Radiology

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

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Background: Awareness of energy efficiency has been rising in the industrial and residential sectors but only recently in the health care sector.

Purpose: To measure the energy consumption of modern CT and MRI scanners in a university hospital radiology department and to estimate energy- and cost-saving potential during clinical operation.

Materials and Methods: Three CT scanners, four MRI scanners, and cooling systems were equipped with kilowatt-hour energy measurement sensors (2-Hz sampling rate). Energy measurements, the scanners' log files, and the radiology information system from the entire year 2015 were analyzed and segmented into scan modes, as follows: net scan (actual imaging), active (room time), idle, and system-on and system-off states (no standby mode was available). Per-examination and peak energy consumption were calculated.

Results: The aggregated energy consumption imaging 40 276 patients amounted to 614 825 kWh, dedicated cooling systems to 492 624 kWh, representing 44.5% of the combined consumption of 1 107 450 kWh (at a cost of U.S. $199 341). This is equivalent to the usage in a town of 852 people and constituted 4.0% of the total yearly energy consumption at the authors' hospital. Mean consumption per CT examination over 1 year was 1.2 kWh, with a mean energy cost (±standard deviation) of $0.22 ± 0.13. The total energy consumption of one CT scanner for 1 year was 26 226 kWh ($4721 in energy cost). The net consumption per CT examination over 1 year was 3580 kWh, which is comparable to the usage of a two-person household in Switzerland; however, idle state consumption was fourfold that of net consumption (14 289 kWh). Mean MRI consumption over 1 year was 19.9 kWh per examination, with a mean energy cost of $3.57 ± 0.96. The mean consumption for a year in the system-on state was 82 174 kWh per MRI examination and 134 037 kWh for total consumption, for an energy cost of $24 127.

Conclusion: CT and MRI energy consumption is substantial. 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.

Awareness of energy consumption of electrical or electronic personal devices and household or office equipment has increased during the past decades. Standby, sleep, and power save modes were introduced and are now commonplace among various consumer devices, from personal computers, notebooks, and smart phones to washing machines and televisions. The European Union, for instance, has established a detailed directive for the setting of ecodesign requirements of energy-using products (European Commission Regulation no. 1275/2008). According to a study performed during the preparation of this directive, annual electricity consumption in the European community related to standby functions and off-mode losses was estimated to be 47 TWh in 2005, which equals 19 megatons of CO_2 emissions, and was predicted to increase to 49 TWh in 2020 (1). This illustrates that power consumption of electrical and electronic devices during nonusage or idling is substantial on a macroscopic level, with economic and ecologic impact.

Although energy-saving capabilities in the residential and office sector have been addressed and appear to have been improved, the health care sector is largely devoid of comparable initiatives aimed at considerably optimizing energy consumption efficiency (2), albeit aside from the self-regulatory initiative of the European Coordination Committee of the Radiological, Electromedical and Healthcare IT Industry, which focused on participating in ecodesign in the medical device industry (3). Radiology departments are major energy consumers within a hospital through operation of CT and MRI scanners, which require energy in the range of 0.5–30 kWh per examination, with peak consumption reaching beyond 100 kW for a short time period.

To gauge the impact of radiologic procedures on the overall power consumption of a hospital and to evaluate the theoretical power-saving potential in the clinical operation of radiologic cross-sectional imaging modalities, the aim of this study was to perform a detailed assessment of

Abbreviation

RIS = radiology information system

Summary

CT and MRI scanners are energy intensive in their operation; considerable energy- and cost-saving potential is present during idle and system-off states.

Key Results

- The energy consumption of CT and MRI scanners was comparable to the energy requirements of a town of 852 people living in four-person households, or 4% of our total yearly hospital energy consumption.
- For CT, two-thirds of energy consumption took place during the nonproductive idle system state.
- For MRI, one-third of energy consumption was attributed to the system-off state owing to the need for constant helium cooling and cooling head operation.

the energy consumption of CT and MRI scanners and their associated cooling systems within a university hospital radiology department over a 1-year period.

Materials and Methods

This study received financial support from Siemens Healthineers (Forchheim, Germany), which was used to equip modalities with sensors and to fund custom software development. The authors who were not employees of Siemens Healthineers had full control of any data and information that might present a potential conflict of interest for authors who were employees.

For this study, we combined several data sources—the local building energy consumption measurement system, scanner log data, and the radiology information system (RIS)—to allow for a detailed and stratified data analysis. The time period of the entire year 2015 was chosen, and the corresponding data were retrieved from each respective source system. We set the study up to investigate the following aspects: *(a)* CT and MRI scanner energy consumption per type of examination, day, month, and year; *(b)* energy consumption distribution for different scanner activity states; *(c)* peak energy consumption and accumulated peak energy consumption, if scanner activities coincided; and *(d)* energy consumption of associated cooling systems required for CT and MRI operation.

Energy Consumption Measurement of CT and MRI Scanners

There were three CT scanners, two in the radiology department (CT1: dual-source Somatom Definition Flash [installed in 2011] and CT2: single-source Somatom Definition Edge [installed in 2014], both from Siemens Healthineers) and one CT scanner in the emergency room (ER-CT: single-source Somatom Definition AS+ [Siemens Healthineers], installed in 2011). All were 128-slice–detector scanners, and all used software version VA48A. The radiology department scanners were in operation from 7:30 AM to 5 PM, and the emergency room scanner was in operation 24 hours a day. The radiology department was also equipped with four clinical MRI units (all from Siemens Healthineers). There were three 1.5-T units: MRI unit 1 (Magnetom Avanto, software version VB17A) had a gradient of 625A/2000 V, a radiofrequency amplifier peak root mean square power of 22.5 kW, and was installed in 2004; MRI unit 2a (Magnetom Espree, software version VB17A) had a gradient of 625A/2000 V, a radiofrequency amplifier peak root mean square power of 22.5 kW, and was installed in 2004; and MRI unit 2b (Magnetom Avanto FIT, software version VB17A) had a gradient of 625A/2000 V, a radiofrequency amplifier peak root mean square power of 22.5 kW, and was installed in 2015. There were two 3.0-T units: Magnetom Verio (software version VB17A), which had a gradient of 900A/2250 V, a radiofrequency amplifier peak root mean square power of 37.5 kW, and was installed in 2008; and Magnetom Skyra (software version VD13A), which had a gradient of 750A/2250 V, a radiofrequency amplifier peak root mean square power of 37.5 kW, and was installed in 2013. One 1.5-T MRI scanner (MRI unit 2a) was replaced in 2015, resulting in 7 months of data acquisition with the old scanner and 3 months with the new scanner (MRI unit 2b), leaving a 2-month gap without data. In these instances, we extrapolated the available data to 12 months for per-year energy consumption summary values. The routine MRI scanners were operated during weekdays from 7 AM to 8 PM; on Saturdays, two MRI scanners (1.5-T and 3.0-T units) were operated from 8 AM to 5 PM. On Sundays, MRI was performed for acute and emergency indications. Data from only one of the 3.0-T MRI scanners (3.0-T MRI Magnetom Verio) were included in this study. If data were needed for summary consumption analysis, we duplicated the data from the available scanner. The routine CT and MRI scanners were shut down outside of operating hours, representing a system-off state; during clinical operation the scanners were in the system-on state, which consisted of net scan, active, and idle system event states (Table 1). There was no standby mode for the scanners, which would have allowed for lower energy consumption.

