**n/a**	**0.0310**	**0.0002**	**0.0311**

n/a – not applicable. Note: Totals may not sum due to independent rounding
Sources: [a] Kusik and Kenahan, 1978; [b]EIA 2001 (the electricity EF was calculated from a weighted average of fuels used in the US)

Exhibit C-6. Transport Emissions for Recycling No.2 Wire Scrap

Fuel Type	(a) Percent of Total Btu[a]	(b) Million Btu used for Clay Brick Production (=2.0400 x a)	(c) Fuel-specific Carbon Coefficient (MTCE/ Million Btu)[b]	(d) Fugitive CH_4 Emissions (MTCE/Million Btu)	(e) Process Energy CO_2 Emissions (MTCE/Ton) (=b x c)	(f) Process Energy CH_4 Emissions (MTCE/Ton) (=b x d)	(g) Total Process Energy Emissions (MTCE/Ton) (=e + f)
Gasoline	0.00%	0.0000	0.0192	0.0001	0.0000	0.0000	0.0000
LPG	0.00%	0.0000	0.0169	0.0001	0.0000	0.0000	0.0000
Distillate Fuel	0.00%	0.0000	0.0199	0.0001	0.0000	0.0000	0.0000
Residual Fuel	0.00%	0.0000	0.0214	0.0001	0.0000	0.0000	0.0000
Biomass/Hydro	0.00%	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
Diesel	100.00%	2.0400	0.0199	0.0001	0.0405	0.0002	0.0407
National Average Fuel Mix for Electricity	0.00%	0.0000	0.0158	0.0006	0.0000	0.0000	0.0000
Coal	0.00%	0.0000	0.0251	0.0009	0.0000	0.0000	0.0000
Natural Gas	0.00%	0.0000	0.0138	0.0007	0.0000	0.0000	0.0000
Nuclear	0.00%	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
Other	0.00%	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
Total	**100.00**	**2.0400**	**n/a**	**n/a**	**0.0405**	**0.0002**	**0.0407**

n/a – not applicable. Note: Totals may not sum due to independent rounding
Sources: [a] Kusik and Kenahan, 1978; [b]EIA 2001 (the electricity EF was calculated from a weighted average of fuels used in the US)

Exhibit C-7. Transport Emissions for Recycling Low Grade Copper Scrap

Fuel Type	(a) Percent of Total Btu[a]	(b) Million Btu used for Clay Brick Production (=1.8600 x a)	(c) Fuel-specific Carbon Coefficient (MTCE/ Million Btu)[b]	(d) Fugitive CH_4 Emissions (MTCE/Million Btu)	(e) Process Energy CO_2 Emissions (MTCE/Ton) (=b x c)	(f) Process Energy CH_4 Emissions (MTCE/Ton) (=b x d)	(g) Total Process Energy Emissions (MTCE/Ton) (=e + f)
Gasoline	0.00%	0.0000	0.0192	0.0001	0.0000	0.0000	0.0000
LPG	0.00%	0.0000	0.0169	0.0001	0.0000	0.0000	0.0000
Distillate Fuel	0.00%	0.0000	0.0199	0.0001	0.0000	0.0000	0.0000
Residual Fuel	0.00%	0.0000	0.0214	0.0001	0.0000	0.0000	0.0000
Biomass/Hydro	0.00%	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
Diesel	100.00%	1.8600	0.0199	0.0001	0.0370	0.0002	0.0371
National Average Fuel Mix for Electricity	0.00%	0.0000	0.0158	0.0006	0.0000	0.0000	0.0000
Coal	0.00%	0.0000	0.0251	0.0009	0.0000	0.0000	0.0000
Natural Gas	0.00%	0.0000	0.0138	0.0007	0.0000	0.0000	0.0000
Nuclear	0.00%	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
Other	0.00%	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
Total	**100.00**	**1.8600**	**n/a**	**n/a**	**0.0370**	**0.0002**	**0.0371**

n/a – not applicable. Note: Totals may not sum due to independent rounding
Sources: [a] Kusik and Kenahan, 1978; [b]EIA 2001 (the electricity EF was calculated from a weighted average of fuels used in the US)

