A New Approach to the Improvement of Energy Efficiency in Radiology Practices

Ein neuer Ansatz zur Verbesserung der Energieeffizienz in radiologischen Versorgungseinheiten

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ABSTRACT

Purpose We examined ways to improve energy efficiency in radiology by using regenerative and energy-friendly technology in the construction and operation of two radiological facilities.

Method In the years 2009 to 2010 an energy-optimized medical center with different clinical disciplines and a radiology practice was built. We used regenerative energy production (photovoltaic system, 29.92 kWp). A heat exchanger was also used to regain thermal energy to support heating of the building, thereby reducing cooling energy consumption. The practice operates a 1.5 T MRI machine and a computed tomography scanner. Derived from our experiences, an open MRI practice was built nearby in 2019. The building was constructed using an energy-saving technique. A photovoltaic system with a 10 kWh lithium-ion battery was installed. The practice operates a 0.35 T open MRI machine.

Results Energy optimization of the medical center resulted in an annual CO_2 reduction of about 54 % from 153 146 to 70 631 kg/year. Energy costs were reduced by 32.5 %. The heat exchanger proved to be highly efficient. For the open MRI practice, energy consumption in 2020 was 38 810 kWh: 14 800 kWh for the heating/cooling of the building, and 24 010 kWh for the imaging systems and IT. Net energy production of the solar array was 30 846 kWh. Net energy consumption for the whole project was 8397 kWh/year. CO_2 production of the practice was 1839 kg CO_2/year.

Conclusion Regenerative energy, energy recuperation, and use of energy-efficient imaging systems can yield considerable improvement of the CO_2 footprint in radiology practices.

Key points:
- Radiology, in particular MRI, has high energy consumption.
- A heat exchanger can regain thermal energy from MRI machines to support room heating.
- Low-field MRI with permanent magnets consumes far less energy.
- Energy optimization results in less CO_2 production and lower operation costs.

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ZUSAMMENFASSUNG

Ziel Wir untersuchten Möglichkeiten zur Verbesserung der Energieeffizienz in der Radiologie durch regenerative Energieerzeugung bei Bau und Betrieb von 2 radiologischen Praxen.

Methode In den Jahren 2009 bis 2010 wurde ein energieoptimiertes Ärztehaus mit mehreren Fachrichtungen und einer radiologischen Praxis erstellt. Wir installierten eine Photovoltaik-Anlage mit einer Nennleistung von 29,92 kWp. Zur Heizung des Gebäudes wurde ein Wärmetauscher eingesetzt, der die Abwärme der Radiologie-Geräte nutzte und damit gleichzeitig die benötigte Kühlenergie reduziert. Die Praxis betreibt ein 1,5 T MRT und eine Computertomografie. Abgeleitet aus den Erfahrungen dieses Projektes wurde 2019 am gleichen Standort eine Praxis für offene MRT realisiert. Auch hier wurde ein energieoptimiertes Gebäude erstellt und eine 29,68 kWp PV-Anlage mit 10 kWh Li-Ionen-Batterie installiert. Die Praxis betreibt eine 0,35 T MRT mit Permanentmagnet.

Ergebnisse : Die Energieoptimierung des Ärztehauses ermöglichte eine jährliche CO_2-Reduktion um etwa 54 % von ca. 153 146 auf ca. 70 631 kg/Jahr. Die Energiekosten verringerten sich um 32,5 %. Von großer Bedeutung war dabei der Einsatz des Wärmetauschers. In der Praxis für offene MRT betrug im Jahr 2020 der Verbrauch 38 810 kWh, davon 14 800 kWh für Heizung/Klimatisierung des Gebäudes und 24 010 kWh für die Praxisgeräte. Der Stromertrag der PV-Anlage lag bei 30 846 kWh. Der Nettoverbrauch lag bei 8397 kWh/Jahr, der CO_2-Ausstoß der Praxis lag bei 1839 kg CO_2/Jahr.

Schlussfolgerung : Durch Einsatz von regenerativer Energie und Wärmerückgewinnung sowie Nutzung energieeffizienter Bildgebungssysteme kann die CO_2-Bilanz von radiologischen Versorgungseinheiten erheblich verbessert werden.

Introduction

Resource conservation is a matter of prudence. This is particularly true for non-renewable resources. An important factor in resource consumption is energy production. Reducing the use of fossil fuels and promoting alternative forms of energy production are thus goals declared by the United Nations [1].

Radiology, particularly MRI using superconducting magnets, is a significant consumer of energy in medicine [2]. Radiology accounts for approximately 4 % of the total energy consumption of a maximum care hospital [3]. Improved energy efficiency in radiology practices is therefore urgently needed [4].

Ecological optimization often also reduces operating costs: Ecology and economy can be congruent principles.

Cost pressure at hospitals and private practices is even greater in times of increasing energy prices. Conserving energy can help to ensure the lasting improvement of the availability of high-quality diagnostics for patients.

There are currently a number of technical and organizational possibilities for increasing energy efficiency in radiology with respect to both the energy consumption of imaging systems and alternative means of energy production and energy recovery.

In two projects involving radiology practices, these techniques were used to reduce primary energy consumption.

Solar energy and heat recovery were planned and implemented at a medical center with a radiology practice.

Under consideration of these results, an open MRI practice with self-consumption of solar energy was subsequently created at the same site. This allowed a comparison of the energy efficiency of a low-field MRI machine with a permanent magnet and that of a high-field MRI machine with a superconducting magnet. A requirement for the use of such a system is diagnostically sufficient image quality as seen in modern low-field MRI [5].

The present study examines the energy consumption and production of the installed components. In addition to a quantitative ecological analysis, the economic effects are evaluated under consideration of the current conditions of the energy market.

