Building Energy Management Systems
Global Potentials and Environmental Implications of Deployment

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Summary

One of the key drivers that influence building energy consumption is the demand for space heating. Particularly in countries with cold climates and a large stock of residential buildings with central heating, building energy management systems (BEMS) are an option to reduce energy consumption and greenhouse gas (GHG) emissions. These systems can be combined with existing space heating technologies and other efficiency measures, such as building insulation. They are ideal for retrofitting purposes owing to their low up-front costs.

A prospective life cycle assessment model is used to analyze the environmental impacts of the technology today, in 2030, and in 2050. This allows for a first-ever, order-of-magnitude assessment of the environmental impacts of BEMS over their life cycle. The assessment is based on manufacturer information and generic life cycle inventory data for electronic components. Future impacts are based on changes in electricity generation following the International Energy Agency’s 2 degree and 6 degree scenarios, and are used to assess the contribution of BEMS to global energy and GHG saving goals. Results show substantially lower life cycle GHG emissions and higher savings of environmental impacts per kilowatt-hour of heating when compared to natural gas or electric heating. Potential net emissions savings range from approximately 0.4 kilograms carbon dioxide equivalent (kg CO$_2$-eq) when avoiding natural gas heating to over 1 kg CO$_2$-eq when avoiding electric heating in regions with GHG-intensive electricity generation. At present, BEMS can avoid at least 40 times the GHG emissions that they require for production and use, when deployed in regions with cold climates.

Introduction

The building sector can play a key role in the reduction of global of greenhouse gas (GHG) emissions. Residential as well as commercial buildings are responsible for over one third of global final energy consumption. Space heating alone accounts for a major portion of the consumption of fossil fuels. In countries with cold climates, space heating together with warm water supply is responsible for 65% of the end-use energy consumption, most of which is provided with fossil fuels such as coal, natural gas, and oil or electricity (IEA 2013). This indicates that space heating of buildings is one of the prevailing global sources of GHG emissions.

This article will assess the environmental and natural resource impacts of building energy management systems (BEMS). This technology allows the controlling and monitoring of heating demand in buildings according to user preferences, building characteristics, and weather forecasts. Although BEMS can be used in different kinds of buildings (residential, commercial, and public), the focus is the residential sector owing to the high demand for their large-scale
refurbishment in Organization for Economic Cooperation and Development (OECD) countries, non-OECD Europe, and Eurasia, as identified by the International Energy Agency (IEA) (IEA 2013). The research and analysis done for this article contributes to a series of reports by the International Resource Panel (IRP) of the United Nations (UN) Environment Program (UNEP) that compares environmental and natural resource benefits as well as costs of low-carbon energy technologies for GHG mitigation on the basis of a consistent methodology, system boundary, and background life cycle inventory (LCI) data.

With no action to improve energy efficiency in the building sector, energy demand is predicted to rise globally by 50% by 2050. Most of this increase will be driven by the rapid growth in the number of households and floor area built (IEA 2013). A similar projection is made by the UN, assuming that by 2050 over 50% (approximately 5 billion) of the world population will live in urban areas in moderate and cold climate zones with an increasing space heating demand (UN 2012). Inefficient space heating could not only increase demand for fossil energy (oil, coal, and natural gas), but also significantly reduce air quality in cities owing to emissions (World Bank 2011).

Common strategies for reducing energy consumption and GHG emissions in the building sector are adapted architecture, modified construction principles, building insulation and envelope improvements, efficient space heating and cooling technologies (including renewable energy), and efficient lighting and appliances (IEA 2013). Over the last years, many efficiency measures have focused on new buildings (e.g., architecture, building codes, and efficient heating and cooling technologies), but a particular challenge arises when retrofitting the existing building stock. The huge number of residential and commercial buildings in Europe, Russia, and the United States—all regions with cold and moderate climates—are of primary concern. They often have a life span of well over 100 years, meaning that approximately 60% of the building stock will still be in use in the year 2050 (IEA 2013).

One option to improve the energy performance of existing buildings is the application of BEMS, a specific category of building management systems or building automation systems with the purpose of lowering heating demand by gathering precise data from individual apartments and rooms. Such technologies have the ability to reduce the energy consumed for heating while maintaining thermal comfort. As this article will show, they also are a cost-effective way to save GHG emissions in existing buildings. Therefore, they are an option to overcome market failures often associated with efficiency measures in the building sector, well described by the principal agent problem (IEA 2007; Murtishaw and Sathaye 2008; Gambardella et al. 2012).

