A national laboratory of the U.S. Department of Energy
Office of Energy Efficiency & Renewable Energy

National Renewable Energy Laboratory

Innovation for Our Energy Future

Preliminary Assessment of the Energy-Saving Potential of Electrochromic Windows in Residential Buildings

David R. Roberts

Technical Report
NREL/TP-550-46916
December 2009

NREL is operated for DOE by the Alliance for Sustainable Energy, LLC   Contract No. DE-AC36-08-GO28308

Preliminary Assessment of the Energy-Saving Potential of Electrochromic Windows in Residential Buildings

Technical Report
NREL/TP-550-46916
December 2009

David R. Roberts

Prepared under Task No. BET98001

National Renewable Energy Laboratory
1617 Cole Boulevard, Golden, Colorado 80401-3393
303-275-3000 • www.nrel.gov

NREL is a national laboratory of the U.S. Department of Energy
Office of Energy Efficiency and Renewable Energy
Operated by the Alliance for Sustainable Energy, LLC

Contract No. DE-AC36-08-GO28308

NOTICE

Available electronically at http://www.osti.gov/bridge

Available for a processing fee to U.S. Department of Energy and its contractors, in paper, from:
U.S. Department of Energy
Office of Scientific and Technical Information
P.O. Box 62
Oak Ridge, TN 37831-0062
phone: 865.576.8401
fax: 865.576.5728
email: mailto:reports@adonis.osti.gov

Available for sale to the public, in paper, from:
U.S. Department of Commerce
National Technical Information Service
5285 Port Royal Road
Springfield, VA 22161
phone: 800.553.6847
fax: 703.605.6900
email: orders@ntis.fedworld.gov
online ordering: http://www.ntis.gov/ordering.htm

Printed on paper containing at least 50% wastepaper, including 20% postconsumer waste

Executive Summary

Electrochromic (EC) windows provide variable tinting that can help control glare and solar heat gain. We used BEopt software to evaluate the performance of EC windows in prototypical energy models of a single-family home in Atlanta. The windows were assumed to operate automatically, tinting in response to incident solar during the cooling season. The models predict the EC windows will produce whole-house source energy savings of 9.1% and whole-house electricity demand savings of 13.5% in a 2006 IECC-compliant home, and source energy savings of 3.2% and demand savings of 10.3% in a 50%-level Building America home.

Contents

Figures

Tables

Introduction

Electrochromic (EC) windows provide variable tinting that can help control glare and solar heat gain. The windows darken in response to changes in applied electrical voltage[1] and can be controlled manually or automatically. EC windows are available commercially, though currently their use is generally limited to commercial building applications and residential skylights. A study by Lee et al. (2006) that focused on commercial building applications reported significant energy and demand savings, based on empirical testing and energy modeling.

This report summarizes the results of a simple energy modeling exercise conducted to assess the impact EC windows might have in residential applications.

Approach

Prototype Model Definitions

We used energy modeling to assess the potential impact of installing EC windows in a single-family home and used the BEopt[2] software to develop and analyze prototype single-family home models. General characteristics of the prototype models are shown in Table 1.

Table 1. General Characteristics of the Prototype Energy Models

Conditioned floor area	2,500 ft^2
Conditioned volume	22,500 ft^3
Number of stories	2
Number of bedrooms	3
Gross above-grade wall area	2,574 ft^2
Window area	450 ft^2 (18% of conditioned floor area)
Window orientation	50% west, 25% east, 12.5% north, 12.5% south
Window interior shading factors	0.85 winter, 0.7 summer*
Door area	40 ft^2
Set point temperatures	71 heating, 76 cooling
Mechanical ventilation	Exhaust only, ASHRAE 62.2 levels
Space/water heating fuel	Natural gas
Internal gains	Building America Benchmark (Hendron 2008)
Lighting/appliance/plug schedules	Building America Benchmark

* This is the standard assumption in Building America, HERS, and IECC analysis.

[1] Nominally averages 0.5 W/m^2 of glazing (Sbar 2009).
[2] The BEopt software tool was developed at NREL to identify optimal building energy designs aimed at minimizing the total of the amortized cost of improvements and the cost of energy. It produces designs that minimize combined construction and energy costs by using the DOE-2.2 and TRNSYS energy simulation programs to automate a sequential search technique for locating least-cost solutions on a path toward net zero energy. The software and underlying methodology are described in detail by Christensen et al. (2005, 2006) and Horowitz et al. (2008).

Atlanta was selected as an appropriate climate for assessing the energy-savings potential of EC windows, as it produces fairly balanced and substantial heating and cooling loads in residential buildings. Solar gain is beneficial at times because it reduces heating loads in the winter and undesirable at times as it contributes to cooling loads in the summer.