Method

Building

Medical center

The medical center is a four-floor solid-construction building. In 2012, the building housed radiology, nuclear medicine, neurology, preventive medicine, physiotherapy, neurosurgery, and a medical training center. The square footage is 1800 m^2. “Energy-saving insulation” was used in accordance with the German Energy Saving Ordinance from 2007 [6]. The radiology practice operates one computed tomography scanner, ultrasound equipment, and a 1.5 T MRI machine. The heat produced by the MRI machine is recovered by a heat exchanger and used to help heat the building. A photovoltaic array was installed on the roof of the building.

Practice for low-field MRI

The building was constructed as an energy-saving structure using a wood frame construction method (Fingerhut-Haus GmbH, Neunkhausen/Germany). The square footage is 240 m^2. The practice operates one 0.35 T MRI machine with a permanent magnet. A photovoltaic array was installed on the roof of the building.

Data collection

The electricity and gas consumption data for the medical center was collected.

Energy monitoring for the open low-field MRI practice was performed using electronic measuring equipment (Sunny Portal, SMA Solar Technology AG, Niestetal).

The consumption values for the system components were measured for the various operating states of the components by 5 measurements each at an interval of 10 s. The arithmetic mean was calculated.

The energy consumers and producers are analyzed in detail in the following. The consumption values are subject to numerous influencing variables. The measurement results were supplemented by data from the manufacturer and the literature as needed.

The generation of carbon dioxide (CO_2) in kilograms (kg) was used as a parameter for energy efficiency. All other energy variables like electricity, gas consumption, and thermal energy (Wh) were normalized to the amount of CO_2 created during generation [7].

Energy consumers

Radiology

MRI 1.5 T

The MRI machine used at the radiology practice of the medical center is a 1.5 T MRI Optima 450w system (GE Healthcare, Solingen/Germany). The installation date was December 2010. The consumption values were determined based on the manufacturer's data [8].

MRI 0.35 T

The MRI machine at the open low-field MRI practice is an open 0.35 T system with a permanent magnet (Magnetom C) (Siemens Healthineers AG, Erlangen/Germany) [9]. Installation date was February 2019. The requirements specified in the Quality Assessment Guidelines for MRI of the Federal Joint Committee were fulfilled [10]. The consumption values for the imaging system and the air-conditioning system were determined with measurement technology.

CT

The CT scanner used at the radiology practice of the medical center is a CT Optima 660 (GE Healthcare, Solingen/Germany). The installation date was December 2010. The consumption values were determined based on the manufacturer's data [11].

Data processing systems

Medical center

The data processing system used by the radiology practice is a RIS/PACS Centricity by General Electrics (GE Healthcare, Solingen/Germany). It includes 10 PCs, 4 printers, and 2 servers (Hewlett-Packard, Böblingen/Germany). A television (UE46/6000, Samsung Electronics, Schwalbach/Germany) is also used for the demonstration of findings. Consumption values were determined based on manufacturer's data and data from the literature [12].

Practice for low-field MRI

The data processing system for the practice for open low-field MRI is made by Digithurst/Telepaxx. The system is comprised of 6 PCs (HP Pavilion 27-d1609nz), 2 servers (Hewlett-Packard, Böblingen/Germany), and 2 printers (Samsung ProXpress SL-C4060FX, Samsung, Schwalbach). Two TVs (one in the waiting room and one in the treatment room for displaying findings) are also used and were included in the energy measurement (Samsung 7 Series 55 Zoll, Samsung Electronics GmbH Schwalbach/Germany). The energy consumption was determined with measurement technology.

Heating

Medical center

The medical house is heated by a condensing gas boiler (Vitodens 200, Viessmann, Allendorf/Germany).

Practice for low-field MRI

The practice for open low-field MRI is heated by an air-water heat pump Vitocal 200 (Viessmann, Allendorf/Germany). Nominal output 6.7 kW. There is no heat recovery.

Air-conditioning

Medical center

The air-conditioning system for the medical center is comprised of a 72-kW unit with variable cooling performance and a non-adjustable 72 kW unit (Johnson Controls, Ratingen/Germany). The air-conditioning system provides climate control only for the technical equipment and the control room. It does not provide cooling for the offices and the data processing systems.

Practice for low-field MRI

The air-conditioning system for the practice for open low-field MRI is comprised of one 10 kW and one 15.5 kW outdoor unit (Toshiba Klimasysteme, Unterschleißheim/Germany). All rooms are climate-controlled.

Energy producers

Heat exchanger (medical center)

For energy recovery and to help heat the building and supply hot water, one 90 kW stainless steel plate heat exchanger with a downstream 2500 l buffer tank was integrated into the cooling circuit of the cross-sectional imaging systems. This is a customized solution created by the installer of the heating (Peter Bohl GmbH, Herdorf/Germany) upon request.

Photovoltaic system

Medical center

The photovoltaic system of the medical center is made by DCH (DCH Energy GmbH, Siegen/Germany). The system outputs 29.92 kWp. To improve efficiency, the panels were installed on an aluminum frame at a 10-degree angle.

Practice for low-field MRI

The photovoltaic system for the practice for low-field MRI includes 106 panels with an output per panel of 280 Wp (Poly Sol 280 Wp) (SMA Solar Technology AG, Niestetal/Germany). The output for the system was thus 29.68 kWp. The panels were installed facing south at a roof pitch of 5 degrees. To smooth the power generation and consumption peaks and to provide partial coverage of nighttime consumption, a 10 kWh lithium-ion battery (LGChem RESU 10H made by LG Energy Solution Europe, Sulzbach/Germany) was installed. The heating/cooling units that were measured by a separate counter are excluded.