This article compares the environmental and natural resource impacts and benefits from using BEMS to reduce space heating demand. This assessment relies on three data sources: (1) a bill of materials from a manufacturer of BEMS, containing information on components and materials used in the systems (see the Supporting Information available on the Journal’s website); (2) LCIs for the technology of BEMS constructed using the ecoinvent database (ecoinvent 2010); and (3) scenario-based predictions for energy consumption in the building sector that are withdrawn from the report “Transition to Sustainable Buildings” (IEA 2013). In addition, this research assesses the degree to which BEMS can contribute to emission reductions in the building sector following the 2 degree scenario provided by the IEA. Results are calculated in kilowatt-hours (kWh) of energy saved per 100 square meters (m²) managed building space for 1 year. This functional unit reflects the potential for energy savings from BEMS in an average residential apartment for 1 year.¹

The IEA scenarios for GHG emissions reductions in the building sector differentiate between a 6 degree scenario (6 DS) and a 2 degree scenario (2 DS). The 2 DS is based on ambitious efficiency improvements resulting in a slower increase of energy consumption reaching 130 exajoules (EJ) in 2050. The 6 DS assumes emissions from the building sector to rise by 40% to 173 EJ in 2050 (IEA 2013).

**Efficiency Approaches and Technologies for Space Heating**

Energy consumption in buildings is influenced by many factors and various measures have been analyzed previously: building design (Bunz et al. 2006; Running and Short 2013); building materials and insulation (Strachan 2008; Xing et al. 2008; Ordoñez and Modi 2011); building automation; and heating, ventilation, and air conditioning (HVAC) systems (Cho and Liu 2010; Guo et al. 2010; Sung et al 2011; Olivieri et al. 2014; Tanner et al. 2013). The following section will give an introduction into selected efficiency measures for a reduction of energy demand in space heating and will explain why BEMS can play an important role in the future.

**Efficiency of Space Heating Technologies**

The efficiency of space heating technologies depends primarily on the fuel used. Natural gas and oil are predominant in many countries with cold climates (IEA 2010, 2013). District heating is popular in Europe, especially Northern and Eastern Europe, in parts of the United States, and Asia. Electricity is used for heating purposes, particularly in countries with high-capacity electric grids and high base-load power supply (e.g., generated by nuclear or coal power plants) or in countries with moderate climate and short heating periods. Natural and renewable resources are being used as well (e.g., solar, heat pumps, or biomass), varying on the country/region, type of building, and available technology.

Equally important for space heating is the efficiency of the technology used for fuel combustion. Significant improvements have been made, and condensing boilers for natural gas and oil are state of the art in many countries, but as table 1 shows, they are not the most efficient heating technology available. Gas-driven or electric heat pumps show better performance. In combination with renewable sources (wind and solar), electric resistance heaters can reach efficiencies well over 100%.
Table 1  Examples of efficiencies and costs of heating technologies today (modified from IEA [2013])

| Heating technology | Efficiency (%) | Typical capital cost | Fuels | Operating cost (per joule of useful heat) |
|--------------------|----------------|----------------------|-------|-----------------------------------------|
| Conventional boilers/furnaces | 60–84 | Low-medium | Oil, natural gas | Medium-high |
| Condensing boilers | 85–97 | Medium | Oil, natural gas | Medium-high |
| Wood stoves/furnaces | <70 | Low | Biomass | Low-medium |
| High-efficiency fireplaces | 70–80 | Low-medium | Biomass, natural gas | Low-medium |
| Pellet stoves | 75–85 | Low-medium | Biomass | Low-medium |
| Masonry heaters | 80–90 | Medium | Electricity | Medium-high |
| Electric resistance heaters | 100<sup>d</sup> | Low | Electricity | Low-medium |
| Heat pumps (electric) | 200–600<sup>b</sup> | Low-medium (air conditioning)/medium-high | Gaseous fuels | Low-medium |
| Heat pumps (gas-driven) | 120–200<sup>b</sup> | Medium-high | Natural gas, oil, bioenergy, solar, waste heat, etc. | Medium-high |
| Sorption chillers | 70–180<sup>c</sup> | Medium | Solar | Low-medium |
| Solar thermal<sup>d</sup> | 100 | Low-high | Solar | Low-medium |

Note: Capital and operating costs (per joule of useful heat) depend on local energy prices and are estimates compared to average life cycle costs.

