Economic, social and environmental impact analysis of an indigenously developed energy optimization system for German office and residential building types

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Abstract

This work addresses the economic, social and environmental analysis of an indigenously developed building energy optimization system for residential and office buildings in Germany. The developed system consists of 14 different wireless network embedded sensors, wireless communication protocol, multi-dimensional data warehouse, graphical user interfaces and energy optimization software with artificial intelligence-backed control algorithms. The R&D activity is accomplished in the 'Intelligent Building Energy Management System' research project, which is funded by the State of Lower Saxony—Germany in the frame of Innovation Support Program between the years 2014 and 2018. The system is tested in two appropriately selected test buildings in Germany. It has been recorded that the system provides energy efficiency levels between 29.34% and 38.18% under different seasonal and occupancy conditions in office and residential building types. The analysis is accomplished within the framework of four main indicators. These are economic indicators including calculations of lifetime cost and payback rate methods, resource use indicators including the calculation of reduced energy use as a result of the energy efficiency provided by the system, social indicator including additional expendable income calculations and environmental indicators including calculations depicting the benefits of reducing harmful emissions. Analysis results illustrate that building energy optimization systems provide a cost-effective method for promoting energy efficiency goals. Results of the indicators prove monetary benefits for the building occupants in terms of resource use, return on investment and social impact, as well as quantifiable benefits for easing the harmful effects of climate change phenomenon.

Keywords: energy efficiency; data warehouse technologies; decision support systems; techno-economic analysis; smart buildings

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Received 8 September 2020; revised 21 December 2020; editorial decision 3 January 20201; accepted 3 January 2021

1. INTRODUCTION

The impact of global warming is transforming our environment, increasing the frequency and intensity of extreme weather events. The past two decades included 18 of the warmest years on record [1]. The EU targets to improve energy efficiency by at least 32.5% and to increase renewable energy to at least 32% of the EU's final energy consumption by 2030 due to the fact that the EU currently imports 94.6% of its oil and 83.2% of its gas, making it the world's leading importer of these fuels [2]. In fact, when the agreed EU legislation is fully implemented, total greenhouse gas (GHG) emission reductions are estimated to reach around 45% by 2030. The policies put in place today will have a continuous impact after 2030 and will therefore already go a long way, with projected emissions reductions of around 60% by 2050 [3].

The German government has also adopted an analogous approach for Germany's national climate change strategy defined in the Climate Action Plan 2050, which sets a long-term roadmap

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International Journal of Low-Carbon Technologies 2021, 16, 747–760

https://doi.org/10.1093/ijlct/ctab002 Advance Access publication 29 January 2021

for sector-specific emissions reductions, as part of the 'Energy Transition (Energiewende)' strategy [4,5]. Compared with the base year of 1990, the key goals are to achieve at least 40% reduction in GHG emissions by 2020, 55% by 2030, 70% by 2040 and 80–95% by 2050, at which point the country expects to be mostly GHG neutral [6].

Despite progress on lowering overall emissions, Germany remains far off its 2020 emissions target of a 40% reduction. Even with a rapid increase in renewable electricity generation, Germany's total emissions have not experienced expected reductions. As of 2018, Germany had reduced its total GHG emissions by around 31% compared with 1990 [6].

The quality of life in Europe's cities states that although quality of life has improved in many areas, in other areas such as environmental issues and energy efficiency have deteriorated [7]. In such places, people, companies and public authorities experience specific needs and demands regarding domains such as energy efficiency, environment and transportation services. One possible solution to these problems is to reduce energy consumption by improving energy efficiency. Policy makers, who focus on energy security, sustainable growth, climate change or the well-being of citizens, recognize energy efficiency as a key target [8–9].

Current residential and office buildings significantly contribute to total energy consumption and CO_2 emissions. Reports by the Intergovernmental Panel on Climate Change and the US Department of Energy note that buildings account for 25–30% of the total energy-related CO_2 emissions [10] and 40% of total energy use in Europe [11].

Cutting energy use in buildings by about 30% would cause 11% reduction in Europe's total energy consumption. This target will be achievable only if buildings are transformed through a comprehensive, rigorous and sustainable approach [12].

On the basis of on-going research in the area of energy efficiency and legislative drivers launched by the national and international organizations, the role of integration concepts, performance monitoring and analysis methodologies with sophisticated control strategies through the seamless integration of people, ICT devices and computational resources gain significant importance for reducing the energy consumption and the operational costs of buildings as well as cities [13].

The International Energy Agency (IEA) set eco-design strategies in order to increase the energy efficiency of buildings. Among these strategies, home automation systems are the most cost-effective solution without requiring heavy refurbishments [14].

According to European standard 'EN 15232 Energy Performance of Buildings-Impact of Building Automation', building operation systems can, depending on building type and equipment standard, produce the following potential savings of energy: restaurants 31%, hotels 25%, offices 39%, shopping centers 49%, hospitals 18%, schools/universities 34% and residential 27% [15]. This is a major contribution to the 'COP 21 Paris Agreement' in which the EU outlined the objective to reduce energy consumption at least 40% by 2030 [16]. Moreover, the control of energy performance of buildings is often provided by an *ad hoc* combination of off-the-shelf building management components, distributed data metering equipment, glued together by monitoring and targeting software tools. The absence of building management systems standardization coupled with competition for market share results in independent and non-compatible system development [17,18].

In order to address these stated deficits above, a cost-effective building energy optimization system is researched, developed and tested. The indigenously developed 'EOS Energy Optimization System', which is subject to this research, reduces the total energy use of buildings through optimization of energy-consuming building systems such as heating, cooling, lighting systems and home/office appliances with the support of an integrated system consisting of artificial intelligence-backed optimization software and wireless network embedded hardware. The developed system has been tested and energy efficiency levels are measured at the Hannover Science Park Technology Centre, EOS Sustainable Energy Solutions GmbH firm's laboratory and in a renovated residential building between the years 2016 and 2018. It has been recorded that the system provides energy efficiency levels between the lowest 29.34% and the highest 38.18% under different seasonal and occupancy conditions in office and residential building types. The developed system can be deployed to all types of historical and new buildings to reduce energy consumption.

In this work, economic, social and environmental analysis of this building energy optimization system is examined based on indicators for the multiple benefits gained through intelligent optimization of energy consumption in the residential and office buildings. The analysis is accomplished within the framework of four main indicators. These are economic indicators including calculations of lifetime cost and payback rate methods, resource use indicators including the calculation of reduced energy use as a result of the energy efficiency provided by the system, social indicator including additional expendable income calculations [19] and environmental indicators including calculations depicting the benefits of reducing harmful emissions. Indicators used as an evaluation pattern in this work are aligned with existing legislative frameworks, specifically the methods and performance indicators presented in IEC 60300-3-3 'Dependability management Part 3-3: Application guide—Life Cycle Costing' [20], ISO 52016 [21] and the European Commission's Delegated Regulation No. 244/2012 (No. 244/2012) [22], proposed to assess the cost optimality of building efficiency when implementing the EU Directive for the Energy Performance of Buildings. Based on test results of the developed system, the analyses were accomplished by targeting multiple impacts that are affecting end users thereby the environment and society.

Analysis results illustrate that the developed building energy optimization system is a cost-effective solution to promote energy efficiency goals. Results of the indicators prove monetary benefits for the building occupants in terms of resource use, return on investment and social impact, as well as quantifiable benefits for easing the harmful effects of climate change phenomenon.