We equipped all MRI and CT scanners with energy consumption measurement sensors that provided a 2-Hz data sampling rate for kilowatt-hour consumption for each scanner. The energy consumption sensors were connected with and accessible by means of a central building information system (APROL 4.0; B&R, Frauenfeld, Switzerland), which enabled data export on the basis of filter criteria. The measured data were stored by means of a smart recording algorithm in which data entries were saved only when they differed from the previous entry. This optimized data storage usage. As a preparatory step for the analysis, the software reconstructed continuous data points with 500-msec intervals (2-Hz sampling rate). Data regarding energy consumption of the associated cooling systems, which operated exclusively for MRI and CT scanners, were available by means of the central building information system.

System Log Data for CT and MRI Scanners

We retrieved the system log files of each scanner and processed their data to identify events that reflected scanner activity states and examination-related information. There were abundant data entries with millisecond temporal resolution time stamps in the scanner log files, representing scanner operation details including but not limited to gantry operation, patient table

Table 1: Definition of Scanner Activity System States

System State	Definition	Data Curation
Net scan	The actual scan event during which energy consumption deviates from the baseline; the productive phase in which images are acquired	Primarily derived from energy consumption data by identifying peak consumption or deviation from baseline consumption, respectively
Active	The time period during which a scanner is used to examine a patient, which includes preparation for and planning of scan, the actual net scan, and reconstruction of raw data into image data. Basically, patient room time	Derived from energy consumption data in conjunction with scanner log file information
Idle	The time interval between "active" time periods within system-on time period; it is merely a defined time interval within system-on state and not a scanner state that can be manually activated	Parameter calculated by subtracting "active" from "system-on" data
System on	A scanner system state derived from the log file; system is powered on and immediate scanning is possible; net scan, active, and idle are system-state events occurring during system-on state	Energy consumption data segmented according to scanner log file information
System off	A scanner system state derived from the log file; in this state, the system is powered down but may still consume energy owing to ancillary systems; immediate scanning is not possible, and a power-up sequence of several minutes is needed before scanning	Energy consumption data segmented according to scanner log file information

Table 2: CT Examination Energy Consumption according to Body Region

	Energy Consumption (kWh)			Duration (min)			Cost ($)*	
Examination Region	Median	Mean	SD	Median	Mean	SD	Median	Mean
Head-neck	0.38	0.44	0.24	5	7	4	0.07	0.08
Head-spine	0.42	0.48	0.34	5	7	5	0.08	0.09
Head-chest	0.51	0.60	0.41	6	7	5	0.09	0.11
Head	0.59	0.68	0.42	9	11	7	0.11	0.12
Chest	0.69	0.77	0.44	8	9	6	0.12	0.14
Pelvis	0.72	0.92	0.53	10	11	7	0.13	0.17
Spine	0.73	0.97	0.50	12	12	7	0.13	0.18
Neck	0.79	0.91	0.48	11	12	7	0.14	0.16
Abdomen-pelvis	0.97	1.28	0.72	12	14	9	0.17	0.23
Extremities	1.01	1.23	0.29	13	16	4	0.18	0.22
Chest-abdomen-pelvis	1.03	1.14	0.58	116	12	7	0.19	0.20
Cardiac	1.26	1.39	0.49	13	17	5	0.23	0.25
Runoff	1.28	1.41	0.50	15	19	7	0.23	0.25
Neck-chest-abdomen-pelvis	1.41	1.44	0.58	14	16	7	0.25	0.26
Trauma	2.01	2.05	0.40	28	29	6	0.36	0.37
Intervention	2.19	3.45	0.71	41	51	14	0.39	0.62
Average of all examination regions	0.99	1.22	0.39	13	16	5	0.18	0.22

Note.—SD = standard deviation.

* Assumed cost per kilowatt-hour = U.S. $0.18.

movement, scanning sequence parameters, and system states such as system on and system off. A major challenge was that every scanner used a different format for the log entries, and logged events were very diverse. Scanner-specific scripts were used to extract important events that were then combined into new time series for analysis.

RIS Data

RIS data contain workflow information describing the type of examination (eg, CT of the chest, whole-spine MRI), the examination start and end time stamps, and other information that was irrelevant in this context. However, the examination start and end times are often manually entered into the system by the operating staff and therefore are limited as a basis for the definition of examination duration. For the purpose of this study, RIS data were mainly used to identify the type of examination.

Data Curation and Analysis

In conjunction with the School of Life Sciences at the University of Applied Sciences and Arts Northwestern Switzerland, we developed an in-house software application to merge the

Table 3: MRI Examination Energy Consumption according to Body Region

Field Strength and Examination Region	Energy Consumption (kWh) Median	Energy Consumption (kWh) Mean	Energy Consumption (kWh) SD	Duration (min) Median	Duration (min) Mean	Duration (min) SD	Cost ($)* Median	Cost ($)* Mean
1.5 T								
Abdomen	14.3	15.5	4.8	50	52	17	2.58	2.78
Abdomen-pelvis	11.8	14.1	3.2	37	48	11	2.12	2.53
Breast	15.8	15.8	0.0	42	42	0	2.84	2.84
Cardiac	15.6	17.4	8.1	57	61	29	2.80	3.13
Chest	17.6	16.8	4.5	47	53	14	3.16	3.03
Extremities	16.1	17.6	3.1	46	51	9	2.89	3.18
Head	16.1	15.9	7.2	43	49	26	2.90	2.86
Head-neck	20.4	21.4	3.7	56	59	11	3.68	3.85
Hip	14.1	14.1	0.0	40	39	0	2.54	2.53
Neck	16.2	15.0	3.7	42	41	9	2.91	2.70
Pelvis	14.4	17.1	6.5	46	57	21	2.59	3.08
Runoff	12.8	11.9	3.6	36	43	15	2.31	2.15
Shoulder	16.2	17.4	3.6	40	43	11	2.91	3.13
Spine	15.4	16.6	6.2	42	50	27	2.78	2.98
Vascular	18.5	19.0	1.9	59	58	7	3.34	3.43
Whole body	24.6	26.7	4.1	71	73	12	4.42	4.81
All	16.2	17.0	4.0	47	51	14	2.92	3.06
3.0 T								
Abdomen	14.7	14.7	0.0	37	37	0	2.64	2.64
Chest	34.2	34.2	0.0	77	77	0	6.15	6.15
Extremities	22.8	23.8	3.1	43	47	7	4.10	4.28
Head	21.4	23.9	9.6	46	50	23	3.85	4.30
Head-neck	25.3	26.2	4.1	48	51	10	4.56	4.72
Hip	21.6	21.1	1.8	39	42	4	3.88	3.79
Neck	30.0	30.4	5.0	64	65	10	5.41	5.48
Pelvis	20.2	21.4	5.5	44	48	15	3.63	3.86
Runoff	17.4	17.5	2.8	43	45	8	3.13	3.16
Shoulder	21.4	23.5	4.6	41	47	12	3.85	4.24
Spine	23.2	22.7	4.4	46	47	10	4.18	4.08
All	22.9	23.6	3.7	48	51	9	4.13	4.25

Note.—SD = standard deviation.