<sup>a</sup>In many regions of the globe, electricity supply relies heavily on fossil fuels such as coal, emitting more GHG emissions than natural gas. Even though an electric furnace may be 100% efficient, in general, electric forced-air systems tend to have low efficiencies.

<sup>b</sup>Efficiencies above 100% indicate that for every unit of energy consumed, more than one unit of energy-equivalent output is achieved. For instance, a 300% efficient heat pump outputs three units of heat equivalent for each unit of energy consumed (or 2-to-1 output).

<sup>c</sup>Today’s sorption chillers used for space cooling typically have efficiencies around 70%, whereas heating using sorption chillers typically ranges from 130% to 180%.

<sup>d</sup>Refers to solar thermal systems and not solar photovoltaic equipment used for electricity production.

Table 1 indicates that although a great variety of space heating technologies exist, capital and operating costs of more advanced systems range from medium to high, resulting in a small replacement rate of furnace, boilers, and whole heating systems (IEA 2013). Costs differ from technology to technology and country to country, owing to local markets, policies, and funding, customer preferences, and so on. The IEA only provides relative information to indicate differences. This article considers only natural gas boilers and electric heating as a basis for comparison, details of which can be found in the Supporting Information on the Web.

**Building Automation and Smart Heating Control**

In addition to the factors mentioned in the previous section, building automation and smart heating control is beginning to play a more important role in the efficient provision of space heating. Although the effect of building automation and HVAC systems on space heating are well covered in the literature, less work has been conducted on BEMS and their application for space heating efficiency in residential buildings. Exceptions are articles by Riedel (2006), Riedel (2007), Baggi and Mara (2012), and Malina (2013), and recent research shows that BEMS have advantages in comparison with other efficiency measures, such as lower costs building envelope improvements or insulation (Beucker et al. 2012). Besides, they can be implemented alone or in combination with other efficiency measures; they are interoperable with most commercially available boilers and furnaces, and, finally, BEMS are versatile and can be used in different types of buildings.

BEMS consist of sensors for temperature and air quality control, actuators for heating and ventilation, and a central control unit that links and controls the individual devices within a building. The main difference between BEMS and a simple thermostat-based heating control lies in the control variables and mechanisms taken into account in the underlying algorithms of the systems (see figure 1).

BEMS are used to set and control space heating individually according to specific user demands. Most systems employ microchip- and software-based intelligence to optimize heating demand in buildings according to preset values and control algorithms. Although it is difficult to strictly differentiate BEMS from other automation systems used for energy management in buildings, the following classifications help to clarify various types of systems and their application area:

- **Smart thermostats**: These are intelligent thermostats that can be programmed according to a user’s needs. They range from programmable thermostatic radiator valves to self-learning and autonomously optimizing heating control units for individual apartments or houses. Typical smart thermostat systems consist of a programmable, microchip-based unit that measures temperature in one or multiple rooms and controls the boiler by reducing its output. In very simple cases, radiator valves can be shut off to reduce warm water or hot air flow through the building. These systems have relatively low up-front costs and are suited to a broad range of heating systems. Potential energy savings depend on the building type, the heating system, and user demands. Savings up to 20% have been
### Properties of systems

| Primary application and purpose | Smart Thermostat | BEMS | HVAC systems |
|--------------------------------|------------------|------|--------------|
| Control of heating in individual apartments or single family houses | Control of heating and ventilation in apartment/ housing complexes or multi-story buildings with central heating systems | Control of heating, ventilation and air conditioning in buildings (residential and commercial), several interconnected devices |

| Technological approach | Single device/ control unit with interface to heating system (boiler) and sometimes actuators like radiator valves | Hierarchical system with interconnected control units, sensors and actuators in individual rooms and apartments/houses | Customized solutions with various components from building technology and automation |

| Optimization level | Individual apartments, single family houses | Housing complexes or multi-story buildings | Buildings with complex heating, ventilation and air conditioning demands |

| Reference input variables | Inside and outside temperature, physical presence of resident, in some cases weather forecast | Inside and outside temperature, physical presence of resident, building specific variables, weather forecast | Inside and outside temperature, physical presence of resident, building and system specific variables, weather forecast |