The research and development activity is accomplished within the 'Intelligent Building Energy Management System' research project, which is granted to EOS Sustainable Energy Solutions

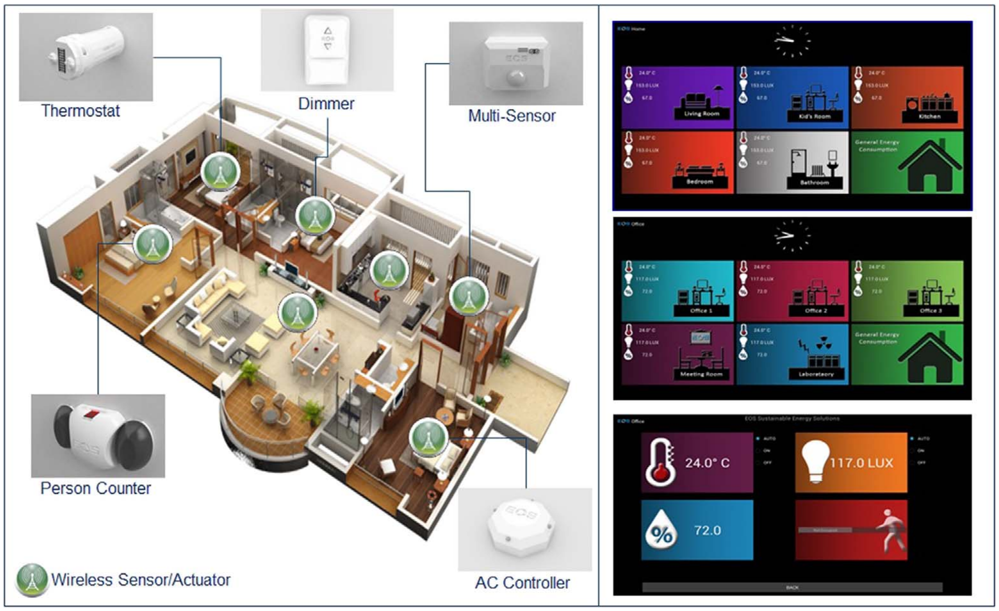

Figure 1. *Energy optimization system hardware and software: left section, ontology of the developed wireless sensors and actuators; right section, graphical user interfaces of the developed system (top, GUI for residential version; middle, GUI for office version; bottom, GUI for controlling comfort parameters).*

GmbH by the State of Lower Saxony Innovation Support Program (Niedersächsischen Innovationsförderprogramms). The project funded by Ministry for Economic Affairs, Labour and Transport of State of Lower Saxony-Germany (Niedersächsisches Ministerium für Wirtschaft, Arbeit und Verkehr), Ministry for Environment, Energy and Climate Protection of State of Lower Saxony-Germany (Niedersächsisches Ministerium für Umwelt, Energie und Klimaschutz), Investment and Support Bank of State of Lower Saxony Nbank (Investitions- und Förderbank Niedersachsen—NBank) and European Union between the years 2014 and 2018.

1.1. Energy optimization system

Considering the different aspects of various disciplines, the developed system seen in Figure 1 is designed to provide the following:

1) Seamless, dynamic, end-to-end network composition and service operation through sensor and actuator hardware,
2) Management of large-scale complex networks, services and mobile users through introducing new network and management approaches,
3) Novel, constraint-based preference models and optimization algorithms, which support the configuration, adaptation and servicing of smart buildings and the network that manage them,
4) A system architecture that supports scale-free composition of service coalitions with managed operation across several administrative and business domains,
5) Better value to customers in terms of efficiency, return of investment and cost/benefit ratios,
6) Modular development approach for possible future expansion and upgrades.

The developed system consists of 14 different network embedded hardware and 1 energy optimization software. The list of the system components are provided in Table 1 below.

1.2. System tests

In order to evaluate the compliance of the integrated system with the corresponding requirements, the developed system has been deployed into two different test buildings located in Hannover, Germany.

The first test building is located at the EOS GmbH—Technology Centre in 'Wissensschaftspark Hollerithallee 17 30419' in Hannover, Germany, which is used as an office building.

This appropriately selected sample office building, which is a living laboratory with real occupants, is composed of four zones. These are circulation hallway, two office spaces and a meeting space for common use as given in Figure 2.

The developed system is further tested in a renovated old residential building located at the 'Ernststr. 17 30559' in Hannover, Germany, as given in Figure 3 during the periods of 2016 and 2017.

This test building is composed of five zones. These are circulation hallway, kitchen, living room, bed bedroom and a bathroom for general use.

The developed system's wireless sensors, actuators and meters are deployed in these two different test buildings. Moreover, EOS gateways are deployed to the circulation hallways of each building. Each zone is equipped with EOS Multi Sensor, EOS Window Sensor and EOS Person Counter. EOS Thermostats are deployed to each heating radiator. The circulation hallways are equipped

Table 1. *The list of system components.*

No.	Hardware, Software	Function
1	EOS Multisensor	Measurement of lighting, temperature, humidity and occupancy levels
2	EOS Door Sensor	Detects the status of doors whether they are opened or closed; provides data for on/off functions of air conditioner and heating controller
3	EOS Window Sensor	Detects the status of windows whether they are opened or closed; Provides data for on/off functions of air conditioner and heating controller
4	EOS Curtain/Blind Controller	Provides control functions for curtain/blinds
5	EOS Air Conditioner Controller	Optimizes air conditioner systems; brand independent solution; compatible with all types of AC Systems.
6	EOS Thermostat	Optimizes heating radiators
7	EOS Person Counter	Counts the number of occupants in a specific area/zone
8	EOS Florescent Dimmer	Optimizes the lighting level of the fluorescent type lighting systems
9	EOS Dimmer	Optimizes the lighting level of the conventional, energy saving and LED type lighting systems
10	EOS On–off Switch	Provides on/off functions for all type of electrical devices
11	EOS Meter	Real-time metering of electricity consumption
12	EOS Clamp Meter	Real-time metering of electricity consumption of specific devices/zones.
13	EOS Gateway	Provides wireless communication
14	EOS Tablet	Visualises GUIs to end user; used as a control panel for the system
15	EOS Optimization Software	Energy optimization system software

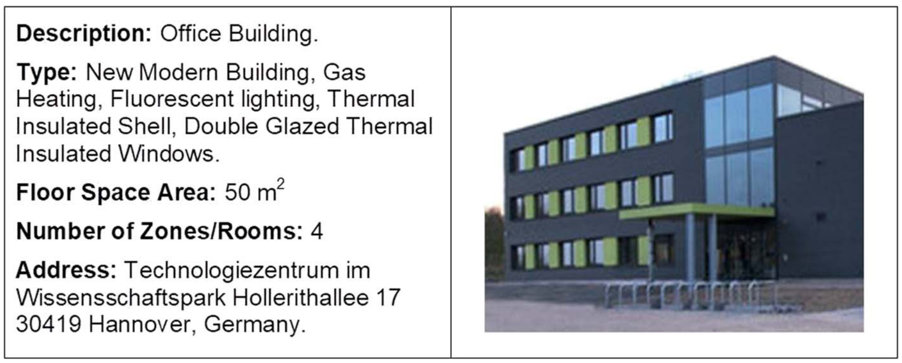

Figure 2. *Test Building 1—office building.*

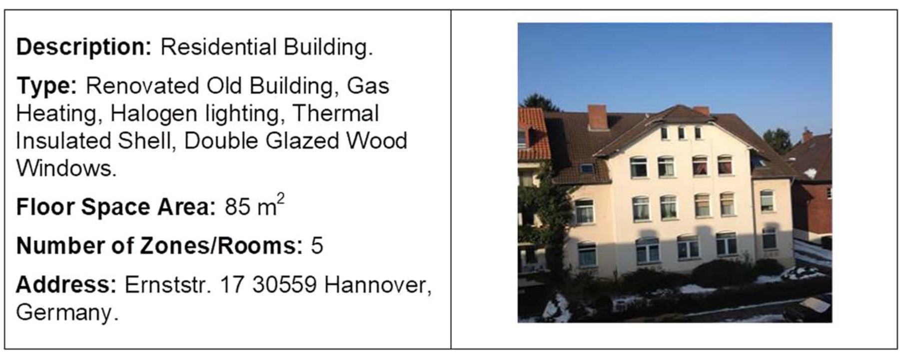

Figure 3. *Test Building 2—residential building.*

with EOS Fluorescent Dimmers. EOS Dimmers are deployed to zones with conventional bulb and energy saving mini fluorescent lighting systems. The main living/meeting rooms are also equipped with EOS Door Sensors, EOS On–Off Switches and EOS Air Conditioner Controllers.

