# LAPORAN AKHIR PENELITIAN TAHUN TUNGGAL

ID Proposal: 3039237c-bc07-43c5-9a8b-ce9e368829b3
Laporan Akhir Penelitian: tahun ke-2 dari 2 tahun

## 1. IDENTITAS PENELITIAN

### A. JUDUL PENELITIAN

| |
|---|
| Sistem Smart Grid Untuk Optimalisasi Pemakaian Daya Listrik Pada Perumahan Dan Gedung Dengan Pemanfaatan Energi Surya |

### B. BIDANG, TEMA, TOPIK, DAN RUMPUN BIDANG ILMU

| Bidang Fokus RIRN / Bidang Unggulan Perguruan Tinggi | Tema | Topik (jika ada) | Rumpun Bidang Ilmu |
|---|---|---|---|
| GREEN and SUSTAINABLE TECHNOLOGY | - | ENERGI BARU DAN TERBARUKAN yang meliputi: - (1) Pengembangan Bahan dasar untuk Pengembangan Energi Baru dan Terbarukan; (2) Pengembangan Konversi Energi; (3) Konservasi Energi | Teknik Elektro |

### C. KATEGORI, SKEMA, SBK, TARGET TKT DAN LAMA PENELITIAN

| Kategori (Kompetitif Nasional/ Desentralisasi/ Penugasan) | Skema Penelitian | Strata (Dasar/ Terapan/ Pengembangan) | SBK (Dasar, Terapan, Pengembangan) | Target Akhir TKT | Lama Penelitian (Tahun) |
|---|---|---|---|---|---|
| Penelitian Desentralisasi | Penelitian Dasar Unggulan Perguruan Tinggi | SBK Riset Dasar | SBK Riset Dasar | 3 | 2 |

## 2. IDENTITAS PENGUSUL

| Nama, Peran | Perguruan Tinggi/ Institusi | Program Studi/ Bagian | Bidang Tugas | ID Sinta | H-Index |
|---|---|---|---|---|---|
| ARYUANTO<br>Ketua Pengusul | Institut Teknologi Nasional Malang | Teknik Elektro | | 168447 | 6 |

|  |  |  |  |  |  |
|---|---|---|---|---|---|
| Ir CHOIRUL SALEH M.T<br>Anggota Pengusul 2 | Institut Teknologi Nasional Malang | Teknik Listrik | Membantu penelitian terkait manajemen energi listrik | 6151826 | 0 |
| Ir YUSUF ISMAIL NAKHODA M.T<br>Anggota Pengusul 1 | Institut Teknologi Nasional Malang | Teknik Elektro | Membantu peneitian terkait dengan energi baru terbarukan | 257098 | 4 |

### 3. MITRA KERJASAMA PENELITIAN (JIKA ADA)

Pelaksanaan penelitian dapat melibatkan mitra kerjasama, yaitu mitra kerjasama dalam melaksanakan penelitian, mitra sebagai calon pengguna hasil penelitian, atau mitra investor

| Mitra | Nama Mitra |
|---|---|

### 4. LUARAN DAN TARGET CAPAIAN

**Luaran Wajib**

| Tahun Luaran | Jenis Luaran | Status target capaian ( *accepted, published, terdaftar atau granted, atau status lainnya*) | Keterangan (*url dan nama jurnal, penerbit, url paten, keterangan sejenis lainnya*) |
|---|---|---|---|
| 2 | Publikasi Ilmiah Jurnal Internasional | accepted/published | Jurnal "Energies" |

**Luaran Tambahan**

| Tahun Luaran | Jenis Luaran | Status target capaian (*accepted, published, terdaftar atau granted, atau status lainnya*) | Keterangan (*url dan nama jurnal, penerbit, url paten, keterangan sejenis lainnya*) |
|---|---|---|---|
| 2 | Prosiding dalam pertemuan ilmiah Internasional | sudah terbit/sudah dilaksanakan | 2019 IEEE/ASME International Conference on Advanced Intelligent Mechatronics (AIM) |
| 2 | Hak Cipta | granted | - |
| 2 | Buku Hasil Penelitian | sudah terbit | Buku monograf tentang Home Energy Management Systems |

### 5. ANGGARAN

Rencana anggaran biaya penelitian mengacu pada PMK yang berlaku dengan besaran minimum dan maksimum sebagaimana diatur pada buku Panduan Penelitian dan Pengabdian kepada Masyarakat Edisi 12.

**Total RAB 2 Tahun Rp. 111,380,000**

**Tahun 1 Total Rp. 0**

**Tahun 2 Total Rp. 111,380,000**

| Jenis Pembelanjaan | Item | Satuan | Vol. | Biaya Satuan | Total |
|---|---|---|---|---|---|
| Bahan | Bahan Penelitian (Habis Pakai) | Unit | 50 | 795,000 | 39,750,000 |
| Pelaporan, Luaran Wajib, dan Luaran Tambahan | Biaya seminar internasional | Paket | 1 | 36,630,000 | 36,630,000 |
| Pelaporan, Luaran Wajib, dan | Publikasi artikel di Jurnal | Paket | 1 | 29,000,000 | 29,000,000 |

| Jenis Pembelanjaan | Item | Satuan | Vol. | Biaya Satuan | Total |
|---|---|---|---|---|---|
| Luaran Tambahan | Internasional | | | | |
| Pelaporan, Luaran Wajib, dan Luaran Tambahan | Biaya Luaran Iptek lainnya (purwa rupa, TTG dll) | Paket | 1 | 3,000,000 | 3,000,000 |
| Pelaporan, Luaran Wajib, dan Luaran Tambahan | Biaya penyusunan buku termasuk book chapter | Paket | 1 | 3,000,000 | 3,000,000 |

## 6. HASIL PENELITIAN

**A. RINGKASAN:** Tuliskan secara ringkas latar belakang penelitian, tujuan dan tahapan metode penelitian, luaran yang ditargetkan, serta uraian TKT penelitian.

Sistem Smart Grid merupakan teknologi kelistrikan terkini yang mampu mengalirkan arus listrik dan informasi secara dua arah, dari pembangkit ke konsumen dan sebaliknya. Kemajuan teknologi ini mulai banyak diimplementasikan dalam pengelolaan energi listrik, salah satunya integrasi dengan sumber energi terbarukan.

Salah satu permasalahan yang banyak ditemui dalam bidang kelistrikan adalah manajemen energi listrik. Pada penelitian ini, peneliti merancang model kelistrikan modern (Smart Grid) untuk manajemen energi di perumahan dan gedung-gedung dalam rangka pengembangan sistem Smart Home dan Smart Building.

Penelitian yang dikembangkan akan mengoptimalkan pemakaian energi listrik secara real-time tergantung kondisi beban dan pembangkit energi yang ada saat itu. Pada tahun pertama dirancang model sistem Smart Grid untuk optimalisasi pemakaian daya listrik rumah (TKT-3). Sedangkan pada tahun kedua dirancang model sistem Smart Grid untuk optimalisasi pemakaian daya listrik gedung (TKT-3). Dengan sistem yang dikembangkan ini, diharapkan pemanfaatan, pengelolaan energi listrik utamanya yang bersumber dari energi surya dapat dimaksimalkan, dan sekaligus merupakan upaya pencapaian sasaran Renstra penelitian perguruan tinggi terutama pada bidang unggulan energi baru dan terbarukan.