### Simplified scheme of system set-up, with:

**Input/Sensor**
- temperature
- humidity
- presence
- weather
- Building par.

**Output**
- Cooling System
- Heating System
- Air flow

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**Figure 1** Properties and differences of systems for heating control in residential buildings. Building par. = Building parameters

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reported and are currently under evaluation (see, e.g., BPA 2015).

- **BEMS**: BEMS are building control systems that measure temperature and heating demands at the room or apartment level. The system continuously adapts the heating output according to building physics, weather predictions, and varying user demands. It consists of distributed sensors, actuators, and chip-based control units. A prognosis of the heating demand of a building can be derived from preset values in apartments or rooms and data from weather forecasts. The systems are mostly used in multi-story buildings with central furnaces, boilers, or district heat transfer stations, but can also be applied in individual houses. Savings up to over 30% of heating energy, particularly in multi-story buildings with central heating systems, are reported (Riedel 2006, 2007; Baggini and Mara 2012; Malina 2013).

- **HVAC systems**: HVAC systems are primarily designed for commercial buildings, but are used in bigger residential buildings as well. They are used to control and optimize indoor comfort, such as temperature, humidity, and air flow (Swenson 1995). Systems often integrate devices from different technological subsections (e.g. HVAC) and require high planning efforts. Energy savings obtained by HVAC systems vary greatly, depending on the layout, setup, and purpose of the system. Savings over 20% for forced air systems are reported (Sung et al. 2011; Olivieri et al. 2014; Tanner et al. 2013; Henze and May-Ostendorp 2012).

Figure 1 summarizes the differences among the described systems and compares their structure and mode of operation.

### Life Cycle Assessment

**Goal and Scope Definition**

The environmental and natural resource impacts of BEMS are explored using life cycle assessment (LCA) for a comprehensive set of environmental indicators. BEMS are first evaluated based on the functional unit of 100 m² managed residential building space for 1 year (per 100 m²-annum). An LCI for the production, use, and end of life of BEMS is calculated for the years 2010, 2030, and 2050 for nine global regions as defined by the IEA (the nine regions are: CN [China], IN [India], RER [OECD Europe], US [OECD North America], PAC [OECD Pacific], EIT [Economies in Transition], LA [Latin America], AS [Other Developing Asia], and AME [Africa and the Middle...
East) (see IEA 2010). Second, the aggregated impacts of the production and use of BEMS devices are calculated for 2030 and 2050 given a potential market penetration and deployment scenarios. Finally, potential global energy savings from BEMS will be compared to energy reduction targets for the building sector under the IEA GHG mitigation scenarios.

To characterize the potential impacts of BEMS, the ReCiPe 2008 midpoint life cycle impact assessment (LCIA) methodology is used. The following impact categories are considered: climate change (kilograms carbon dioxide equivalent; kg CO$_2$-eq); freshwater ecotoxicity (kg 1,4 dichlorobenzene [DCB]-eq); freshwater eutrophication (kg phosphorus [P]-eq); human toxicity (kg 1,4-DCB-eq); metal depletion (kg iron [Fe]-eq); particulate matter formation (kg PM10-eq); photochemical oxidant formation (kg nonmethane volatile organic compounds [NMVOC]-eq); terrestrial acidification (kg sulfur dioxide [SO$_2$]-eq); and land occupation (m$^2$-annum) (Goedkoop et al. 2009).

To understand the environmental benefits or trade-offs of BEMS in the context of heating technologies or other energy-saving technologies, such as building insulation improvements, the life cycle impacts of BEMS are computed based on the functional unit of 1 kWh of energy saved. To calculate these results, the environmental burdens of producing and using BEMS are divided by the quantity of energy (kWh) that they save over their lifetime. Using this functional unit, this article compares the impacts of producing and using BEMS to the impacts of simply using natural gas or electricity to provide space heating.

