Technical Paper

What's the Score?

A Method for Quantitative Estimation of Energy Use and Emission Reductions for UV/EB Curing

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A number of case studies have demonstrated that replacement of thermally cured solvent or waterborne inks, coatings and adhesives with ultraviolet (UV)/electron beam (EB) curing systems can not only reduce uncontrolled volatile organic compound (VOC) release, but can also reduce energy demand and greenhouse gas (GHG) emissions by up to 90 percent.[1-6] These results for individual industrial applications provide a strong indication that UV or EB technology should have an impact on reducing energy use and GHG emissions, but until now no general methods for calculating the quantitative significance of these benefits have been proposed.

This paper outlines a method for calculating a first-order estimate of the relative energy requirements for thermal and UV/EB-curing of inks, coatings and adhesives from a limited number of prior publications that include quantitative data for side-by-side comparison of each process. Using this method, it is possible to calculate a total annual "sustainability scorecard" benefit of radiation curing for reducing energy use and GHG emissions. The same methodology can be generally applied to individual curing installations that wish to estimate energy demand and GHG emissions for their particular case.

Table 1

Energy demand in Btu/m² to decorate metal cans

(Calculated from Coors data)

	W/B Thermal Curing + Incineration	UV Curing
Electricity	795.8	648.9
Natural Gas	2,452.6	0
Total Energy Demand	3,248.4	648.9
Electricity/Total Energy Usage Ratio*	24%	100%

*The average of these ratios will be used later to calculate comparative electrical and natural gas requirements and GHG emissions (Tables 7 and 9).

Quantitative Comparison of Radiation and Thermal Curing

Two of the cited studies include detailed quantitative data for side-by-side comparison of the amount of electrical and natural gas combustion energy used by UV and thermal curing in the same industrial process, notably the "Coors" can coating study published under a DOE/EPA jointly funded NICE/3 Grant[2] and an adhesive "eco-efficiency" study published by BASF authors.[3] A previous publication[4] analyzed the data from the BASF case study to compare the normalized energy demand to apply and cure an adhesive on one square meter of plastic film with thermal- and UV-adhesive formulations. Another earlier publication[5] summarized energy and emissions data from the "Coors" study. That data can be combined with the surface area of a typical 12-ounce

Table 2

Energy demand in Btu/m² to apply coated adhesive *(Calculated from BASF data)*

	Solvent Thermal Curing + Incineration	W/B Thermal Curing	UV Curing
Electricity	430	1,400	508
Natural Gas—Curing	2,355	3,072	0
Natural Gas—VOC Incineration	1,024	0	0
Total	3,851	4,497	508
Electricity/Total Energy Usage Ratio*	11%	31%	100%

**The average of these ratios will be used later to calculate comparative electrical and natural gas requirements and GHG emissions (Tables 7 and 9).*

beverage can to calculate the energy demand in Btu/m² required to apply and cure inks and coating on a metal substrate. As shown in Tables 1 and 2, the energy requirements to coat plastic film with adhesive at 20 g/m² were very similar to those reported for decorating and coating metal at about 3 to 6 g/m².

A third study by Lapin and Minon on a UV/EB/thermal pilot steel coil coating line[6] provides additional support for a consistent ratio of the normalized energy demand for UV/EB and thermal curing of coatings. In this case, a multilayer primer and coating were applied at a total of 25 to 30 g/m². Based on annual operational hours for the line, line width, line speed and the estimated annual cost for electricity, the energy demand for UV/EB curing in this application is 661 Btu/m² (Table 3). This value is in excellent agreement with the values calculated from the Coors and BASF studies, even though the processes and types of coatings and coat weights are quite different for all three cases.

Table 3

Energy demand for UV/EB coating steel coil
(Calculated from Lapin and Minon data)

Annual Operating Time	5,500 hr
Line Width	1.25 m
Line Speed	90 m/min
Surface Coated/yr	37,125,000 m²
Coat Weight	ca. 30 microns
Electrical Cost	0.065 €/kWh
Electricity Cost/yr[7]	159,445 €
kWh/yr	2.45 million
Electrical Btu/yr	24.5 billion*
Btu/m²	661

**See energy conversion factors in Table 6.*

Lapin and Minon reported that total energy costs for conventional thermally cured coil coatings were between seven and nine times higher than for the UV/EB configuration,[8] putting these in the range of 4,600 to 5,900 Btu/m², again on the same order of magnitude calculated from the Coors and BASF studies. Although data from additional quantitative studies would be desirable to gain a statistical measure of the validity and degree of variation of the normalized energy cost to cure UV/EB and thermal coatings, the average values from the three published