**B. KATA KUNCI:** Tuliskan maksimal 5 kata kunci.

Smart grid, optimasi, energi terbarukan, rumah, gedung

Pengisian poin C sampai dengan poin H mengikuti template berikut dan tidak dibatasi jumlah kata atau halaman namun disarankan seringkas mungkin. Dilarang menghapus/memodifikasi template ataupun menghapus penjelasan di setiap poin.

**C. HASIL PELAKSANAAN PENELITIAN:** Tuliskan secara ringkas hasil pelaksanaan penelitian yang telah dicapai sesuai tahun pelaksanaan penelitian. Penyajian dapat berupa data, hasil analisis, dan capaian luaran (wajib dan atau tambahan). Seluruh hasil atau capaian yang dilaporkan harus berkaitan dengan tahapan pelaksanaan penelitian sebagaimana direncanakan pada proposal. Penyajian data dapat berupa gambar, tabel, grafik, dan sejenisnya, serta analisis didukung dengan sumber pustaka primer yang relevan dan terkini.

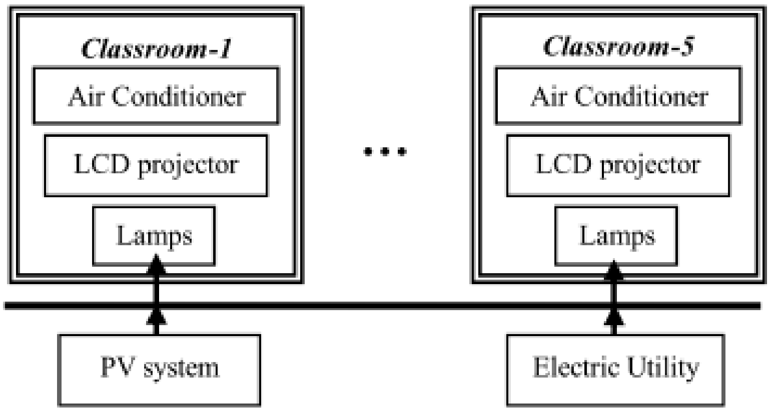
Pengisian poin C sampai dengan poin H mengikuti template berikut dan tidak dibatasi jumlah kata atau halaman namun disarankan seringkas mungkin. Dilarang menghapus/memodifikasi template ataupun menghapus penjelasan di setiap poin.

C. **HASIL PELAKSANAAN PENELITIAN:** Tuliskan secara ringkas hasil pelaksanaan penelitian yang telah dicapai sesuai tahun pelaksanaan penelitian. Penyajian dapat berupa data, hasil analisis, dan capaian luaran (wajib dan atau tambahan). Seluruh hasil atau capaian yang dilaporkan harus berkaitan dengan tahapan pelaksanaan penelitian sebagaimana direncanakan pada proposal. Penyajian data dapat berupa gambar, tabel, grafik, dan sejenisnya, serta analisis didukung dengan sumber pustaka primer yang relevan dan terkini.

## C.1.Manajemen Energi Listrik Ruang Kuliah Menggunakan Multi-Agent System (MAS)

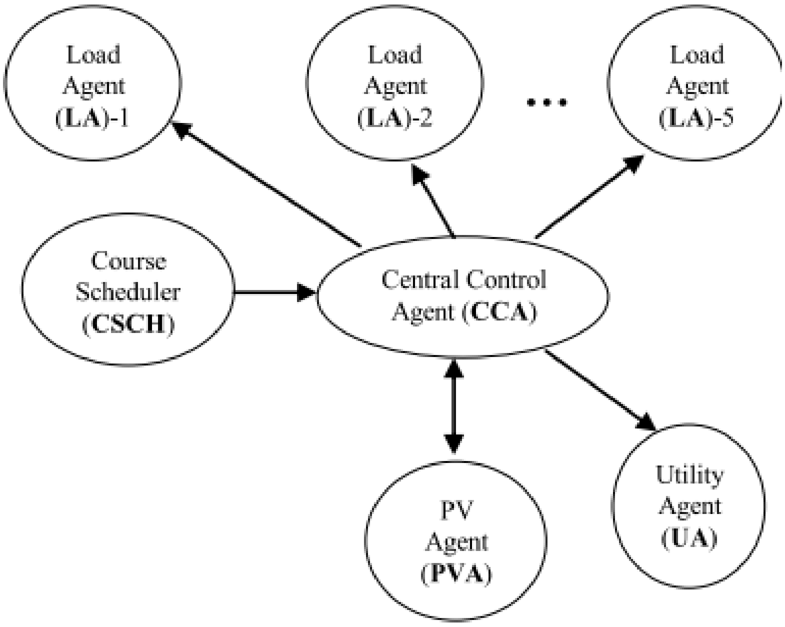
Sistem Smart Grid merupakan teknologi kelistrikan terkini yang mampu mengalirkan arus listrik dan informasi secara dua arah, dari pembangkit ke konsumen dan sebaliknya [1]. Kemajuan teknologi ini mulai banyak diimplementasikan dalam pengelolaan energi listrik, salah satunya integrasi dengan sumber energi terbarukan [2,3]. Pada penelitian ini, peneliti mengembangkan salah satu aspek dalam Sistem Smart Grid yaitu sistem manajemen energi listrik di gedung, dalam hal ini manajemen energi listrik di ruang kuliah.

Hasil rancangan sistem manajemen energi listrik ruang kuliah menggunakan Multi Agent System (MAS) diperlihatkan pada Gambar 1 dan Gambar 2. Gambar 1 adalah konfigurasi jaringan listrik di beberapa ruang kuliah, di mana sumber listrik diperoleh dari jaringan listrik PLN dan pembangkit tenaga surya (PV).Sedangkan beban listrik di setiap ruang terdiri dari pendingin ruangan (AC), LCD proyektor dan lampu.