Two prototypical models were developed with the general characteristics outlined in Table 1, but differing performance characteristics. The first meets the requirements of the 2006 International Energy Conservation Code (IECC) for Atlanta, climate zone 3. The second includes performance characteristics of an Atlanta home using 50% less source energy than the Building America Benchmark, as described by Anderson and Roberts (2008). The performance characteristics of both are shown in Table 2.

Table 2. Prototype Model Performance Levels

Component	2006 IECC	50% Building America
Walls	2 × 4, R-13 cavity	2 × 6, R-21 cavity
Ceiling	R-30	R-40
Infiltration	0.00050 SLA	0.00015 SLA
Window U-value	0.65	0.30
Window SHGC	0.40	0.26
Lighting	14% fluorescent	90% fluorescent
Air conditioner	SEER 13	SEER 15
Furnace	80 AFUE	92 AFUE
Ducts	R-8, in crawl space	In conditioned space
Water heater	0.59 EF	0.77 EF
Appliances	Standard	ENERGY STAR®

AFUE = Annual Fuel Utilization Efficiency
EF = Energy Factor
SEER = Seasonal Energy Efficiency Ratio
SHGC = Solar Heat Gain Coefficient
SLA = Specific Leakage Area

DOE-2 Modeling Capabilities

The BEopt software was modified to accommodate and model EC windows in the DOE-2.2 simulation engine. DOE-2.2 provides a broad range of EC windows and controls. An EC window that best matches those currently available[3] was selected from the DOE-2.2 window library (see Table 3).

[3] Sage Electrochromics, Inc. is currently the only producer of commercially available EC glazing.

Table 3. Characteristics of SageGlass EC Glazing and DOE-2.2 Window Library Entry

	U-Value		SHGC	
	Sage*	**DOE-2****	**Sage***	**DOE-2****
Clear state	0.29	0.29	0.48	0.51
Tinted state	0.29	0.29	0.09	0.13

* SageGlass Classic™ (source: Sage Electrochromics Web site: www.sage-ec.com/pages/technol.html)
** DOE-2 2 library entries 2842/2843.

EC window controls available in DOE-2.2 include:

- Direct or total solar incident on the window
- Direct or total solar transmitted through the glazing
- Total horizontal solar
- Outside temperature
- Space load
- Interior daylight level.

These controls can also be combined with a seasonal/hourly time schedule.

We selected total solar incident on the window for control, as it allows the windows on each orientation to respond independently and is straightforward to implement in the field.

DOE-2.2 provides for low and high limits for the control variable. We assumed that tinting begins when solar incident on the window exceeds 100 Btu/h·ft^2; the window is fully tinted at 150 Btu/h·ft^2. Figure 1 shows how the window tinting responds to incident solar in the DOE-2.2 model.