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Results

Energy consumers

Heating/air conditioning

Medical center

The calculated annual primary heat demand was approx. 125 000 kWh/year for heat, approx. 30 000 kWh/year for hot water, totaling approx. 155 000 kWh/year.

This corresponds to consumption of approx. 37 000 l liquefied petroleum gas. 1 liter of liquefied petroleum gas releases 2.16 kg CO_2. The expected CO_2 production was thus approx. 80 000 kg/year [7]. In contrast, the measured annual gas consumption was 4600 l in the year 2020, and the resulting CO_2 production for heating the practice was approx. 9927 kg/year.

Practice for low-field MRI

The energy demand for heating and cooling calculated according to the German Energy Saving Ordinance was 14 944 kWh. The measured energy consumption in the year 2020 was 14 800 kWh. The deviation of the measured from the calculated primary energy consumption was less than 1 %. The resulting CO_2 production was thus approx. 3241 kg/year.

Radiology

MRI 1.5 T

According to the manufacturer's data, the average power consumption in standby mode for our system is 12.25 kW. Consumption is approx. 19.65 kW in active mode without image acquisition and 32.44 kW during image acquisition, resulting in an average value of 28.6 kW during work hours [8].

If the system is used 250 days/year for 10 hours per day, the annual consumption during work hours is approx. 71 500 kWh. In standby mode, the annual consumption is approx. 76 685 kWh. Therefore, the total consumption is approx. 148 200 kWh. The energy consumed for cooling is in addition to this. According to a study by Heye et al. [3], cooling comprises approx. 44.5 % of the total energy consumption. This was verified by a study by the Hamm-Lippstadt University of Applied Sciences [13]. Based on this value, the estimated annual energy demand for climate control for an MRI machine is approx. 121 200 kWh. The expected annual total energy consumption of a 1.5 T MRI machine is approx. 269 400 kWh. The expected CO_2 production is approx. 59 000 kg/year.

MRI 0.35 T

The average power consumption with the system powered off was 700 W. With the system switched on but not in scan mode and with the air-conditioning system on, the average power consumption was 3.1 kW. In scan mode and with the air-conditioning system on, the average power consumption of the system was 9.5 kW. The measured values coincide with the manufacturer's data [9].

On average, the air-conditioning system consumed 3 kW. In the case of a work year including two hundred work days, with each day including eight work hours and an average of twelve patients (20 min. scan time per patient), consumption of approx. 7600 kWh in scan mode, approx. 2500 kWh for work time without scan mode, and approx. 6000 kWh for idle time can be expected, resulting in a total of approx. 16 100 kWh. The resulting CO_2 production was approx. 3526 kg/year.

CT

According to the manufacturer's data, the power consumption during daytime operation is approx. 2.56 kW. The power consumption during nighttime operation is approx. 2.11 kW largely due to the gantry. The average power consumption per examination is approx. 160 W, resulting in consumption of approx. 3.2 kW/day in the case of 20 examinations per day. The total annual power consumption for CT is approx. 20 200 kWh. Approx. 50 kWh for calibration scans must be additionally included. The expected annual power consumption is thus approx. 20 250 kWh [11].

According to the manufacturer's data, approx. 17 558 kWh/year are used for cooling the CT unit in the case of the number of scans specified above. This corresponds to 46.4 % of the energy consumption for the total CT unit.

The expected annual total energy consumption for CT is approx. 37 800 kWh with a resulting CO_2 production of approx. 8278 kg/year (▶ **Fig. 1**).

Data processing systems

Medical center

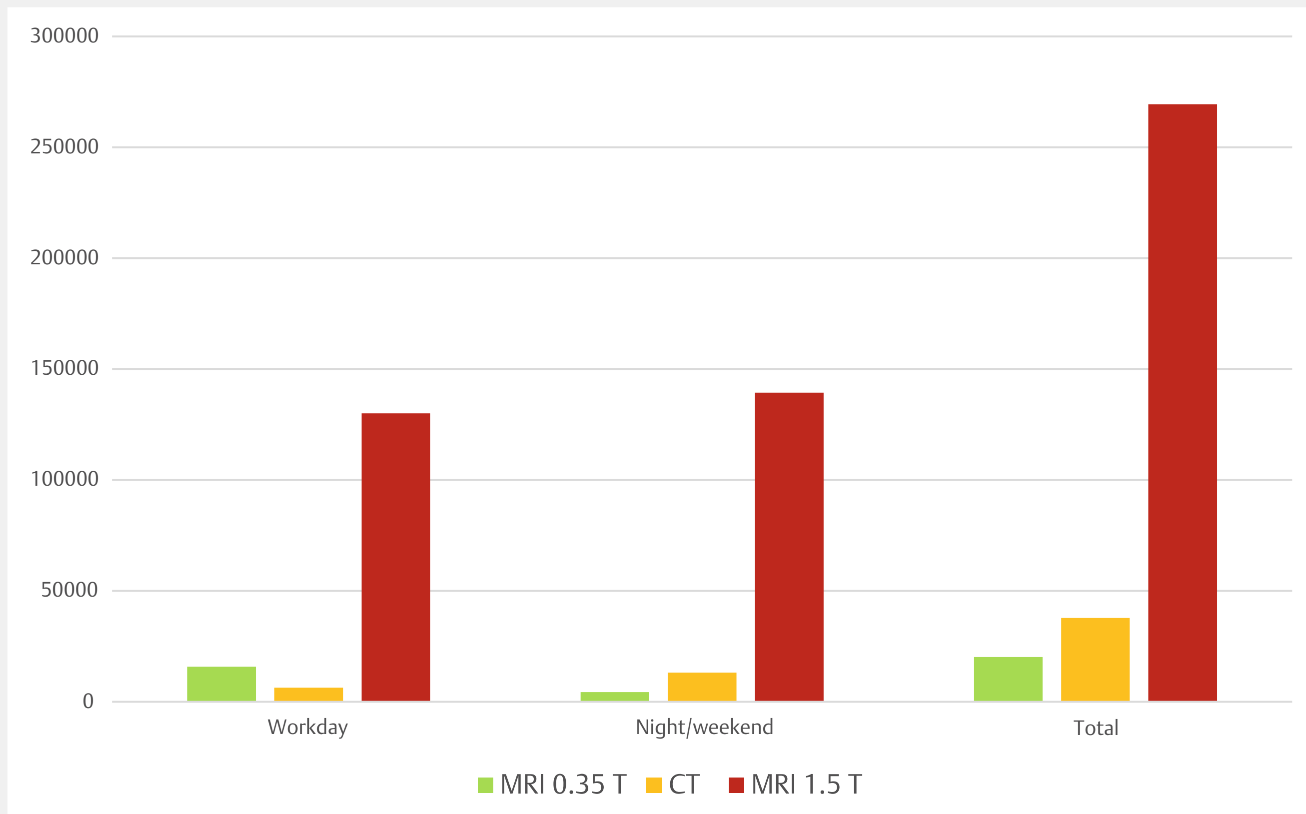
The power consumption of 10 workstation computers is approx. 450 W during operation resulting in consumption of approx. 4.5 kW for all computers during hours of operation. The power consumption of each of the 4 printers is approx. 400 W and approx. 1.6 kW for all printers during the hours of operation. Each of the two servers has a power consumption of approx. 700 W during continuous operation. The power consumption in standby mode is 1.4 kW (server) and approx. 7.5 kW when in operation [12].