LCIs for the production and use of a BEMS in each region and year are computed using the THEMIS model (Technology Hybridized Environmental-economic Model with Integrated Scenarios) (Hertwich et. al 2014), an integrated hybrid LCA model (Su$^2$b 2004) developed to analyze the impacts of low-carbon technologies from the years 2010–2050. THEMIS consists of nine regionalized versions of the ecoinvent 2.2 database, the EXIOBASE multiregional input-output database (Tukker et al. 2013), and original LCIs for renewable and low-carbon electricity generation technologies developed by Hertwich and colleagues (2014). In this model, the impacts of electricity generation and materials production in each region in 2030 and 2050 were modeled to follow the IEA 2 DS and the 6 DS, taking into account expected future improvements in material efficiency, energy efficiency, and pollution control in key sectors of the global economy. For each region and year, different technologies are used for electricity generation, resulting in changing environmental impacts for electricity under each scenario.

The Supporting Information on the Web provides details on electricity generation mixes given by the IEA scenarios and their calculated environmental impacts.

**Inventory Models of Building Energy Management Systems**

No reports or journal articles that would allow a precise modeling of the LCI of BEMS have been published so far. Previous literature mainly focuses on building automation and HVAC systems and their performance in different building types and conditions. LCIs cannot be deduced from these sources alone. In addition, the number of manufacturers of BEMS is limited and bills of materials of BEMS are not publicly available. One manufacturer provided a simplified parts list and information on production processes that allows estimations on the components, manufacturing processes, and their consumption in the use phase. The BEMS technology modeled in this analysis consists of the following components (see the Supporting Information on the Web for more details):

- Sensors to measure temperature in individual rooms and/or apartments,
- Valves (actuators) that regulate the flow of warm water or air through the heating system,
- Apartment manager, a control unit based on an embedded personal computer (PC) that computes heating demand on the apartment level and communicates with the building manager,
- Building manager, the central control unit based on an embedded PC that aggregates data from apartments in the building and controls the heat output of the central burner or furnace in accord with weather and building performance data.

An LCI model for a typical BEMS was developed based on the known materials composition and energy consumption of the devices (see the Supporting Information on the Web). For the LCI, data from the bill of materials was combined with data of comparable components in the ecoinvent 2.2 database. This allows for a first-ever, order-of-magnitude assessment of the environmental impacts of BEMS over their life cycle.

**Technological Improvements of Building Energy Management Systems from 2010 to 2050**

The technological progress of BEMS depends on a number of factors. Core components of the systems are embedded PCs that calculate and control the heating demand of an apartment and the building and adapt the heating power. Although the development of BEMS is not limited by the computing performance of embedded PCs, improvements such as decreasing costs, miniaturization, and energy efficiency are factors that could influence their deployment. Because the technological improvements of BEMS devices would be difficult to predict with accuracy, we assume no changes in the production of BEMS and their components in 2030 and 2050, only the changes in upstream electricity generation and materials production according to the IEA scenarios.

**Life Cycle Assessment Results**

LCAs were calculated for BEMS using the THEMIS model in all nine IEA regions of the 2 DS. This section presents the LCIA results for selected ReCiPe 2008 indicators for the
years 2010, 2030, and 2050. Further details on the assumptions and data used to construct inventory models and numerical results are presented in the Supporting Information on the Web. The following section summarizes insights obtained from the analysis.

Environmental Impacts Resulting from Building Energy Management Systems

Because the mitigation of climate change is the driving motivation of the IEA 2 DS, we first discuss the life cycle GHG emissions resulting from the production and use of BEMS to manage a residential apartment area in Europe for 1 year.

The analysis shows that 35 kg CO₂-eq would be generated to manage a 100 m² apartment in Europe for 1 year, decreasing to approximately 9 kg CO₂-eq/100 m² by 2050. The decline is mainly a result of the decarbonization of the electricity generation and the emissions reductions in the production of materials used for the electrical components in the devices (e.g., copper) over the course of the 2 DS. The embodied energy and GHG emission of the BEMS is much smaller in comparison to the amount of energy and emissions that can be saved by the use of the system. For this calculation, conservative energy savings of 20% (32 kWh/m²/year) were assumed, reducing typical space heating demand, in a partially retrofitted apartment in a cooler European country (e.g., Germany) from 160 (Dena 2010) to 128 kWh/m²-year. In reality, energy consumption for heating depends on the heating days and is more complex to calculate. Germany depicts though of a good average value of heating days and energy consumption for space heating in Europe (EUROSTAT 2015). In a 100 m² apartment, the saved space heating per year would sum up to 3,200 kWh, while avoiding the emissions of over 1,300 kg of CO₂-eq from natural gas boilers. Hence, the energy and GHG payback of the BEMS can be quite rapid.