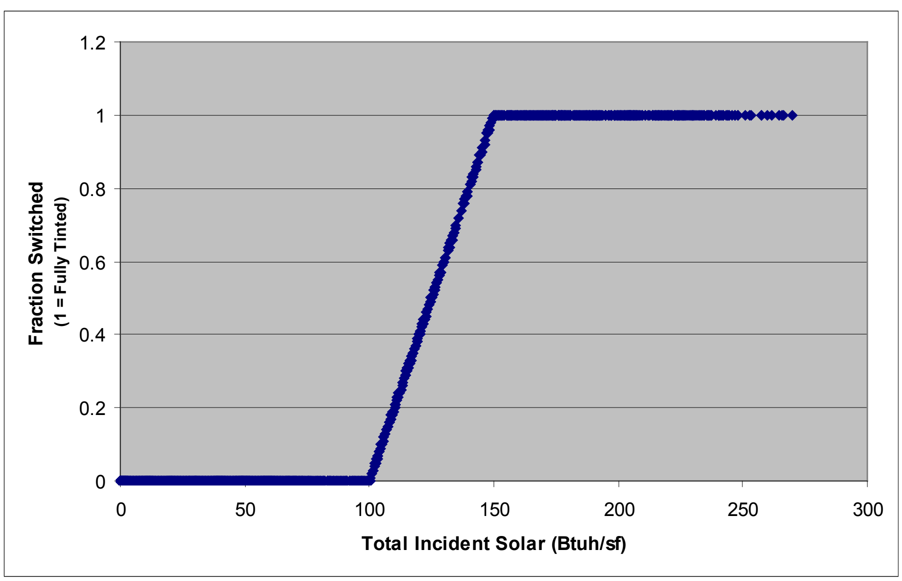

Figure 1. EC window tinting response to total solar incident on window

Impact of Seasonal Control

As mentioned earlier, it is beneficial to maximize solar gain during the heating season. Figure 2 shows the monthly source energy use for space heating and cooling for the Atlanta prototype model with standard glazing. Ideally, the EC windows would not reduce solar gain during periods with large heating loads and small cooling loads. We "locked out" the EC window control during the heating season in the BEopt/DOE-2 model and examined the impact. Based on the heating and cooling loads in Figure 2, the EC control was fixed in the "Clear" mode from October 15 through April 15, and then switched into "Auto" mode during the balance of the year. In "Auto" mode the glazing responds to total solar incident on the window.

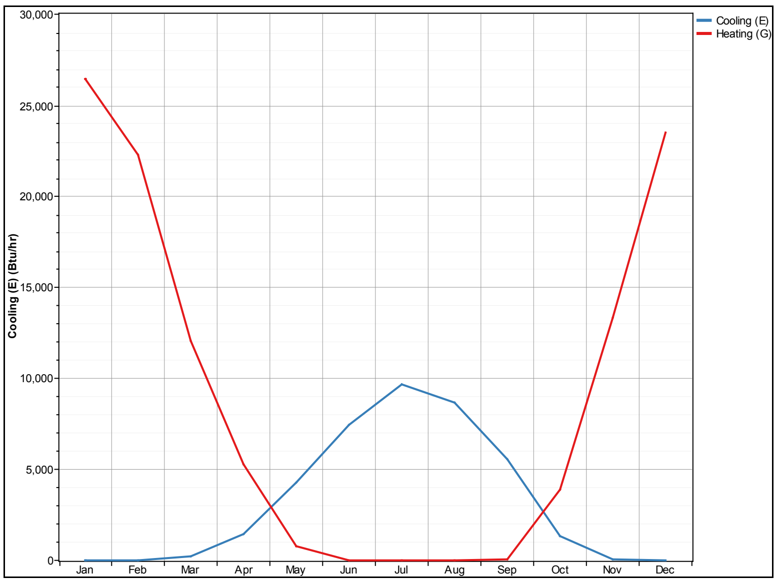

Figure 2. Heating and cooling source energy use in Atlanta reference home

The energy and cost impacts associated with locking out the EC windows during the heating season are shown in Table 4 and Table 5. It is clearly beneficial to lock out automated window tinting during the heating season. Based on these results, automated EC control is assumed to function from April 15 to October 15 only.

Table 4. Source Energy Impacts of Disabling EC Control During Heating Season (MMBtu/yr)

	Heating*	Cooling*	Total
Automated year-round	71.2	29.3	100.5
Automated April 15 to October 15	67.1	29.9	97.0
Absolute savings	4.2	–0.6	3.6
Percent savings	5.9%	–2.1%	3.5%

* Includes fan energy

Table 5. Energy Cost Impacts of Disabling EC Control During Heating Season ($/yr)

	Heating*	Cooling*	Total
Automated year-round	1105	202	1307
Automated April 15 to October 15	1040	206	1246
Absolute savings	65	–4	60
Percent savings	5.9%	–2.1%	4.6%

* Includes fan energy

Response to Controls

Figure 3 shows the level of window tinting on the west-facing windows during each hour of the year. The windows do not tint during the lock-out period between April 15 and October 15.

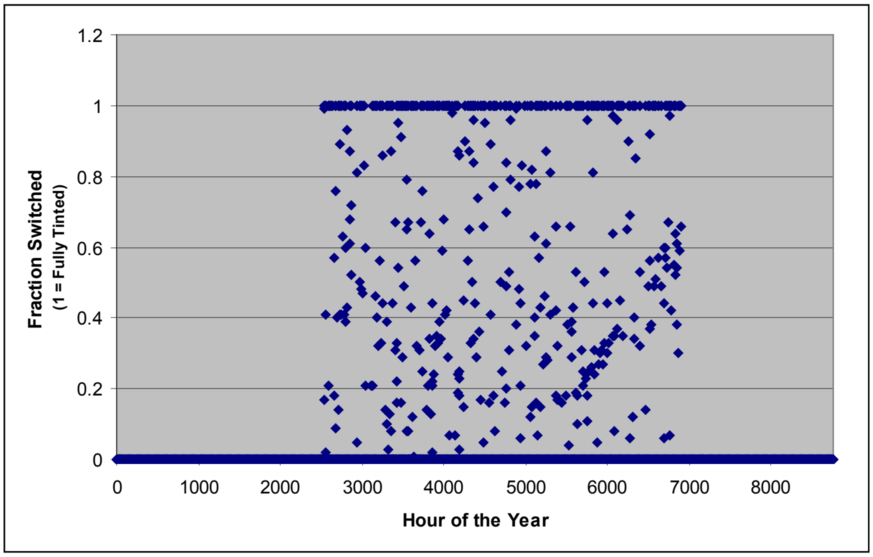

Figure 3. EC window tinting for each hour of the year—west-facing window

Figure 4 shows window tinting for all orientations by hour of the day. This graph demonstrates how the windows tint in response to the position of the sun throughout the day.