The electricity is being monitored at the main fuse panel through EOS Electricity Meters attached to electricity grid inlet cable. The wireless scheme provides a self-contained and practical wireless control system for heating, ventilation and lighting within these test buildings.

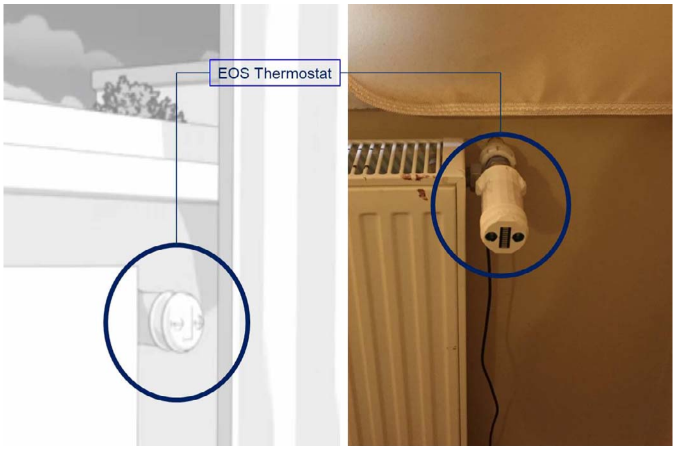

Figure 4. *Illustration and photo of the installed thermostat in the test building.*

1.3. Test results—Test Building 1: Technologiezentrum office

In order to validate the system requirements and targeted energy savings, system software and hardware are integrated and deployed to the Technologiezentrum office building with real occupants in Germany. Test procedures and results for the office building namely 'Test Building 1' are explained below.

Tested parameters:

- Building heating/cooling systems are controlled by EOS AC Controller:
  - One air conditioner (Airfel AP09–3102/R2 Cooling: 9000BTU/h Heating: 9000BTU/h) with cooling and heating functionality
- Building heating systems are controlled by EOS Thermostat (Please see figure 4)
  - Four double panel double convector radiator for heating functionality
    - Office 1 (600 × 1400mm, 8545 BTUs, 2503 W)
    - Office 2 (600 × 1400mm, 8545 BTUs, 2503 W)
    - Meeting Room (2 × 600 × 1800mm, 10987 BTUs, 3218 W)
- Building lighting systems are controlled by EOS Dimmer and EOS Fluorescent Dimmer:
  - 13 lights with energy saving light bulbs (Philips 40W Dimmable)
  - Two lights with energy saving fluorescent bulbs (Philips 60 W)
- Office appliances connected to EOS On–Off Switch:
  - 8 HP Pavilion 23 Inch Xi Monitor
  - 8 HP Pavilion Intel-Core i7 Desktop PC
  - One HP Office Jet 7500A Printer
  - One Brother MFC-J5910W Printer

Test procedures:
For each period, the following procedure applied:

1. Heating/cooling systems, lighting systems and office appliances are connected to EOS Energy Optimization System.
2. Heating/cooling systems, lighting systems and office appliances are connected to a separate electricity meter.
3. Measured 'Outside Temperature, and Inside Temperature' are logged into the table.
4. Total real electricity consumption of the connected building systems is measured while EOS System is not functioning (Test Name: Default Test). Measured electricity consumption is logged into the table (please see kW/h values provided in tables).
5. Total real electricity consumption of the building systems is measured while EOS System is functioning (Test Name: Test 1). Measured electricity consumption is logged into the table (please see kW/h values provided in tables).
6. Test values are compared with the most recent 'Default Test' values.
7. Occupancy levels, behavioral patterns of the occupants, internal and external environmental conditions are correlated with the performance of the system. In order to minimize the discrepancy between the default test conditions and the tested conditions, hourly measured energy savings are calculated and logged into the table (please see Energy Saving column provided in Table 2).
8. Daily average energy savings are calculated and logged into the table (please see Daily Energy Saving Average column provided in Table 2).

The system tests were conducted in Technlogiezentrum office spaces with the deployment of initial system prototypes. Tests were carried out in different seasons in order to evaluate the system's performance under different weather conditions. Also, system's software updates and hardware upgrades were made during the R&D life cycle. The average energy efficiency measured for the developed system between the years 2014 and 2015 is 30.32% (please see Table 2 and Figure 5).

1.4. Test results—Test Building 2: residential building

In order to validate the system requirements and targeted energy savings, indigenously developed system software and hardware are integrated for function tests then deployed to a renovated old residential building with real occupants in Hannover, Germany. Test procedures and results for the residential building are explained below.

Tested parameters:

- Building heating/cooling systems are controlled by EOS AC Controller:
  - One air conditioner (Siemens, with cooling and heating functionality)
- Building heating systems are controlled by EOS Thermostat:

Table 2. *Sample test results—Test Building 1: Technologiezentrum office.*

Test name: Technologiezentrum													
Date	Start time	End time	Test name	Outside temperature (celsius)	Inside temperature (celsius)	A/C set value (celsius)	Dimmer value (%)	Temperature comfort parameter (celsius)	Lighting comfort parameter (LUX)	On–off switch mode	Energy consumption (KW/h)	Energy saving (%)	Daily energy saving average (%)
3 February 2014	9:00	9:59	Default test	−0.5	16	Manuel (3rd level)	Manuel 100%	-	-	Manuel ON	1.926	N.A	32.64
	10:00	10:59	Test 1	0.2	18	EOS_Auto_Mode	EOS_Auto_Mode	25	200	EOS_Auto_Mode	1.314	31.78	
	11:00	11:59	Test 2	0.4	20	EOS_Auto_Mode	EOS_Auto_Mode	25	200	EOS_Auto_Mode	1.316	31.67	
	12:00	12:59	Default test	1.8	22	Manuel (3rd level)	Manuel 100%	-	-	Manuel ON	1.989	N.A	
	13:00	13:59	Test 3	2.6	22	EOS_Auto_Mode	EOS_Auto_Mode	25	200	EOS_Auto_Mode	1.308	34.24	
	14:00	14:59	Test 4	3.4	23	EOS_Auto_Mode	EOS_Auto_Mode	25	200	EOS_Auto_Mode	1.313	33.99	
	15:00	15:59	Default test	2.7	22	Manuel (3rd level)	Manuel 100%	-	-	Manuel ON	1.955	N.A	
	16:00	16:59	Test 5	1.9	22	EOS_Auto_Mode	EOS_Auto_Mode	25	200	EOS_Auto_Mode	1.326	32.17	
	17:00	17:59	Test 6	1.2	21	EOS_Auto_Mode	EOS_Auto_Mode	25	200	EOS_Auto_Mode	1.330	31.97	
7 April 2014	9:00	9:59	Default test	14.4	19	Manuel (3rd level)	Manuel 100%	-	-	Manuel ON	1.938	N.A	29.34
	10:00	10:59	Test 1	14.8	24	EOS_Auto_Mode	EOS_Auto_Mode	23	200	EOS_Auto_Mode	1.358	29.93	
	11:00	11:59	Test 2	15.2	24	EOS_Auto_Mode	EOS_Auto_Mode	23	200	EOS_Auto_Mode	1.364	29.62	
	12:00	12:59	Default test	15.6	24	Manuel (2nd level)	Manuel 100%	-	-	Manuel ON	1.913	N.A	
	13:00	13:59	Test 3	17.8	23	EOS_Auto_Mode	EOS_Auto_Mode	23	200	EOS_Auto_Mode	1.332	30.37	
	14:00	14:59	Test 4	18.7	23	EOS_Auto_Mode	EOS_Auto_Mode	23	200	EOS_Auto_Mode	1.336	30.16	
	15:00	15:59	Default test	18.9	24	Manuel (1st level)	Manuel 100%	-	-	Manuel ON	1.908	N.A	
	16:00	16:59	Test 5	20.2	23	EOS_Auto_Mode	EOS_Auto_Mode	23	200	EOS_Auto_Mode	1.371	28.14	
	17:00	17:59	Test 6	20.5	23	EOS_Auto_Mode	EOS_Auto_Mode	23	200	EOS_Auto_Mode	1.377	27.83	
2 June 2014	9:00	9:59	Default test	11.8	17	Manuel (3rd level)	Manuel 100%	-	-	Manuel ON	1.928	N.A	29.90
	10:00	10:59	Test 1	15.6	21	EOS_Auto_Mode	EOS_Auto_Mode	23	200	EOS_Auto_Mode	1.347	30.13	
	11:00	11:59	Test 2	17.2	23	EOS_Auto_Mode	EOS_Auto_Mode	23	200	EOS_Auto_Mode	1.353	29.82	
	12:00	12:59	Default test	17.8	24	Manuel (2nd level)	Manuel 100%	-	-	Manuel ON	1.913	N.A	
	13:00	13:59	Test 3	18.2	24	EOS_Auto_Mode	EOS_Auto_Mode	23	200	EOS_Auto_Mode	1.336	30.16	
	14:00	14:59	Test 4	18.5	23	EOS_Auto_Mode	EOS_Auto_Mode	23	200	EOS_Auto_Mode	1.342	29.85	
	15:00	15:59	Default test	18.7	24	Manuel (1st level)	Manuel 100%	-	-	Manuel ON	1.908	N.A	
	16:00	16:59	Test 5	19.1	24	EOS_Auto_Mode	EOS_Auto_Mode	23	200	EOS_Auto_Mode	1.339	29.82	
	17:00	17:59	Test 6	19.6	23	EOS_Auto_Mode	EOS_Auto_Mode	23	200	EOS_Auto_Mode	1.343	29.61	
28 April 2015	9:00	9:59	Default test	11.5	18	Manuel (3rd level)	Manuel 100%	-	-	Manuel ON	1.935	N.A	30.22
	10:00	10:59	Test 1	12.9	24	EOS_Auto_Mode	EOS_Auto_Mode	23	200	EOS_Auto_Mode	1.344	30.54	
	11:00	11:59	Test 2	14.5	24	EOS_Auto_Mode	EOS_Auto_Mode	23	200	EOS_Auto_Mode	1.349	30.28	
	12:00	12:59	Default test	15.2	24	Manuel (2nd level)	Manuel 100%	-	-	Manuel ON	1.913	N.A	
	13:00	13:59	Test 3	15.9	23	EOS_Auto_Mode	EOS_Auto_Mode	23	200	EOS_Auto_Mode	1.328	30.58	
	14:00	14:59	Test 4	16.5	23	EOS_Auto_Mode	EOS_Auto_Mode	23	200	EOS_Auto_Mode	1.335	30.21	
	15:00	15:59	Default test	16.8	24	Manuel (1st level)	Manuel 100%	-	-	Manuel ON	1.908	N.A	
	16:00	16:59	Test 5	17.6	23	EOS_Auto_Mode	EOS_Auto_Mode	23	200	EOS_Auto_Mode	1.336	29.98	
	17:00	17:59	Test 6	18	23	EOS_Auto_Mode	EOS_Auto_Mode	23	200	EOS_Auto_Mode	1.341	29.72	

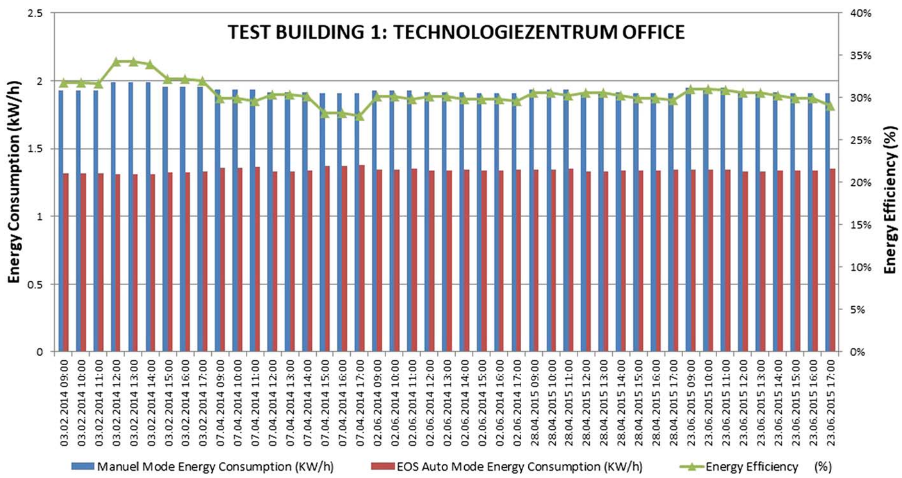

Figure 5. *Energy optimization test results for the office building.*

– Four double panel double convector radiator for heating functionality.

■ Living room (600 × 1800mm, 10987 BTUs, 3218 W)
■ Bed room (600 × 1800mm, 10987 BTUs, 3218 W)
■ Kitchen (600 × 1400 mm, 8545 BTUs, 2503 W)
■ Bathroom (600 × 1000mm, 6104 BTUs, 1788 W)

• Building lighting systems are controlled by EOS Dimmer and EOS Fluorescent Dimmer:

– Five lights with energy saving light bulbs (Philips Tornado 20 W Dimmable),

■ Living room (Philips Tornado 20 W Dimmable)
■ Bed room (Philips Tornado 20 W Dimmable)
■ Kitchen (Philips Tornado 20 W Dimmable)
■ Bathroom (Philips Tornado 20 W Dimmable)
■ Hallway (Philips Fluorescent 60 W Bulb)

– Two stand-alone lights with energy saving light bulbs (Philips Tornado 20 W Dimmable)

• Home appliances connected to EOS On–Off Switch

■ Samsung 55 K6000 55" Full HD LED TV
■ Harman Kardon HD COM 1515 Home Theatre System
■ Siemens iQ 500 Dishwasher
■ Bosch Serie 4 Washing Machine
■ Bosch Serie 4 Refrigerator
■ 27 Inch Apple iMac
■ HP Office Jet 7500 A Printer,
■ HP Server Pavilion G6
■ Electric Water Boiler (Kettle)
■ Bosch Steam Iron TDA 2301