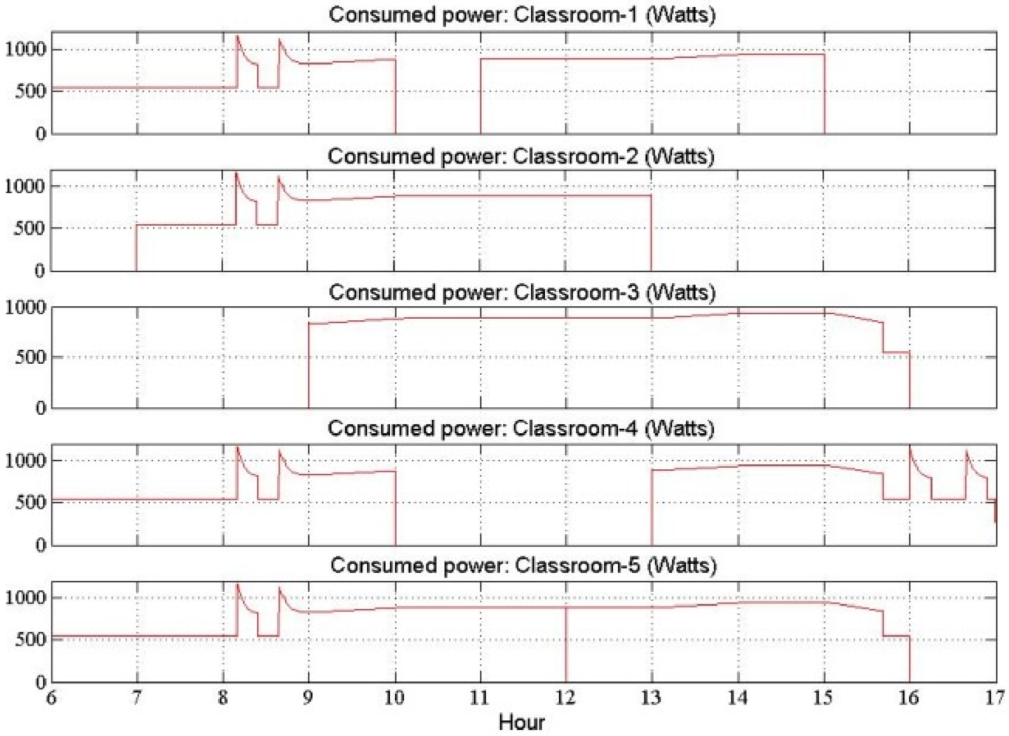


Gambar 1. Konfihurasi jaringan listrik dan beban di riang kuliah [4].

Konfigurasi MAS untuk manajemen energi pada ruang kuliah diperlihatkan pada Gambar 2. MAS terdiri dari PV Agent, Utility Agent, Load Agent, Central Control Agent dan Course scheduler. Central Control Agent berfungsi untuk mengendalikan keseluruhan sistem. Pada PV Agent, sisten kendali fuzzy digunakan mengatur setpoint suhu berdasarkan masukan suhu luar ruangan dan tingkat ketersediaan sumber energi terbarukan. Pada Central Control Agent, sistem kendali fuzzy digunakan untu menentukan tingkat ketersediaan sumber energi terbarukan berdasarlan sumber energi surya dan energi yang dikonsumsi oleh ruangan kuliah.



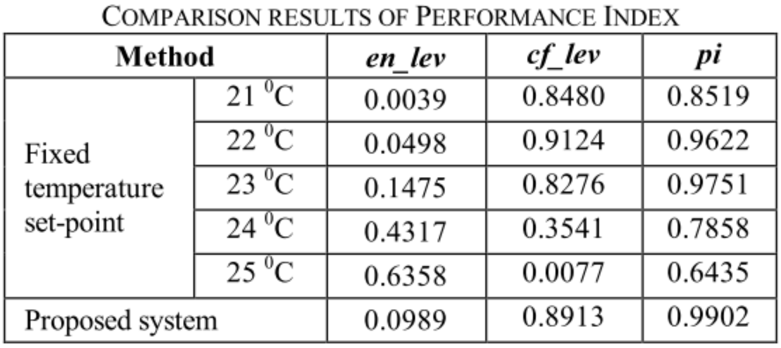
Gambar 2. Konfigurasi MAS untuk manajemen energi ruang kuliah. [4]



Gambar 3. Hasil simulasi – konsumsi daya di ruang kuliah [4]

Hasil simulasi konsumsi daya di setiap ruang kelas dari jam 6:00 sampai 17:00 diperlihatkan pada Gambar 3. Sedangkan hasil perbandingan performance index antara metode yang dikembangkan dengan metode sebelumnya diberikan pada Tabel 1. Dari tabel tersebut terlihat bahwa metode yang dikembangkan oleh peneliti memiliki performance index yang paling tinggi.

Tabel 1. Hasil perbandingan antara metode yang diusulan dengan metode setpoint suhu tetap [4]



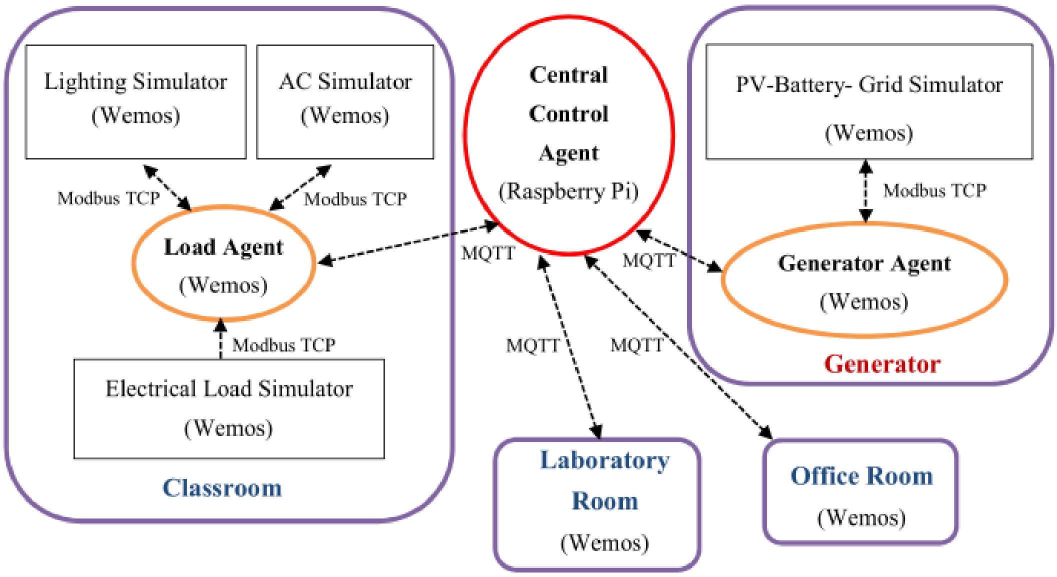
COMPARISON RESULTS OF PERFORMANCE INDEX

| Method | | *en_lev* | *cf_lev* | *pi* |
|---|---|---|---|---|
| Fixed temperature set-point | 21 $^{0}$C | 0.0039 | 0.8480 | 0.8519 |
| | 22 $^{0}$C | 0.0498 | 0.9124 | 0.9622 |
| | 23 $^{0}$C | 0.1475 | 0.8276 | 0.9751 |
| | 24 $^{0}$C | 0.4317 | 0.3541 | 0.7858 |
| | 25 $^{0}$C | 0.6358 | 0.0077 | 0.6435 |
| Proposed system | | 0.0989 | 0.8913 | 0.9902 |

C.2 Mult Agent System (MAS) Berbasis sistem Embeded untuk…Manajemen Energi Listrik Gedung

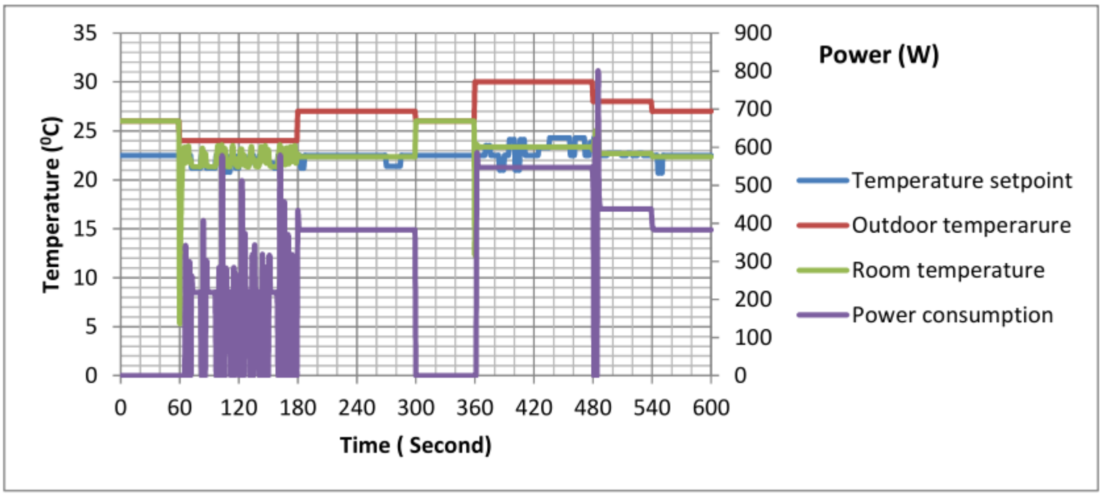
Sistem Multi Agent System (MAS) yang merupakan suatu sistem dengan banyak agen yang masing-masing agen bekerja secara otonom untuk mencapai tujuan global, banyak diaplikasikan di sistem microgrid [5].