Figure 2 shows the potential savings in life cycle GHG emissions from using BEMS to save 1 kWh of space heating provided by a natural gas boiler (top) and electricity (bottom) in locations with moderate and cold climates in the nine IEA regions. Variations in impacts among regions and years are owing to differences in the mix of technologies used to generate electricity in each region and year of the IEA 2 DS. Presently, the potential GHG emissions savings are highest for electric heating in regions with carbon-intensive electricity mixes, such as China, India, developing Asia, and Africa and the Middle East. If BEMS are used to reduce the demand for heating by natural gas boilers, the potential GHG emissions savings are similar among regions and years of the scenario. This homogeneity is owing to the fact that the combustion of natural gas itself is the main contributor to the life cycle GHG emissions of using a gas boiler. Also, the regional differences in the impacts of electricity consumed by the BEMS are small compared to the GHG savings. This analysis does not consider all potential heating technologies that may be used in the developing world (e.g., simple wood, biomass, and other coal-fired furnaces that do not dispose of a control unit with an interface are not compatible with BEMS systems). If electricity is decarbonized following the 2 DS, emissions savings from using BEMS to reduce the demand for electric heat would become negligible, but the potential emissions savings from avoiding natural gas combustion would increase in all regions by 2050. Overall, BEMS devices avoid at least 40 times as many GHG emissions because they require to produce and use when deployed today in regions with cold and moderate climates.

Results indicate that if BEMS are used to reduce the demand for heat from gas boilers, the largest emissions reductions can be achieved in regions with less GHG-intensive electricity production (e.g., OECD Europe, OECD Pacific, North America, and Latin America). Even in regions with more GHG-intensive electricity production (e.g., China, India, Asia, and Africa/ Middle East), using BEMS systems to save energy results in 96% lower GHG emissions than providing heat with conventional natural gas boilers. Accounting for climate (measured by the number of heating days) and the prevalence of modern space heating technologies (e.g., natural gas boilers and furnaces as well as central district heating), the most promising regions for BEMS deployment are OECD Europe, OECD North America, and the economies in transition EIT.

Figure 3 presents the environmental impacts of BEMS using a more comprehensive set of indicators. Impact assessment results were calculated for the production and use of BEMS in all regions individually, accounting for regional differences of electricity generation and materials production as specified in the THEMIS model. For simplicity of visualization, figure 3 shows a global average of the impacts of BEMS system use and the generation of heat following the 2 DS. The global average was calculated by weighting the impacts of BEMS in each region by the projected gross domestic product (GDP) of each region in the IEA 2 DS. Finally, figure 3 compares the impacts of producing and using BEMS to save heating energy to the impacts of simply generating heat with natural gas (top) and electricity (bottom). To generate this comparison, the life cycle impacts of BEMS production and use are divided by the total amount of heating demand saved by that BEMS device (32 kWh/m²/year). The impacts of generating heat with natural gas boilers were computed using data on the production and annual fuel utilization efficiency (AFUE) of residential boilers (assumed to be 80%) from Shah and colleagues (2007), and the emissions from the combustion of natural gas were estimated from relevant processes in the ecoinvent database. The life cycle impacts of electricity generation in each region for 2010, 2030, and 2050 are calculated by the THEMIS model, and the efficiency of electric heating is assumed to be 100%.

