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

The case of magnetic resonance imaging

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Abstract

Purpose – The purpose of this paper is to provide a detailed accounting of energy and materials consumed during magnetic resonance imaging (MRI).

Design/methodology/approach – The first and second stages of ISO standard (ISO 14040:2006 and ISO 14044:2006) were followed to develop life cycle inventory (LCI). The LCI data collection took the form of observations, time studies, real-time metered power consumption, review of imaging department scheduling records and review of technical manuals and literature.

Findings – The carbon footprint of the entire MRI service on a per-patient basis was measured at 22.4 kg CO_2eq. The in-hospital energy use (process energy) for performing MRI is 29 kWh per patient for the MRI machine, ancillary devices and light fixtures, while the out-of-hospital energy consumption is approximately 260 percent greater than the process energy, measured at 75 kWh per patient related to fuel for generation and transmission of electricity for the hospital, plus energy to manufacture disposable, consumable and reusable products. The actual MRI and standby energy that produces the MRI images is only about 38 percent of the total life cycle energy.

Research limitations/implications – The focus on methods and proof-of-concept meant that only one facility and one type of imaging device technology were used to reach the conclusions. Based on the similar studies related to other imaging devices, the provided transparent data can be generalized to other healthcare facilities with few adjustments to utilization ratios, the share of the exam types, and the standby power of the facilities' imaging devices.

Practical implications – The transparent detailed life cycle approach allows the data from this study to be used by healthcare administrators to explore the hidden public health impact of the radiology department and to set goals for carbon footprint reductions of healthcare organizations by focusing on alternative imaging modalities. Moreover, the presented approach in quantifying healthcare services' environmental impact can be replicated to provide measurable data on departmental quality improvement initiatives and to be used in hospitals' quality management systems.

Originality/value – No other research has been published on the life cycle assessment of MRI. The share of outside hospital indirect environmental impact of MRI services is a previously undocumented impact of the physician's order for an internal image.

Keywords Environmentally sustainable practices, ISO 14001, Quality management, Life cycle assessment, Magnetic resonance imaging, Hospital energy consumption

Paper type Research paper

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1. Introduction

The US healthcare sector contributes 7 percent of the nation's carbon dioxide-equivalent emissions (6,103m metric tons CO_2eq) in 2007 (Chung and Meltzer, 2009), annually consumes 73 bn kWh of electricity in high energy-intensive healthcare facilities (Campion *et al.*, 2012) and generates approximately 1.54 bn kg of solid waste (Thiel *et al.*, 2015). This large contribution, in addition to overall concerns about global warming, leads to a call for the healthcare industry to reduce its environmental impact (Holmner *et al.*, 2012; Moynihan, 2012; Cosford, 2009; Sarfaty and Abouzaid, 2015). In order to respond to these expectations, many hospitals have begun to implement environmental management systems (EMSs) (ISO 14001) with the goal of measuring and reducing their carbon footprint. Practice Greenhealth initiatives are good examples of these efforts: they have targeted green procurement, green operating rooms and environmental health improvements in the healthcare sector (Johnson, 2010). Until now, many of these initiatives have focused solely on reducing energy and water consumption and waste without connecting these efforts to the day-to-day decisions of healthcare providers.