* Assumed cost per kilowatt-hour = U.S. $0.18.

data streams of continuous energy consumption measurement, scanner log information, and RIS examination details for the entire year 2015. The data streams were synchronized to temporally align any differences in data entry time stamps. The software allowed for segmentation of the energy consumption signal based on scanner system activity states as defined by means of log file or RIS data (Table 1). For instance, a scan event on a CT scanner was defined as the time period between the scanner log events "patient open" and "patient closed" (Fig 1). This corresponds to loading patient data from the Digital Imaging and Communications in Medicine worklist onto the CT control console ("patient open") to plan and perform scanning and to closing the same patient case ("patient closed") when scanning was finished and image reconstruction was performed. This time period is interpreted as patient room time (the time during which the patient is likely in the CT room), which includes patient preparation, patient positioning, scanning, and patient exiting.

The algorithm of the software uses the defined event time stamps to identify segments of scanner energy consumption different from the baseline energy consumption signal. A scan event is included in the per-examination summary statistics (Tables 2, 3) only if a typical energy consumption profile of increased consumption is found (Figs 1, 2); otherwise, the scan event is excluded (approximately 5% of scans were excluded). This was done to exclude data that were not representative of a regular patient examination, such as checkup scans without a patient present, research scans in which a phantom was used, or instances of temporally mismatched data streams. With this approach, all RIS-defined examinations (eg, "chest CT") performed in the year 2015 with a given scanner could be projected onto the energy consumption signal to segment the data and extract summary statistics including number of examinations; maximum, sum, mean, standard deviation, and median energy consumption in kilowatts and kilowatt-hours; and duration (Figs 1, 2).

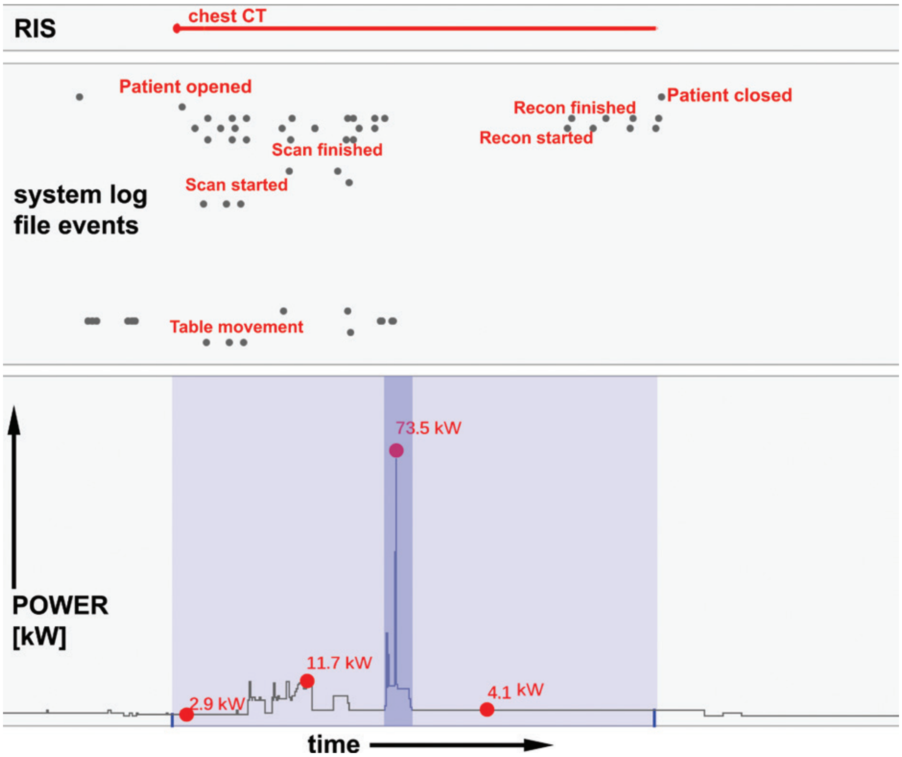

Figure 1: Diagram shows depiction and analysis of energy consumption by software application by means of synchronization of radiology information system (RIS), CT system log file events, and energy data streams. A chest CT examination is segmented (blue area) based on CT system log file events such as "patient open" and "patient closed" and identified by means of the RIS examination label matching the CT system log file–defined segment. Kilowatt-hour consumption is calculated by integrating the area under the energy signal within a defined segment. Duration of an event is given according to the length of the segmented area. Red dots on energy consumption signal exemplify consumption in kilowatts at the respective location on the graph. Darker blue area segmented in energy consumption signal demonstrates identification of instance of peak energy consumption, which is used to define net scan energy consumption and duration. Recon = reconstruction.

We used additional scanner system states defined in log file information, such as system active, on, and off, to extract summary statistics regarding general scanner operation. Another algorithm of the analysis software enabled the analysis of peak energy consumption by segmenting the energy consumption signal based on a desired threshold value for kilowatts and duration, effectively excluding the baseline energy consumption. Peak energy consumption coincidence detection—that is, detection of two scanners scanning at the same time—was done by using a script that detects and flags overlapping examination duration time stamps between two CT scanners. We performed overall theoretical peak power consumption estimation of the entire scanner fleet by means of summation of the daily peak power consumption value per scanner per day in 2015. Therefore, the theoretical maximum combined peak power consumption of all scanners, if coincidence occurred, could be determined to gauge the resulting load on the hospital power grid.

We based cost calculation for energy consumption on 0.18 Swiss francs per kilowatt-hour, which corresponded to 0.18 U.S. dollars per kilowatt-hour. To facilitate international comparison of the provided data, herein costs are presented in U.S. dollars. We used the average energy consumption of a two-person household (3550 kWh) and a four-person household (5200 kWh) for a detached building per year in Switzerland as a reference for comparing energy consumption (4). The study took place in a level 1 trauma tertiary care center university hospital with 773 beds, approximately 1 million outpatient visits, and 35 000 inpatients treated in 2015. The radiology department performed approximately 130 000 imaging examinations in 2015.

Statistical Analysis

Data are given in absolute numbers and relatively in percentages. Graph creation was performed with commercially available software (JMP, version 14.2.0; SAS Institute, Cary, NC).