Dalam penelitian ini, peneliti mengembangkan MAS untuk manajemen energi listrik gedung. Hasil penelitian terkait arsitektur MAS untuk manajemen energi listrik gedung diperlihatkan pada Gambar 4. MAS yang dirancang terdiri Central Control Agent, Load Agent dan Generator Agent. Load Agent simulasikan pada tiga macam ruangan, yaitu ruang kuliah, ruang laboratorium, dan ruang kantor/administrasi. Antar agen berhubungan menggunakan komunikasi wireless (WiFi) dengan protocol MQTT (Protokol IoT).



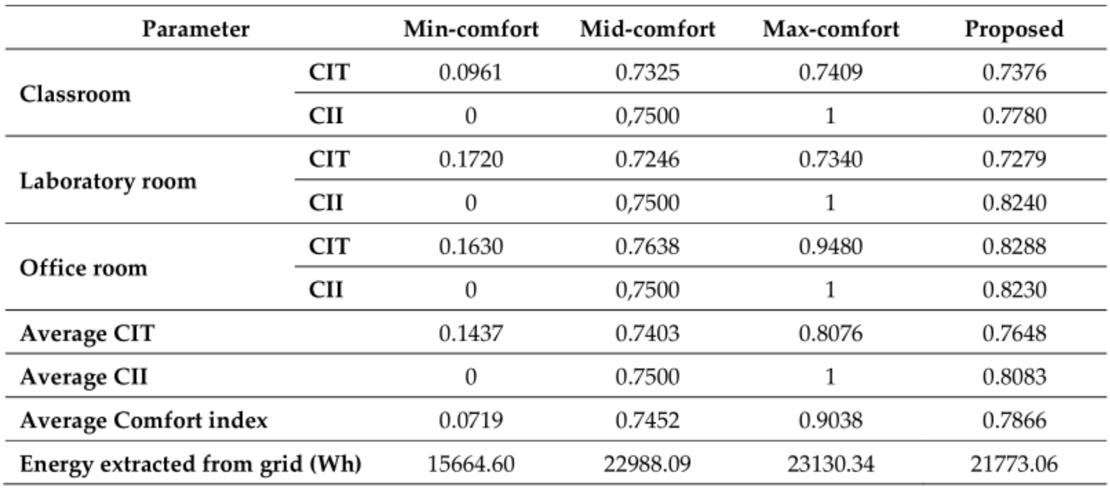
Gambar 4. Aristekur MAS untuk manajemen energi listrik gedung [6]

Hasil pengujian model AC diperlihatkan pada Gambar 4. Seperti terlihat pada gambart,setpoint suhu selalu berda pada batas suhu yang diinginkan, yaitu 200C – 250C. Hasil penguian confort index dan knsumsi energi yang diserap dari jaringan PLN diberikan pada Tabel 2. Dari tabel terlihat bahwa pada metode yang diusulkan, nilai comfort index dan energi yang dikonsumsi merupakan nilai yang optimal dibandingkan dengan metoda lainnya.



Gambar 5. Profil simulator AC [5]

Tabel 2. Hasil pengujian comfort index dan energi yang diserap dari jaringan PLN [5]



| Parameter | | Min-comfort | Mid-comfort | Max-comfort | Proposed |
|---|---|---|---|---|---|
| Classroom | CIT | 0.0961 | 0.7325 | 0.7409 | 0.7376 |
| | CII | 0 | 0,7500 | 1 | 0.7780 |
| Laboratory room | CIT | 0.1720 | 0.7246 | 0.7340 | 0.7279 |
| | CII | 0 | 0,7500 | 1 | 0.8240 |
| Office room | CIT | 0.1630 | 0.7638 | 0.9480 | 0.8288 |
| | CII | 0 | 0,7500 | 1 | 0.8230 |
| Average CIT | | 0.1437 | 0.7403 | 0.8076 | 0.7648 |
| Average CII | | 0 | 0.7500 | 1 | 0.8083 |
| Average Comfort index | | 0.0719 | 0.7452 | 0.9038 | 0.7866 |
| Energy extracted from grid (Wh) | | 15664.60 | 22988.09 | 23130.34 | 21773.06 |

D. **STATUS LUARAN**: Tuliskan jenis, identitas dan status ketercapaian setiap luaran wajib dan luaran tambahan (jika ada) yang dijanjikan pada tahun pelaksanaan penelitian. Jenis luaran dapat berupa publikasi, perolehan kekayaan intelektual, hasil pengujian atau luaran lainnya yang telah dijanjikan pada proposal. Uraian status luaran harus didukung dengan bukti kemajuan ketercapaian luaran sesuai dengan luaran yang dijanjikan. Lengkapi isian jenis luaran yang dijanjikan serta mengunggah bukti dokumen ketercapaian luaran wajib dan luaran tambahan melalui Simlitabmas mengikuti format sebagaimana terlihat pada bagian isian luaran

D.1. Luaran Wajib

Artikel ilmiah di Jurnal Internasional bereputasi.

Artikel ilmiah dengan judul “Embedded Platform for Testbed Implementation of Multi Agent System in Building Energy Management System” sudah terbit/Published di Jurnal Internasional Energies, Vol. 12 Issue 19, September 2019. (Scopus Q1)

(https://doi.org/10.3390/en12193655)

D.2. Luaran Tambahan:

Prosiding di Seminar Internasional

Artikel ilmiah berjudul “Intelligent Multi Agent System for Energy Management in the Classrooms with Grid Connected PV” sudah diseminarkan di “The 2019 IEEE International Conference on Mechatronics and Automation (ICMA 2019) “ di Tianjin, Cina tanggal 4-7 Agustus 2019.
(**DOI:** 10.1109/ICMA.2019.8816347 )

Hak Cipta

Hak Cipta Program Komputer dengan Judul “SOLAR PV SIMULATOR (SIMULATOR PANEL SURYA)” sudah GRANTED dengan Nomor Permohonan: EC00201980748, 9 November 2019 dan Nomor Pencatatan: 000163262.

Buku Monograf

Buku monograf yang berjudul “Sistem Manajemen Energi Listrik Rumah dan Gedung“ sudah dikirimkan ke penerbit Dream Litera dan sedang dalam proses pendafataran ISBN.

