Medical Imaging Equipment Energy Efficiency

Dr. Kim Trenbath, Omkar Ghatpande, and Amy LeBar, NREL

Updated March 15, 2023

Overview

- Background
- MRI technology & energy use
- Relevant work
- Summary & next steps

Acronyms

- CBECS – Commercial Buildings Energy Consumption Survey
- COCIR – European Coordination Council of the Radiological, Electromedical, and Healthcare IT Industry
- CT – Computerized Tomography
- GPP – Green Public Procurement
- MIE – Medical Imaging Equipment
- MRI – Magnetic Resonance Imaging
- PET – Positron Emission Tomography
- RF – Radio Frequency

Terminologies

- Low Power Mode - In this mode the system functions at its lowest energy consuming state that the user can select according to the user manual.
- Ready-to-scan/Standby Mode - This mode represents the state of the system between individual scans, where no scan has been prescribed.
- Scan Mode - The system is actively scanning the patient to generate images.
- OFF Mode - The system is shut down with AC mains off, according to the user manual and consumes NO energy.

Introduction

Background

Healthcare industry is interested in energy-efficient medical imaging equipment (MIE).

Purpose of presentation:

- Provide overview of existing work.
- Review existing literature on MIE energy use.
- Identify opportunities.

Overarching goal: Transform the MIE market by providing energy-efficient options.

Background

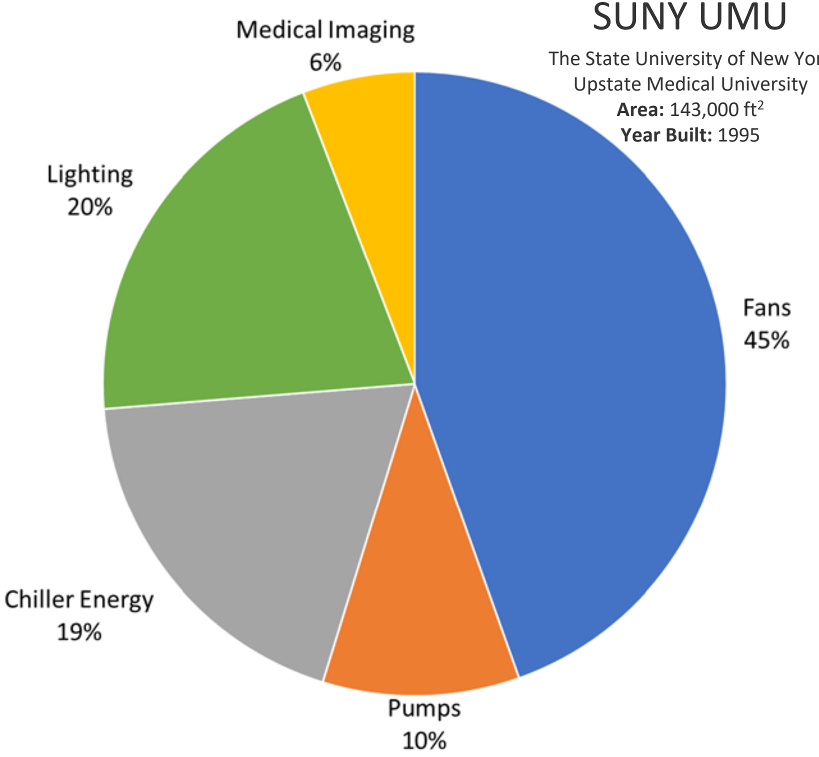
- MIE energy use in healthcare buildings is expected to grow as technology advances, more MIE arrives on the market, and more facilities install MIE.
- MIE energy use is estimated to be around 5% of site energy use, but the quantity is uncertain due to lack of data and studies.
- Healthcare organizations want to purchase reliable and energy-efficient MIE, but there is limited information regarding energy use and lifetime energy costs for MIE.
- There are currently no MIE energy or efficiency standards in the U.S.
- There is a need for commercially available energy-efficient MIE options.

MIE Technology & Energy Use

End-Use Breakdown in Healthcare—Site Electricity [Sheppy et al. 2014]

SUNY UMU

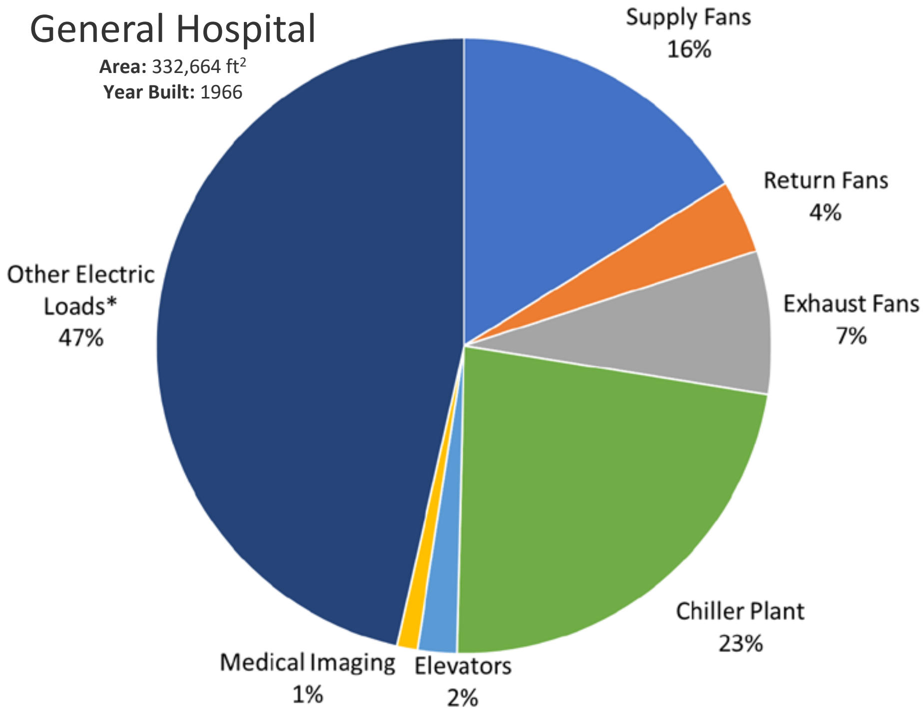
The State University of New York Upstate Medical University
Area: 143,000 ft^2
Year Built: 1995



This pie chart does not represent 100% of the site's electricity use. Monitoring at SUNY UMU excluded several items (cooling tower fans, six fractional-hp motors, preheat, humidification, steam piping losses, plug loads, and a 10-ton process cooling unit that serves the MRI device rooms), as installing meters for the loads would have required interrupting hospital operations. The site did not have whole-building meters.