Results

The aggregated energy consumption of three CT and four MRI scanners amounted to 614 825 kWh in 2015. Adjunct cooling systems required 492 624 kWh in 2015, which is 44.5% of the combined energy consumption. Therefore, the operation of seven cross-sectional imaging units, including examination of 40 276 patients and cooling, resulted in a total energy consumption of 1 107 450 kWh and a cost of $199 341. This is equivalent to the usage in a town of 852 people living in four-person households, each requiring 5200 kWh annually. The aggregated energy consumption of scanners and cooling repre-

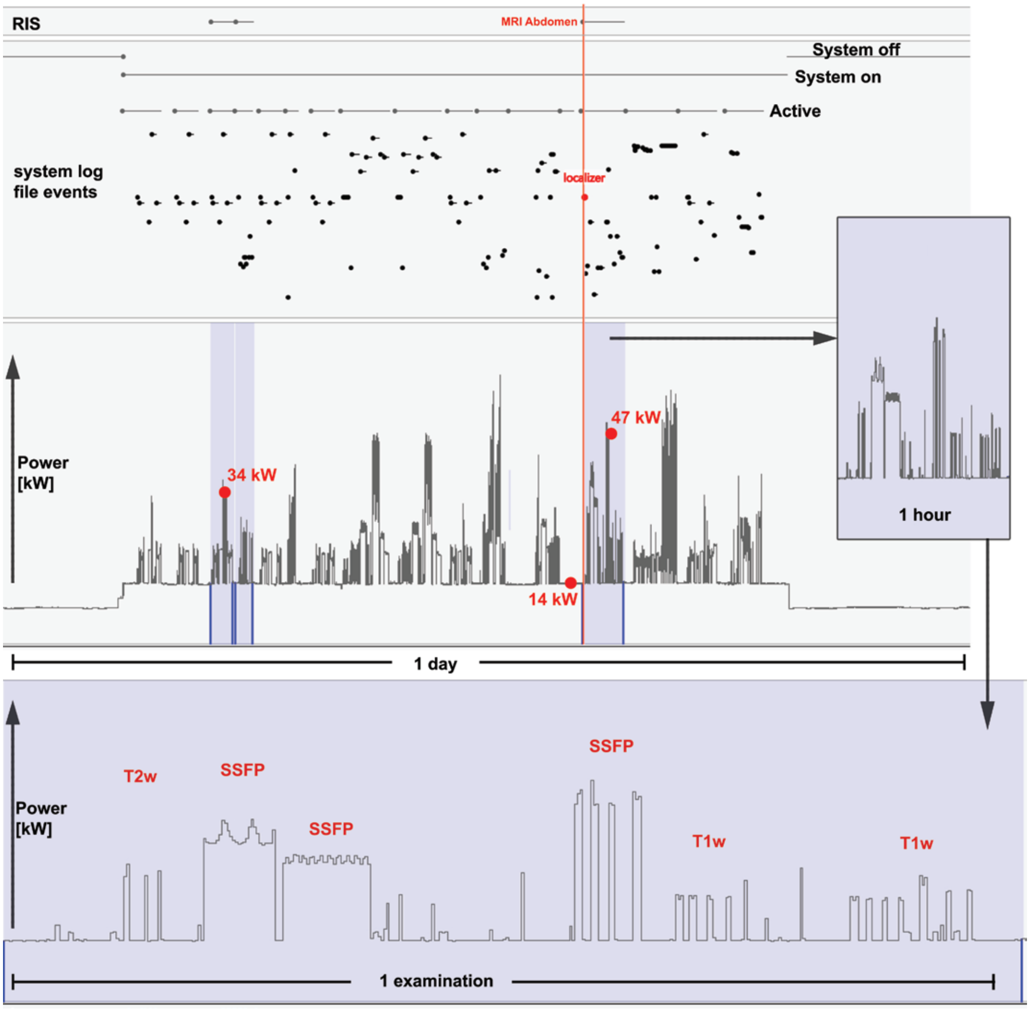

Figure 2: Diagram shows 1 day of synchronized radiology information system (RIS), MRI system log file events, and energy consumption data streams for a 1.5-T MRI scanner as depicted by the software application. The same principle as in Figure 1 applies, in which MRI system file events define segments (blue areas) on energy consumption signal and are labeled according to RIS examination information (eg, MRI of abdomen). On bottom image, an MRI examination is zoomed in to demonstrate distinct energy consumption footprint of various types of imaging sequences (eg, T2-weighted [T2w], steady state free precession [SSFP], and T1-weighted [T1w] sequences).

sented 4.0% of the total yearly university hospital energy consumption of 27 905 332 kWh in 2015. The theoretical combined peak power consumption of all scanners, analyzed per aggregated daily maxima, was 380 kW ± 118 (range, 25–570 kW). The assumed maximal peak load on the hospital electricity grid was 1029 kW, whereas the vendor`s sum maximal peak load was listed as 1390 kW. Hence, the theoretical but rarely occurring maximum of the aggregated peak load on the electricity grid if all seven systems were simultaneously operating at peak consumption would be 41.0% of the accumulated vendor peak specifications and only 27.3% of the average aggregated daily maximum.

CT Scanners

The summary of CT energy consumption, examination duration, and examination energy cost per examination body region is given in Table 2 and illustrated in Figure 3. The mean energy consumption per body region was 1.2 kWh ± 0.7 (minimum, 0.4; maximum, 3.5 kWh) including single- or multiphase acquisitions, with a mean energy cost of $0.22 ± 0.13 per examination. The daily energy consumption for a clinical scanner in operation for 12 hours was 92 kWh for CT scanner 1 and 50 kWh for CT scanner 2 in comparison to 88 kWh for the emergency room CT scanner, which is in operation for 24 hours. Figure 4 summarizes the energy consumption and duration for each scanner system state (net scan, active [patient room time], idle, on, and off). Overall, the three CT scanners consumed 10 741 kWh (mean, 3580 kWh per scanner) for actual scanning, 23 797 kWh during the patient room time period, 42 867 kWh (mean, 14 289 kWh per scanner) during idle time, 66 664 kWh during the system-on state, and 78 679 kWh (mean, 26 226 kWh; $4721 in energy cost per scanner) in total per year. The operation of one CT scanner during a year, on average imaging 7904 patients, was comparable in terms of energy consumption to the usage of five four-person households. On average over a year, a scanner spent