Exhibit C-8. Transport Emissions for Recycling Brass and Bronze Scrap

Fuel Type	(a) Percent of Total Btu[a]	(b) Million Btu used for Clay Brick Production (=1.3000 x a)	(c) Fuel-specific Carbon Coefficient (MTCE/ Million Btu)[b]	(d) Fugitive CH_4 Emissions (MTCE/Million Btu)	(e) Process Energy CO_2 Emissions (MTCE/Ton) (=b x c)	(f) Process Energy CH_4 Emissions (MTCE/Ton) (=b x d)	(g) Total Process Energy Emissions (MTCE/Ton) (=e + f)
Gasoline	0.00%	0.0000	0.0192	0.0001	0.0000	0.0000	0.0000
LPG	0.00%	0.0000	0.0169	0.0001	0.0000	0.0000	0.0000
Distillate Fuel	0.00%	0.0000	0.0199	0.0001	0.0000	0.0000	0.0000
Residual Fuel	0.00%	0.0000	0.0214	0.0001	0.0000	0.0000	0.0000
Biomass/Hydro	0.00%	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
Diesel	100.00%	1.3000	0.0199	0.0001	0.0258	0.0001	0.0260
National Average Fuel Mix for Electricity	0.00%	0.0000	0.0158	0.0006	0.0000	0.0000	0.0000
Coal	0.00%	0.0000	0.0251	0.0009	0.0000	0.0000	0.0000
Natural Gas	0.00%	0.0000	0.0138	0.0007	0.0000	0.0000	0.0000
Nuclear	0.00%	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
Other	0.00%	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
Total	**100.00**	**1.3000**	**n/a**	**n/a**	**0.0258**	**0.0001**	**0.0260**

n/a – not applicable. Note: Totals may not sum due to independent rounding
Sources: [a] Kusik and Kenahan, 1978; [b]EIA 2001 (the electricity EF was calculated from a weighted average of fuels used in the US)

Appendix D: Comment-Response Document

The purpose of this appendix is to document the record of responses made to the expert review comments received for this report. This appendix is intended to serve both as a record of all comments received and also as a record of how the comments were addressed.

Reviewer: Dr. Paul Queneau– Colorado School of Mines

1. You have already spotted the same problem that I did – that key sources upon which you have relied are long out of date. The result is the reliability of your output will likely be low. As you indicated in your last e-mail, there have been huge changes in the energy efficiency in our copper industry since the mid-80s. Hopefully *FAL, 2002* did not rely on similar outdated sources.

Response: We acknowledge that the data we used for certain components of the report is somewhat outdated (specifically the virgin copper ingot and copper wire scrap data). However, this data is cited in publications by the Copper Development Association (CDA) and Noranda-Recycling as recently as 2003. In addition, the Franklin & Associates personal computer life-cycle analysis in 2002 (the source for virgin copper wire data) was created in active consultation with copper wire industry experts.

2. The energy information that you need is almost certainly out there. It may take a day or two of phone calling to find and to verify it. If your final report becomes available to the public in electronic form, be all means consider passing along a copy to me.

Response: During the research phase of this project we contacted a number of experts with very little success in locating detailed energy consumption data for the various copper wire manufacturing processes. We received the *Technical Report: Copper, Brass, Bronze. The U.S. Copper-base Scrap Industry and Its By-products* from the Copper Development Association which contained life-cycle data for copper which we traced back to the older source. As noted in the response to comment 1, this data is still cited regularly by industry.

Reviewer: Copper Development Association Anonymous Reviewer #1 (European)

3. First of all, the CE Delft report, as well as all other work we have done in this field can be found at http://ecodesign.leonardo-energy.org/. In particular, the case study 'building wire' is relevant in this context (a cradle-to-grave analysis of building wire, with impact categories greenhouse gasses and acidification).

Response: We have evaluated the findings of this study for comparative purposes to our report. The CE Delft report estimates copper production emissions to be between 6-4 MTCO2E, while our analysis estimates 7.3 MTCO2E. Assuming a precombustion scale-up for their numbers of 20 percent, the new CE Delft range would be 7.2-4.8 MTCO2E. An additional factor that would produce higher results for our analysis is differing fuel mixes for electricity generation (the EU has more nuclear and renewables, while the US utilizes a larger amount coal and would have more GHG emissions). In light of these considerations, our estimates are very close to those found in the CE Delft report.

4. The most important point to make on the ICF report is that it does not provide a cradle-to-grave analysis. Rather, it is cradle-to-gate and end-of-life (EOL), ignoring gate-to-EOL. Since the last step is typically 90% (and in extreme cases even 99%) of life-cycle impact, we have to keep in mind that the report focuses on a small part of the life-cycle impact. My worry is that the report may lead to the interpretation that reducing Cu use and recycling Cu are prime resource conservation strategies. However, from an integrated resource management viewpoint, the use of an additional tonne of Cu in electrical systems leads to a net reduction of 200 tonnes CO2 emissions over the lifetime use, primarily due to increased efficiency.

Response: The boundaries of our "streamlined" life-cycle analysis do not include increased energy efficiencies of copper wire during the use phase. This is consistent with our treatment of other materials (e.g., light weighting using aluminum and decreased fuel consumption is not part of our analysis).