Massachusetts General Hospital

Area: 332,664 ft^2
Year Built: 1966

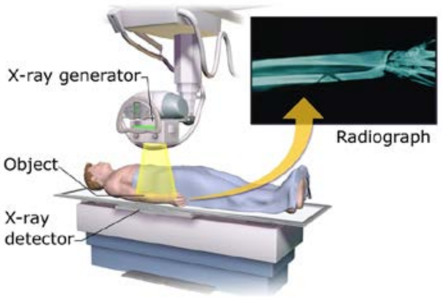


* The "other electric loads" category includes lighting systems and plug/process load equipment that were not directly monitored during the study, calculated using whole-building meter data.

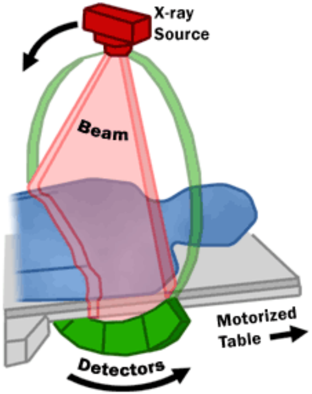
Types of MIE

- Nuclear Magnetic Resonance Imaging (MRI)
- Nuclear imaging—Positron Emission Tomography (PET) scanner
- Computerized Tomography (CT) scanner
- Ultrasound imaging/sonography
- X-ray radiography

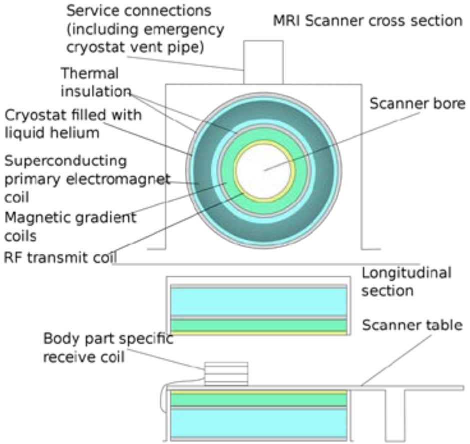
Ultrasound Scanner
[Wikipedia and Daniel R. 2006]



X-ray radiography
[Wikipedia and Mikael H. 2017]



CT imaging system
[Wikipedia and FDA 2019]



Schematic of cylindrical Superconducting MRI scanner
[Wikipedia and Chiswick C 2017]

MIE Overview

	CT Scanner	X-Ray	Ultrasound	PET Scan	MRI
Imaging Method	Ionizing radiation	Ionizing radiation	Sound waves	Radiotracers	Magnetic resonance
Technology	Uses rotating X-ray generator to reconstruct tomographic images of the body	Uses high energy electro-magnetic radiation to create 2-D image of body part	Uses high frequency sound waves to create image of internal body structure	Uses radioactive substances to visualize and measure physiological process changes	Uses strong magnetic fields gradients, and radio waves to generate images of the body organs
Sub-Types	• Fixed • Mobile	• Fixed • Mobile • Portable	• Basic • Doppler • 3-D/4-D Ultrasound	Fixed	• Closed • Open • Standing/sitting machine
Typical Energy Consuming Systems	• Gantry • X-ray generators • X-ray detector array • Computer/display • Patient table • Cooling system	• X-ray generators • X-ray detectors • Computer • Display • Anode cooling system	• Computer • Display • Ultrasound probe & sensor	• Gantry • PET detector array • Computer/display • Patient table • Cooling system	• Magnet • Gradient & radio frequency (RF) coils • Computer/display • Helium cryocooler (for superconductor magnets) • Patient table

MIE Energy Breakdown

Imaging Systems*

- **Scan mode** (energy used during image recording)
- **Standby / Ready-to-Scan** (energy used when system is ready for image capture)
- **System Off / low-power mode** (energy used during unoccupied hours)

Auxiliary Systems

- Lighting
- Additional display monitors & computer equipment
- MIE emergency electrical & cooling backup systems

Indirect Systems

- **Space Heating Cooling & Air Conditioning (HVAC)** - energy used to maintain patient, technician & diagnosis room environment conditions
- Electrical distribution system loss

* Imaging system examples: magnets, gradient and RF coils, cooling systems, primary display monitors, detector arrays

MIE Energy Consumption

- There are no energy conservation goals, standards, or regulations for MIE manufacturers in the United States [Knott et al. 2017].
- The medical efficacy of MIE is the primary procurement criterion; energy costs are not considered.
- Operational reliability is a paramount priority for healthcare facilities. MIE must operate accurately and reliably to address medical emergencies.
- Most MIE are on “standby” mode for a quick startup for emergency use.
- The majority of medical facilities do not record or actively analyze any energy consumption data for MIE.
- There are limited data sets available on MIE energy consumption in different operation modes.

MIE Typical Energy Use

MIE Typical Energy Use [Knott et al. 2017]	MRI	X-Ray	CT Scanner
Average Annual Energy Consumption (kWh/unit/yr)	111,000	9,500	41,000
Average Annual Energy Operating Costs (USD/unit/yr)	$20,000–$30,000	$100–$400	$3,000–$6,000
Rated Power Range	50–100 kVA	0.5–1.5 kVA	50–100 kVA

The remainder of this slide deck focuses on energy use of MRI because:

- MRIs consume more than 2x the energy of CT scanners and more than 10x compared to X-rays.
- A study investigating energy savings potential for U.S. commercial building appliances estimated the annual energy consumption of MRI machines increased by 66% from 0.009 to 0.015 quads/yr from 2008 to 2015 [Goetzler et al. 2016].
- The European Union Green Public Procurement criteria for healthcare sector electrical and electronic equipment estimates energy saving opportunities of 50% for MRI/CT and 80% for X-ray by including energy efficiency criteria in tender during procurement. This would result in MRI savings up to €6,700 ($7,000) per unit annually [Knott et al. 2017, GPP 2014].
- U.S. Environmental Protection Agency analysis of ENERGY STAR® Portfolio Manager data found that the addition of an MRI causes a significant increase in building energy consumption.