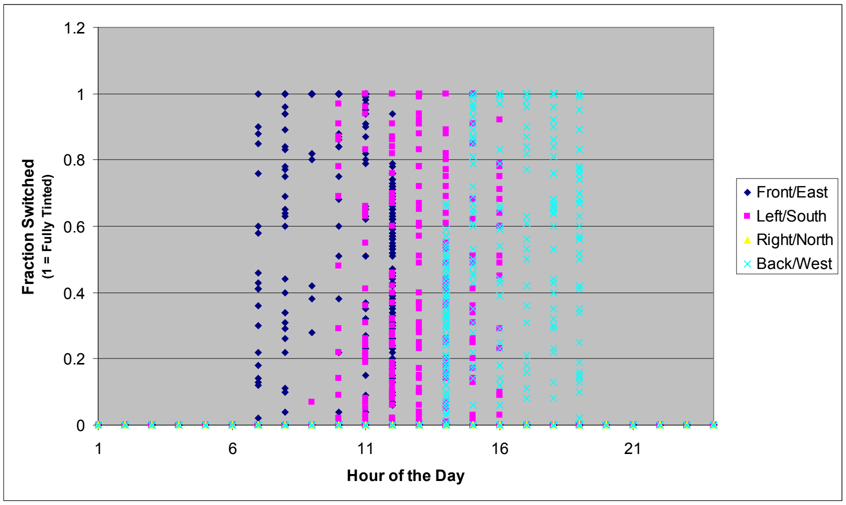

Figure 4. EC window tinting for each hour of the day

Figure 5 quantifies the level of tinting that occurs on each orientation using "fully tinted hours"—the sum of all tinting that occurs throughout the year. As one might expect, with winter hours locked out, most tinting occurs in east- and west-facing windows. The north-facing windows never tint.

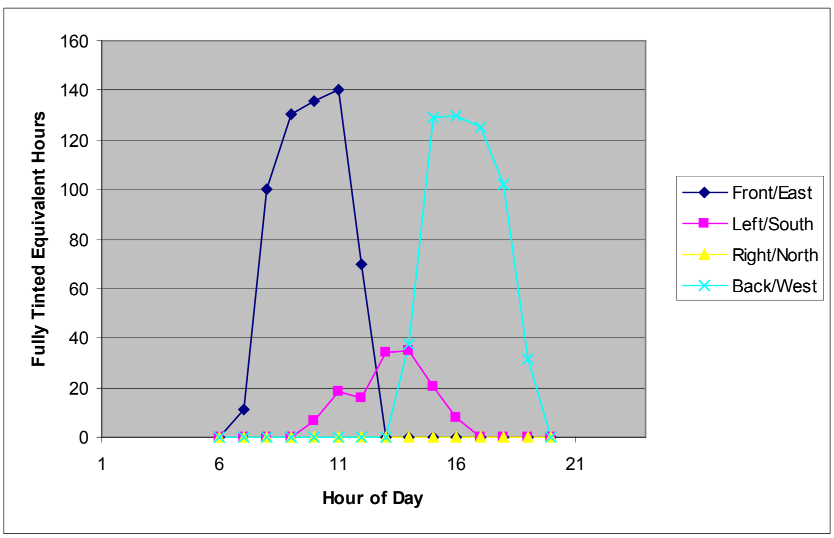

Figure 5. Fully tinted equivalent hours for each hour, by orientation

Results

Savings in a 2006 IECC-Compliant Home

Results of BEopt runs compare the source energy of the 2006 IECC prototype home with EC windows to the home with code-level windows (see Figure 6). The EC windows result in 9.1% savings in whole-house source energy. Table 6 shows 18.2% source energy savings for the heating and cooling end uses; Table 7 shows analogous cost savings of 19.5%.