E**. PERAN MITRA:** Tuliskan realisasi kerjasama dan kontribusi Mitra baik *in-kind* maupun *in-cash* (jika ada). Bukti pendukung realisasi kerjasama dan realisasi kontribusi mitra dilaporkan sesuai dengan kondisi yang sebenarnya. Bukti dokumen realisasi kerjasama dengan Mitra diunggah melalui Simlitabmas mengikuti format sebagaimana terlihat pada bagian isian mitra

Tidak ada mitra

F. **KENDALA PELAKSANAAN PENELITIAN**: Tuliskan kesulitan atau hambatan yang dihadapi selama melakukan penelitian dan mencapai luaran yang dijanjikan, termasuk penjelasan jika pelaksanaan penelitian dan luaran penelitian tidak sesuai dengan yang direncanakan atau dijanjikan.

Beberapa kendala yang dihadapi adalah:

Pemilihan seminar Imternasional yang terkendala dengan batas waktu pengiriman makalah (deadline) yang biasanya di bulan-bulan awal tahun, sedangkan penelitian sedang/baru dimulai dan dana penelitian belum diterima.

Beberapa permintaan reviewer artikel ilmiah baik di seminar Internasional dan Jurnal Inteernasional memerlukan tambahan/revisi percobaan yang seringkali memerlukan waktu tambahan dan parameter-parameter penelitian lain di luar yang direncanakan di awal

Kendala teknis penelitian terkait dengan kebaruan/novelty. Karena topik yang diisulkan merupakan topik yang popular dan sedang trend, maka banyak sekali penelitian-penelitian terkait yang sudah ada. Sehingga diperlukan pemikiran, ide-ide baru yang tepat untuk mendapatkan kebaruan penelitian yang diusulkan. Hal ini seringkali memerlukan waktu yang agak lama dan tidak terduga

G. **RENCANA TINDAK LANJUT PENELITIAN:** Tuliskan dan uraikan rencana tindaklanjut penelitian selanjutnya dengan melihat hasil penelitian yang telah diperoleh. Jika ada target yang belum diselesaikan pada akhir tahun pelaksanaan penelitian, pada bagian ini dapat dituliskan rencana penyelesaian target yang belum tercapai tersebut.

Rencana tindak lanjut penelitian adalah:

Mengembangkan dan menyempurnakan model sistem manajemen energi pada rumah dan gedung menggunakan algoritma yang lebih efisien

Mengimplementasikan sistem manajemen energi pada sistem embeded

Merancang dan membuat prototipe sistem manajemen energi dalam kerangka Smart Home

Merancang dan membuat prototipe sistem manajemen energi dalam kerangka Smart Building

**H. DAFTAR PUSTAKA:** Penyusunan Daftar Pustaka berdasarkan sistem nomor sesuai dengan urutan pengutipan. Hanya pustaka yang disitasi pada laporan akhir yang dicantumkan dalam Daftar Pustaka.

1. X Fang, S Misra, G Xue, D Yang, “Smart Grid–The New and Improved Power Grid: A Survey,” IEEE Communications Surveys & Tutorials, Vol.14, Issue 4, 2012, pp. 944-980.
2. S. Zafar, K. Nawaz, S.A.R. Naqvi, T.N. Malik, “Integration of Renewable Energy Sources in Smart Grid: A Review,” The Nucleus, Vol. 50, No. 4, 2013, pp. 311-327.
3. A.R. Al-Ali, A. El-Hag, M. Bahadri, M. Harbaji, Y.A. El Haj, “Renewable and Storage Energy Integration for Smart Grid Housing,” Journal of Electronic Science and Technology, Vol. 10, No. 1, 2012, pp. 7-14.
4. A. Soetedjo, Y. I. Nakhoda, C. Saleh, “Intelligent Multi Agent System for Energy Management in the Classrooms with Grid Connected PV,” Proceedings of 2019 IEEE International Conference on Mechatronics and Automation (ICMA), Tianjin, China, 2019.
5. A. Kantamneni, L.E. Brown, G. Parker, W.W. Weaver,” Survey of multi-agent systems for microgrid control,” Engineering Applications of Artificial Intelligence, Vol.45, 2015, pp. 192-203.
6. A. Soetedjo, Y. I. Nakhoda, C. Saleh, “Embedded Platform for Testbed Implementation of Multi Agent System in Building Energy Management System,” Energies, Vol. 12, Issue 19, 2019.

Dokumen pendukung luaran Wajib #1

Luaran dijanjikan: Publikasi Ilmiah Jurnal Internasional

Target: accepted/published
Dicapai: Published

Dokumen wajib diunggah:
1. Artikel yang terbit

Dokumen sudah diunggah:
1. Artikel yang terbit

Dokumen belum diunggah:
-

Nama jurnal: Energies
Peran penulis: first author | EISSN: 1996-1073
Nama Lembaga Pengindek: SCOPUS
URL jurnal: https://www.mdpi.com/journal/energies
Judul artikel: An Embedded Platform for Testbed Implementation of Multi-Agent System in Building Energy Management System
Tahun: 2019 | Volume: 12 | Nomor: 19
Halaman awal: 1 | akhir: 29
URL artikel: https://www.mdpi.com/1996-1073/12/19/3655
DOI: 10.3390/en12193655

energies

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*Article*

# An Embedded Platform for Testbed Implementation of Multi-Agent System in Building Energy Management System

**Aryuanto Soetedjo** *, **Yusuf Ismail Nakhoda and Choirul Saleh**

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Received: 20 August 2019; Accepted: 20 September 2019; Published: 25 September 2019

**Abstract:** This paper presents a hardware testbed for testing the building energy management system (BEMS) based-on the multi agent system (MAS). The objective of BEMS is to maximize user comfort while minimizing the energy extracted from the grid. The proposed system implements a multi-objective optimization technique using a genetic algorithm (GA) and the fuzzy logic controller (FLC) to control the room temperature and illumination setpoints. The agents are implemented on the low cost embedded systems equipped with the WiFi communication for communicating between the agents. The photovoltaic (PV)-battery system, the air conditioning system, the lighting system, and the electrical loads are modeled and simulated on the embedded hardware. The popular communication protocols such as Message Queuing Telemetry Transport (MQTT) and Modbus TCP/IP are adopted for integrating the proposed MAS with the existing infrastructures and devices. The experimental results show that the sampling time of the proposed system is 16.50 s. Therefore it is suitable for implementing the BEMS in a real-time where the data are updated in an hourly or minutely basis. Further, the proposed optimization technique shows better results in optimizing the comfort index and the energy extracted from the grid compared to the existing methods.

**Keywords:** BEMS; MAS; embedded system; multi-objective optimization; genetic algorithm

## 1. Introduction

An energy management system is one of the popular and challenging topics in the electrical power system. In recent modern Smart Grid technology, the research topics in the energy management system field have increased significantly, especially in the areas of home energy management systems (HEMSs) and building energy management systems (BEMSs). The authors in [1] propose a method to reduce the energy consumption by switching on/off the air conditioning (AC) and adjusting the temperature setpoint. The objectives are to reduce the electricity consumption of the AC unit in a way that the users do not feel any changes in temperature comfort. In the experiments, they change the temperature setpoint of the AC during a certain time interval and observe whether the comfort changes are felt or not by the users. The temperature setpoints are changed remotely using a centralized server.