Energy Consumption of MRI Machines

- Studies* show that
  - Approx. 25%–40% of the total energy is consumed when the machine is not operational during nights and weekends.
  - Less than half of the total energy is consumed during scanning.
- Majority of energy is consumed by magnets, followed by cryocoolers for superconducting magnet-based MRIs, which operate constantly. More research is required to determine the energy breakdown for different types of MRIs.

*Sheppy 2014, Heye et al. 2020, COCIR 2018, Esmaeili et al. 2018, 2017, COCIR 2015, Tran et al. 2019.

MRI Magnet Types

Tesla (T) is the unit of magnetic flux density. Theoretically, higher Tesla can offer higher sensitivity, accuracy, and lower scan times, but there is no definitive validation.

There are three different magnet types used in MRI scanners:

- **Permanent:** These magnets retain magnetic field without any inducing field or current. Energy is not consumed to maintain the magnetic field but use in MRI machines is limited due to very weak magnetic field strength required for diagnostic imaging.
- **Resistive:** Resistive magnets are electromagnets controlled by electrical current flow. These machines are generally left on during the day but can be turned off during extended unoccupied hours because they typically take only 30-60 minutes for their magnetic fields to stabilize before use [MRI Questions, 2021]. Majority of the system energy use is to maintain magnetism. They are not economical for higher-Tesla machines.
- **Superconducting:** Superconducting magnet-based MRIs rely on helium cryogen to maintain superconducting temperatures of 9.4°K (-263.8°C or -442.8 °F). These ultra-low temperatures drop the niobium-titanium (Nb-Ti) conductor resistance to almost zero to produce the required magnetic field. It could be multi-day process to get the magnets in superconducting state, so the cryogenic coolers are always operational for these machines.

U.S. MRI Landscape

List of major MRI manufacturers in the U.S.

- Canon Medical Systems
- GE Healthcare
- Philips Healthcare
- Siemens Healthineers

MRI machine market share based on magnet strength [Rinck, 2018]

- 0–1.5 T: <25%
- 1.5 T: 60%–75%
- 3.0 T: <10 %

Total Number of MRI Units in the USA [OECD, 2022]

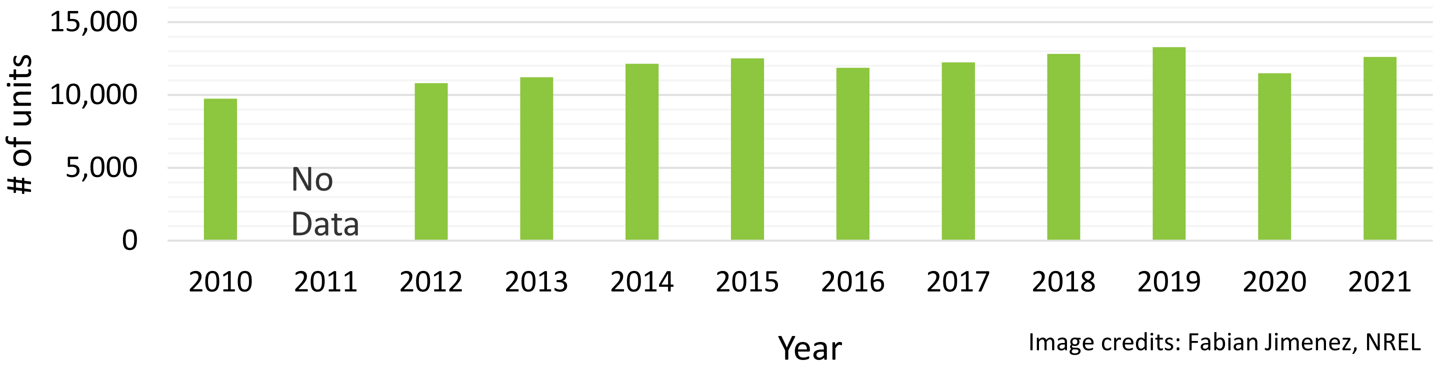


Image credits: Fabian Jimenez, NREL

Example Load Profile: MRI


NREL
Healthcare Energy End-Use Monitoring
Michael Sheppy, Shanti Pless, and Feitau Kung
National Renewable Energy Laboratory

[Sheppy 2014]