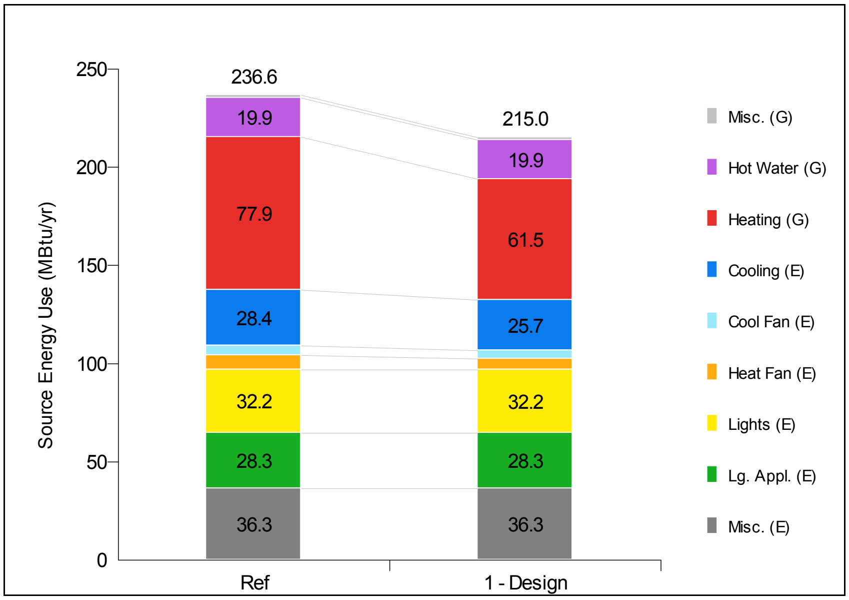

Figure 6. BEopt output for source energy savings for EC windows relative to low-e, low-SHGC windows

Table 6. Source Energy Savings From EC Windows in 2006 IECC home (MMBtu/yr)

	Heating*	Cooling*	Total
2006 IECC-compliant home	85.2	33.3	118.5
2006 IECC with EC windows	67.1	29.9	97.0
Absolute savings	18.1	3.4	21.5
Percent savings	21.3%	10.2%	18.2%

* Includes fan energy

Table 7. Energy Cost Savings From EC Windows in 2006 IECC Home ($/yr)

	Heating*	Cooling*	Total
2006 IECC-compliant home	1319	230	1549
2006 IECC with EC windows	1040	206	1246
Absolute savings	279	23	302
Percent savings	21.1%	10.2%	19.5%

* Includes fan energy

The BEopt/DOE-2 model predicts a peak-day electricity demand reduction of 0.7 kW, a 13.5% reduction in whole-house demand. Figure 7 shows the electricity demand for cooling for the two days with the highest predicted demand. Table 8 shows the demand savings at 7:00 p.m. on July 3, the peak hour for the year.

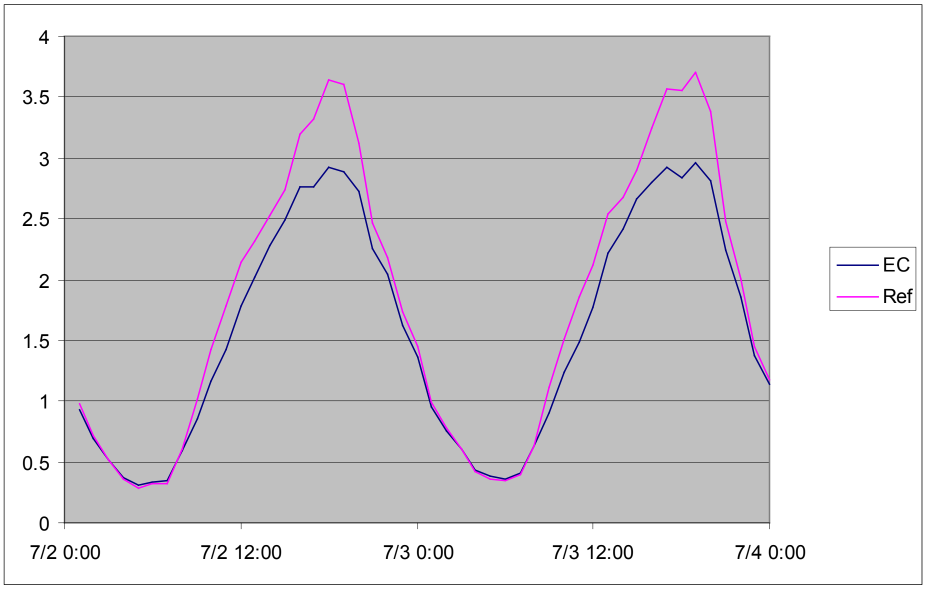

Figure 7. Electricity demand for cooling with EC windows and code-compliant reference windows in 2006 IECC home on July 2 and 3