In a complex healthcare facility, such as a hospital, many emission sources are associated with patient-centered decisions. Patient-centered decisions include choice of medical procedures, consumption of pharmaceuticals or consumables, use of machines and devices, etc. In instances in which patient outcomes would not be negatively affected, healthcare providers can choose alternative medical interventions that have a smaller carbon footprint (Harper, 2014; Wichita State University, 2012). However, today's patient care teams are substantially limited by a lack of data regarding the relationship between their decisions and the cascading environmental effects of those decisions. Consequently, the process life cycle assessment (P-LCA) was introduced as an approach to evaluate the emission profiles of medical practices (Zumsteg *et al.*, 2012), as it can integrate both hospital energy (electricity, natural gas, etc.) and upstream energy used to manufacture consumables (disposables and reusables) into a detailed energy profile for each medical treatment. The application of LCA for healthcare practices has been proven by environmental impact quantification in services such as nephrology, anesthesiology, radiology, obstetrics and hysterectomy. The LCA study conducted by Connor *et al.* (2011) described the carbon footprint of different hemodialysis regimes, and Soltani *et al.* (2015) addressed the choices of water purification systems and their effect on reduction of the overall dialysis energy footprint. Based on the carbon footprint profiles of five anesthetic drugs, Sherman *et al.* (2012) suggested strategies for reduction of the environmental impact of anesthesiology (Sherman *et al.*, 2012). Other LCA studies related to vaginal birth vs Cesarean section (Campion *et al.*, 2012); abdominal, vaginal, laparoscopic and robotic hysterectomy surgery methods (Campion *et al.*, 2012); and comparison of laparotomy, conventional laparoscopy and robot-assisted laparoscopy surgical modalities (Woods *et al.*, 2015) emphasized that more environmentally friendly treatment options have the same patient outcomes. A more comprehensive systematic literature review of 53 articles was conducted recently (Esmaeili *et al.*, 2016). While most of the studies were conducted in the UK after 2009, the year that NHS set carbon reduction targets (NHS, 2009), the chronological order of the published articles (Figure 1) shows that the US researchers adapted a similar approach to reduce the environmental impact of healthcare practices. Among these activities, the surgical and dialysis practices – because of the level of required energy and the magnitude of waste generation – and the outpatient service – mostly due to the potential carbon reduction of telemedicine – were targeted and quantified by healthcare scholars. Computed tomography and x-ray diagnostic imaging modalities have been evaluated recently by the life cycle methodology (Esmaeili *et al.*, 2015; Smith *et al.*, 2014; Esmaeili *et al.*, 2011), but no life cycle assessment study for magnetic resonance imaging (MRI) diagnostic service was found in the literature. Here, a detailed accounting of energy and material use for MRI is presented. This study is part of a larger body of research with the aim of quantifying healthcare services'

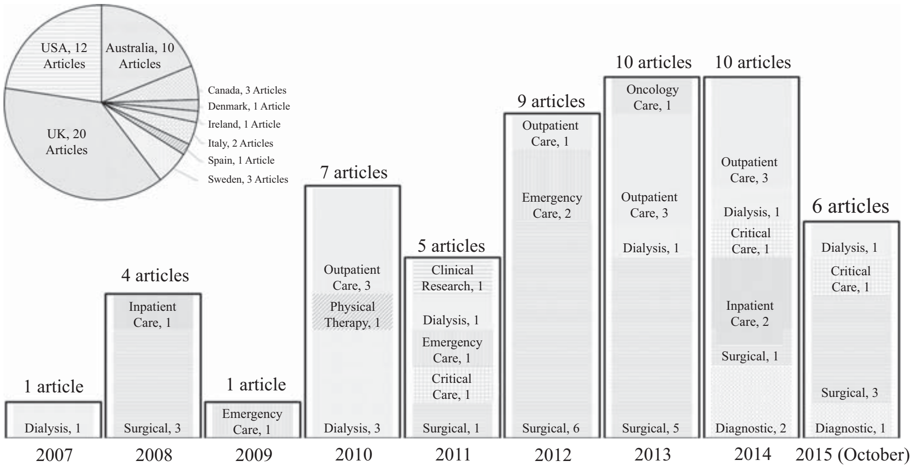


Figure 1.
The timeline and the country of origin of 53 articles in Esmaeili *et al.* (2016)

environmental impact (Wichita State University, 2012). As many healthcare facilities intend to integrate their quality management systems (QMSs) and EMSs (Detroit Medical Center, 2007; Life Healthcare Group, 2016), the approach of this research and its outcomes can define a new avenue for measurement of hospital services quality in terms of its environmental impact and help to quantify the improvement efforts as suggested by ISO 9001:2015 (European Committee for Standardization, 2011).

2. Materials and methods

The first and second stages (Figure 2) of ISO standard (ISO 14040:2006 and ISO 14044:2006) were followed for the development of life cycle inventory (LCI) (Horne *et al.*, 2009; Finkbeiner *et al.*, 2006). The LCA process quantifies the environmental impact of a product or service throughout its life cycle, including the extraction of raw materials, manufacturing, use, disposal and any transportation between these steps. Data collection took the form of observations, time studies, real-time metered power consumption, review of imaging department scheduling records and review of technical manuals and literature. These were