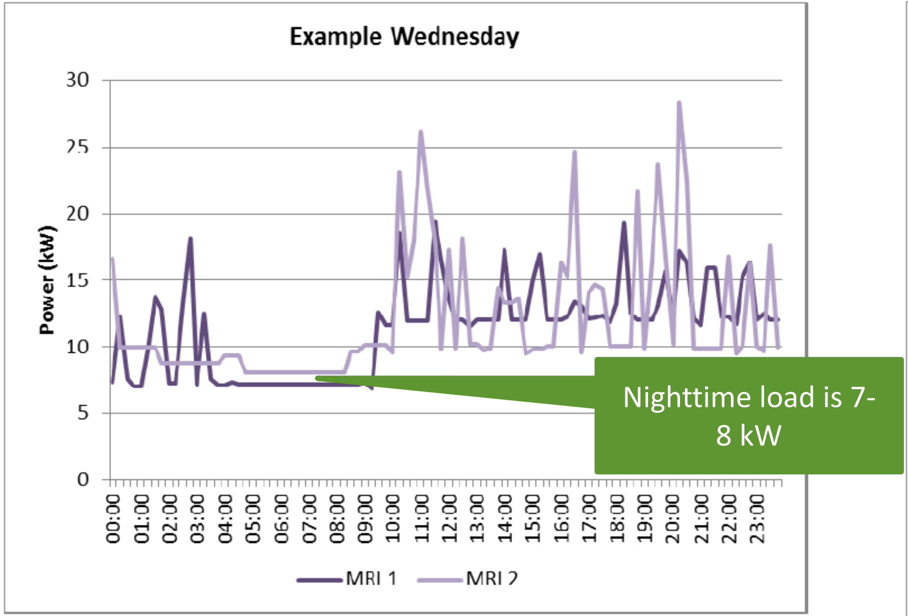


Figure 4-8 **MRI 15-minute load profiles for an example weekday (Wednesday)**

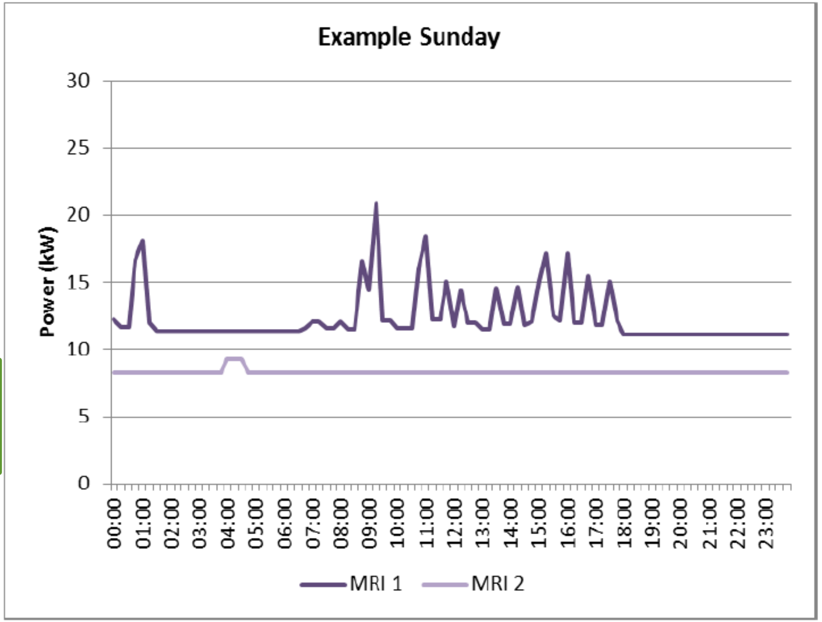
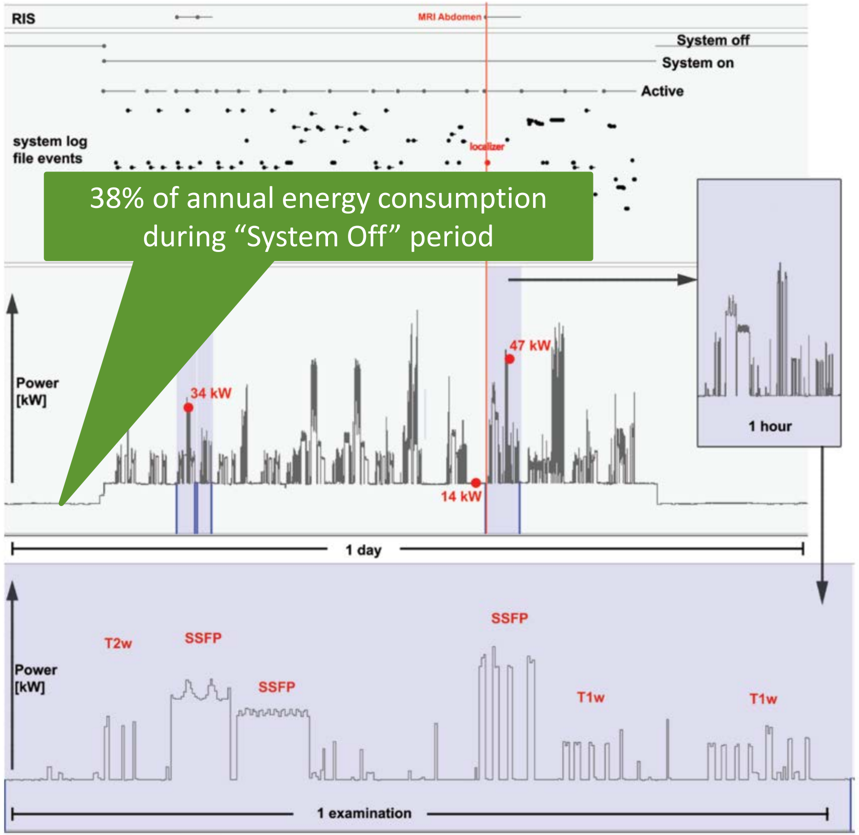
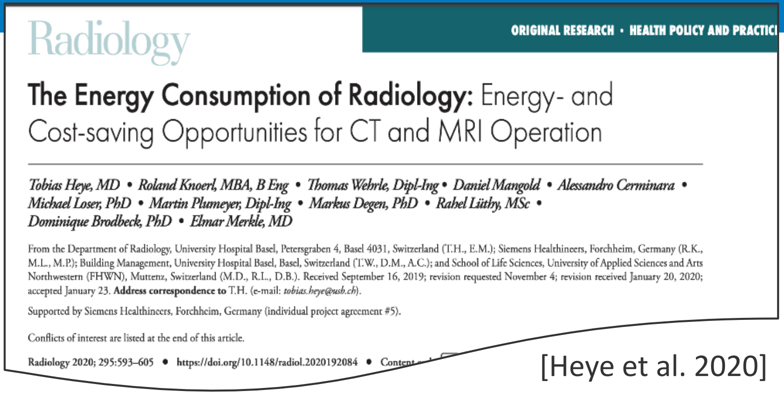


Figure 4-7 **MRI 15-minute load profiles for an example weekend day (Sunday)**

Example Load Profile: 1.5T MRI Scanner





Radiology

ORIGINAL RESEARCH • HEALTH POLICY AND PRACTICE

The Energy Consumption of Radiology: Energy- and Cost-saving Opportunities for CT and MRI Operation

Tobias Heye, MD • Roland Knoerl, MBA, B Eng • Thomas Wehrle, Dipl-Ing • Daniel Mangold • Alessandro Cerminara • Michael Loser, PhD • Martin Plumeyer, Dipl-Ing • Markus Degen, PhD • Rahel Lüthy, MSc • Dominique Brodbeck, PhD • Elmar Merkle, MD

From the Department of Radiology, University Hospital Basel, Petersgraben 4, Basel 4031, Switzerland (T.H., E.M.); Siemens Healthineers, Forchheim, Germany (R.K., M.L., M.P.); Building Management, University Hospital Basel, Basel, Switzerland (T.W., D.M., A.C.); and School of Life Sciences, University of Applied Sciences and Arts Northwestern (FHWN), Muttenz, Switzerland (M.D., R.L., D.B.). Received September 16, 2019; revision requested November 4; revision received January 20, 2020; accepted January 23. **Address correspondence to** T.H. (e-mail: *tobias.heye@usb.ch*).

Supported by Siemens Healthineers, Forchheim, Germany (individual project agreement #5).

Conflicts of interest are listed at the end of this article.

Radiology 2020; 295:593–605 • https://doi.org/10.1148/radiol.2020192084 • Content...