In the case of 250 10-hour work days per year, approx. 8764 kWh/year are consumed in standby mode. During operation, approx. 18 750 kWh/year are consumed. In total, the expected annual consumption for the data processing system in the case of 250 10-hour work days per year is approx. 27 500 kWh/year.

The resulting CO_2 production is approx. 6000 kg/year.

Practice for low-field MRI

According to the manufacturer's data, the power consumption for compact PCs is max. 135 watts. The average measured energy consumption for workstation computers, lights, and TV was 1.2 kW. The energy consumption of the server was 800 W. In the case of 200 8-hour work days per year, the energy consumption was approx. 5700 kWh in standby mode and 3200 kWh during hours of operation. The annual power consumption for lights, TV, and data processing systems was approx. 8900 kWh.



▶ **Fig. 1** Annual energy consumption of cross-sectional imaging systems (kWh/a). For high-field MRI and CT, the energy consumption is higher under our conditions in standby mode than in measurement mode due to the only slight reduction in energy consumption.

The resulting CO_2 production was approx. 1949 kg/year (▶ **Table 1**).

Energy producers

Heat exchanger

The expected annual primary energy demand for heat and hot water was approx. 155 000 kWh/year, corresponding to approx. 37 000 l liquefied petroleum gas. The actual annual gas consumption was 4600 l in the year 2020. The expected value was thus approx. 85 % higher than the actual value due to the heat exchanger.

Photovoltaic system

Medical center

The photovoltaic system generated an average of 29 800 kWh/year. Due to the compensation rate of 0.39 EUR/kWh that was still very advantageous in 2010, the energy that was produced by the solar array was not used directly but rather was fed into the grid.

Practice for low-field MRI

The power generated in 2020 was 30 846 kWh. Due to changes in net metering, self-consumption currently has both ecological and economic advantages. Almost the entire daytime power demand is met with direct consumption during the months with high sun exposure. Moreover, a significant portion of the generated solar power is fed into the power grid (▶ **Fig. 2**).

The percentage of direct consumption was 33 %. Use of a battery made it possible to increase the self-consumption rate to 41 %. The degree of self-sufficiency was 51 %. In the annual comparison, the energy production was consistent, which is important

▶ **Table 1** Energy consumers. All data relates to consumption for the operation and cooling of equipment as well as the energy demand for the heating and cooling of the building (see text).

	Consumption	CO_2 [kg/a]
Medical center:		
MRI 1.5 T (incl. air conditioning)	269,400 kWh/a	59,000
CT	37,800 kWh/a	8,278
Data processing	27,500 kWh/a	6,000
Heating	37,000 l gas/a	79,846
Heating with heat exchanger	4,600 l gas/a	9,927
Open low-field MRI practice:		
MRI 0.35 T	16,100 kWh/a	3,526
Data processing	8,900 kWh/a	1,949
Heating/air conditioning (practice)	14,800 kWh/a	3,241