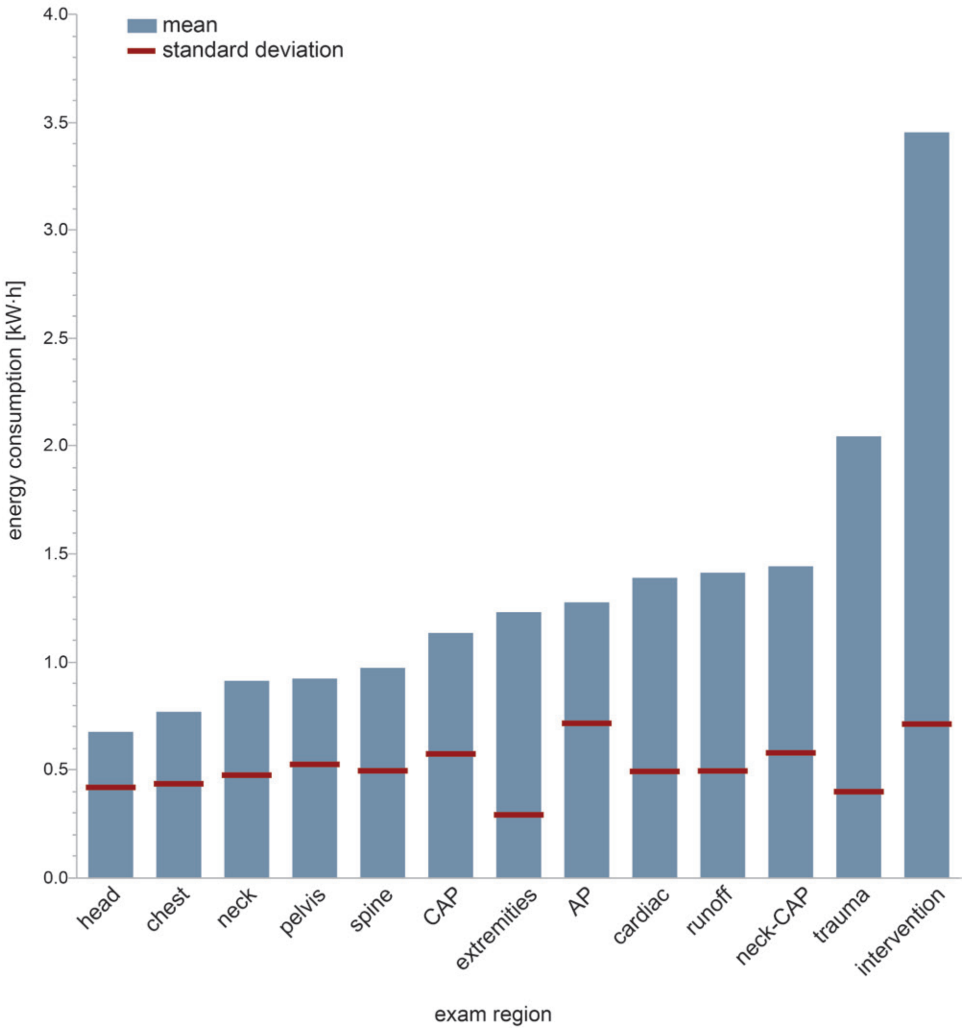

Figure 3: Bar graph shows mean energy consumption of CT examination and standard deviation in kilowatt-hours per body region averaged from 1 year of data. AP = abdomen and pelvis, CAP = chest, abdomen, and pelvis.

4.2% (mean, 1.36 weeks; range, 2.58 days to 2.33 weeks) of its system-on time scanning, 27.2% with the patient being in the room, and 72.8% (23.8 weeks) idle. A coincidence of scans between two of the three CT scanners occurred in 4.8% of all actual scan events in 2015, resulting in a combined mean peak energy demand of 65 kW ± 38 (range, 0.8–266.7 kW) (Fig 5).

MRI Scanners

The summary of MRI energy consumption, examination duration, and examination energy cost per examination body region is given in Table 3 and illustrated in Figure 6. The mean energy consumption per body region was 20 kWh ± 5 (range, 12–34 kWh), with a mean energy cost per examination of $3.57 ± 0.96. The daily energy consumption for a clinical scanner in operation for 13 hours was 363 kWh with 1.5-T units and 530 kWh with 3.0-T units. Table 4 and Figure 7 summarize the energy consumption and duration for each scanner system state: net scan, active (patient room time), idle, on, and off. In comparison, 25.8 four-person households expend the same amount of energy per year as one MRI scanner that imaged an average of 4140.5 patients (overall averages: 134 037 kWh, $24 127 in energy cost; 3.0-T MRI: 149 655 kWh, $26 938 in energy cost). MRI scanners consumed 35 478–46 704 kWh per year during the scanner-off system state, representing 31.2%–38% of their total yearly energy consumption owing to the continuous operation of the cold head cooling system. In contrast to CT operation, MRI idle-time energy consumption was lower, at 5.5%–13.4% (range, 8177–16 038 kWh). The mean monthly energy consumption (corrected for number of patients scanned) did not change after replacement of 1.5-T MRI scanner 2a with the newer 1.5-T MRI model scanner 2b.

Discussion

We investigated the energy consumption of CT and MRI operation in a university hospital setting on various levels, ranging from a microscopic perspective focused on individual examinations to a macroscopic view of scanner activity system-state energy consumption aggregated over an entire year. The data analysis revealed the following aspects of relevance and energy-saving opportunities. The operation of cross-sectional imaging systems is energy intensive, and in this study the energy usage was comparable to that of a town of 852 people living in

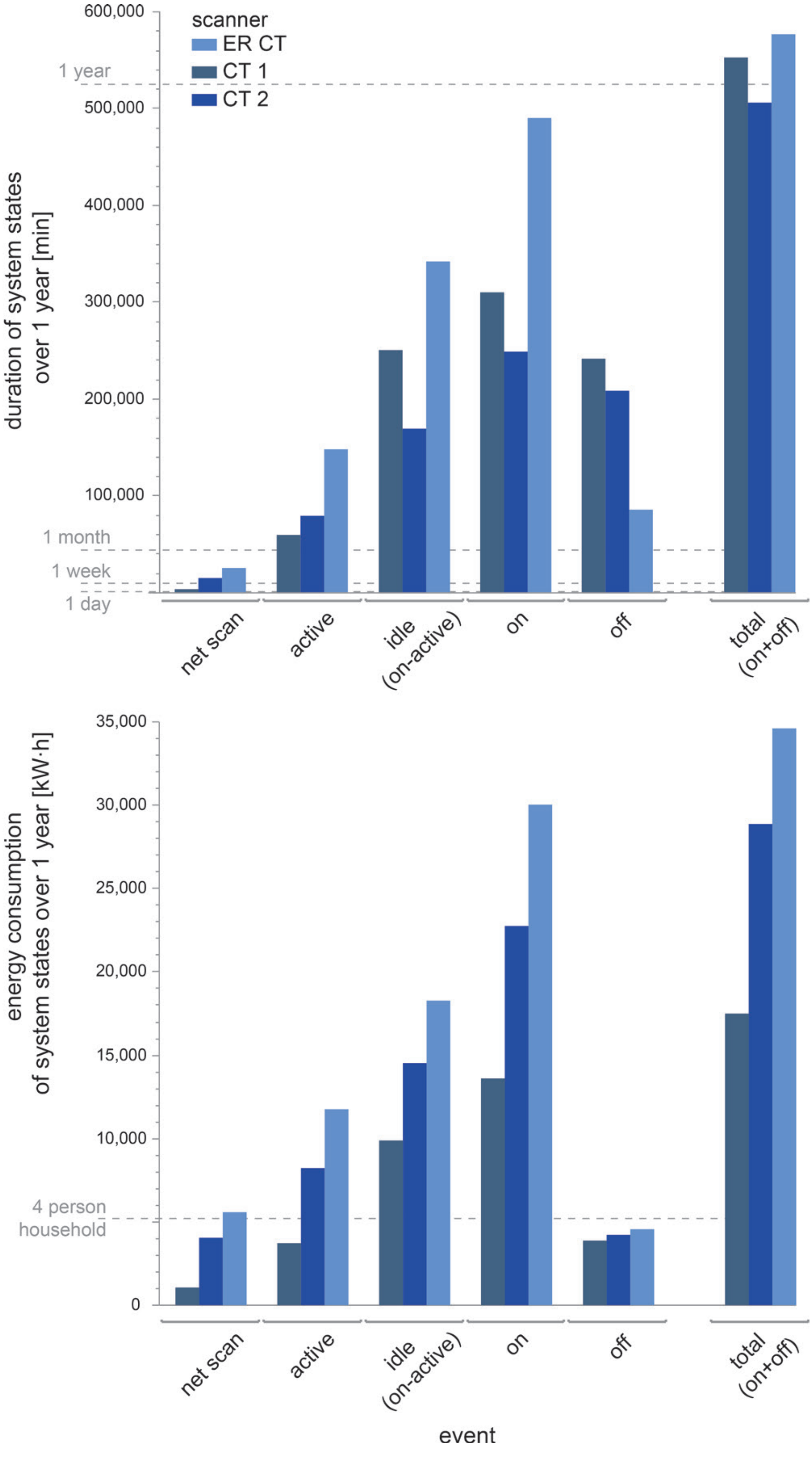

Figure 4: Bar graphs show distribution of system states for each CT scanner for sum duration in minutes and for sum energy consumption in kilowatt-hours during 1 year of data. Owing to some inaccuracies in energy consumption curve segmentation, aggregated totals for each scanner do not result in duration of exactly 1 year. Net scan consumption for the emergency room (ER) CT scanner is comparable to that of four-person household; however, idle state consumption is fourfold that of net consumption and therefore contributes largely to total energy consumption.