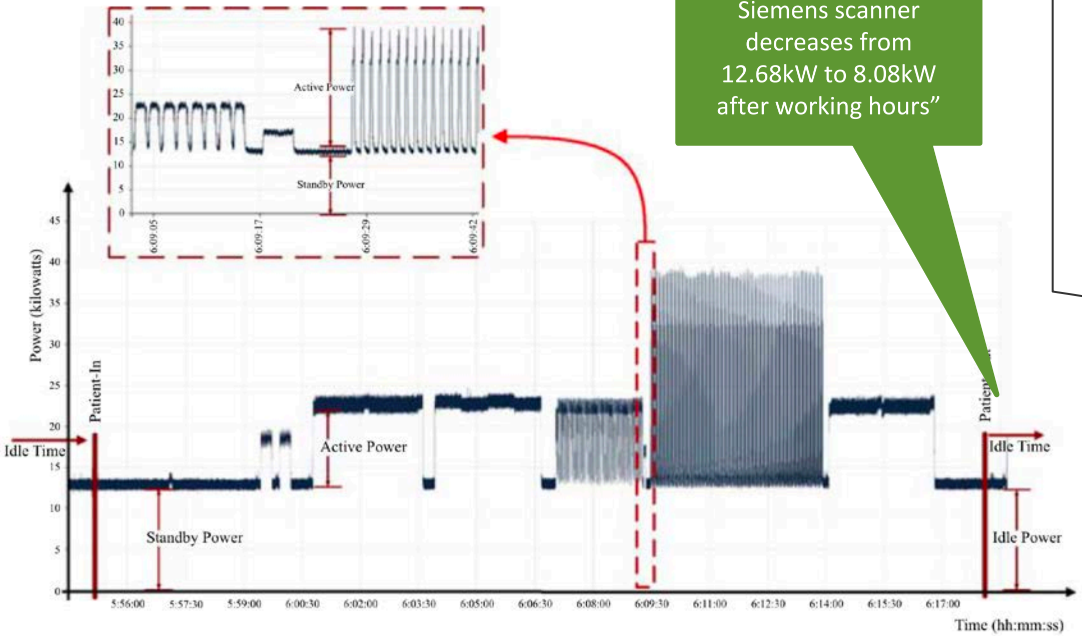
[Heye et al. 2020]

"Considerable energy- and cost-saving potential is present during nonproductive idle and system-off modes, and this realization could decrease total cost of ownership while increasing energy efficiency."

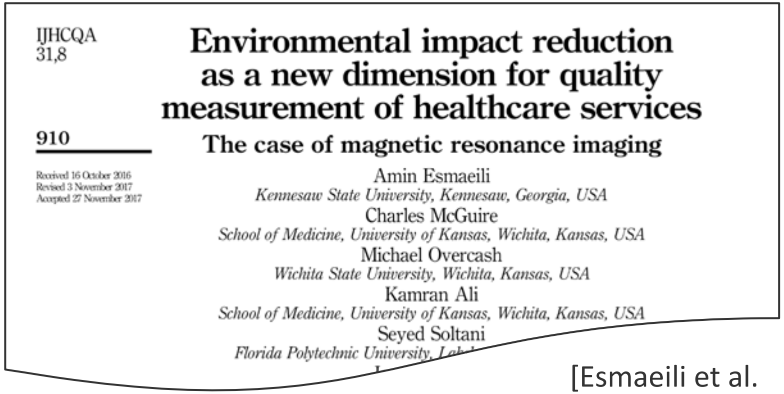
[Image Credits: Heye et al. 2020]

Example Load Profile: 1.5T MRI Scanner

“the idle power of Siemens scanner decreases from 12.68kW to 8.08kW after working hours”



[Image Credits: Esmaeili et al. 2018, 2017]



IJHCQA
31,8

910

Received 16 October 2016
Revised 3 November 2017
Accepted 27 November 2017

Environmental impact reduction as a new dimension for quality measurement of healthcare services

The case of magnetic resonance imaging

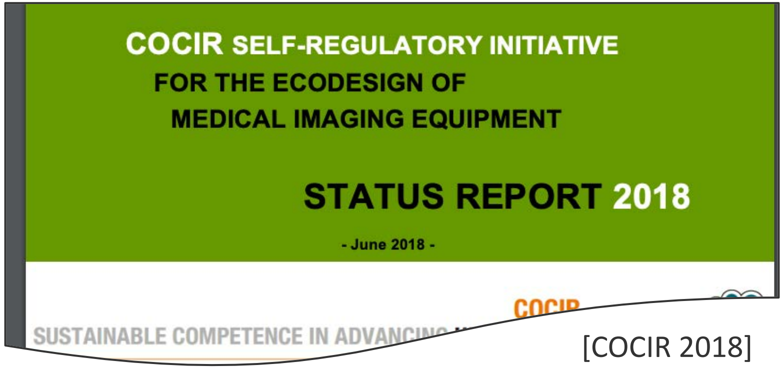
Amin Esmaeili
Kennesaw State University, Kennesaw, Georgia, USA
Charles McGuire
School of Medicine, University of Kansas, Wichita, Kansas, USA
Michael Overcash
Wichita State University, Wichita, Kansas, USA
Kamran Ali
School of Medicine, University of Kansas, Wichita, Kansas, USA
Seyed Soltani
Florida Polytechnic University,

[Esmaeili et al. 2018, 2017]

“The in-hospital energy use (process energy) for performing MRI is 29 kWh per patient for the MRI machine, ancillary devices and light fixtures.”