Results indicate that using BEMS is environmentally beneficial as compared to simply generating heat from natural gas or electricity for most impact categories, showing a clear advantage of implementing BEMS. Again, the saved energy and environmental impacts clearly outweigh the embodied energy and life cycle environmental impacts of the BEMS. Also, the impacts of BEMS reduce over time are mainly owing to the decarbonization of electricity generation over the 2 DS scenario.
Figure 2  Life cycle GHG emissions (top) and net savings (kg CO₂ equivalents) from using BEMS to reduce 1 kWh of space heating demand in each of the 9 IEA regions in 2010, 2030 and 2050 of the IEA 2 DS scenario. Note the different y-axis scale in the top graph. The mean represents the global average weighted by the projected gross domestic product by each IEA region in each year. Net savings are the emissions of saving 1 kWh of heat with BEMS minus the emissions of generating 1 kWh of heat with electricity or natural gas. Energy savings are assumed to be the same in each region (32 kWh/m²/year). GHG = greenhouse gas; kg CO₂ = kilograms carbon dioxide; BEMS = building energy management systems; kWh = kilowatt-hours; IEA = International Energy Agency; m² = square meter.

The potential impacts on human toxicity and eutrophication in figure 3 are similar in magnitude to those of heat provided by natural gas for two reasons (89% and 75%, respectively). First, the impacts of natural gas heating on human toxicity and eutrophication are already rather low. Second, more than 50% of these impacts are owing to the production of materials used in the device, as shown in figure 4 (production of metals, e.g., copper).

Scenario Analysis for the Deployment of Building Energy Management Systems

Global space heating demand in residential housing is a major contributor to energy consumption in buildings and responsible for a significant share of global GHG emissions. According to the IEA 6 DS, energy demand in the building sector is predicted to rise by 50% until the year 2050 (see figure 4). GHG emissions are expected to grow with a similar ratio from approximately 8 gigatonnes (Gt) CO₂ in 2010 to approximately 12 Gt CO₂ in 2050 (IEA 2013). In order to meet 2 DS targets, 8.9 Gt CO₂ must be saved by a bundle of measures, including fuel switching, efficient appliances, building envelope improvements, and so on. Figure 4 contains modified data from IEA showing the contributions of specific technologies to GHG reduction targets until 2050. To visualize the share to which BEMS could contribute to the overall savings in the 2 DS, the potential savings were put in the context of the data from other measures given in the IEA report.

Under the assumption that BEMS can reach a similar level of deployment as building envelope measures and provide comparable energy and emission savings, they could contribute to the objectives of the 2 DS with at least 0.5 Gt CO₂ savings per year in 2050. Taking the aforementioned savings per apartment into account, it would require equipping globally approximately 360 million residential apartments or individual houses with BEMS technology until the year 2050 to achieve the said savings.

This assumption appears to be realistic given that the cost of GHG emissions abatement using BEMS can be as low as one third of that of building insulation (see chapter “Technology Deployment Scenarios”). Deployment of BEMS could easily be doubled, if incentivizing policies and legal measures,
such as stricter building or retrofitting codes for residential buildings, would support their deployment and commercial buildings would be equipped as well. Hence, this analysis strongly suggests that BEMS can play a significant role in reaching the 2DS targets either by achieving the goal faster and/or by lowering the share of other measures.

Another important question is to which extent BEMS can contribute to reduced space heating demand in residential buildings in different regions of the world. The technology is primarily suitable for countries with cold and moderate climates. Thus, it can be expected that impacts are strongest in countries with high heating demands (many heating days) and existing multistory building structures with central heating systems. Such structures are predominantly found in urban areas in North America, Europe, Russia, and parts of China and Asia.

**Uncertainties of the Scenario Analysis**

As contribution analysis shows, most of the environmental impacts of BEMS technology depend on the electricity
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Figure 4  Contribution of CO$_2$ emissions of selected technologies to IEA 2 DS and 6 DS (based on modified data from IEA [2013]). CO$_2$ = carbon dioxide; IEA = International Energy Agency; DS = degree scenario.

consumed by the device during its use, implying that uncertainty in the present and future impacts of electricity generation would most significantly affect the results of this analysis. If global electricity generation is decarbonized according to IEA scenarios, the impacts of using a BEMS to manage building heating demand will likely decline, as shown in the results of this article. For some other impact categories, the production of the device itself (metals and electronic components) is the main contributor to impacts (over 60% for human toxicity and over 95% for metal depletion). Because this analysis has used a simplified bill of materials to build a generic LCI model for the production of BEMS, there is greater uncertainty in the results for categories dominated by the production of the BEMS device, and future analyses using more detailed data of the production and the components could yield more accurate results.