The fuzzy logic controller (FLC) is employed in [2] to adjust the temperature setpoint of the AC units for energy management in residential buildings. The temperature setpoint is adjusted by a fuzzy inference system that considers four parameter inputs, i.e., (a) initial temperature setpoint; (b) outdoor temperature; (c) home occupancy; (d) electricity price. The system consists of two optimization units for handling the hot temperature setpoint and the cold temperature setpoint.

An energy management system to control the AC unit and the electrical loads using control logic is proposed in [3]. The control logic covers six functions i.e., (a) comfort, (b) economy, (c) emergency,

(d) energy, (e) power, (f) thermal storage. The comfort function is used to ensure that the AC units and the electrical loads can be supplied with maximum comfort. The economy function optimizes the configuration of the AC unit and the electrical loads to minimize the cost. The emergency function is used during grid failures and allows the priority loads to be supplied by a battery system. The energy function is used to allocate energy consumption at a predefined time. The power function is used to ensure that the active power consumption does not exceed a fixed threshold. The thermal storage function is used to change the temperature setpoint of AC unit when the generated PV energy is greater than the consumption.

The authors in [4] employed a fuzzy system in their BEMS as the control strategy and prediction tool. In the control strategy, the FLC is used to control the solar thermal air system and the window-related use such as controlling the indoor temperature and light. The fuzzy prediction system is used to predict the energy demand and solar energy. The prediction system improves the energy efficiency due to the ability to predict the behavior of building in advance. A system to predict the energy demand of the building using the Artificial Neural Network (ANN) is proposed in [5]. The ANN model is trained using the dataset of monthly historical energy consumption of the building.

Due to the distributed components (sensors, actuators, generators, loads) of the HEMS/BEMS, an intelligent multi-agent system (MAS) is widely adopted [6–23]. The MAS is a distributed control system where each agent works autonomously and coordinates with each other to achieve the global goal. The implementation of MAS in the HEMS is proposed in [6–8]. The MAS in [6] consists of the permanent agent, the temporary agent and the coordinator agent. The permanent agent is used to control the permanent loads, i.e., the appliances which run in a whole-time such as the refrigerator the air conditioner, the water heater. The temporary agent controls the temporary loads, which are divided into two categories: (a) the must run loads such as the lighting, the television, the cooking appliances, etc.; (b) the shiftable loads such as the washing machine, the dishwasher, etc. The coordinator agent is used for the message coordination, controlling and the decision making among the agents. The fuzzy logic controller (FLC) is employed by each agent to manage energy consumption.

The agents in [7] are grouped into three main agents, i.e., management agents, electrical supply system agents, and home appliance agents. The management agents consist of a supply side management (SSM) agent, which manages the electrical flow from the generator system, a demand side management (DSM) agent, which manages the electrical flow to the appliances, and the HEMS agent, which manages both SSM and DSM agents. The electrical supply system agents consist of a solar panel and storage system agent, main grid agent, and electric vehicle agent. The electric vehicle agent controls the charging/discharging of the battery of electric vehicle. Under normal conditions, the battery of electric vehicles will be charged. However under power shortage conditions, the battery may be discharged to supply the energy. The home appliance agents consist of the standing fan agent, rice cooker agent, air condition agent, television agent, etc.

A different MAS architecture of the HEMS is proposed in [8], where the agents are divided into four categories: (a) control and monitoring agents (CMAs), which are used to control and monitor the actuators and sensors; (b) information agents (IAs), which is used to handle the data related to the home devices; (c) application agents (AAs), which are used for prediction, scheduling and feedback functions; (d) management and optimization agents (MOAs), which are used for the optimization tasks. To manage the energy, the HEMS adopts four optimization strategies consisting of the comfort for user satisfaction, the reduction costs, the green energy efficiency, and the smart demand response.

The agents of the MAS employed in the BEMS [9–23] can be classified into four main agents, i.e., load agents, generator agents, central agents, and other agents as given in Table 1. The load agent handles the electrical loads in the buildings. The generator agent controls the generation system which supplies the electrical energy to the building. The central agent controls or coordinates the load and the generator agents. The MASs in [9,10,20] do not have a control agent, thus in [9], the load agent and the storage agent coordinate with the generator agent directly. Similarly, the heating agent and the cooling agent are connected to the electricity agent directly [10], while in [20], each local agent such as the local temperature agent is controlled by a load agent, then the load agents were connected to an intelligent coordinator.

**Table 1.** Typical agents of MAS in BEMS.

| Reference | Load Agent | Generator Agent | Central Agent | Other Agent |
|---|---|---|---|---|
| [9] | Load agent | Generator agent | - | Storage agent |
| [10] | Heating agent, Cooling agent | Electricity agent | - | - |
| [11] | Consumption agent, Load shifting agent | Production agent | Aggregation agent | Storage agent |
| [12] | Local control agent, Load agent | Switch agent | Central coordinator agent | - |
| [13] | Local zone agents, Zone agent | On-site generation agent | Building agent | - |
| [14] | - | - | Control agents, Data processing agent | Sensing agents, Prediction agent |
| [15] | - | - | Room agent | Personal agent, Environment agent |
| [16] | Local controller-agent, Local agent | Switch agent | Central coordinator-agent | - |
| [17] | Load agent | - | Central agent | - |
| [18] | Peripheral coordinator agents | - | Master coordinator agent | - |
| [19] | Local agent | - | Central agent | - |
| [20] | Local agents, Load agents | - | - | - |
| [21] | - | Renewable energy agent | Central coordinator agent, Building management agent | Battery bank agent, Service agent |
| [22] | Local controller agents | - | Central coordinator agent | - |
| [23] | Room agents | - | Coordinator agent | - |

In [11], the load agents are classified into consumption agents and load shifting agents. The consumption agent is used to control the regular devices such as the lighting, while the load shifting agent is used to control the intelligent devices which could be shifted the start and stop time. Similar to [7], the storage agent is used to control the electricity storage such as the battery of electric vehicle. In [12], the load control agent is used to control the critical loads such as the lighting and air conditioning system, while the load agent is used to control the noncritical loads such as the fountain and swimming pool pumps. In [13], the local zone agent controls the loads such as the heating systems, the electrical systems on a local zone. The different local zone agents are aggregated by the zone agent. The load agent in [16] is divided into two categories, i.e., the local controller agent and the load agent. The local controller agent controls the loads that are related to the user comfort such as the lighting (visual comfort), the air conditioning (thermal comfort), the air quality. The load agent controls the loads that are not related to the comfort index.

The MAS in [14] is focused on measuring the environment variables, thus sensing agents are employed. The prediction agent predicts the environment conditions such as the occupancy and the weather information based-on the sensing agents. Meanwhile, the MAS in [15] is focused on detecting the presence of occupant in a room using personal and environment agents.

The architectures listed in Table 1 are the common approaches used in energy management systems. Meanwhile other approaches are proposed by [24–27]. The authors in [24] proposed an energy router called the Duindam-Stramigioli Energy Router System that manages the electrical energy from multiple sources. It works by controlling the direction and amplitude of the electrical flow in the multiports system using the power electronic devices. In [25], an energy hub is used to convert and store the various forms of energy resources such as electricity, natural gas, district heat, and wood chips. The hub contains the heat exchanger, the power electronic devices, the compressors, the transformers, the battery and the hot water storage. This approach may reduce the energy cost and air pollution.