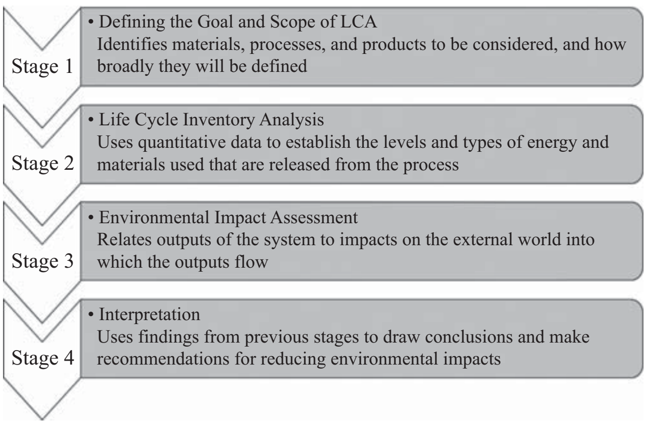


Figure 2.
Four stages of life cycle assessment, standardized by ISO 14040/14044

not plug studies as such information does not focus on the actual patient needs or actual medical decisions. We measured the amount of time it took to set up the MRI room and equipment, prepare a patient to undergo MRI, process the resulting images and clean the MRI room after the procedure. Table I lists data collection categories and sources. The data were collected during four days in January 2012 in the radiology department of an outpatient facility in Wichita, Kansas. This facility uses a Siemens MRI scanner (MAGNETOM® Symphony 1.5T) for diagnostic purposes. The MRI components are illustrated in Figure 3, and more information about the data collection methods and study scope are provided in MRI Transparency Document (Esmaeili *et al.*, 2017).

The two functional units for this study are the monthly energy consumption of the MRI department and energy consumption for MRI of one patient. Additionally, the documented rate of textile and disposable material consumption and conversion of these manufacturing steps to natural resource energy (NRE) use provides a new avenue for hospitals to obtain energy reduction credit through consumables reduction. The energy for manufacturing all consumables with typically large, even global, supply chains is known as cradle-to-gate (CTG) life cycle energy. Moreover, LCA information in our study was separated based on the stages at which greenhouse gas (GHG) emissions occur. Thus, the in-hospital energy (process electrical energy) – which is direct electricity costs and appears to be fully clean (comes from the wall, powers the MRI scanners and the ancillary devices) – was linked to outside-the-hospital carbon emissions sources as well. The outside-the-hospital environmental effects include combustion emissions to air, chemicals to wastewater and

	Data collected	Source of energy information	Observations
Power	Siemens MRI scanner	Portable power cell meter	4 days – 59 patients
	Ancillary devices	Equipment information/ratings	–
	Lighting	Equipment information/ratings	–
	HVAC	TRACE™ 700 software	–
Materials	Medical textiles	Sample amounts	59 patients
	Medical consumables	Sample amounts	59 patients
	Cleaning products	Sample amounts	59 patients

Table I. Collected data and method

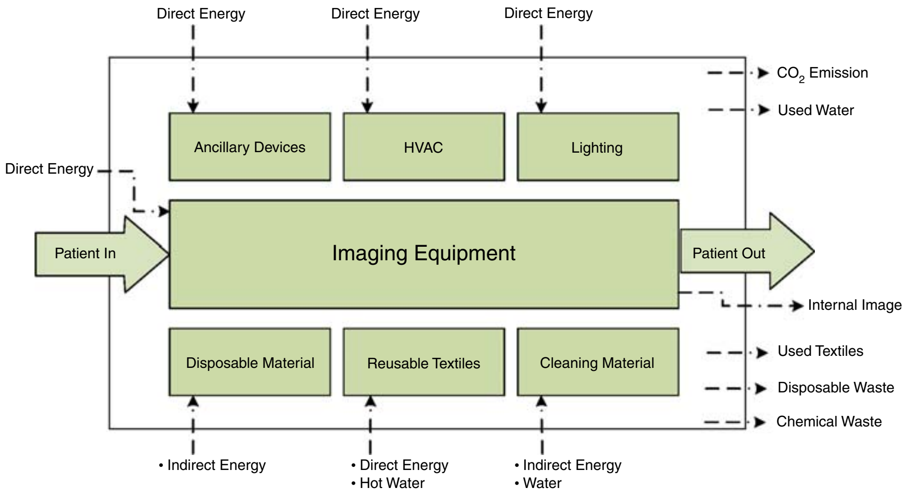


Figure 3. Components of magnetic resonance imaging study with inputs and outputs for LCA