Potential Savings by Using “Off” Mode During Nights and Weekends

MRI		
MODE	**Average Power Consumption (kW)**	**Average distribution of daily energy consumption %**
Off	9.3	34
Ready to scan	14.6	34
Scan	22.3	32



[COCIR 2018]

YEARLY ENERGY SAVINGS

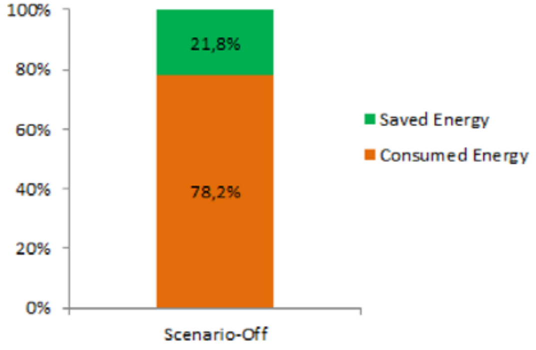
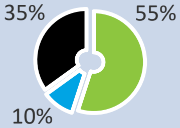
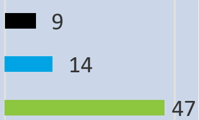
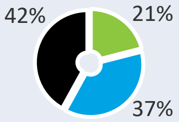
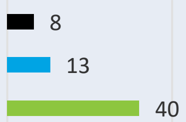
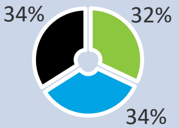
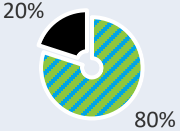
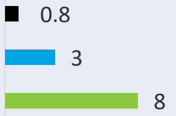


Figure 3: *MRI energy savings by using Off-mode* [Image Credits: COCIR, 2018]

“Considering that during the weekend the scanner can be in Off-mode or Ready-to-scan mode for 24 hours, the use of the Off-mode allows for saving up to 21.8% of the annual energy consumption which on the average corresponds to 29.2 MWh/y.”

Energy Consumption of MRI Machines

Reference Name	Year	Region	Energy Use in Each Mode	Avg. Power (kW) Reading in Each Mode	Test Period
The Energy Consumption of Radiology: Energy- and Cost-saving Opportunities for CT and MRI Operation [Heye et al. 2020]	2020	Switzerland (Europe)			12 months
MRI Transparency Document [Esmaeili et al. 2018, 2017]	2012	USA			4 days
COCIR MRI Guidelines for Users on Saving Energy [COCIR 2015]	2015	Europe			Daily avg.
Energy usage of a newly operational GE Healthcare Signa Premier 3T MRI* [Tran et al. 2019]	2019	USA			Daily avg.

■ Active Mode ■ Standby/ Idle Mode ■ System OFF/ Low Power Mode

* This study consolidates active mode and standby (ready-to-scan) mode for energy use analysis

Energy Consumption of MRI Machines

Subsystem	System Type	Typical Operating Modes		
		Scan Mode	Ready-to-Scan/Idle	Low-Power/Off
Magnet—permanent magnet (PM)	Primary	🟢	🟢	⚫
PM cooling system	Primary	🟢	🟢	⚫
Magnet—superconducting magnet	Primary	🟢	🟢	🟢
Helium cryocooler for superconducting magnet	Primary	🟢	🟢	🟢
RF coils/gradient coils/shim coils/receiver	Primary	🟢	🔵	⚫
Patient table	Primary	🟢	🟢	⚫
MRI room/patient's room/technician's room lighting	Auxiliary	🟢	🟢	⚫
HVAC	Indirect	🟢	🟢	🟢
Electrical distribution system loss	Indirect	🟢	🟢	🟢
Primary display, computer and data storage	Primary	🟢	🔵	🔵
Additional display monitors	Auxiliary	🟢	🟢	🔵

🟢 Normal subsystem power 🔵 Reduced subsystem power ⚫ Subsystem power off

MRI subsystems may still be powered even though the machine is in low-power or off mode. This table shows the power level (normal, reduced, off) of the different MRI subsystems during each operating mode. Note that when the MRI is in low-power or off mode, some subsystems, including the magnet, helium cryocooler, and HVAC, are still at normal power.

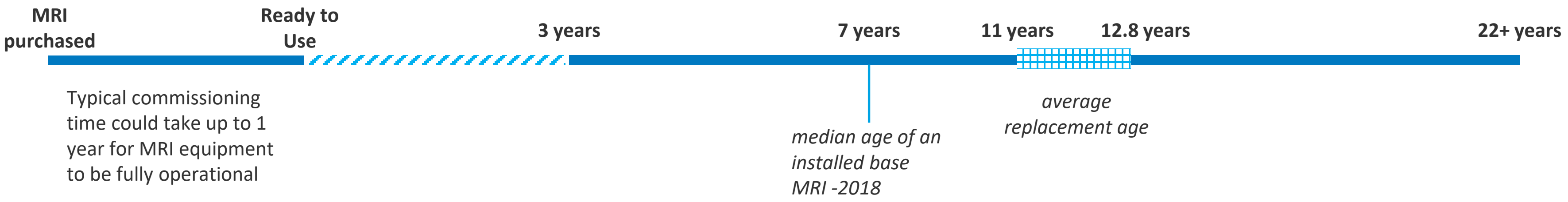
MRI Startup/Shutdown Time

Data Source	Location / Year	MRI Model	Magnet Type	Startup Time	Shutdown Time
UCLA Brain Mapping Center [UCLA 2022]	U.S. / 2021	Siemens Prisma 3T MRI Scanner	Superconducting	15 minutes	20 minutes
Ghent Institute for functional and Metabolic Imaging [Bogaert 2019]	Belgium / 2019	Siemens Prisma 3T MRI Scanner	Superconducting	10 minutes	No information*
How To Turn On GE MRI Scanner [GE MRI Power On Procedure, MRIPETCTSOURCE 2022, MRIPETCTSOURCE 2021]	U.S. / 2022	GE Signa series MRI Scanner	Superconducting	12-20 minutes	~5 minutes

Startup: From "low-power/off" to "ready-to-scan/idle" mode
Shutdown: From "ready-to-scan/idle" to "low-power/off" mode

* This study did not document the MRI shutdown time.

MRI Equipment Lifespan



2018 MRI Buyer's Guide (GE Healthcare) – "*50% of installed MRI base will be replaced within 11 years of their installation. The average replacement cycle is 11.5 years, ranging from 3-22+ years. The general feeling is that one out of every five MRI systems is older than 10 years.*" ["2018 MRI Buyer's Guide"]