Table 8. July 3 Peak Electricity Demand Savings From EC Windows in 2006 IECC-Compliant Home (kW)

	Cooling*	**Whole-House**
2006 IECC-compliant home	3.7	5.5
2006 IECC with EC windows	3.0	4.7
Absolute savings	0.7	0.7
Percent savings	19.9%	13.5%

* Includes fan energy

Savings in a 50% Building America Home

Results of BEopt runs comparing the source energy of the 50% Building America prototype home with EC windows, to the home with low-e, low-SHGC, argon-filled windows, are shown in Figure 8. The EC windows result in 3.2% savings in whole-house source energy. Table 9 shows 8.2% source energy savings for the heating and cooling end uses; Table 10 shows analogous cost savings of 9.4%.

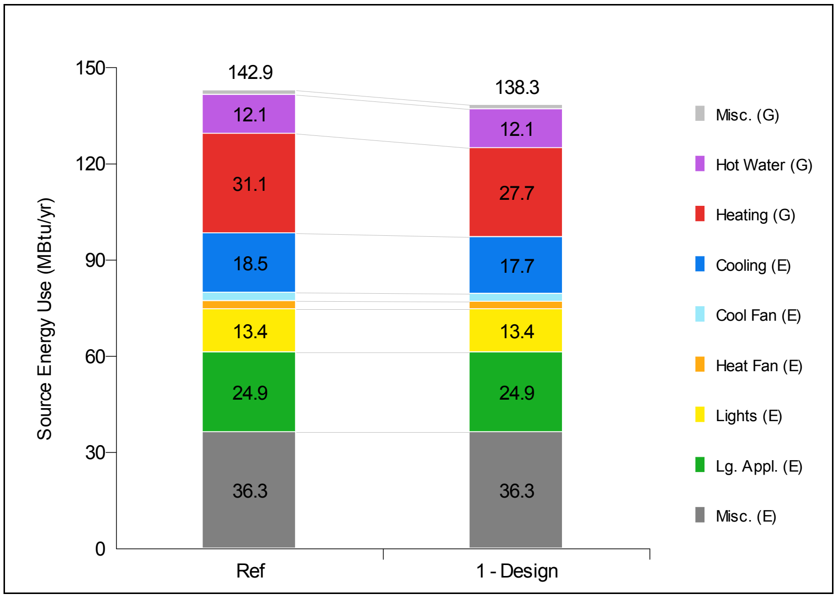

Figure 8. BEopt output for source energy savings from EC windows in 50% Building America home

Table 9. Source Energy Savings From EC Windows in 50% Building America Home (MMBtu/yr)

	Heating*	Cooling*	Total
50% Building America home	33.6	21.1	54.7
50% Building America home with EC windows	30.0	20.2	50.2
Absolute savings	3.6	0.9	4.5
Percent savings	10.7%	4.2%	8.2%

* Includes fan energy

Table 10. Energy Cost Savings From EC Windows in 50% Building America Home ($/yr)

	Heating*	Cooling*	Total
50% Building America home	524	145	670
50% Building America home with EC windows	468	139	607
Absolute savings	57	6	63
Percent savings	10.8%	4.2%	9.4%

* Includes fan energy

The BEopt/DOE-2 model predicts a peak-day electricity demand reduction of 0.4 kW, a 10.3% reduction in whole-house demand. Figure 9 shows the electricity demand for cooling for the two days with the highest predicted demand. Table 11 shows the demand savings at 7:00 p.m. on July 3, the peak hour for the year.