Test procedures:
For each period, the following procedure applied:

1. Heating/cooling systems, lighting systems and home appliances are connected to EOS Energy Optimization System.
2. Heating/cooling systems, lighting systems and home appliances are connected to a separate electricity meter.
3. Measured 'Outside Temperature, Inside Humidity Level and Inside Temperature' are logged into the table.
4. Total real electricity consumption of the connected building systems is measured while EOS System is not functioning (Test Name: Default Test). Measured electricity consumption is logged into the table (please see kW/h values provided in Table 3).
5. Total real electricity consumption of the building systems is measured while EOS System is functioning (Test Name: Test 1). Measured electricity consumption is logged into the table (please see kW/h values provided in Table 3).
6. Test values are compared with the most recent 'Default Test' values.
7. Occupancy levels, behavioral patterns of the occupants, internal and external environmental conditions are correlated with the performance of the system. In order to minimize the discrepancy between the default test conditions and the tested conditions, hourly measured energy savings are calculated and logged into the table (please see Energy Saving column provided in Table 3).
8. Daily average energy savings are calculated and logged into the table (please see Daily Energy Saving Average column provided in Table 3).

Based on the tests applied in an appropriately selected residential test building located at Kirchrode, Hannover, Germany, an average of 37.53% energy saving result is logged in the period of 9 February 2017 to 6 July 2017. (Please see Table 3 and Figure 7) Test periods have been selected based on seasonal changes and new updates on the system.

1.5. Economic, social and environmental impact analyses

In this section, multiple impacts of the indigenously developed building energy optimization system are analyzed.

Table 3. *Test result samples—Test Building 2: residential building.*

Date	Start time	End time	Test name	Outside temperature (celsius)	Inside temperature (celsius)	A/C set value (celsius)	Dimmer value (%)	Temperature comfort parameter (celsius)	Heating thermostat mode	Energy consumption heating (KW/h)	Lighting comfort parameter (LUX)	On–off switch mode	Energy consumption lighting (KW/h)	Energy saving (%)	Daily energy saving average (%)
09/02/2017	9:00	9:59	Default test	4	16	Manuel 19	Manuel 100%	-	Manuel On		-	Manuel ON	0.856	N.A	34.60
	10:00	10:59	Test 1	5	23	EOS_Auto_Mode	EOS_Auto_Mode	23	EOS_Auto_Mode		200	EOS_Auto_Mode	0.580	32.24	
	11:00	11:59	Test 2	5	23	EOS_Auto_Mode	EOS_Auto_Mode	23	EOS_Auto_Mode		200	EOS_Auto_Mode	0.550	35.75	
	12:00	12:59	Default test	6	24	Manuel 19	Manuel 100%	-	Manuel On		-	Manuel ON	0.770	N.A	
	13:00	13:59	Test 3	6	23	EOS_Auto_Mode	EOS_Auto_Mode	23	EOS_Auto_Mode		200	EOS_Auto_Mode	0.490	36.36	
	14:00	14:59	Test 4	6	23	EOS_Auto_Mode	EOS_Auto_Mode	23	EOS_Auto_Mode		200	EOS_Auto_Mode	0.480	37.66	
	15:00	15:59	Default test	6	24	Manuel 19	Manuel 100%	-	Manuel On		-	Manuel ON	0.775	N.A	
	16:00	16:59	Test 5	6	23	EOS_Auto_Mode	EOS_Auto_Mode	23	EOS_Auto_Mode		200	EOS_Auto_Mode	0.480	38.06	
	17:00	17:59	Test 6	6	23	EOS_Auto_Mode	EOS_Auto_Mode	23	EOS_Auto_Mode		200	EOS_Auto_Mode	0.490	36.77	
	18:00	18:59	Default test	5	24	Manuel 19	Manuel 100%	-	Manuel On		-	Manuel ON	0.900	N.A	
	19:00	19:59	Test 7	5	23	EOS_Auto_Mode	EOS_Auto_Mode	23	EOS_Auto_Mode		200	EOS_Auto_Mode	0.600	33.33	
	20:00	21:00	Test 8	5	23	EOS_Auto_Mode	EOS_Auto_Mode	23	EOS_Auto_Mode		200	EOS_Auto_Mode	0.610	32.22	
02/03/2017	9:00	9:59	Default test	4	19	Manuel 28	Manuel 100%	-	Manuel On		-	Manuel ON	0.910	N.A	30.11
	10:00	10:59	Test 1	4	24	EOS_Auto_Mode	EOS_Auto_Mode	25	EOS_Auto_Mode		200	EOS_Auto_Mode	0.600	34.07	
	11:00	11:59	Test 2	5	24	EOS_Auto_Mode	EOS_Auto_Mode	25	EOS_Auto_Mode		200	EOS_Auto_Mode	0.580	36.26	
	12:00	12:59	Default test	6	24	Manuel 28	Manuel 100%	-	Manuel On		-	Manuel ON	0.760	N.A	
	13:00	13:59	Test 3	7	24	EOS_Auto_Mode	EOS_Auto_Mode	25	EOS_Auto_Mode		200	EOS_Auto_Mode	0.550	27.63	
	14:00	14:59	Test 4	7	24	EOS_Auto_Mode	EOS_Auto_Mode	25	EOS_Auto_Mode		200	EOS_Auto_Mode	0.530	30.26	
	15:00	15:59	Default test	6	24	Manuel 28	Manuel 100%	-	Manuel On		-	Manuel ON	0.790	N.A	
	16:00	16:59	Test 5	5	24	EOS_Auto_Mode	EOS_Auto_Mode	25	EOS_Auto_Mode		200	EOS_Auto_Mode	0.570	27.85	
	17:00	17:59	Test 6	4	24	EOS_Auto_Mode	EOS_Auto_Mode	25	EOS_Auto_Mode		200	EOS_Auto_Mode	0.590	25.32	
	18:00	18:59	Default test	3	24	Manuel 28	Manuel 100%	-	Manuel On		-	Manuel ON	0.820	N.A	
	19:00	19:59	Test 7	3	24	EOS_Auto_Mode	EOS_Auto_Mode	25	EOS_Auto_Mode		200	EOS_Auto_Mode	0.600	26.83	
	20:00	21:00	Test 8	2	24	EOS_Auto_Mode	EOS_Auto_Mode	25	EOS_Auto_Mode		200	EOS_Auto_Mode	0.610	25.61	
03/04/2017	9:00	9:59	Default test	3	26	Manuel 19	Manuel 100%	-	Manuel On		-	Manuel ON	0.870	N.A	38.18
	10:00	10:59	Test 1	3	24	EOS_Auto_Mode	EOS_Auto_Mode	23	EOS_Auto_Mode		200	EOS_Auto_Mode	0.580	32.24	
	11:00	11:59	Test 2	5	24	EOS_Auto_Mode	EOS_Auto_Mode	23	EOS_Auto_Mode		200	EOS_Auto_Mode	0.540	36.92	
	12:00	12:59	Default test	6	24	Manuel 19	Manuel 100%	-	Manuel On		-	Manuel ON	0.790	N.A	
	13:00	13:59	Test 3	7	23	EOS_Auto_Mode	EOS_Auto_Mode	23	EOS_Auto_Mode		200	EOS_Auto_Mode	0.470	38.96	
	14:00	14:59	Test 4	7	23	EOS_Auto_Mode	EOS_Auto_Mode	23	EOS_Auto_Mode		200	EOS_Auto_Mode	0.460	40.26	
	15:00	15:59	Default test	7	24	Manuel 19	Manuel 100%	-	Manuel On		-	Manuel ON	0.760	N.A	
	16:00	16:59	Test 5	8	23	EOS_Auto_Mode	EOS_Auto_Mode	23	EOS_Auto_Mode		200	EOS_Auto_Mode	0.460	39.47	
	17:00	17:59	Test 6	7	23	EOS_Auto_Mode	EOS_Auto_Mode	23	EOS_Auto_Mode		200	EOS_Auto_Mode	0.480	36.84	
	18:00	18:59	Default test	6	24	Manuel 19	Manuel 100%	-	Manuel On		-	Manuel ON	0.830	N.A	
	19:00	19:59	Test 7	5	23	EOS_Auto_Mode	EOS_Auto_Mode	23	EOS_Auto_Mode		200	EOS_Auto_Mode	0.500	39.76	
	20:00	21:00	Test 8	4	23	EOS_Auto_Mode	EOS_Auto_Mode	23	EOS_Auto_Mode		200	EOS_Auto_Mode	0.490	40.96	