four-person households. The operation of cross-sectional imaging systems such as MRI and CT scanners, including indispensable adjunct cooling systems, comprised 4% of our total yearly hospital energy consumption. In general, the energy consumption of dedicated cooling systems comprised almost half of the total energy needed for operation of cross-sectional imaging systems in a radiology department. For CT, the largest share of energy consumption—approximately two-thirds—took place during the nonproductive idle system state; therefore, the degree of utilization was low and energy inefficient. For MRI, approximately one-third of energy consumption was attributable to the system-off state, inherently owing to the need for constant helium cooling and operation of the cooling head.

On the basis of our results, some energy-saving opportunities can be identified and potentially pursued. Increasing energy efficiency may be achieved either by decreasing scanner energy consumption during nonproductive idle and system-off states or by increasing the degree of utilization per time period. The first aspect can be addressed only by vendors through introduction of low–energy consumption idle and system-off states (5). As with consumer electronics, the

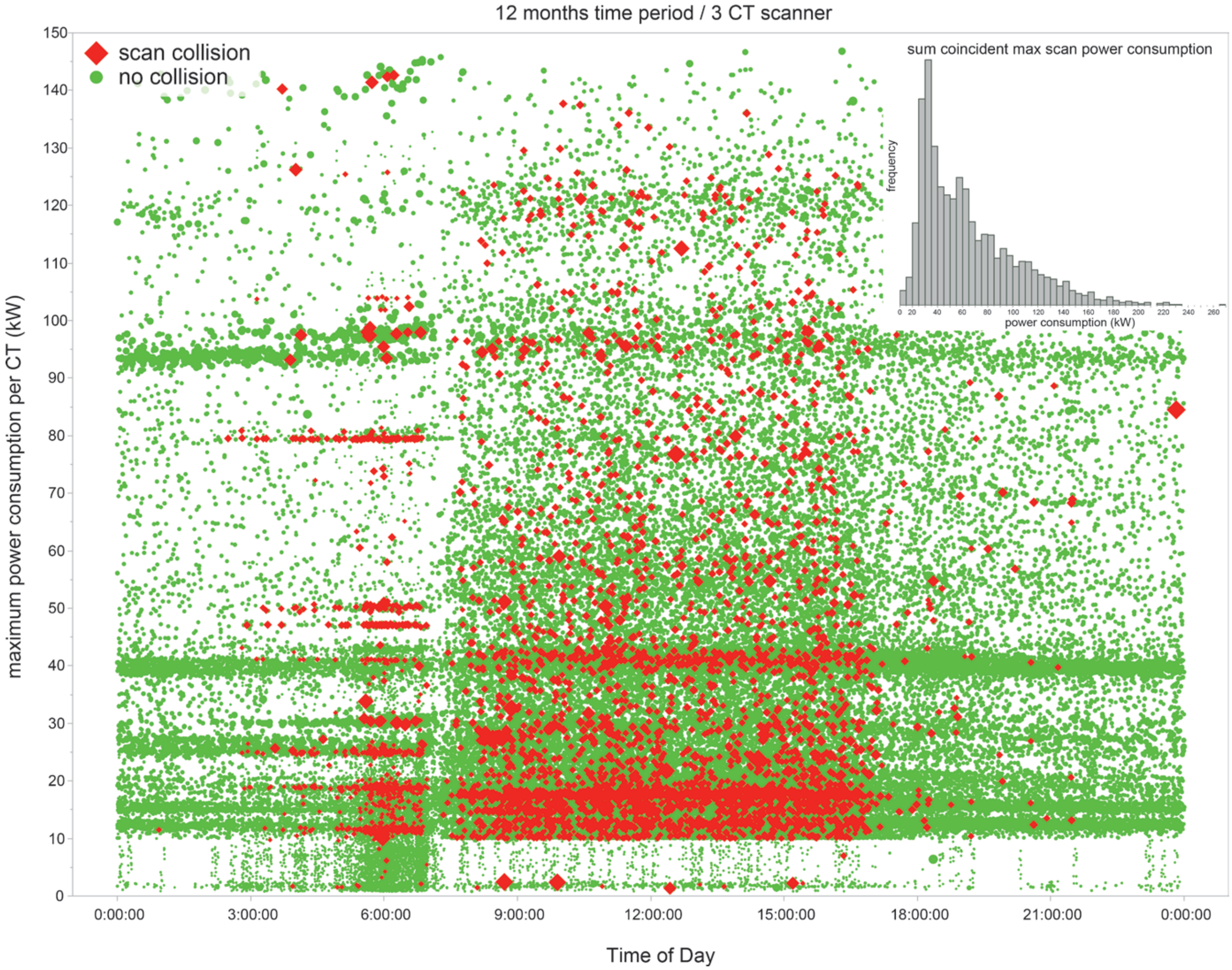

Figure 5: Graph shows frequency of simultaneous scanning events (◊) occurring between any two CT scanners in a three-scanner setting during 12 months and the resulting distribution of accumulated peak energy consumption (inset, top right). The y-axis demonstrates maximum energy consumption during a CT examination, and the x-axis shows time of day. Each point represents a CT scan event; the size of the symbol reflects scan duration.

introduction of power-down or standby modes may allow for considerable energy savings in the operation of CT scanners because their actual productive energy demand is confined to the short time span within seconds of actual scanning, a fraction of the system-on state. The latter point may be optimized by radiology departments through improved workflow and optimized patient throughput, resulting in a larger proportion of the energy spent during productive states of scanners compared with nonproductive idle and system-off states.

Furthermore, because energy demands for adjunct cooling systems are considerable, alternative methods of counteracting waste heat may be pursued. Waste heat recovery methods such as heat transfer by means of heat pipes or heat-storing technologies such as thermal banks may be used to recycle heat-related energy rather than spending additional energy to neutralize excess heat (2,6–8).

In general, in planning a radiology department, building floor plans may be optimized to facilitate synergetic use of cooling systems or scanner architecture. For instance, scanner signals informing ancillary systems of the current system state may help regulate the operation of adjunct cooling systems, decreasing the output during idle or system-off states instead of operation at a fixed value. In addition, in the case of radiology departments with multiple scanners installed, a fleet concept may be used, with a modular setup of ancillary systems such as those for cooling in general or, in the case of MRI systems, specific cold head helium cooling. This would allow scaling up of ancillary systems instead of requiring that each newly installed scanner have its own separate adjunct system.