The energy management system proposed by [26] allows the users (Smarthome or Smartbuilding) to exchange the local jointly renewable energy resources. This approach is based on the decentralized algorithm to optimize the energy from the renewable resource, i.e., to be exchanged with the neighbors, and to optimize the energy of the distribution network, i.e., to be delivered to the network or extracted from the network. The similar approach is proposed by [27], in which renewable energy is shared among the users. The users may lend/borrow the renewable energy to/from the neighbors.

The main objectives of the energy management systems [9–27] are usually to minimize the energy cost and/or maximize user comfort. In addition to these two optimization objectives, the objective function of maximizing the energy usage from the local renewable energy source is also employed [28,29]. Since our proposed system deals with the MAS-based BEMS and without loss of generality, we may classify the MAS implementation in BEMS as given in Table 2. The MAS-based BEMS could be classified into three groups, i.e., based-on: the number of criteria to be optimized, the optimization algorithm, and the implementation platform. In the first group, they are divided into single-objective optimization [10–17] and multi-objectives optimization [18–23]. Based on the optimization algorithm, they are divided into the conventional-based optimization techniques [10,11,13,15,17,21,23] and the artificial intelligent (AI)-based optimization techniques [12,14,16,18–20,22]. Based-on the implementation platform, they are divided into the simulation-based implementation and the hardware-based implementation.

**Table 2.** Classification of MAS implementation in BEMS.

| **Reference** | **Optimization Objective** | | **Optimization Technique** | | **Implementation Platform** | |
|---|---|---|---|---|---|---|
| | **Single Objective** | **Multi Objective** | **Conventional** | **AI** | **Simulation** | **Hardware** |
| [10] | Energy cost | - | Sequential quadratic programming | - | EnergyPlus [30],<br>AMPL [31] | - |
| [11] | Energy cost | - | ND * | - | Smart Grid Simulator [32] | - |
| [12] | Energy cost | - | - | Genetic algorithm | Matlab Simulink | - |
| [13] | Energy cost | - | ND * | - | Matlab Simulink | - |
| [14] | Energy cost | - | - | Fuzzy logic | - | Hardware |
| [15] | Energy cost | - | ND * | - | - | Hardware |
| [16] | Comfort | - | - | Particle Swarm Optimization | ND * | - |
| [17] | Comfort | - | Incremental function | - | Matlab Simulink | - |
| [18] | - | Comfort and Energy cost | - | Genetic algorithm | Matlab Simulink | - |
| [19] | - | Comfort and Energy cost | - | Genetic algorithm | ND * | - |
| [20] | - | Comfort and Energy cost | - | Genetic algorithm | ND * | - |
| [21] | - | Comfort and Energy cost | Mixed-integer programing | - | Java, Matlab, Gams | - |
| [22] | - | Comfort and Energy cost | - | Evolutionary algorithm | ND * | - |
| [23] | - | Comfort and Energy cost | Defeasible logics | - | - | Hardware |

* ND = Not defined clearly in the paper.

Most of the BEMSs described previously are simulated by software. The BEMS implementation on the hardware testbed is developed in [14,15,23,33–35]. The Zigbee [36] networks are commonly employed as the communication protocol in the lower layer (field layer) such as the sensors and actuators [14,23,33–35]. While the upper layer (application layer) employs the TCP/IP protocol using the WiFi network [15,23,33–35]. The main algorithms (optimization techniques) are usually implemented on the computer server (web-server), equipped with web interfaces.

As discussed previously, the BEMS, especially MAS-based BEMSs, are still rarely implemented on a hardware platform (more specifically an embedded platform), especially when AI techniques are adopted for solving the optimization problems. In this paper, we propose a hardware testbed implementation of the MAS-based BEMS. The novelty of our proposed system is the implementation of a GA-based optimization technique on an embedded platform to optimize the energy cost and user comfort in the building using only a few optimized parameters. Our proposed hardware testbed is focused on the electronics and communication parts for the real-time implementation of the algorithm. Our proposed MAS consists of the central control agent which is implemented on a Raspberry Pi module [37], the generator agent and the load agents which are implemented on Wemos modules [38]. The main contributions of our hardware testbed system are fivefold: (a) It implements the genetic algorithm (GA) technique on the embedded hardware for real-time optimization of the BEMS; (b) It emulates the generator system and the loads on the embedded hardware; (c) It adjusts the room temperature and illumination setpoints according to the optimized power; (d) It implements the popular industrial communication protocol, i.e., Modbus protocol [39] for interfacing between the agents and the devices; (e) It implements the state of the art communication protocol in the Internet of Things (IoT) technology, i.e., the Message Queuing Telemetry Transport (MQTT) protocol [40] for communicating between the agents.

To the best of our knowledge, there are no prior works related to the first and second contributions or they are very rare. Furthermore, our proposed optimization technique, which is used to minimize the energy cost while maximizing the user comfort, utilizes a few parameters for calculating the objective function. Instead of using both the energy cost and the comfort parameters in the objective function explicitly [18–23,28,29], our method uses the energy cost parameter only, since the comfort parameters could be represented in the term of energy cost parameter as described in the following. The power consumption in each room, which is calculated by the load agent, reflects the user comfort (the thermal comfort and the illumination comfort) of the room, in the sense that high power consumption represents high comfort, and low power consumption represents low comfort. Then the total power consumptions of all rooms are considered as the energy cost that should be minimized. The advantage of using this approach is that only the power consumption data should be sent to the central control agent for the optimization calculation. The comfort data are handled by each load agent.

Related to the third contribution, compared to [2] where the method to adjust temperature setpoint is used to minimize the energy cost only, our method considers both the energy cost and user comfort. While the adoption of Modbus protocol provides a wide range implementation without replacing the existing sensor and actuator devices.

The selection of the MQTT protocol rather than the Lightweight Machine to Machine (LWM2M) protocol [41] is discussed as follows. Both the MQTT and the LWM2M protocols are lightweight protocols, which are suitable for the IoT applications. While the LWM2M protocol has a well-defined data and device management model, the communication data of the MQTT protocol must be developed from scratch. However, in the case of our testbed, we may have more flexibility to define the structure of communication data to fulfill the requirement of our proposed BEMS, when the MQTT protocol is employed.

The rest of the paper is organized as follows: Section 2 describes our proposed system. Section 3 presents the experimental results and discussion. Conclusions are covered in Section 4.

## 2. Proposed System

### 2.1. System Overview

The architecture of the proposed system is depicted in Figure 1. The proposed BEMS adopts the MAS to manage the energy and user comfort in a building, more specifically a university building. The testbed consists of the central control agent, the generator agent, and the load agents. In this work, the load agents consist of three load agents which are located in the classroom, the laboratory room, and the office room. Each load agent controls three kinds of loads, namely the lighting, the air conditioning (AC), and the electrical load such as the computer and the printer. The generator agent controls the utility grid, the photovoltaic (PV) and the battery systems. Meanwhile, the central control agent is used to control all the agents.