The analyses are accomplished within the framework of four main indicators. These are (1) economic indicators including calculations of life cycle cost method, (2) resource use indicators including the calculation of reduced energy use, as a result of the energy efficiency provided by the system, (3) social indicators including additional disposable income calculations and (4) environmental indicators including calculations depicting the benefits of reducing harmful emissions.

Indicators used as an evaluation pattern in this work are aligned with existing legislative frameworks, specifically the methods and performance indicators presented in IEC 60300-3-3 'Dependability management Part 3-3: Application guide—Life Cycle Costing', ISO 52016 and the European Commission's Delegated Regulation No. 244/2012 (No. 244/2012) proposed to assess the cost optimality of building efficiency when implementing the EU Directive for the Energy Performance of Buildings.

Developed system increases energy saving consciousness and reduces behavioral energy consumption mistakes of the building occupants. Occupants who have relatively low energy saving consciousness tend to make more mistakes, which increases energy consumption. This instance causes relatively higher energy saving levels for the developed system.

In order to eliminate the possible deviations in the test results due to differences among the energy saving conscious end users and other users, the analyses are made based on an average of 25% energy savings.

1.6. Economic impact indicators

Economic impact analysis is performed based on the cost–benefit comparison using life cycle cost analysis method. This analysis is used to evaluate the economic feasibility of the developed system, to examine cash flows throughout the system's lifecycle, to help comparing different technologies similar to the developed system that provide the same service.

1.7. Life cycle cost method

In this context, the life cycle cost method is applied based on the IEC 603003-3 'Dependability Management Part 3-3: Application guide—Life cycle costing'.

Based on the IEC 60300-3-3 application guide, the life cycle of an element/system is sub-divided into seven cost-causing phases:

Concept/definition: costs that occur associated with the concept during the specification or planning phase.

Design/development: costs addressing design, documentation and engineering that are combined.

Manufacturing: these costs cover the expenses for production and sales of the product.

Installation: costs occurred on the jobsite by installation before operation of the system. Operation: costs of the operation of the whole system. These costs also include expenses for power losses of overhead lines or transformers, controlling and staff training.

Maintenance: includes the maintenance expenditures due to different approaches e.g. time based, condition based or corrective.

Disposal: costs for work, material and disposal in conjunction with the rebuild of the existing system.

In many cases, different elements of costs are combined into (a) investment, (b) operating and (c) recycling costs.

The investment costs comprise of (a) concept/definition, (b) design/development and (c) manufacturing and (d) installations are in return to the operating costs (operation, maintenance). The installation costs can be counted under the investment or the operating costs.

In order to perform a more precise cost assessment, a further differentiation between operational and maintenance costs should be made. Such a differentiation permits an easier benchmarking of different maintenance approaches, as these turn out to be the main cost drivers for the analysis.

Further data must be also considered for the calculation of the life cycle cost of a product or service, for example, (a) interest rate, (b) inflation rate and (c) useful lifetime of the equipment.

1.8. Life cycle cost equations

Life cycle costs can be calculated with the combination of several equations as given below. In order to simplify, each cost item can be calculated separately and combine under the main life cycle cost equation.

In this context, associated equations are provided below:

LCC—life cycle cost in present value, II—initial investment, OM—operating and maintenance costs, R—repair and replacement costs, RES—salvage costs, (salvage value).

$$LCC = II + OM + R - RES \qquad \text{(Equation 1)}$$

The present value PV of an investment with a current value CV, with N—number of years and with i—interest rate.

$$PV = CV\,\frac{1-(1+i)^{-N}}{i} \qquad \text{(Equation 2)}$$

The equation for calculating the present value of the operating and maintenance (OM) costs that will occur during the whole life cycle of a system is given in equation 3. The value of OMA refers to the annual operation and maintenance cost and can be taken as 1% of the initial investment.

$$OM = OMA\,\frac{1-(1+i)^{-N}}{i} \qquad \text{(Equation 3)}$$

For repair and replacement (R) costs, the service life of each component is considered separately according to replacement date based on the service life of the whole system. As an example in Equation 4, the cost of updating EOS System Software is reduced to its present value. The life cycle of other system components of the EOS Energy Optimization System is considered as 10 years.

$$R = EOSS\left(\frac{1}{1+i}\right)^{N} \quad \text{(Equation 4)}$$

Equation 5 is used when calculating the present value of the total salvage cost (Res). Here, SV value is the scrap value and taken as one tenth of the initial investment.

$$\mathrm{Res} = \mathrm{SV}\left(\frac{1}{1+\mathrm{i}}\right)^{\mathrm{N}} \quad \text{(Equation 5)}$$

After the life cycle cost (LCC) is calculated, the annual usage cost (ASC) can be found by Equation 6.

$$ASC = \frac{(LCC).i}{1-(1+i)^{-N}} \quad \text{(Equation 6)}$$

The payback period (PP) (equation 7) is calculated by dividing the annual usage cost by the total amount of energy saved per year, which shows us how many years needed that the system would pay for itself.

$$\mathrm{PP} = \frac{\mathrm{ASC}}{\mathrm{E}} \quad \text{(Equation 7)}$$

1.9. Social impact indicator

Social improvements are made by increasing energy efficiency and reducing harmful GHG emissions. These can be classified under several social indicators, such as improving air quality, comfort improvements, health, increasing expendable income and poverty reduction [18]. However, most of these are context specific, such as indoor air quality or higher comfort levels. As home automation becomes more common and datasets from indoor sensors emerge, statistics that can be expected as plausible indicators may evolve. Therefore, the analysis focused in this study is on a single social indicator; expendable additional income (EAI) for energy-poor households (Equation 8). The indicator is based on the principle that the upfront investment will be provided by social benefits or state subsidies.

$$\mathrm{EAI} = \sum\nolimits_{\mathrm{t}=1}^{\mathrm{T}}\left(\frac{\Delta\mathrm{OMt}}{(1+\mathrm{r})\mathrm{t}}\right) \quad \text{(Equation 8)}$$

1.10. Environmental impact indicator

The environmental benefit of the developed system is calculated by using energy specific emission impact conversion factors of German electricity mix, which are prepared by the German Environmental Protection Agency [23].

The equation used for the calculation is given below (equation 9).

$$\text{Environmental Impact} = \mathrm{ec}\left[\sum\nolimits_{\mathrm{t}=1}^{\mathrm{T}}(\mathrm{Eref}-\mathrm{Ei})\right] \quad \text{(Equation 9)}$$

The annex in Equation 9 indicates the emission coefficient (ec) taken from Table 4 and shows the emission values when the system is not used (Eref) and the emission values that will occur if the system is used (Ei).