Table 4

Generic energy demand factors used in the calculations

Average Energy Demand Factor	Thermal	UV/EB
Curing Energy Demand (Btu/m²)	4,200	600
Electricity/Total Energy Usage Ratio	22%	100%

Table 5

Annual surface area coated by UV/EB formulations

Market Segment	2011 Volume (1,000 M Tons)	Applied Coat Weight (g/m²)	Total Coated Surface (Billion m²)
Graphic Arts	59,730	2-15	13.8
Wood Finishes	23,200	10-60	1.22
Plastic Coatings	9,600	10-20	0.62
Adhesives and Silicone Release Coatings	7,045	0.5 to 40	2.45
Metal Decorating and Coating	3,775	3-30	0.66
Electronics	4,040	25-50	0.14
Miscellaneous*		Not Included	Not Included
Total Used for Calculation	**107,390**		**18.9**

**Miscellaneous UV/EB curing formulation volume in 2011 that is difficult to treat using this simplified coating model is omitted, including optical fiber coating, printing plates, stereolithography/solid modeling, dental applications and medical apparatus.*

quantitative studies provide at least an order of magnitude basis for comparison (Table 4).

North American UV/EB Scorecard

RadTech regularly conducts a survey of the total annual volume of UV/EB-curing formulations sold in North America. Table 5 shows how the RadTech data can be combined with typical applied film weights for various applications to calculate the total annual surface area coated by UV/EB formulations.

This annual coated surface area can be combined with the generic demand energy factors in Table 4 and the natural gas consumption and electrical generation factors in Table 6 to calculate an order of magnitude for the annual energy savings achieved by substituting UV/EB curing for thermal-curing formulations that otherwise would have been used (Table 7). The breakdown for electrical MWh and million cubic feet of natural gas is based on the average of the Electricity/Total Energy Usage Ratio noted in Table 4.

Table 6

Energy conversion factors used in the calculations

1,024	Btu/cu ft of natural gas[9]
10,000	Benchmark Electrical Heat Rate in Btu/kWh[10]

Greenhouse Gas Emissions

Government agencies publish data on emissions from electricity generation

Table 7

North American annual energy usage for coating equivalent surface areas

Curing Process	Million Btu	Electrical Million MWh	Billion Cubic Feet of Natural Gas
Thermal	7.94E+7	1.75	60
UV/EB	1.13E+7	1.13	0
Annual UV/EB Curing Energy Savings	-6.81E+7	-0.62	-60

Table 8

Greenhouse gas emission factors

120	lb. CO_2/1,000 cu ft of natural gas combustion[11]
2,157	lb. CO_2 Eq/MWh produced by coal (Calculated[12])
1,131	lb. CO_2 Eq/MWh produced by natural gas (Calculated[12])
1,644	lb. CO_2 Eq/MWh produced by electrical power from a 50-50 mix of coal and natural gas*

**The actual mix of fuel sources for electrical power generation varies widely by region of the country. For these calculations, the electricity generating fuel mix is assumed to be 50% coal, 50% natural gas and 0% other.*

and from combustion of various fuels, and these can be used to calculate factors for emissions of carbon dioxide and other greenhouse gases from electricity generation (Table 8).

Based on the annual energy usage values for UV/EB versus thermal curing in Table 7, the average Electricity/Natural Gas Usage Ratio and the greenhouse gas emission factors in Table 4 can be used to calculate total annual carbon dioxide emissions from each type of process. Table 9 shows the annual reduction in GHG emissions achieved by substitution of UV/EB curing for thermal curing formulations.

Transport Sustainability Benefits

Finally, assuming an average solvent and W/B thermal formulation percent solids of 50%, transport of UV/EB formulations requires half as much diesel fuel and emits half as much carbon dioxide. Table 10 estimates the annual transport sustainability benefit of 100% solids radiation-curable formulations, using the volume of shipments from Table 5 and the following factors—20 MT shipped per truckload, 22.2 pounds of CO_2 per gallon of diesel fuel combustion,[13] an estimated 500-mile freight haul trip[14] and average diesel carrier fuel mileage of 6.0 mpg.[15]

General Application

While statistical analysis of data from additional independent studies still would be needed to confirm the concept, based on the limited data available, the order of magnitude difference between thermal and radiation-curing energy demand appears to be relatively insensitive to the type of printing or coating process, and to the applied coat weight. Companies that would like to quantify energy savings and emissions reductions to support their own sustainability programs, or those who are deciding between thermal and UV or EB processes for new installations, can use the same methodology to estimate order-of-magnitude comparisons between the two types of processes.