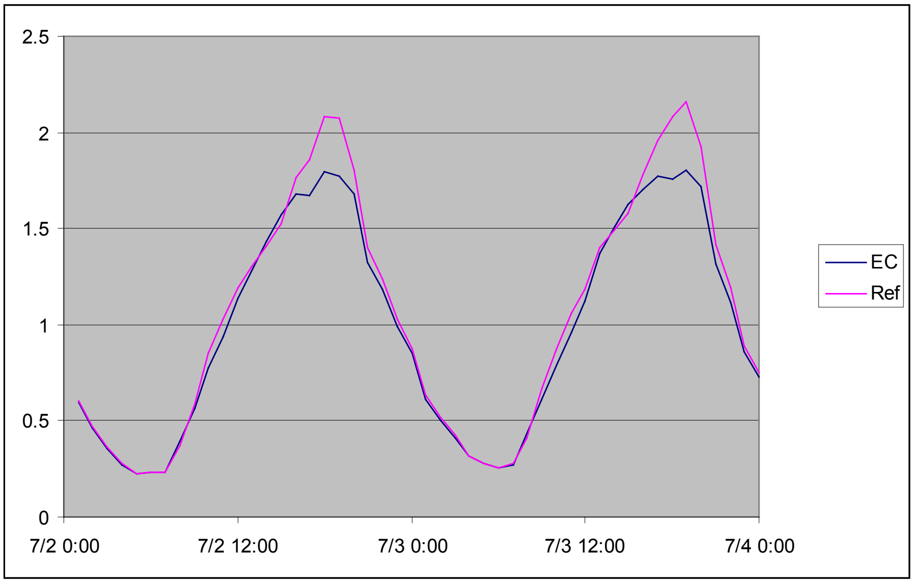

Figure 9. Electricity demand for cooling (compressor and fan) with EC windows and reference windows in 2006 IECC home on July 2 and 3

Table 11. July 3 Peak Electricity Demand Savings From EC Windows in 50% Building America Home (kW)

	Cooling*	**Whole House**
50% Building America home	2.2	3.4
50% Building America home with EC windows	1.8	3.1
Absolute savings	0.4	0.4
Percent savings	16.4%	10.3%

* Includes fan energy

Cost-Competitive Electrochromic Windows

We used the Atlanta 2006 IECC-compliant prototype model to run BEopt with a number of above-code features to identify the optimal non-EC windows for this home. BEopt identified low-e, low-SHGC, argon-filled windows as the most cost-effective upgrade at $16/ft^2. This window was selected as an appropriate "competing technology" and the basis of this analysis. These same windows are in 50% Building America home.

To determine the cost at which EC windows will be competitive, we ran BEopt with EC windows at different price points: from $40/ft^2 down to $10/ft^2. Figure 10 shows the BEopt curves for these windows along with the "competing technology": low-e, low-SHGC, argon-filled at $16/ft^2. The graph indicates that EC windows would have to reach a price point of approximately $20/ft^2 before they would be competitive with this window. EC windows currently cost $50–$100/ft^2; residential applications are on the higher end (Sbar).

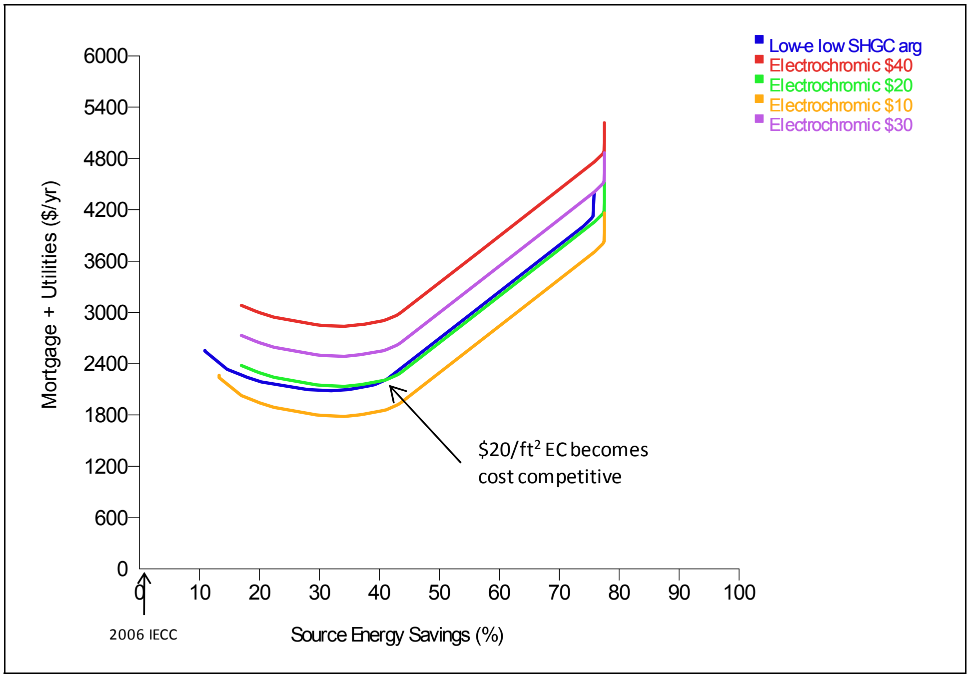

Figure 10. BEopt output. EC glazing is competitive at approximately $20/ft^2.

Conclusion

A simple modeling study was undertaken to assess the potential energy savings of EC windows in residential applications. We used BEopt software to evaluate the performance of EC windows in prototypical energy models of a single-family home in Atlanta. The windows were assumed to operate automatically, tinting in response to incident solar during the cooling season. The model predicted the EC windows would produce whole-house source energy savings of 9.1%, and whole-house electricity demand savings of 13.5% in a 2006 IECC-compliant home and source energy savings of 3.2% and demand savings of 10.3% in a 50%-level Building America home. Comparing the cost and modeled performance of EC windows to "competing technology" indicates EC windows would be competitive at a price point of approximately $20/ft^2.