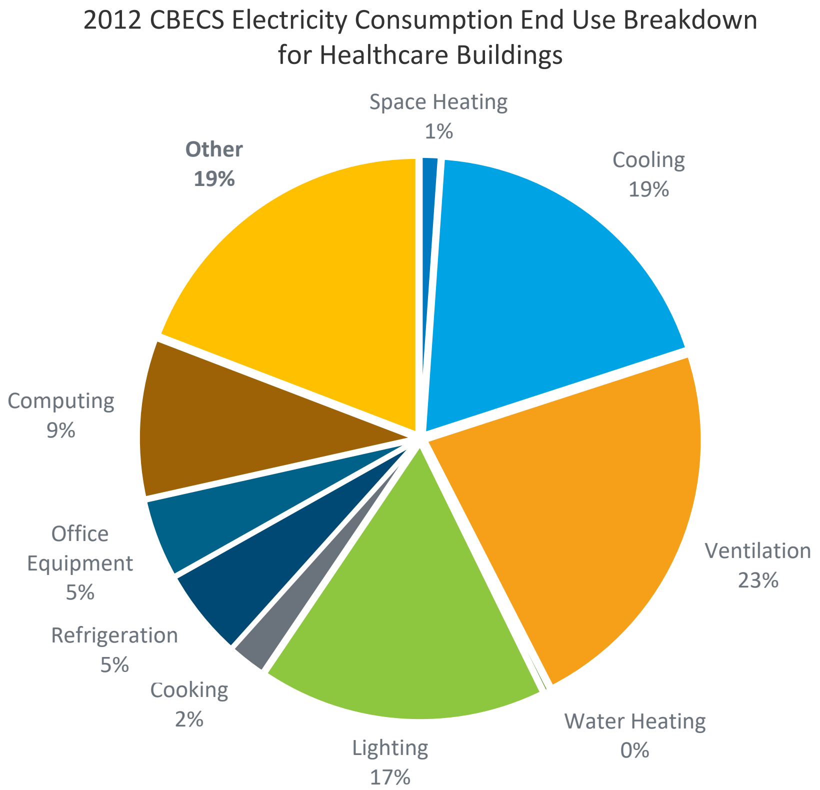
The guide to upgrading an MRI scanner (GE Healthcare) – "*2018 median age of an installed base MRI system was 7 years, average replacement cycle of MRI scanner was 12.8 years.*" ["The guide to upgrading an MRI scanner"]

GE Healthcare article (2019) - *The average lifespan of an MRI scanner is about 11 years, though some are used for over 20 years*. ["Opportunities The First MR Scanner Brings To Your Private Hospital"]

Relevant Work

Healthcare Microdata in CBECS

- EIA CBECS 2012 data consolidates medical equipment energy consumption in "Other" [CBECS, 2012]
- CBECS 2012 surveyed the quantity of X-ray units
- CBECS 2018 (released Nov. 2021) includes latest MIE statistics
  - 2018 questionnaire surveys for MIE (MRI, CT scan, and ultrasound) quantity in addition to X-ray for healthcare facilities.



Relevant Work Abroad

COCIR Ecodesign Self-Regulatory Initiative

- Non-profit trade organization representing MIE and healthcare IT industry in EU.
- Participating companies adopt an internal company target and commit to not increase the average energy consumption in “off” and “ready-to-scan” modes compared to the 2011 baseline, saving an estimated 12% daily energy by 2017 [“Ecodesign Initiative”]
- 5 participating MRI companies:
  - GE Healthcare, Hitachi Medical System Europe, Philips Healthcare, Siemens Healthcare, and Canon Medical Systems

The Canadian Coalition for Green Health Care [Knott et al. 2017]

- Representatives from some of Canada’s largest healthcare associations and environmental groups.
- Involved in local and national initiatives.
- Provides virtual platform for sharing ideas and resources for stakeholders to work together.
- Affiliation with Canadian Healthcare Engineering Society and Ontario Hospital Association.

Siemens Carbon-Neutral Radiology Imaging Service

[Berthold 2021]

- Through an agreement, Siemens Healthineers and University of California, San Francisco (UCSF) formed research and innovation-driven collaboration.
- Carbon-neutral radiology imaging service at UCSF
  - Monitor power consumption of radiology equipment at UCSF.
  - Leverage new Siemens scanner technology, the MAGNETOM Free.Max: a small (0.55 Tesla) MRI scanner.
  - Explore ways to reduce standby energy consumption of MRIs.
  - Explore the potential for turn-key eco-friendly scanners.
  - UCSF will have a carbon-neutral imaging fleet by supplementing with renewable energy certificates (RECs).

* Agreement will also explore Artificial Intelligence (AI) in radiology, clinical data and image integration, and quantitative imaging.

Summary & Next Steps

Summary

- MIE electricity consumption could account for up to 5% or more of a hospital's site energy use [Sheppy 2014]. More work is needed to determine a better estimate.
- The addition of an MRI to a healthcare facility results in a statistically significant increase in energy consumption.
- MRIs can consume 9 kW in system off/low-power mode, and MRIs are often left in standby/idle mode, consuming around 14 kW [COCIR 2018].
- There are opportunities to reduce energy consumption of MIE, including MRIs. Implementing low-power modes is one strategy and can save 21.8% energy [COCIR 2018].

Opportunities for Energy and Cost Savings

- Some subsystems need to run constantly, while others do not (non-critical). There is the opportunity to use occupancy measurements to control MRI subsystem loads that are non-critical. When unoccupied, turn off non-critical loads such as screens and lights, and reduce HVAC load.
- In some instances, energy savings can be achieved by transitioning MRIs that are in standby/idle mode to system off/low-power mode as long as the standby/idle functionality is not needed. Healthcare providers who operate MIE would like transitions into and out of low power to be seamless, easy, and incorporated into use cases and documentation.
- For cost clarity, healthcare companies can define a framework for total ownership cost or life cycle cost, which includes first costs, remodel construction costs, direct energy cost, auxiliary cost, and indirect cost.

Opportunities for Indirect Energy Savings

- Energy consumption of auxiliary equipment, such as display monitors, can be reduced by using sleep settings.
- Lighting in the imaging, technician’s, and patient’s rooms can be dimmed or turned off during unoccupied hours through scheduling or occupancy sensors.
- During unoccupied hours, the room does not need to be conditioned for human comfort but might still need to be conditioned (temperature & relative humidity) for the MIE.

Future Research Work Opportunities

- Documenting detailed MRI load profiles
- Component-level MIE efficiency analysis and improvement
- Load flexibility opportunities using MIE and energy storage
- Stress testing MRI machines for switching to standby mode more frequently
  - Existing resources for stress testing are focused on mechanical stress testing of the MRI equipment.