1.11. Economic impact analysis results

Energy prices and energy consumption facts (typical practice) of residential and office buildings are as follows:

- Average electricity price in Hannover [24]: €0.283 kWh
- Average natural gas price in Hannover [25]: €0.0619 kWh
- Average electricity consumption for residential and office buildings [26]: 42 kWh/m^2 per annum.
- Average fossil fuel (Gas) consumption for residential and office buildings [26]: 172 kWh/m^2 per annum.

Calculation of the energy consumption costs for residential and office buildings:

- Electricity cost: €0.283 kWh∗42 kWh/m^2 = 11.89€/m^2 per annum.
- Natural gas cost: €0.0619 kWh∗172 kWh/m^2 = 10.65€/m^2 per annum.
- Total energy consumption cost = 22.54€/m^2 per annum.

Total energy consumption costs based on m^2:

- Test Building 1—office building: 50m^2 ∗ 22.54€/m^2 = 1127.00 Euro per annum.
- Test Building 2—residential building: 80m^2 ∗ 22.54€/m^2 = 1803.20 Euro per annum.

The benefit—when 25% of energy savings can be achieved:

- Test Building 1—office building: €1127.00 ∗ 25% = 281.75 Euro monetary benefit per annum.
- Test Building 2—residential building: €1803.20 ∗ 25% = 450.80 Euro monetary benefit per annum.

1.12. Life cycle cost method

The life cycle cost method is processed separately for Test Building 1 and Test Building 2 as shown in Table 5.

- Interest rates: % 4 annum [27].
- System life cycle period: 10 years.

As provided in Table 4, the end user invests 700 Euro (system sales price—cost of the system to the end user) for an office building composed of four zones (rooms) with 50 m^2 and for the five zones with 80 m^2 net usage area residential the required initial investment is 1000 Euro. In both cases, the payback period is less

Table 4. *Emission factors due to energy use.*

Emission type	Unit	Emission coefficient (2019)
Sulphur dioxide	g/kWh	0.224
Nitrogen dioxide	g/kWh	0.408
Particle substance	g/kWh	0.011
PM_{10}	g/kWh	0.010
Carbon monoxide	g/kWh	0.184
CO_2	Kg/kWh	0.468
NO	g/kWh	0.013
CH_4	g/kWh	0.167
Volatile organic compounds	g/kWh	0.015
Mercury	mg/kWh	0.008

than 3 years, for the office space the payback period is 2.74 years and for the residential flat this is 2.45 years.

1.13. Payback period analysis

Payback period and end user monetary benefit analyses are calculated using the life cycle cost method. The results are provided in Table 6 below. Ten years of service life and 25% of energy saving rate are used for calculations. As a result of the analyses, payback period of the developed system for office buildings and residential buildings are 2.74 and 2.45 years, respectively. Since the service life of the developed system is 10 years, total usage period after payback period is 7.26 years for offices and 7.55 years for residential buildings.

1.14. Social impact analysis results

The social impact of the developed system is calculated using the additional expendable income method, considering that it provides a more objective evaluation among different social indicators such as health, comfort and air quality. With this analysis, it is aimed to make a comparison in terms of poverty reduction by calculating the additional expendable income with the usage of the developed system for a period of 10 years. In the calculations, it is assumed that the system saves an average of 25% energy and the annual average inflation rate in Germany for the years 2017, 2018 and 2019 [28] is considered as 1.67% per annum. As can be seen in Graphic 2, year 0 shows the initial investment cost of the system, while the remaining years depict the annual amount of additional expendable income which is gained by energy savings of the developed system.

The developed system generates end users 2118 Euros of total additional disposable income for a 50 m^2 four zones of office building and 3862 Euros of total additional disposable income for an 80 m^2 five zones of residential based on the pessimistic saving scenario rate of 25%. If the test average of 35% of efficiency rate, which is observed mainly in two sample buildings, would be used instead of pessimistic scenario rate, the available additional income will be more than the above figures. As a result of the energy efficiency of the developed system in different building types, it is foreseen that the additional income can be spent for nutrition, education and health expenditures, which contributes to relative reduction of poverty in society.

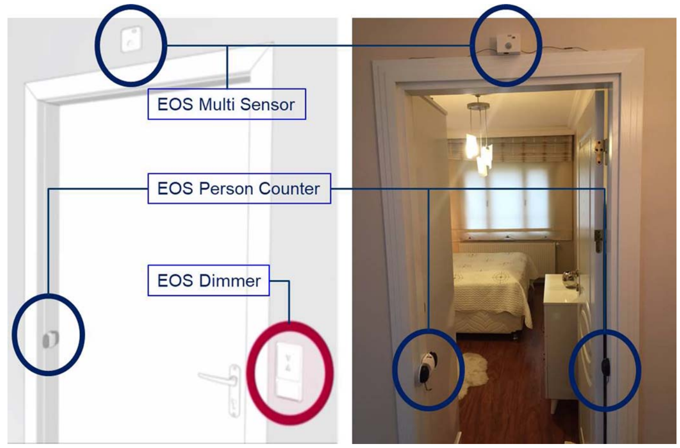

Figure 6. *Illustration and photo of the installed system in the test building.*

1.15. Environmental impact analysis results

The calculation method specified in the environmental indicators section is used to determine the environmental benefit to be provided by the developed system. This calculation is made by taking into consideration of 25% of average energy saving rate.

The benefit to be provided by the system in terms of resource consumption is shown in Table 7. Accordingly, it is calculated that the system can provide 2675 kWh and 4280 kWh of energy savings per location annually.

Figure 9 indicates the change in annual emission values through the utilization of the developed optimization system in the sample buildings. Columns 1 and 3 depict the emission values that will occur without the system, respectively, while Columns 2 and 4 show the emission values that will occur if the developed optimization system is utilised in those test buildings.

Considering only the CO_2 emission levels, the system prevents 1252 kg of carbon dioxide emission into the atmosphere for a 50 m^2 office building and 2003 kg for an 80 m^2 residential flat. In addition to the positive effect of decreasing carbon levels on global warming, the system improves air quality by reducing volatile particles and other harmful emissions. This will also contribute positively to human health and quality of life.

2. CONCLUSION

In this work, economic, social and environmental impacts of an indigenously developed cost-effective building energy optimization system are analyzed. The system is developed within the frame of the 'Intelligent Building Energy Management System' research project, which is funded by the State of Lower Saxony Germany—Innovation Support Program between 2014 and 2018. In order to perform the analysis, four indicators comprising different aspects of the developed system are considered. These are the

Table 5. *Life cycle cost analyses.*

Building type	Actual value (€)	$PV = CV\,\frac{1-\left(1+i\right)^{-N}}{i}$	$OM = OMA\,\frac{1-\left(1+i\right)^{-N}}{i}$	$R = EOSS\left(\frac{1}{1+i}\right)^{N}$
Test Building 1—office	700.00 €	5,670.00 €	567.00 €	67.50€
Test Building 2—residential	1000.00 €	8,125.00 €	812.50€	67.50 €
Building Type	Actual value (€)	$Res = SV\left(\frac{1}{1+i}\right)^{N}$	$ASC = \frac{(LCC).i}{1-\left(1+i\right)^{-N}}$	$P\,P = \frac{ASC}{E}$
Test Building 1—office	700.00 €	47.30 €	772.53€	2.74 years
Test Building 2—residential	1000.00 €	67.50 €	1,103.40 €	2.45 years