In comparison with natural gas and electrical heating, the BEMS devices are favorable in all environmental impacts categories considered. For this and economic reasons, BEMS are a desirable choice for efficient and short- to medium-term reduction of space heating demand. In the future, when renewable sources, such as wind and solar, might dominate energy and electricity production, other space heating technologies could become more prominent, such as electrical or solar hot water heating. In these cases, the efficiency and environmental benefits of using a BEMS system to reduce heating demand may need to be reevaluated.

Another uncertainty results from the regional differences in the potential deployment of BEMS. Future analyses with a more precise differentiation of the climate of different regions, their space heating demand (e.g., measured in heating days), the physical conditions of the building stock, and the resulting saving potentials of BEMS would be necessary to estimate regional savings potentials more accurately.

In addition, the LCIA results of BEMS need to be evaluated against the saving potentials of other GHG mitigation technologies, such as insulation, building envelope, cooling technologies for moderate and warm climates, and fuel switching to determine the most effective and environmentally benign strategies for achieving the IEA 2 DS energy savings goals.

Finally, cost savings that can be obtained from efficiency technologies are subject to rebound effects, meaning that they could result in increased consumption of heating (direct rebound) as well as an increased consumption of other goods owing to higher income (indirect rebound) (Lovins et al. 1988; Hertwich 2005; Hong et al. 2006). The magnitude and significance of rebound effects and its resultant environmental impacts are controversial, and they are dependent on a number of macro- and microeconomic factors that cannot be fully considered in the scope of this article. These include energy prices, technology prices, income, human behavior, and time frame. In the case of BEMS, a defensible prediction of rebound effects would be outside the scope of this life cycle analysis.

Limitations and Future Research

This article presents a first-ever estimate of the environmental and natural resource impacts of BEMS in comparison to the impacts of the energy they save. Further research is needed to refine these results in a number of ways. First, more precise modeling of the bill of materials and LCI for the variety of BEMS devices on the market is needed to confirm the benefits of BEMS in impact categories that are closely tied to materials production (i.e., metal depletion, eco-toxicity, and human toxicity). Next, a more precise estimation of the likely energy savings of implementing BEMS in different types of buildings and climate regions (i.e., in combination with heating days) would improve the LCA and better inform policy makers on the benefits of implementing BEMS in specific regions, countries, and cities. This may also include estimating the potential reduction of energy demand for space cooling (in addition to just heating). Finally, more detailed building modeling would be needed to estimate the energy savings and environmental benefits from deploying BEMS in concert with other building efficiency measures, such as improvements to the building envelope (insulating walls, ceiling, and windows) and use of more efficient heating and cooling technologies (e.g., heat pumps, passive solar design, or desiccant cooling).
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Notes

1. For reasons of simplification and comparability, it is assumed that 100 m² of apartment space are a reasonable indicator for different regions analyzed. The authors are aware that in reality occupied space per household differs greatly, but refrain from a further differentiation owing to the complexity of factors that influence this indicator (e.g., income, availability of space, culture, and climate). A more differentiated model could take dynamic developments of the building sector into account, but was not covered by the objectives of the UN IRP.

2. The authors know of three German manufacturers that provide systems that fulfill the characteristics of BEMS and can be applied in multistory residential buildings with centralized heating systems: Adapterm by the company Techem (www.techem.de/wohnungswirtschaft/energiemanagement/techem-smart-system/, accessed May 2015); enkey by Kieback & Peter (www.enkey.de/, accessed May 2015); and the Smart Home System RIEcon by Riedel Automatisierungstechnik (www.riedel-at.de/, accessed May 2015).

3. The simplified bill of material was obtained by the manufacturer Riedel Automatisierungstechnik through a series of telephone interviews and the exchange of component-specific information, including type and manufacturer of component, weight, size, and electricity consumption of the component in operation and standby mode.

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**Supporting Information**

Additional Supporting Information may be found in the online version of this article at the publisher’s web site:

**Supporting Information S1:** This supporting information contains information on determining the baseline technologies for space heating and the methods for the assessment of life cycle impacts. It also presents the inputs for the life cycle inventory.

**Supporting Information S2:** This supporting information contains worksheets of life cycle impact assessment results for electricity generation, building energy management systems (BEMS), and heat from natural gas boilers in years 2010, 2030, and 2050.