References

- " 2018 MRI Buyer's Guide" [Online] Availaible: https://www.gehealthcare.com/-/media/636f157facc24202aa28f14fbbf1fd35.pdf [Accessed: 02-Feb-2022].
- A. Esmaeili, J. M. Twomey, M. R. Overcash, and S. A. Soltani, "MRI Transparency Document," 2017.
- Esmaeili A, McGuire C, Overcash M, Ali K, Soltani S, Twomey J. Environmental impact reduction as a new dimension for quality measurement of healthcare services. Int J Health Care Qual Assur. 2018 Oct 8;31(8):910-922. doi: 10.1108/IJHCQA-10-2016-0153. PMID: 30415627.
- European Coordination Committee of the Radiological, "Ecodesign Initiative." [Online]. Available: https://www.cocir.org/initiatives/ecodesign-initiative.html. [Accessed: 28-Oct-2021].
- European Coordination Committee of the Radiological Electromedical and Healthcare IT Industry, "COCIR Self-Regulatory Initiative for the Ecodesign of Medical Imaging Equipment Status Report 2018," 2018. [Online]
- European Coordination Committee of the Radiological, "COCIR GUIDELINES FOR USERS ON SAVING ENERGY," 2015. [Online]
- "GE MRI Power On Procedure" [Online] Available: https://www.mripetctsource.com/turn-on-ge-mri/ [Accessed: 14-Dec-2022].
- Geraldine N Tran, Maria K Pamatmat, Craig Devincent, Gail Lee, and Alastair J Martin. "Energy usage of a newly operational GE Healthcare Signa Premier 3T MRI", *ISMRM 27th Annual meeting and Exhibition*, 2019
- Goetzler, William, Matt Guernsey, Kevin Foley, Jim Young, and Greg Chung. "Energy Savings Potential and RD&D Opportunities for Commercial Building Appliances (2015 Update)," June 1, 2016. https://doi.org/10.2172/1420229.
- Green Public Procurement, "EU GPP Criteria for Electrical and Electronic Equipment used in the Health Care Sector (Health Care EEE)," 2014.
- J. J. Knott, L. Varangu, K. Waddington, T. Easty, and S. Shi, "Assessing Opportunities to Reduce Energy Consumption in the Health Care Sector," 2017.
- Jess Berthold, "Siemens Healthineers and UCSF Create First Carbon-Neutral Radiology Imaging Service", 2021 [Online]. Available: https https://www.ucsf.edu/news/2021/11/421756/siemens-healthineers-and-ucsf-create-first-carbon-neutral-radiology-imaging
- M. Sheppy, S. Pless, and F. Kung, "Healthcare Energy End-Use Monitoring," 2014.
- MRIPETCTSOURCE, "How to Shut Down GE MRI (Signa LX to Signa Excite HDxt) GE MRI Training Technologist Video Series," YouTube Video, 1:21, March 7, 2021, https://youtu.be/etqCVWIhDKQ.
- MRIPETCTSOURCE, "How To Turn On GE MRI Scanner w/ subtitles," YouTube Video, 3:36, March 9, 2022, https://www.youtube.com/watch?v=2UadBjHBZeA.
- "OECD health statistics 2022 definitions, sources and methods: magnetic resonance imaging units," OECD, 2022, [Online]. Available: http://stats.oecd.org/wbos/fileview2.aspx?IDFile=80130ebd-5f8d-482f-9613-2891b0fc0fcf
- "Opportunities The First MR Scanner Brings To Your Private Hospital" [Article] Availaible: https://www.gehealthcare.com/article/opportunities-the-first-mr-scanner-brings-to-your-private-hospital [Accessed: 02-Feb-2022].
- Peter A. Rinck, "Chapter Twenty-One Facts and Figures", 2018 [Online]. Available: https://www.magnetic-resonance.org/ch/21-01.html
- Siemens, "MRI stress-testing" [Online]. Available: https://www.*siemens-healthineers.com/perspectives/mri-stress-testing*
- S. Bogaert, P. Vandemaele, P. Pullens, "*GIfMI MRI user manual SIEMENS PRISMA*", 2019, [Online]. Available: http://gifmi.ugent.be/drupal/system/files/documents/GIfMI_MRI%20user%20manual_BASIC_SiemensPrisma_EN.pdf.
- "The guide to upgrading an MRI scanner" [Online] Availaible: https://www.gehealthcare.com/-/jssmedia/gehc/us/files/products/magnetic-resonance-imaging/mri-upgrades-and-lifecycle-guide.pdf?rev=-1 [Accessed: 02-Feb-2022].
- T. Heye et al., "The energy consumption of Radiology: Energy- And cost-saving opportunities for CT and MRI operation," *Radiology*, vol. 295, no. 3, pp. 593–605, 2020, doi: 10.1148/radiol.2020192084.
- "Turning off the Magnet," MRI Questions, 2021, [Online]. Available: https://mriquestions.com/is-field-ever-turned-off.html
- U.S. Energy Information Administration, "Commercial Buildings Energy Consumption Survey (CBECS) ," 2018.
- *UCLA, "Siemens Prisma 3T MRI Scanner User Guide",* Ahmanson-Lovelace Brain Mapping Center University of California, Los Angeles, [Online]. Available: http://www.bmap.ucla.edu/docs/PrismaUserGuide.pdf, 2022
- Wikipedia and Chiswick Chap, "Mri scanner schematic labelled," 2017. [Online]. Available: https://en.wikipedia.org/wiki/File:Mri_scanner_schematic_labelled.svg. [Accessed: 9-Feb-2023].
- Wikipedia and Daniel W. Rickey, "Medical Ultrasound Scanner ," 2006. [Online]. Available: https://commons.wikimedia.org/w/index.php?curid=2137444. [Accessed: 28-Oct-2021].
- Wikipedia and FDA, "Drawing of CT fan beam (left) and patient in a CT imaging system," 2019. [Online]. Available: https://commons.wikimedia.org/w/index.php?curid=99627315. [Accessed: 28-Oct-2021].
- Wikipedia and Mikael Häggström, "Projectional radiography components," 2017. [Online]. Available: https://commons.wikimedia.org/w/index.php?curid=58054654. [Accessed: 28-Oct-2021].

Thank You!

www.nrel.gov

NREL/PR-5500-83743

This work was authored by the National Renewable Energy Laboratory, operated by Alliance for Sustainable Energy, LLC, for the U.S. Department of Energy (DOE) under Contract No. DE-AC36-08GO28308. Funding provided by the U.S. Department of Energy Office of Energy Efficiency and Renewable Energy Building Technologies Office. The views expressed in the article do not necessarily represent the views of the DOE or the U.S. Government.

NREL Transforming ENERGY