solid waste to land and are currently unquantified public health impacts resulting from MRI. Thus, for every kWh of process energy, the NRE was calculated by multiplying the electrical energy by a 3.44 factor (Esmaeili *et al.*, 2015). This factor is the product of 1.1 that reflects the energy use in delivery of fuel to the power plant (pre-combustion factor), multiplied by 3.13 that is related to the fuels (US grid mix of fuels) consumed to generate the electricity and the transmitting losses in the grid. In this study, the heating, ventilation and air conditioning energy was not considered a medical-based source of energy consumption as it is not under the control of the imaging department staff and is not central to the comparison of imaging alternatives. However, the calculated values are reported in MRI Transparency Document (Esmaeili *et al.*, 2017).

3. Results

3.1 In-hospital sources of energy consumption

A major source of process energy consumption for delivering the imaging service is the MRI scanner; Figure 4 depicts the power signal and timeline of a patient lumbar diagnostic MRI without contrast. In the shown power signature, the first two small spikes (from 5:59:00 to 6:00:30) represent the required power for the MR localizers, and the bigger spikes depict the machine power consumption patterns of T2 Sagittal, T1 Sagittal, STIR Sagittal, T2 Space Axial, and T2 Axial scan sequences of a without-contrast lumbar imaging protocol.

The MRI scanner energy consumption (kWh) is calculated by multiplying the power (kW) by the time (hour) and was categorized in three segments: idle energy, standby energy and active energy:

(1) Idle: energy used during the 24-h cycle when the MRI room is unoccupied. The idle energy reported in Table II was estimated based on two sets of assumptions: observed 72.5 percent utilization ratio during a 12-h shift of a working day in the outpatient facility, and during weekends and nights the system partially turns off; and for a more typical hospital with 50 percent utilization ratio during one 8-h shift and all equipment remains ON during weekends and nights. The second scenario has considerably more idle energy. The detailed assumptions are given in MRI Transparency Document (Esmaeili *et al.*, 2017).

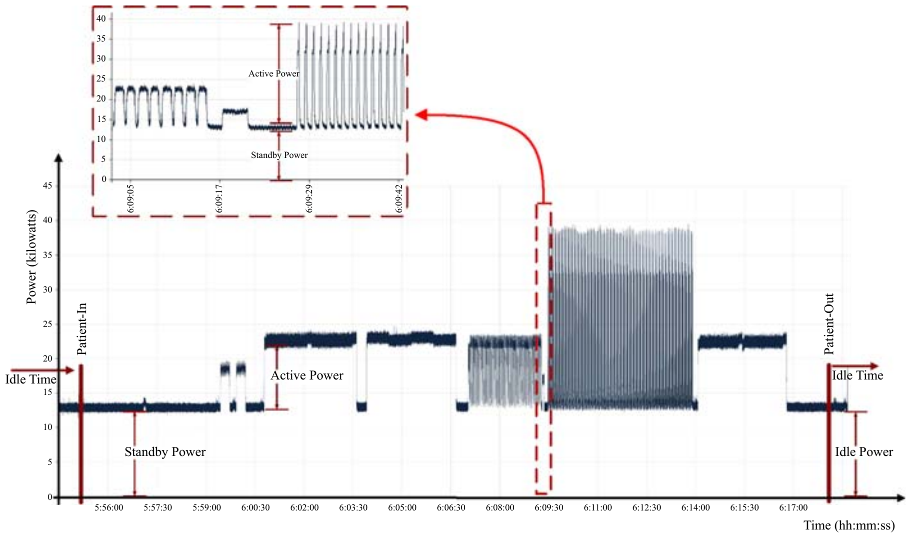


Figure 4.
Power signal for a patient's lumbar MRI (without contrast) with timeline of the service