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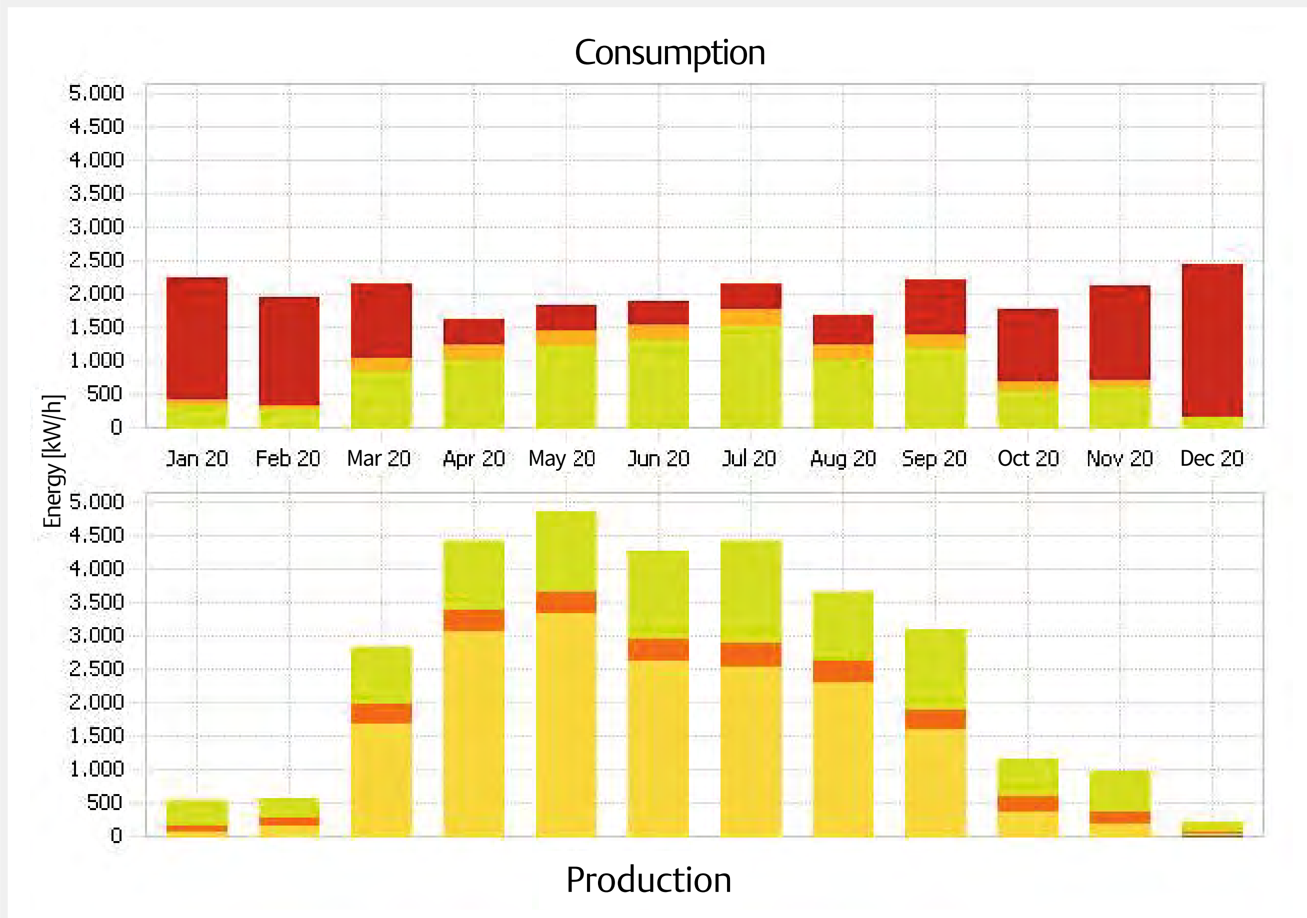


▶ **Fig. 2** Energy profile of the photovoltaic system in the year 2020. In the sunny months, self-consumption (direct consumption: green, battery supply: red) and feeding of the grid far exceed withdrawal from the grid (dark red). In the months with low sun exposure, energy demand is primarily covered by withdrawal from the grid.

for the planning of self-sufficiency concepts. The reduction of CO_2 was 6755 kg in the year 2020 (▶ **Table 2**).

Energy footprint

Medical center

The expected energy demand for heat and hot water was 155 000 kWh/year. This corresponds to approximately 37 000 l gas. The actual energy requirement was 4600 l gas/year, corresponding to 19 270 kWh. The power required for heating was reduced by the heat exchanger by approx. 85 %. 1 liter of liquefied petroleum gas produces 2.16 kg CO_2 [7]. 37 000 l gas correspond to 79 846 kg CO_2. 4600 l gas correspond to 9927 kg CO_2.

Consequently, consumption was reduced by 32 400 l gas/year, corresponding to approx. 69 000 kg CO_2.

The expected annual power consumption for MRI, CT, and data processing was approx. 334 700 kWh. The measured energy consumption in the years 2012–2020 was 307 000 kWh. 334 700 kWh correspond to approx. 73 300 kg CO_2, while 307 000 kWh correspond to approx. 67 230 kg CO_2, i. e.,