Future Work

Suggested future work to further assess the potential impact of EC windows in residential applications includes:

- Additional modeling
  - Additional climates
  - Compare performance to orientation-tuned glazing
  - Examine other control strategies
  - Optimize controls
- Monitoring installed performance
  - Test facility
  - Unoccupied lab homes
  - Occupied homes.

References

Anderson, R.; Roberts, D. (2008). *Maximizing Residential Energy Savings: Net Zero Energy Home (ZEH) Technology Pathways.* Golden, CO: National Renewable Energy Laboratory, NREL/TP-550-44547.

Christensen, C.; Horowitz, S.; Givler, T.; Courtney, A.; Barker, G. (2005). *BEopt: Software for Identifying Optimal Building Designs on the Path to Zero Net Energy.* Golden, CO: National Renewable Energy Laboratory, NREL/CP-550-37733.

Christensen, C.; Anderson, R.; Horowitz, S.; Courtney, A.; Spencer, J. (2006). *BEopt(TM) Software for Building Energy Optimization: Features and Capabilities.* Golden, CO: National Renewable Energy Laboratory, NREL/TP-550-39929.

Horowitz, S.; Christensen, C.; Brandemuehl, M.; Krarti, M. (2008). *Enhanced Sequential Search Methodology for Identifying Cost-Optimal Building Pathways.* Golden, CO: National Renewable Energy Laboratory, NREL/CP-550-43238.

International Code Council, Inc. (2006). 2006 International Energy Conservation Code. ISBN-13: 978-1-58001-270-6.

Lee, E.; Selkowitz, S; Clear, R; DiBartolomeo, D; Klems, J; Fernandes, L; Ward, G; Inkarojrit, V.; Yazdanian, M. (2006). *Advancement of Electrochromic Windows*, Sacramento, CA: California Energy Commission, PIER, 500-01-023, LBNL-59821.

Sbar, N. (2009). Vice President Technology, Sage Electrochromics, Inc. Personal communication, October 23.

REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

1. REPORT DATE *(DD-MM-YYYY)* December 2009	**2. REPORT TYPE** Technical Report	**3. DATES COVERED** *(From - To)*

4. TITLE AND SUBTITLE Preliminary Assessment of the Energy-Saving Potential of Electrochromic Windows in Residential Buildings	**5a. CONTRACT NUMBER** DE-AC36-08-GO28308
	5b. GRANT NUMBER
	5c. PROGRAM ELEMENT NUMBER
6. AUTHOR(S) D.R. Roberts	**5d. PROJECT NUMBER** NREL/TP-550-46916
	5e. TASK NUMBER BET98001
	5f. WORK UNIT NUMBER
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) National Renewable Energy Laboratory 1617 Cole Blvd. Golden, CO 80401-3393	**8. PERFORMING ORGANIZATION REPORT NUMBER** NREL/TP-550-46916
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)	**10. SPONSOR/MONITOR'S ACRONYM(S)** NREL
	11. SPONSORING/MONITORING AGENCY REPORT NUMBER

12. DISTRIBUTION AVAILABILITY STATEMENT
National Technical Information Service
U.S. Department of Commerce
5285 Port Royal Road
Springfield, VA 22161

13. SUPPLEMENTARY NOTES

14. ABSTRACT *(Maximum 200 Words)*

Electrochromic (EC) windows provide variable tinting that can help control glare and solar heat gain. We used BEopt software to evaluate the performance of EC windows in prototypical energy models of a single-family home in Atlanta. The windows were assumed to operate automatically, tinting in response to incident solar during the cooling season. The models predict the EC windows will produce whole-house source energy savings of 18.2% and whole-house electricity demand savings of 13.5% in a 2006 IECC-compliant home, and source energy savings of 8.2% and demand savings of 10.3% in a 50%-level Building America home.

15. SUBJECT TERMS
electrochromic; ec; windows; tinting; glare; solar heat gain

16. SECURITY CLASSIFICATION OF:			**17. LIMITATION OF ABSTRACT**	**18. NUMBER OF PAGES**	**19a. NAME OF RESPONSIBLE PERSON**
a. REPORT	**b. ABSTRACT**	**c. THIS PAGE**			
Unclassified	Unclassified	Unclassified	UL		**19b. TELEPHONE NUMBER** (*Include area code*)