	Outpatient facility (12-h shift, 72.5% utilization ratio)				Estimation for a hospital (8-h shift, 50% utilization ratio)			
	Per patient		Per month (317 patients)		Per patient		Per month (146 patients)	
	Process energy (kWh)	Cradle-to-gate energy (NRE-kWh)	Process energy (kWh)	Cradle-to-gate energy (NRE-kWh)	Process energy (kWh)	Cradle-to-gate energy (NRE-kWh)	Process energy (kWh)	Cradle-to-gate energy (NRE-kWh)
Active energy	4.10	–	1,300	–	4.10	–	599	–
Standby energy	7.48	–	2,371	–	7.48	–	1,092	–
Idle energy	14.86	–	4,711	–	56.02		8,165	–
Ancillary devices energy	1.99	–	632	–	12.28		1,793	–
Lighting energy	0.55	–	173	–	3.36		490	–
Total in-hospital electrical use	28.98	–	9,187	–	83.24	–	12,152	–
Electric power generation and transmission losses (based on total process energy)		70.71	–	22,415	–	203.10	–	29,652
Disposable materials energy		0.64		203		0.64		93
Reusable textile energy		3.57		1,132		3.57		521
Total outside-the-hospital energy		74.92		23,750		207.31		30,267
Total energy (NRE-kWh)		103.90		32,937		290.54		42,419

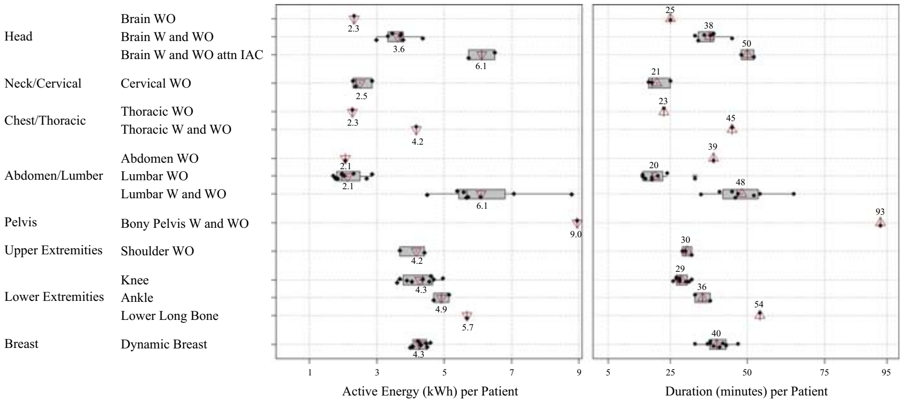
Table II. Comparison of different sources of energy consumption

(2) Standby: energy used when the patient enters the room until he or she departs, hence patient diagnostic time. The average duration (patient-in to patient-out) of a single MRI session is 35.4 min (0.59 h). The standby power was measured as 12.68 kW for the Siemens scanner, and includes the constant power required to maintain the machine's magnetic field, to cool down the magnet and to power the computing console of the equipment. Therefore, the average standby energy per patient is the product of 12.68 kW and 0.59 h, 7.48 kWh.

(3) Active: energy is consumed to excite nuclei within the body and create the images. The area under the power signal curve and above the standby power line is the incremental active power for the MRI. It is mainly associated with the gradient amplifier parts of the MRI machine. It includes the required power of the radiofrequency (RF) sender, the RF receiver and the heat exchanger during the high-performing gradients. The average active energy per patient is 4.10 kWh. Figure 5 depicts the average active energy and skew in the data collected for different observed MRI exam types. It also shows the average and skew in the duration data (hence the standby energy) of those 59 imaging services. More information is reported in the TD. The substantially higher energy expenditure of with vs without contrast in MRI is clearly shown.

In addition to the scanner's energy consumption, two other sources of process energy consumption – ancillary devices (including an injection system) and lighting fixtures required for service delivery (more detail in MRI Transparency Document; Esmaeili *et al.*, 2017) – are reported in Figure 6. All of these values have been converted to NRE.

The significant difference in idle energy of the MRI machine, ancillary devices and lighting in the outpatient facility vs a hospital stems from two factors. First, at the hospital, it was assumed that the MRI scanner remains ready for emergency imaging during night hours and weekends (regardless of whether there is more than one MRI machine or how quickly an MRI machine can be brought to full power), whereas, at the outpatient facility, technicians partially turn off the scanner and only the machine's magnetic field and cooling system remain



Notes: W, with contrast; WO, without contrast

Figure 5.
Box plots for active process energy and full patient duration of different exam types