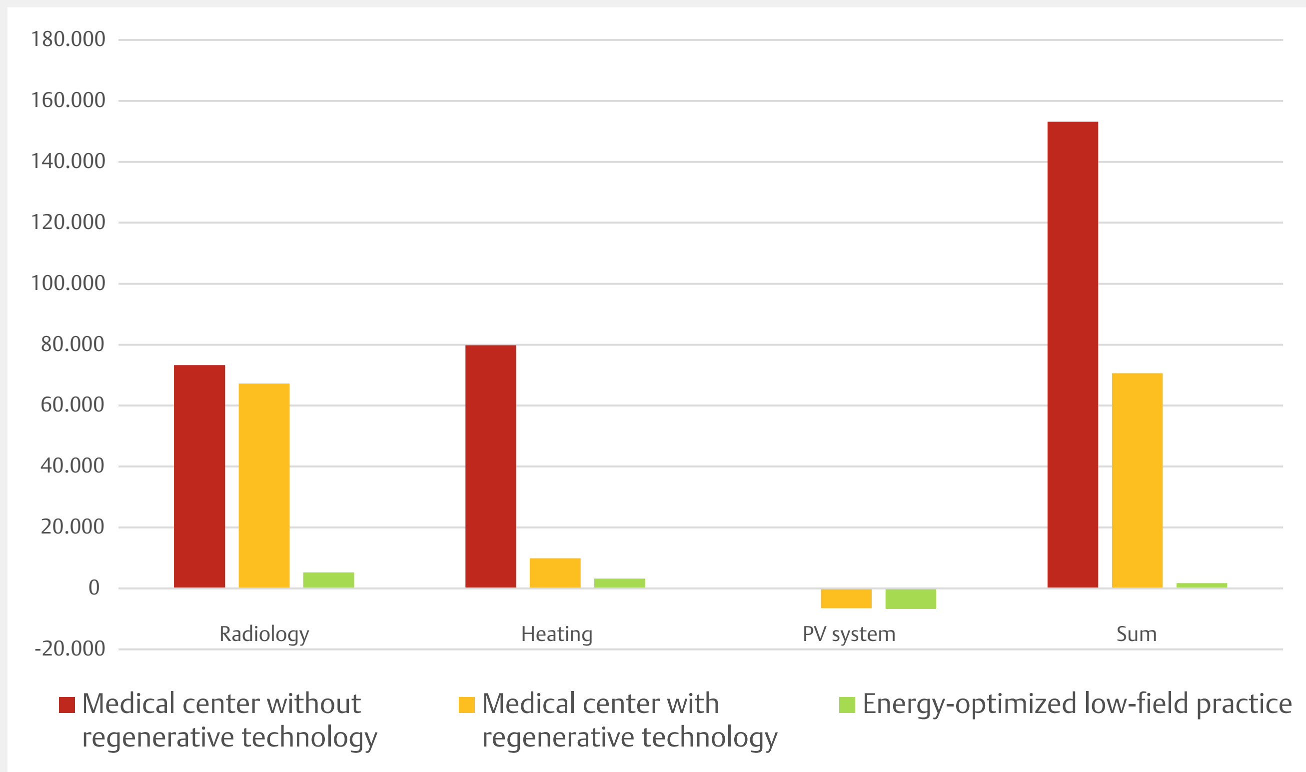
consumption was reduced by approx. 27 700 kWh/year and carbon emissions were reduced by approx. 6066 kg CO_2/year.

▶ **Table 2** Energy producers. Effect of regenerative energy measures. The cost savings is based on direct consumption of the power generated by the photovoltaic systems and current electricity and gas prices (0.46 EUR/kWh and 1.28 EUR/l, as of May/June 2022).

	Savings	CO_2 [kg/a]	Cost reduction [EUR]
Medical center:			
Heat exchanger	32,400 l gas	69,000	47,360
Photovoltaic system	29,800 kWh	6,526	13,708
Open low-field MRI practice:			
Photovoltaic system	30,846 kWh	6,755	14,189

The photovoltaic system generated an average of 29 800 kWh/year, corresponding to a CO_2 reduction of 6526 kg CO_2/year.

Without regenerative methods, CO_2 production of 153 146 kg/year would be expected. With regenerative technology, CO_2 emissions were able to be lowered by approx. 54 % to 70 631 kg CO_2.



▶ **Fig. 3** Ecological effect (in kg CO2/a) of radiology equipment (imaging systems, cooling, IT), heating, and power generation by photovoltaic system. Red: Medical center without regenerative technology, orange: Medical center with regenerative technology, green: Low-field practice

Practice for low-field MRI

The power generated by the photovoltaic system was 30 846 kWh in the year 2020, corresponding to approx. 6755 kg CO_2.

The measured annual consumption of the heating and cooling generators was 14 800 kWh, corresponding to 3241 kg CO_2. This energy was supplied by power from the grid.

The power needed for the systems in the practice (MRI and data processing) was 24 010 kWh in the year 2020 and was thus less than the expected value of 25 000 kWh/year. This energy consumption was primarily covered by the PV system.

Excess power was fed into the power grid and insufficient power was supplemented by power from the grid. 10 130 kWh were consumed directly. 2524 kWh were stored in the battery, and 2064 kWh were withdrawn from the battery (efficiency 82 %). 18 218 kWh were fed into the grid. 11 815 kWh were withdrawn from the grid. The degree of self-sufficiency was 51 %. The energy balance for the devices in the practice was negative (–6.403 kWh/year, corresponding to –1.402 kg CO_2/year).

If the consumption of the heating and cooling units is corrected to include this negative number, the annual net energy consumption is 8397 kWh corresponding to 1839 kg CO_2 (▶ **Fig. 3**).

Economic effect of the use of regenerative methods

Medical center

The amount of gas expected to be needed to heat the building was approx. 37 000 l. In the case of a current gas price of 1.28 EUR/l incl. value added tax, this corresponds to 47 360 EUR/year.

The actual energy consumption was 4600 l gas/year, corresponding to 5888 EUR.

The expected energy consumption was 334 714 kWh/year. At the current electricity price of 46 ct/kWh (bulk consumer, as of May 2022), this corresponds to a price of 153 968 EUR. The actual energy consumption was 307 000 kWh/year, corresponding to 141 220 EUR.