Table 6. *End user monetary benefit.*

Building type	Current value (€)	Payback period according to the life cycle cost method (year)	Total usage period after payback period according to the life cycle cost method (year)	%25 Annual average energy savings (€)
Test Building 1: office building	700€	2.74	7.26	281.75 €
Test Building 2: residential building	1000 €	2.45	7.55	450.80 €

Table 7. *Resource consumption table.*

Building type	Energy consumption (kWh)	Energy consumption realized with EOS System (kWh)	Difference (kWh)
Office—50 m^2	10700	8025	2675
Apartment −85 m^2	17120	12840	4280

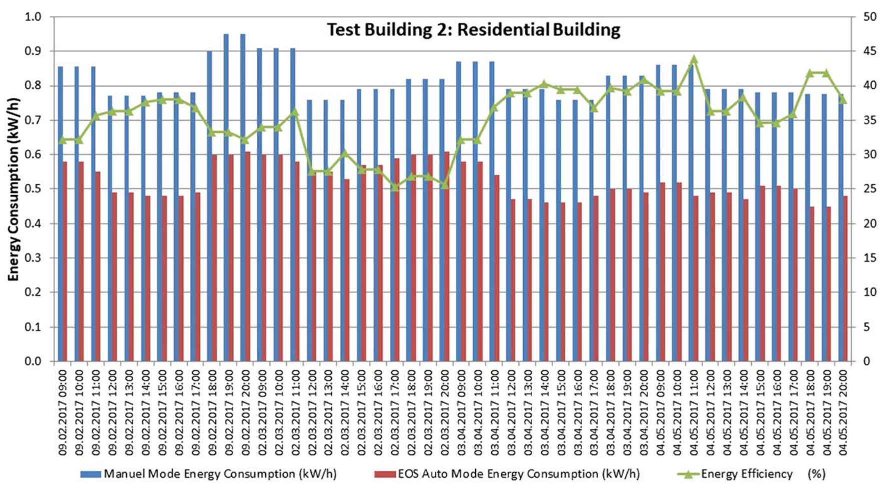

Figure 7. *Energy optimization test results for the residential building.*

following: (1) economic indicators, (2) resource use indicators, (3) social indicators and (4) environmental indicators. While determining these indicators, the IEC 60300-3-3 'Dependability management Part 3-3: Application guide—Life cycle costing', ISO 52016 and the European Union Building Energy Performance Regulation (No. 244/2012) are used for deriving the indicators.

The economic indicators include calculations of lifetime cost of the system to find out the return on investment, resource use indicators include the calculation of reduced energy use as the result of the energy efficiency provided by the system, social indicators target the additional expendable income calculations and environmental indicators address the calculations depicting the benefits of reducing harmful emissions.

The analysis results illustrate that the developed building energy optimization system can be considered as a cost-effective solution for promoting energy efficiency goals. Results of the multiple analyses prove monetary benefits for the building occupants in terms of resource use and return on investment.

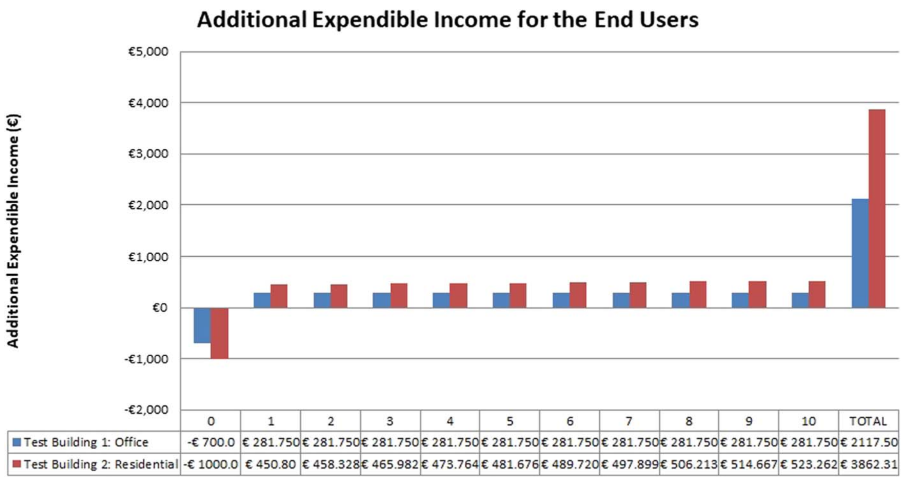

Figure 8. *Additional expendable income.*

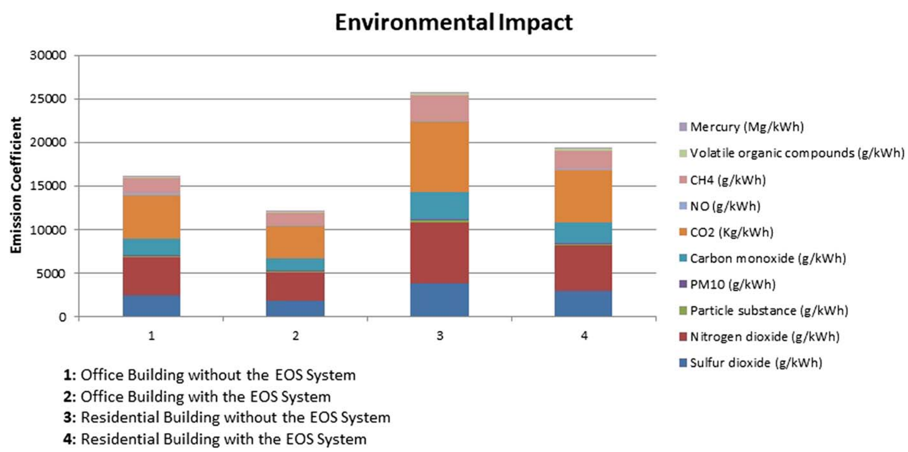

Figure 9. *Emission values.*

In addition, system has quantifiable social and environmental benefits.

The system investment to be made by the end user for an office and residential building yields a positive return on investment. Payback period of the initial investment cost of the system is less than 3 years.

The developed system generates 2118 Euros of net additional expendable income for the end users of a 50m^2 office building and 3867 Euros of net additional income for the residents of an 80 m^2 apartment flat based on energy efficiency rate of 25%. If this additional income is spent for nutrition, education and health care expenditures, this will contribute to relative reduction of poverty in society.

The developed system has positive impact on the environment. Considering the CO_2 emission levels, the system prevents 1252 kg of carbon dioxide emission into the atmosphere for a 50 m^2 office building and 2003 kg for an 80 m^2 residential flat. In addition to the positive effect on global warming by decreasing carbon emission levels, the system improves air quality by reducing volatile particles and other harmful emissions. This will also positively contribute to human health and quality of life.

ACKNOWLEDGEMENTS

The research described in this work is funded by the Ministry for Economic Affairs, Labour and Transport of State of Lower Saxony-Germany (Niedersächsisches Ministerium für Wirtschaft, Arbeit und Verkehr), Ministry for Environment, Energy and Climate Protection of State of Lower Saxony-Germany (Niedersächsisches Ministerium für Umwelt, Energie und Klimaschutz), Investment and Support Bank of State of Lower Saxony Nbank (Investitions- und Förderbank Niedersachsen—NBank) and the European Union. Project name: Intelligent Building Energy Management System (Intelligentes Gebäudeenergie Management System). Funding Program: State of Lower Saxony Innovation Support Program (Niedersächsischen Innovationsförderprogramms). Grant no: ZW3-80143818.

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