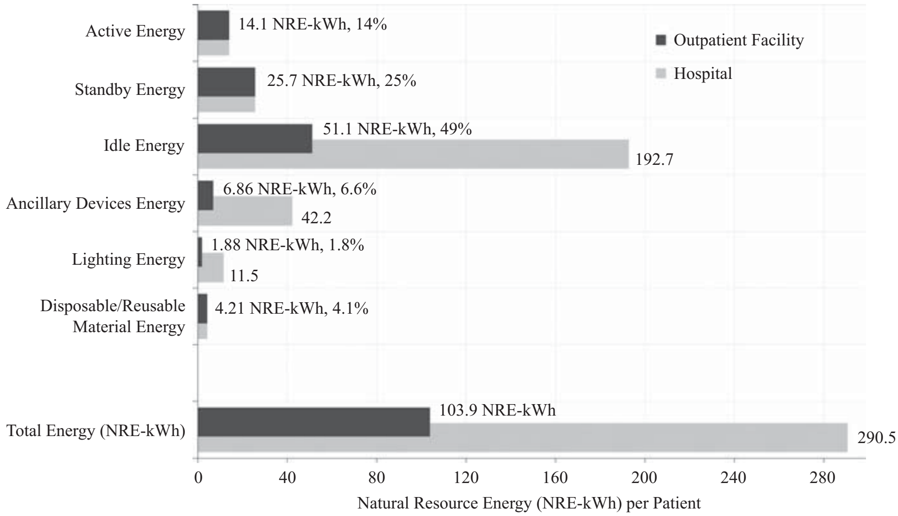


Figure 6.
The natural resource energy (NRE) for different sources of consumption per patient basis at an outpatient facility and a representative hospital (percent of total also shown)

(reducing standby power to 8.08 kW). Second, the outpatient facility uses a 12-h shift with a high utilization ratio of 72.5 percent due to scheduled appointments and high patient volume. For the hospital, an 8-h shift with 50 percent utilization was assumed in order to make the result comparable to other radiology LCA studies (Esmaeili *et al.*, 2015; Esmaeili *et al.*, 2011; Smith *et al.*, 2014). The in-hospital energy use per patient has been plotted in Figure 7 for different levels of utilization. The monthly number of patients associated with the utilization ratios in the outpatient facility and the hospital is also stated in the plot. The results of this utilization-dependent plot are adjustable for use by other healthcare facilities' utilization studies. The other assumptions about shift duration and partially turning off the equipment remained the same for the outpatient facility and the hospital.

3.2 Outside-the-hospital energy consumption derived from MRI service

Two other sources of downstream energy consumption were calculated in this section: fuel energy needed for electricity generation/transmission; and the manufacture of disposables

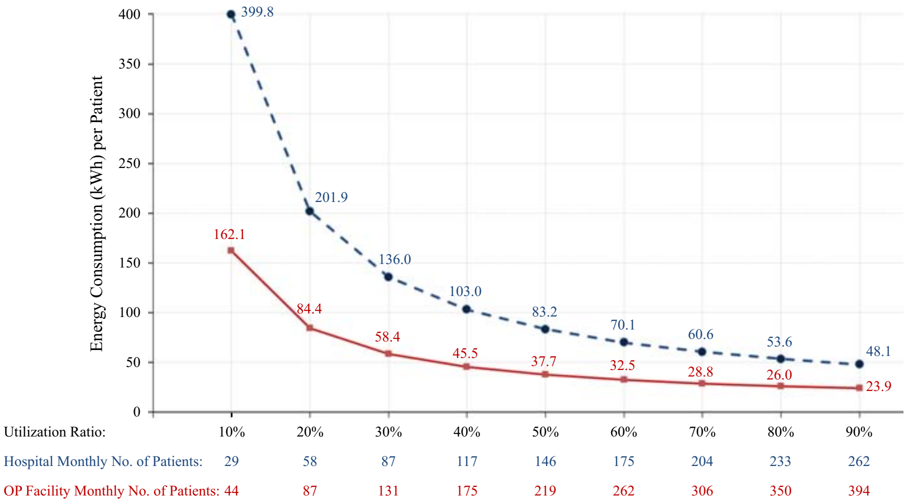


Figure 7.
Dependency of the patient-based process energy consumption on room utilization (for one MRI machine)

in addition to the manufacture/maintenance of reusable textiles. The outside-the-hospital energy leads to direct emissions to the environment and hence has a public health impact on both patients and the community:

(1) Electricity generation and transmission energy loss: as previously described, the NRE minus the actual process electrical energy gives the electricity generation and transmission energy loss for delivery of the MRI service. Thus, the outside-the-hospital energy is 2.44 times the in-hospital process electrical consumption, as shown in Table II.