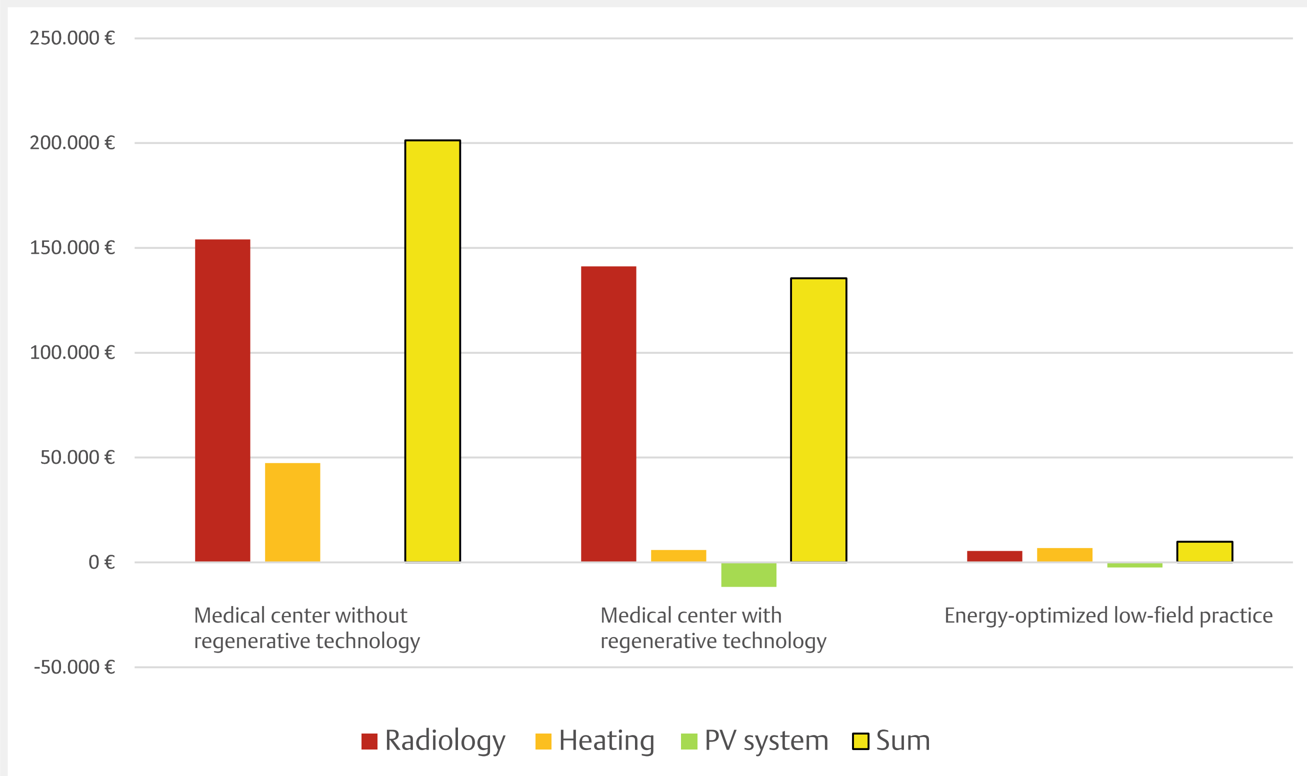
The photovoltaic system generated an average of 29 800 kWh/year. The electricity was fed into the power grid at a price of 39 ct/kWh, resulting in compensation of 11 622 EUR/year.

The expected total costs for energy was 201 328 EUR/year.

The actual energy costs (with conclusion of a new supply contract) were approx. 135 486 EUR. The energy costs were thus able to be lowered by regenerative measures by approx. 32.7 % or approx. 65 842 EUR/year. With direct power consumption, an even greater cost savings would be possible at present (▶ **Fig. 4**).

Practice for open low-field MRI

Electricity was the only energy source. The total power consumption was 38, 810 kWh/year. This corresponds to a cost of 17 853 EUR at the current rate for electricity.



▶ **Fig. 4** Reduction of energy costs by using regenerative technology for the three scenarios: medical center without regenerative technology, medical center with regenerative technology, and energy-optimized low-field practice.

The photovoltaic system generated 30 846 kWh/year. Total self-consumption would result in primary energy consumption of 7964 kWh/year at a cost of 3663 EUR. However, this is currently not possible due to the lack of long-term storage of excess energy.

The power needed for heating and cooling (14 800 kWh) cost 6808 EUR.

12 646 kWh were covered by self-consumption. 11 815 kWh were withdrawn from the grid at a price of 5434 EUR. 18 218 kWh were fed into the grid at a price of 13 cents, thereby reducing costs by 2368 EUR.

At current energy prices, the total energy costs for the energy-optimized low-field practice were 9874 EUR in the year 2020.

Discussion

The material is complex and outside the field of radiology at first glance. Nonetheless, the logistics of radiology practices and thus the development and implementation of concepts for optimizing economic efficiency and, increasingly in recent years, also the ecological efficiency of our work environment are part of the radiologist's scope of responsibility [4, 14, 15]

Three areas must be taken into consideration:

Building technology, energy consumers, and energy producers. This also includes work and process optimization that will not be discussed in greater detail here.

The planning of new buildings must take energy-saving measures into account. The requirements of the German Energy Saving Ordinance from 2007 were met for the construction of the medical center in 2009 [6]. The energy demand of new non-residential buildings must not exceed that of a reference building with defined technical equipment. According to § 4, Sentence 4 of the German Energy Saving Ordinance, regenerative heating systems are given preference. These include heat recovery from the cooling circuit of an MRI system. In addition to meeting the other requirements, a heat exchanger was therefore used for heat recovery and to support heating of the building [16].

The building housing the low-field practice was constructed using an energy-optimized timber frame construction method. This type of construction allows excellent heat transfer coefficients and fast completion. Heat recovery was initially disregarded due to the low expected heat quantity.

Superconducting MRI machines are the greatest energy consumers in radiology [3, 14]. In addition to RF transmitters and gradients, magnet cooling consumes energy both during scanning and in standby mode [13]. The power consumption of our device in standby mode is approx. 12.2 kW. It is responsible for over 50 % of the total energy consumption of the MRI machine.