Table 9

North American carbon dioxide emissions for coating equivalent surface areas

Curing Process	CO_2 Emissions (Million MT)
Thermal	4.60
UV/EB	0.85
Annual UV/EB CO_2 Reduction	-3.75

Conclusions

Analysis of energy demand data from three completely different side-by-side comparative case studies shows quite consistent differences in normalized energy requirements in Btu/m^2 required to coat one square meter of substrate using thermal and UV/EB-curing processes. Overall, thermal-curing energy requirements consistently were found to be five to nine times higher than UV/EB curing in the same processes.

Based on these findings, average order-of-magnitude estimates for UV/EB versus thermal-curing energy demand were used in combination with 2011 North American market data reported by RadTech to calculate a "Sustainability Score" for UV/EB (i.e., the total energy savings and greenhouse gas reductions achieved when UV/EB was used in

Table 10

Annual transport fuel and carbon dioxide emissions for coating equivalent surface areas

Formulation Type	Diesel Fuel (gal)	CO_2 Emissions (Thousand MT)
Thermal	4.47E+05	4.52
UV/EB	2.24E+05	2.26
Annual UV/EB Transport Savings	-2.23E+05	-2.26

place of comparable thermal curing alternatives). The method can also be applied to individual curing installations to aid in estimating and/or reporting energy savings and emission reductions achieved by using or switching to UV/EB systems.

Data from more studies will be required for statistical treatment, but—for the moment—the results suggest a general method for at least an order-of-magnitude comparison of thermal and UV/EB-curing energy demand.

References

1. (a) Linda M. Gustafsson and Pål Börjesson, Life Cycle Assessment in Green Chemistry, A comparison of various industrial wood surface coatings, Int J LCA 12 (3) 151–159 (2007); (b) Anthony J. Berejka, Electron Beam Curing of Coil Coatings, September/October 2003 *RadTech Report;* (c) Kevin Joesel, UV Curing Reducing VOC, CO^2 Emissions and Energy Consumption, European Coil Coating Association Autumn Conference, November, 2008.
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4. Ronald Golden, Sustainability Advantages of Ultraviolet and Electron Beam Curing, July/August 2008 *RadTech Report*, pp 13-17.
5. Ronald Golden, "Low-Emission Technologies: A Path to Greener Industry," *RadTech Report*, May/June, 2005, p 14.
6. Stephen Lapin and Marc Minon, Energy Savings: RadCure, a Real Breakthrough!, ECCA European Coil Coating Association Energy-Saving Seminar, November, 2008.
7. Annual energy cost data obtained in a private communication from one of the authors.
8. The energy demand reported by Lapin and Minon for convection heating was over 10 times that required for UV/EB curing, while induction heating was on the lower end of the range.
9. US DOE/EIA Annual Energy Outlook 2012, Table G1 Heat Rates, (June, 2012).
10. The electrical generation Heat Rate is a measure of the amount of energy it takes to produce a unit of electricity. Multiple sources indicate 10,000 Btu/kWh as a reasonable benchmark for calculations.
11. Calculated from 14.47 kg C/mmbtu from combustion of natural gas, U.S. EPA Clean Energy, Calculations and References, *http://www.epa.gov/cleanenergy/energy-resources/refs.html.*
12. Calculated by dividing 2010 total CO_2 emissions from electrical generation by fuel source (US EPA Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990 – 2010, APRIL 15, 2012,Table 2-13: Electricity Generation-Related Greenhouse Gas Emissions (Tg CO2 Eq.)) by billion kWh generated in 2010 (US Energy Information Administration, Annual Energy Outlook 2011, Electricity Supply, Disposition, Prices, and Emissions, Reference case, *http://www.eia.gov/oiaf/aeo/tablebrowser/#release=AEO2011&subject=0-AEO2011&table=8-AEO2011&region=0-0&cases=ref2011-d020911a).*
13. U.S. DOE Transportation Energy Data Book: Edition 30, June 2011, Table 11.11 Carbon Dioxide Emissions from a Gallon of Fuel.
14. The estimated freight haul mileage used in this calculation combines shorter trips from regional warehouses and much longer direct bulk truckload shipments direct to customers from a manufacturing site or central terminal.
15. 2009 mpg average from U.S. DOE Transportation Energy Data Book: Edition 30, June 2011, Table 5.2, Summary Statistics for Combination Trucks, 1970–2009.

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