To date, the awareness of energy conservation in hospitals appears low, and the focus in planning and operating hospitals is more bound to workflow, redundancy, and high quality standards (9). However, hospitals have a high energy use intensity and demand use intensity owing to their 24 hours a day, 7 days a week operation; large building footprint; and special requirements for redundancy and quality standards (10,11). As shown, radiology departments claim a large proportion of the total hospital energy consumption. Consequently, the leverage or

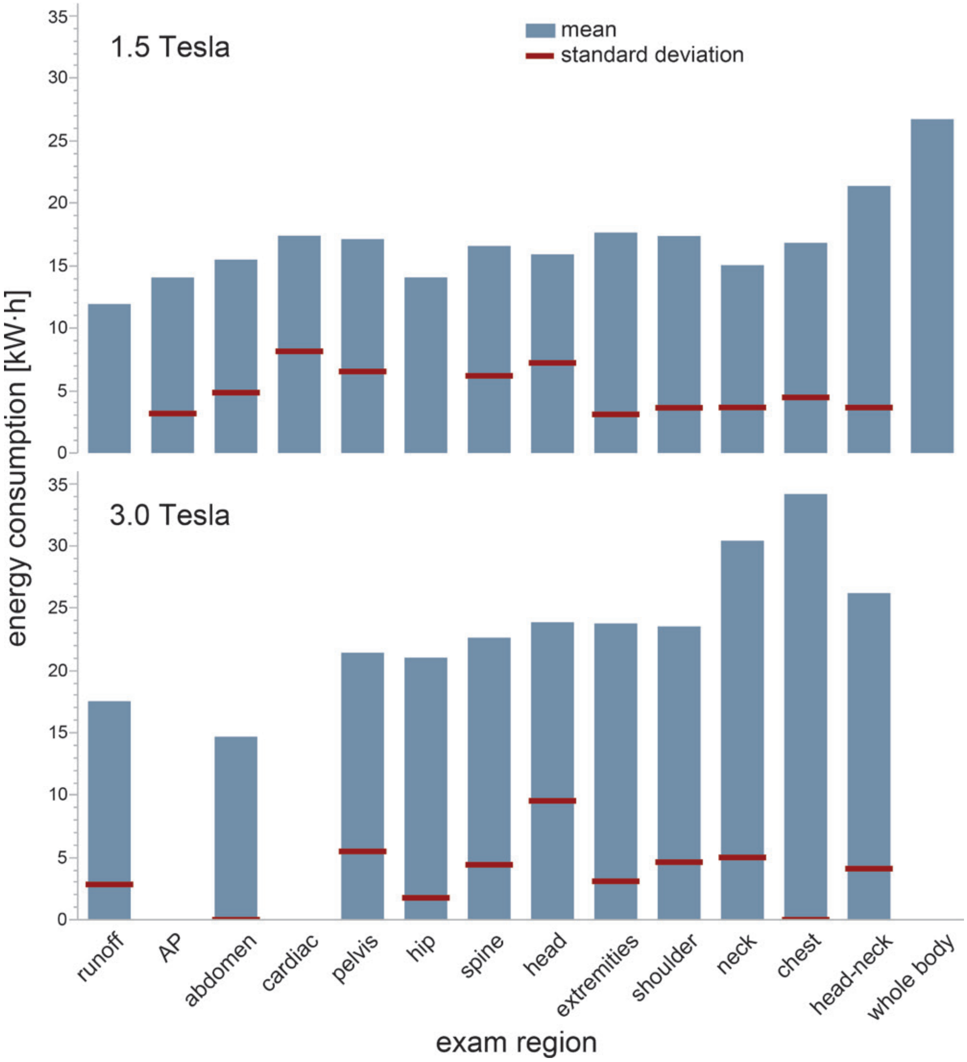

Figure 6: Bar graphs show mean energy consumption of MRI examinations and standard deviations in kilowatt-hours per body region stratified according to field strength and averaged from 1 year of data. AP = abdomen and pelvis.

potential for energy savings appears sufficiently large to warrant exploring these opportunities from an ecologic as well as an economic perspective. Energy conservation technologies developed, implemented, and established in other residential or commercial sectors may be transplanted to the health care sector without considerable investment. In addition, apart from the urgently required reduction in energy consumption and its associated CO_2 emission footprint, the return on investment in terms of reducing energy costs is similarly beneficial and likely more convincing for executives. Nevertheless, with carbon emission reduction goals from the Paris Agreement (12), it is mandatory that we look into all possible carbon emission reduction opportunities to mitigate climate change.

There have been some activities to improve the energy efficiency of medical devices, such as the self-regulatory initiative of the European Coordination Committee of the Radiological, Electromedical and Healthcare IT Industry. For instance, there was a reduction of 20% in average annual energy consumption for U.S. devices in 2012 compared with 2005 (3). However, although energy savings were achieved in MRI systems owing to technical improvements and in CT scanners owing to low-power mode or shutdown during off hours, the European Coordination Committee of the Radiological, Electromedical and Healthcare IT Industry report acknowledges that for these modalities, saving energy through reduction of system idle state consumption is complex and some technical developments may further increase energy consumption. On the other hand, refurbishment of medical devices is increasing and able to reduce the energy needed to manufacture a medical device, with approximately 5% of MRI and CT scanners sold as refurbished units in 2016 (3).

Aside from energy conservation implications, our study provides sufficient data to model and extrapolate the energy consumption of any given radiology department based on certain parameters, such as scanner fleet details, profile of service and type, and number of examinations performed per year. These models may be used for planning new installations or radiology department expansions and may also help identify the size and scope of required ancillary systems—for

Table 4: Distribution of MRI Energy Consumption and Duration during 12-month Period Stratified according to Scanning Events

	Energy Consumption (kWh)					Duration (min)				
Scanner and System State	Sum	Total (%)*	Mean	SD	Median	Sum	Total (%)†	Mean	SD	Median
1.5-T MRI scanner 1										
Active	59 634	63.3	15	13	13	207 245	99.8	54	66	44
Idle	NA‡	NA‡	NA§	NA§	NA§	302	0.2	NA§	NA§	NA§
On	58 672	62.3	177	86	213	207 547	44.8	625	296	754
Off	35 478	37.7	107	51	90	255 629	55.2	772	373	659
Total	94 150	100.0	NA§	NA§	NA§	463 176	100.0	NA§	NA§	NA§
1.5-T MRI scanner 2a‖										
Active	58 857	49.0	15	15	13	154 426	69.9	38	80	32
Idle	16 038	13.4	NA§	NA§	NA§	66 528	30.1	NA§	NA§	NA§
On	74 895	62.3	243	61	255	220 954	43.7	718	147	755
Off	45 238	37.7	147	116	106	284 256	56.3	923	709	694
Total	120 133	100.0	NA§	NA§	NA§	505 210	100.0	NA§	NA§	NA§
1.5-T MRI scanner 2b‖										
Active	52 069	50.4	15	13	14	156 730	76.4	45	54	37
Idle	12 053	11.7	NA§	NA§	NA§	48 384	23.6	NA§	NA§	NA§
On	64 122	62.0	213	94	229	205 113	43.3	680	316	721
Off	39 288	38.0	130	88	99	268 704	56.7	710	512	716
Total	103 410	100.0	NA§	NA§	NA§	473 817	100.0	NA§	NA§	NA§
3.0-T MRI scanner										
Active	94 774	63.3	22	18	20	197 770	86.9	46	53	39
Idle	8177	5.5	NA§	NA§	NA§	29 837	13.1	NA§	NA§	NA§
On	102 951	68.8	321	112	344	227 606	45.5	709	265	750
Off	46 704	31.2	146	100	113	272 462	54.5	851	560	691
Total	149 655	100.00	NA§	NA§	NA§	500 068	100.0	NA§	NA§	NA§

Note.—Mean, standard deviation (SD), and median are calculated based on the number of events per system-state category. For each system-state category, this translates to a different meaning (eg, basic statistics for "active" reflect per-individual scan data). For "on" or "off" states, basic statistics represent per-day data because an MRI scanner is usually powered down in the evening. However, there is some variance in usage (eg, number of "on" and "off" system states, respectively) owing to power up and down for emergency scans during night times or weekend shifts. NA = not applicable.