5. The report studies only greenhouse gas emissions. However, the lifecycle of cable also has significant other environmental impacts (mainly acidification, eutrophication, particle emissions), which can be improved with proper design.

Response: See response to comment 4. The life-cycle impacts of acidification and particle emissions are important considerations for a full life-cycle study of copper, however they are outside the scope of this study's methodology.

6. Cables are conductors and insulation materials. The latter are ignored. Their impact can be considered minor compared to metals use in manufacturing. However, the environmental impact of the insulation materials (PVC, rubber, PE) will be significantly above many of the other impacts studied in the report.

Response: The environmental impacts of the insulation and coating material are not included in this analysis. Our methodology is based on an assumption of copper-only materials in the manufacturing and disposal processes.

7. On specifics, the reference to the Franklin & Associates report on PC's: this is a very marginal application for copper wire use, and in PC's, copper wire use is marginal. Extrapolation based on such application may not be robust.

Response: We believe that the copper wire use in PCs is an adequate proxy for copper wire use in other applications such as residential/commercial electrical wiring. Copper wire is produced utilizing roughly the same process regardless of the gauge or exact electrical application.

8. The figures are 5-6 tonnes of CO2 per tonne of Cu. This is ballpark, but needs to be compared to the few hundred tonnes that copper can save in use.

Response: See response to comment 3. Also, the use-phase component is outside the scope of our methodology.

9. Finally, for your information, European Copper Institute is working on a project to develop parameterized models for cradle-to-grave impact assessment for various components in the electrical systems (cable, busbar, motors, transformers, ballasts, ...). This will result in a toolbox for very fast turnaround impact assessment, using bill-of-materials and load profile as inputs. We expect the results in 6 months.

Response: We look forward to the results of this project and will attempt to incorporate any useful information when it becomes available.

Reviewer: Copper Development Association Anonymous Reviewer #2 (American)

10. Page 2: LCA emissions factors for copper, if cradle-to-gate, should not reflect conditions associated with any end-use product. Yet this analysis seems to be specifically tied to copper's use in downstream computer applications. The analysis should not make reference to any downstream application unless full cradle-to-cradle lifecycle energy inputs and outputs are considered. Further, as an upstream cradle-to-gate analysis, downstream applications data should not be considered in the setting of emissions factors. Such is not the case in this analysis.

Response: See response to comment 4. This life-cycle component is outside the scope of our methodology.

11. Page 2: Ore production, extraction, and refinement is cradle-to-gate production of intermediate products of fabrication (in this case, copper wire), not end-use consumer-product manufacturing. Since the system boundaries of this analysis end with the production gate, the analysis is only a partial LCA and the application to computers or any other end-use product is irrelevant.

Response: See response to comment 4. We do not incorporate material use-phase in our life-cycle methodology.

12. Page 2: LCA's and their energy flows are typically comparative (comparing the performance of one material versus another). As such, this analysis as presented is of limited value unless compared with aluminum and other forms of wiring. Further the analysis should include life stages of use-phase and recycling or disposal.

Response: See response to comment 4. We do not incorporate material use-phase in our life-cycle methodology.

13. Page 2: The assumption of 95% virgin is probably incorrect for copper wire. Faced with uncertainty, a best-case-to-worst-case range of assumed virgin copper should be used until the mix data are available.

Response: We believe that this value is probably more accurate than the commenter notes because it is based on post-consumer scrap. The recycled content of current mix material based on "new" scrap is probably higher, but is not a part of our methodology. In addition, the *Technical Report: Copper, Brass, Bronze. The U.S. Copper-base Scrap Industry and Its By-products* (2003) from The Copper Development Association notes that only a "small amount of scrap is used by wire rod mills," and the May 2004 *Technical Bulletin* published by the Metal Construction Association notes that "Copper wire is the biggest consumer of copper and that copper must be pure. As a result, copper wire production uses little copper scrap."

14. Page 3: The transportation energy data cited in the production (not manufacture) of one ton of intermediate product are outdated (Battell 1975).

Response: See response to comment 1. While these data may be outdated, they are still cited by industry in recent publications. Should more recent data become available we will utilize it accordingly.

15. Page 4: Copper wire as an intermediate product is not landfilled. To the extent that end-use products at their end-of-life are landfilled, the emission factor is product-specific. However, this cradle-to-gate analysis does not include end-use products and therefore should not have any landfill emissions factors associated with it.

Response: See response to comment 4. We do not incorporate material use-phase in our life-cycle methodology. While it is unlikely that large amounts of copper wire are landfilled, this disposal factor is provided for completeness of our waste management methodology.