(2) Reusable textiles and disposable consumables: the disposable medical consumables and laundered and sterilized medical textiles are the sources of indirect or upstream energy consumption in the delivery of MRI. These sources can be quantified using the CTG life cycle energy, which is the energy required to manufacture a given product (resource extraction from earth through to product manufacturing). Based on recorded data, each patient uses an average of 126.6 g of disposable medical materials. The list of products consumed per patient for service delivery at the outpatient facility is reported in Table III. These products are then expressed as chemical or material constituents based on the information published by the manufacturer(s) or found on the internet, generally from the material safety data sheets.

Using the product consumption rates, the disposable constituent analyses, and the product constituents' CTG energy obtained from LCI (Overcash and Griffing, 1998/2014), we calculated the consumables energy consumptions per patient and report them in Table II. Medical textile rate of consumption was also recorded as 525.1 g per patient for the MRI room. The medical textile NRE consumption, shown in Table II, is associated with manufacturing, laundry, sterilizing, packaging and transport processes for patient gowns and shorts, fitted sheets and pillow covers. For all four reusable textiles, the CTG energy information is based on 75 gown uses per cycle. The LCI information shows that for 75 gown uses per cycle, 24.5 MJ NRE is expended for every kg (Overcash and Griffing, 1998/2014; Overcash, 2012). The detailed information for disposable materials and medical textiles is available in MRI Transparency Document (Esmaeili *et al.*, 2017).

Table III. Disposable materials' rate of consumption during delivery of MRI service

Cradle-to-gate energy	(NRE-MJ per kg)	8E-04	7.6	33.5	62.6	30	5.6	N/A	N/A	27.9	19.7	33	21.6	9.75	
Products-materials matrix		Water	NaCl	Ethylene-propylene block copolymer	Isopropyl Alcohol	Airlaid cellulose	Glass	Gadopentate dimeglumine	Maglumine & Diethylenetriamine	Butiadiene	Acrylonitrile	Polypropylene (PP)	PVC	Cotton	Constituents total mass (grams/patient)
Saline	(grams/patient)	39.63	0.04												39.67
Injector&Tube	(grams/patient)			21.97											21.97
Super Sani Cloth	(grams/patient)				5.64	4.61									10.25
Contrast Container	(grams/patient)						9.07								9.07
Contrast (Magnivest)	(grams/patient)	5.17						3.29	0.01						8.47
Syringe	(grams/patient)			7.81											7.81
Gloves	(grams/patient)									3.32	3.32				6.64
Saline Package	(grams/patient)											6.41			6.41
Super Sani Container	(grams/patient)												5.48		5.48
Injector Package	(grams/patient)											4.27			4.27
Coban Roll	(grams/patient)													2.63	2.63
Rubber Band	(grams/patient)									1.13	1.13				2.25
Autoguard	(grams/patient)											1.22			1.22
Conncector	(grams/patient)											0.46			0.46
Total Constituents Consumption	(grams/patient)	44.81	0.04	29.78	5.64	4.61	9.07	3.29	0.01	4.45	4.45	12.36	5.48	2.63	126.60

(continued)

Products-materials matrix		Water	NaCl	Ethylene-propylene block copolymer	Isopropyl Alcohol	Airlaid cellulose	Glass	Gadopentate dimeglumine	Maglumine & Diethylenetriamine	Butiadiene	Acrylonitrile	Polypropylene (PP)	PVC	Cotton	Constituents total mass (grams/ patient)
Cradle-to-gate energy	(NRE-MJ per kg)	8E-04	7.6	33.5	62.6	30	5.6	N/A	N/A	27.9	19.7	33	21.6	9.75	
CTG life cycle energy	(NRE-MJ/ patient)	4.E-05	3.E-04	0.998	0.353	0.138	0.051	–	–	0.124	0.088	0.408	0.118	0.026	2.303 NRE-MJ
CTG life cycle energy	(NRE-kWh/ patient)	1.E-05	8.E-05	0.277	0.098	0.038	0.014	–	–	0.034	0.024	0.113	0.033	0.007	0.640 NRE-kWh

Table III.