* Percentage of the total.

† Active + idle = 100% of on duration. On + off duration = 100% of total.

‡ Negative value due to some overlap in energy signal segmentation.

§ There was not a meaningful denominator to calculate basic statistics. There was no data event that is identified as idle or total; these data are calculated from active, on, off events.

‖ One MRI system (1.5-T MRI scanner 2a) was replaced during 2015 with a new MRI scanner (1.5-T MRI scanner 2b). Numbers are extrapolated 12-month data based on measurement during 3 months (scanner 2a) and 7 months (scanner 2b).

instance, the required energy capacity of the local hospital electricity grid.

Peak energy consumption is a cost factor because it determines the theoretical capacity of the hospital electricity grid and its magnitude is priced in by the electricity provider. Coincidence of peak power consumption across a scanner fleet may be compensated for either by ancillary energy buffer systems to reduce the load on the electricity grid or by traffic control of scan events to avoid simultaneity of peak consumption.

This study had some limitations. The measured energy consumption was based on information from one vendor. Although values from other vendors might differ, the variation should reside within an acceptable range, possibly within 1 standard deviation per examination measured in this study, because of technical and physical requirements necessary for operating MRI and CT scanners. The scanner fleet composition measured in this study may not be representative of other departments and installations, but the detailed measurements should allow for a reasonable estimation and extrapolation for a differing infrastructure and usage profile.

The energy cost calculations in this study are based on the kilowatt-hour price specific to our hospital and may not be comparable to that of other countries—for instance, the United States—or a region such as Asia, because energy costs differ greatly. However, with simple multiplication, the provided kilowatt-hour values can be converted to the respective local kilowatt-hour price, allowing for comparable cost calculations.

In conclusion, CT and MRI scanners are energy intensive in their operation and constitute a large proportion of total hospital

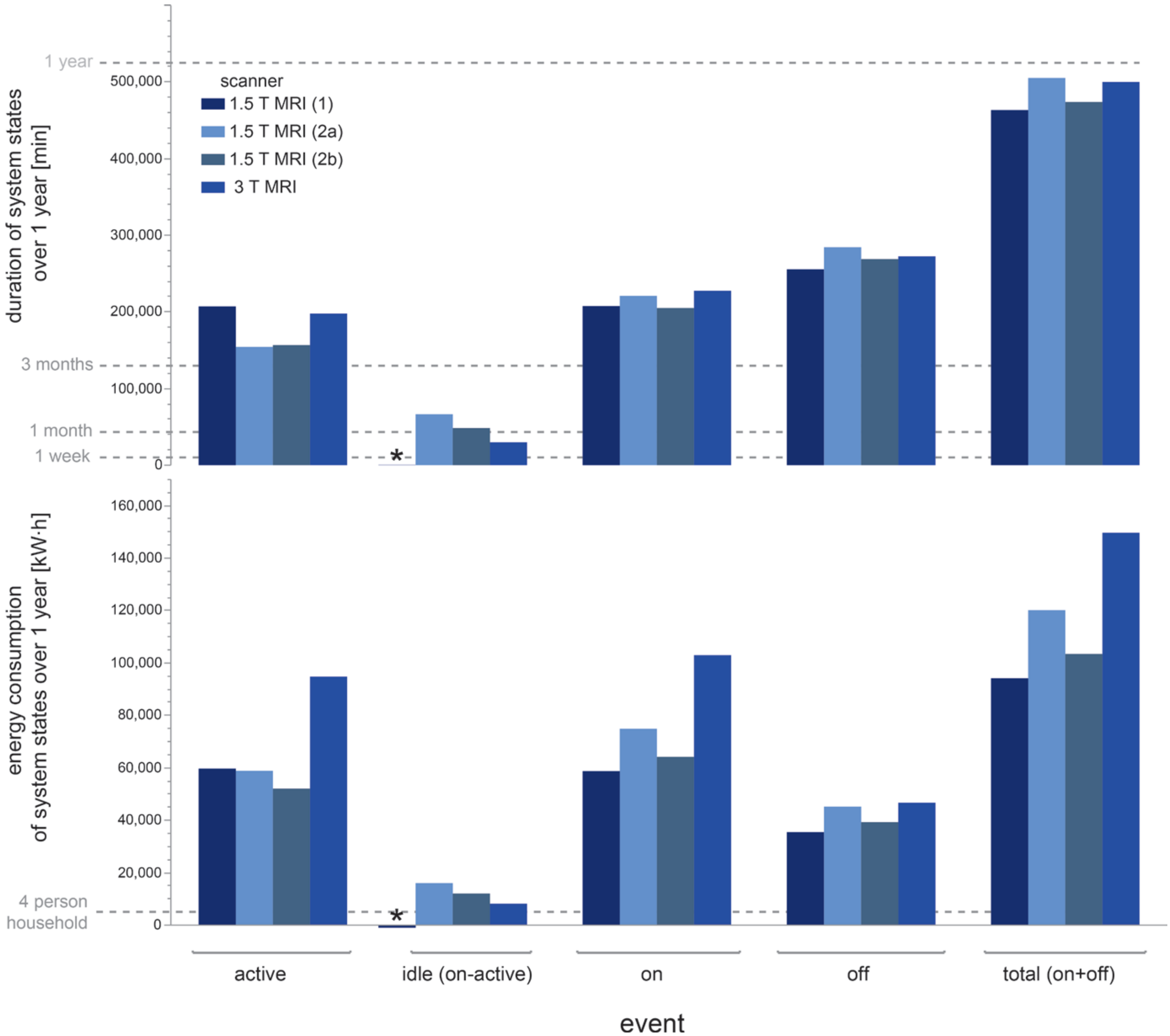

Figure 7: Bar graphs show distribution of system states for each MRI scanner for sum duration in minutes and for sum energy consumption in kilowatt-hours during 1 year of data. * = minimal idle time for one MRI scanner, which is possibly a false estimate resulting from summation errors and variance in energy signal segmentation. One MRI system (1.5-T MRI scanner 2a) was replaced during 2015 with a new MRI scanner (1.5-T MRI scanner 2b). Presented data are extrapolated for a 1-year time period.

energy consumption. However, considerable energy- and cost-saving potential is present during idle and system-off states, which can be converted to more energy-efficient operating modes. Our data may allow for detailed modeling of the energy consumption of a given radiology department infrastructure for planning and optimization purposes.

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