The manufacturers identified this problem and lowered the energy demand of newer systems to less than 10 kW in standby mode and less than 20 kW in scan mode [17, 18]. A further ecologically relevant factor is the need for liquid helium as a cooling agent. Due to changes in coil design, newer helium-saving systems only require approx. 7 liters instead of the previously required approx. 1000 liters.

In recent years, MRI systems with a lower field strength have been reevaluated [5, 19–21]. By using modern techniques for signal and image processing, devices with field strengths of 0.5 T and lower can meet the requirements regarding diagnostic image quality. Further improvement can be expected due to methods of AI-based image reconstruction [22]. A lower field strength also has advantages due to fewer susceptibility artifacts, a shorter T1 time, better T1 contrast, and a significantly lower exposure to RF energy [6, 20, 23, 24]. For this reason new high-performance MRI machines with a field strength of 0.55 T are currently being developed and are already commercially available [6]. MRI systems with permanent magnets have the lowest energy consumption. These magnets have the advantages of an open design, almost unlimited service life (neodymium magnets), and helium-free operation.

However, their weight is approximately four times greater than that of superconducting systems. The production of 1 ton of crude steel consumes approx. 2600 kWh of energy and releases approx. 1.7 t CO_2 [25]. The production of a permanent magnet thus releases approx. 24 tons of CO_2, while a superconducting magnet releases approx. 7 tons. At a CO_2 savings during operation of approx. 56 tons/year using an MRI machine with a permanent magnet, the difference of 17 tons CO_2 would be canceled out after approx. 4 months.

For MRI systems with a lower field strength, additional alternative magnet technology is conceivable. An open 0.35 T magnet with a high-temperature superconductor was developed and implemented in the clinical routine already in the 1990s [26].

In computed tomography, the tube current during scanning plays only a secondary role in energy consumption [3, 11, 13]. In contrast, the consumption of the gantry both in standby mode and during scanning remains constant at approx. 2 kW. Some new generation CT scanners have an energy-saving mode resulting in a significant improvement of energy efficiency.

The contribution of data processing to energy consumption is not insignificant. The major difference in the energy consumption for data processing between the radiology practice at the medical center and the low-field practice can be explained in part by the greater number of workstations. In addition, energy-saving PCs and printers were used in the practice for low-field MRI. The energy consumption of IT systems may increase in the coming years, e. g. due to neuronal networks with powerful graphics cards [22].

As a result of the high and continuous energy consumption, superconducting magnets are a heat source of approx. 10–15 kW that is available year round and can be used particularly in the winter months to almost completely heat the building [16, 18]. Consequently, there is true potential to improve the energy efficiency of radiology, but this requires coordination with building technology. The recovery of the thermal energy generated by MRI operation resulted in a reduction in heating costs of significantly more than 80 % in our project. Since the primary energy consumption for heating without a heat exchanger was not measured but was only calculated based on the expected values for the structure, a miscalculation cannot be ruled out. Agreement was largely seen for any calculations validated by measurements.

In addition to the direct savings of heating energy, energy for cooling the practice rooms and the radiology equipment is also saved. A heat exchanger in combination with heating system support is capable of at least partially equalizing a significant ecological disadvantage of superconducting high-field MRI machine.

In both building projects, the use of a photovoltaic system resulted in a significant improvement in the ecological balance. When the medical center was built, the price for electricity fed into the grid (39 ct/kWh) was significantly higher than the price of electricity. Today, that rate is only approximately 25 % of the cost of electricity in new contracts so that self-consumption of solar energy is economically and ecologically advantageous and should be given preference.

Over time, the production of photovoltaic systems decreases. This process is referred to as “degradation”. However, in modern PV panels, this degradation occurs so slowly that it can barely be detected by measurement equipment. According to a study by the Fraunhofer Institute, the average degradation in Germany is 0.15 kWp/year [27] (see ▶ **Fig. 4**).

The energy produced by a photovoltaic system is location-dependent. The estimated annual sun exposure at our location is approx. 1100 kWh/year [28]. In the Freiburg region, the comparison value is approx. 1300 kWh/m^2. The best absorption is achieved with southern alignment of the panels and an installation angle of 30 %. The production profile is surprisingly consistent and exceeds the location-based projection by approx. 10 %.

To improve the self-consumption rate, it makes sense to use a battery to store excess power for use at times with insufficient sun exposure or increased consumption. Use of a battery thus compensates for fluctuations in production and consumption over the course of the day. The CO_2 produced during the manufacture of batteries must be taken into consideration. For lithium-ion batteries, this value is approx. 80 kg CO_2/kWh. Producing a 10-kWh lithium-ion battery generates 800 kg of CO_2 that can then be equalized in almost 2 years in our operating concept by increasing direct consumption [29].

As soon as a concept for the long-term storage of electricity is available, self-sufficient operation can be achieved [30]. Excess energy produced by the photovoltaic system could then be stored during the summer months and then used in the winter months when less solar energy is produced. One such concept could be a chemical energy storage device, achieved, e. g., by combining a hydrogen generator with a fuel cell. In addition, concepts for generating synthetic fuels (e-fuels) will soon be ready for mass production [31].

Optimization of the energy efficiency of modern radiology practices is a technical and organization challenge. A number of technical options are available.

Our task is to systematically implement them with the goal of achieving high-performance and sustainable radiology practices.

KEY POINTS

- The high energy consumption of radiology equipment, particularly MRI, can be compensated by the use of regenerative energy and energy recovery.
- The use of a heat exchanger in the cooling chain of the MRI machine is extremely important here.
- Low-field MRI with permanent magnets consume significantly less energy compared to superconducting systems.
- Improving energy efficiency results in a reduction of CO_2 emissions as well as a decrease in energy costs.

Conflict of Interest

The authors declare that they have no conflict of interest.

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