4. Discussion

Medical decisions for quality patient care represent a new dimension for hospital energy and sustainability improvement, and these efforts – if integrated with hospitals' QMSs – can result in a substantial reduction in overall GHG emissions by healthcare facilities. These improvements will come from selecting medical alternatives that provide quality care but at a lower environmental burden as well as from changes to the technological and operational procedures used in all areas of the services provided. In order to develop such energy-improvement strategies, one should first assess the sources of energy consumption, the share of each source in total consumed energy and the relationship of the consumed energy by each source to patient outcome. In the case of MRI, the required electrical energy for image creation (active energy) is a small portion of in-hospital electricity consumption, whereas the full energy needs of the patient expand beyond this direct active energy to much more significant in-hospital energy consumption (standby, idle, ancillary devices, etc.). Further, the MRI footprint then goes substantially beyond in-hospital electrical energy consumption when the loss of energy in generation and transmission of electricity and the manufacturing of consumables needed for service delivery are considered. This larger life cycle footprint is outside the hospital and represents a direct impact not just on patients receiving the MRI diagnosis, but also on the broader community (through emissions to air, water and land).

The total MRI diagnostic footprint is 104 kWh of NRE per patient (outpatient facility), but the energy required to prepare the patient and acquire the images (active and standby energy converted to NRE) is only about 38 percent of this total (Table II). This multiplier (2.6fold higher = 1/0.38) to get total energy is a previously undocumented environmental effect of the MRI prescription. The total in-hospital electrical energy of MRI is about 28 percent of the total energy footprint, whereas the generation/transmission of the electricity from the grid contributes to 68 percent of NRE loss, and the other 4 percent is for the energy required to make the consumables. The above estimates are related to the outpatient facility's high 72.5 percent room utilization rate; with the assumption of 50 percent utilization, the share of direct required energy for obtaining the image (standby and active energy) will decrease to 14 percent of the total NRE of the service on a per-patient basis. The MRI service energy values (NRE) can also be directly converted to the carbon dioxide-equivalent (CO_2eq). By use of the 0.06 kg CO_2eq per NRE-megajoule (Soltani *et al.*, 2015) ratio, the carbon footprints are 22.44 kg CO_2eq per patient (interestingly, this is about one-quarter to one-third of the weight of each patient). Therefore, performing 35m MRI procedures in the USA annually (IMV, 2014) emitted 785 m kg of CO_2eq into the environment. This is equivalent to the CO_2eq emissions of 160,000 US automobiles per year (EPA, 2011).

5. Conclusion

The carbon footprint of the entire MRI service on a per-patient basis was measured at 22.4 kg CO_2eq. The in-hospital energy use (process energy) for performing MRI is 29 kWh per patient for the MRI machine, ancillary devices and light fixtures, while the out-of-hospital energy consumption is approximately 260 percent greater than the process energy, measured at 75 kWh per patient related to fuel for generation and transmission of electricity for the hospital, plus energy to manufacture disposable, consumable and reusable products. The actual MRI and standby energy that produces the MRI images is only about 38 percent of the total life cycle energy. The radiology and imaging community can use the new information reported here to examine other imaging modalities and/or the influence of patient distribution on these potential energy improvements. The radiology community can also examine the consumables, utilization factor and strategies to reduce idle energy. MRI equipment companies can focus on design features that lower total energy use. The WSU research group is seeking interested radiology groups to examine potential changes to lower energy use and improve hospital sustainability programs, including the comparison of MRI equipment.

Direct recommendations are avoided herein as this approach has historically had difficulty in gaining acceptance by the radiology community. Instead, our goal is to provide science-based methods to obtain information and results for healthcare teams. The purpose is to engage healthcare specialists and to encourage them to use their ingenuity and creativity to examine procedures, patient-based decisions, and other avenues to seek hospital sustainability improvements. This could lead to an engineering–medical team approach to seek changes that have a high likelihood of adoption and could form the basis of departmental quality improvement initiatives for radiologists as part of their certification maintenance. We also now have a methodology for comparative assessment of the full energy of MRI machines that might be used as third-party testing for hospitals or healthcare firms.

At the hospital level, the long-term goal of this research is to provide healthcare nurses, physicians and administrators with a model to reduce the energy, environmental impact and cost of services.

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