As described in [8], the MAS-based BEMS can participate in a demand response program, i.e., the user can change the power consumption to response the changes in the electrical price or the incentive tariff introduced by the utility grid, due to the availability of the smart metering and intelligent control system of the BEMS. As illustrated in Figure 1, the load agent, the generator agent, and the central control agent provide the functionality of smart metering and intelligent control. Further, the MAS-based BEMS could be extended to interact with the larger Smart Grid system [13]. In the case of our proposed system, the integration with the Smart Grid could be done easily by extended the functionality of the central control agent to exchange information with the Smart Grid system such as the environment and the weather data, the generator, the storage, the loads, and the electrical networks.

In a more complex system such as the smart city [42,43], there are five energy-related activities, i.e., the generation, the storage, the infrastructure, the facilities and the transport [42]. In this context, our proposed BEMS takes part in the facility activity that consumes the energy. The energy management of smart city as proposed in [43] employs the hierarchical decision control where each subsystem may have different control decision scheme. Due to the decentralized scheme of our proposed BEMS, it is suitable to be adopted in such hierarchical decision control architecture.

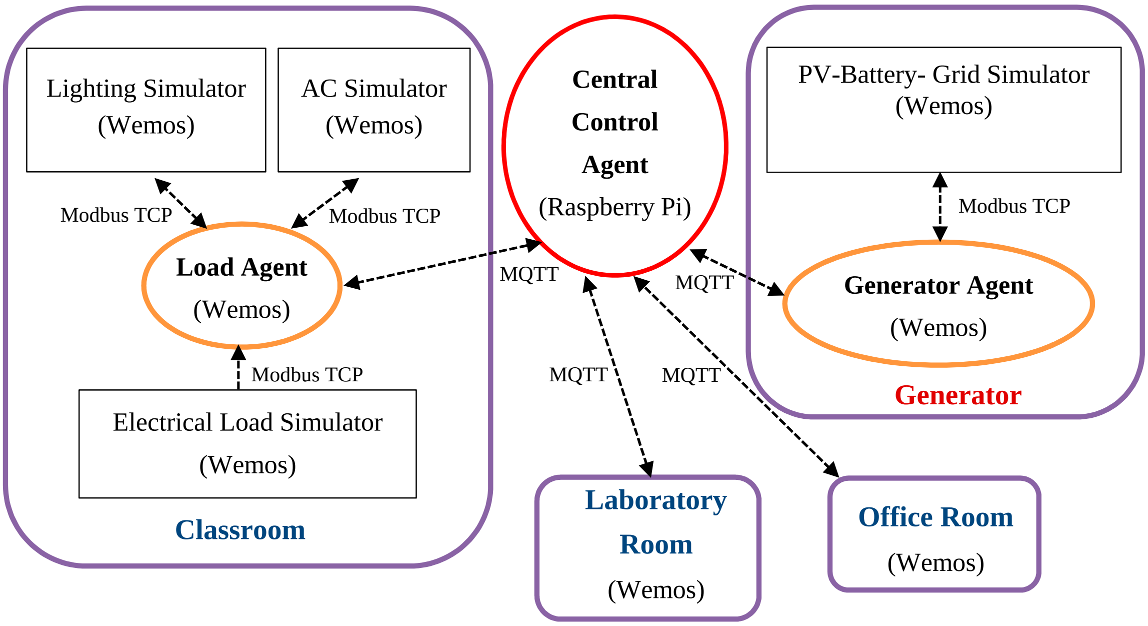


**Figure 1.** Architecture of the proposed system.

Since our proposed system divides a whole system into agents, it provides the flexibility to add the new agents to fit the requirements, for instance, to be extended to multi-commodity smart energy systems [44], where the hybrid energy systems (the heat and the electricity) are controlled. It is also possible to extend the agents to form the group of interconnected users/buildings with the shared generator agents as proposed in [45]. It is worthy to note that several MAS-based BEMS as illustrated in Figure 1 could be interconnected and coordinated in the energy district system as proposed in [46], where the several central control agents appoint a coalition coordinator to manage the energy in the district.

As shown in Figure 1, agents are implemented on the embedded systems in which the load agents and the generator agent are implemented on Wemos modules, while the central control agent is implemented on a Raspberry Pi module. A lighting simulator, AC simulator, and electrical load simulator are used to simulate the lighting, the AC, and the electrical load in the classroom, respectively. To provide a flexible implementation, a popular Modbus TCP/IP protocol is employed to communicate between the load agent and the devices. Fortunately, the Wemos is equipped with a built-in WiFi module, thus the Modbus TCP/IP protocol could be implemented easily via WiFi communication. A PV-battery simulator is developed to simulate the PV-battery system. Similar to the classroom, the simulator is implemented on Wemos modules and communicates with the generator agent using the Modbus TCP/IP protocol. The simulators in the laboratory room and the office room are developed in a rather different way. Instead of implementing the simulators on the separate modules, they are implemented in the same Wemos module with the load agent.

The objective of our proposed BEMS is to minimize the energy extracted from the grid while maximizing the user comforts. It deals with the multi-objective optimization problem. Instead of using the scheduling techniques [47,48], that manages the operation time of the controllable loads, our method controls the amount of power required by the loads. Thus it offers better control, in the sense that rather than switching-on/off the loads in a specific time interval (one-hour [47,48]), our method can adjust the power consumption of the loads in real-time, i.e., in one-minute intervals.

In this work, we propose a GA technique to solve the optimization problem and implement it on the control central agent. To provide a real-time implementation of the BEMS, the control central agent is implemented on a Raspberry Pi module. The Raspberry Pi communicates with the other agents (Wemos) via WiFi communication. Further, the MQTT protocol, a lightweight IoT protocol, is employed as the communication protocol. Compared to the method in [49] that combining the SCADA system and the Matlab software for implementing the optimization technique, our proposed method offers a simple and flexible approach due to the embedded hardware implementation. Thanks to the Raspberry Pi module that provides a small and powerful embedded computer. Further, our proposed testbed implements the Modbus protocol which is commonly used in the SCADA system.

### 2.2. Multi Agent Systen

To provide an easy explanation, the variables used in the proposed MAS-based BEMS are listed in Table 3.

**Table 3.** Description of variables in the proposed MAS-based BEMS.

| Variable Name | Abbreviation | Unit | Type |
|---|---|---|---|
| Power consumption of the classroom | $p_1$ | W | Real |
| Power consumption of the office room | $p_2$ | W | Real |
| Power consumption of the laboratory room | $p_3$ | W | Real |
| Minimum power consumptions of the classroom | $p_{1min}$ | W | Integer |
| Minimum power consumption of the office room | $p_{2min}$ | W | Integer |
| Minimum power consumption of the laboratory room | $p_{3min}$ | W | Integer |
| Maximum power consumptions of the classroom | $p_{1max}$ | W | Integer |
| Maximum power consumption of the office room | $p_{2max}$ | W | Integer |
| Maximum power consumption of the laboratory room | $p_{3max}$ | W | Integer |
| PV power | $p_{PV}$ | W | Integer |
| Battery power | $p_{Bat}$ | W | Real |

**Table 3.** *Cont.*

| Variable Name | Abbreviation | Unit | Type |
|---|---|---|---|
| Maximum power that could be supplied by the utility grid | $P_{Gridmax}$ | W | Integer |
| Power required by the classroom | | W | Real |
| Power required by the office room | | W | Real |
| Power required by the laboratory room | | W | Real |
| Power supplied by the utility grid | | W | Real |
| Outdoor temperature | $Out_{ttemp}$ | °C | Real |
| Room temperature | $R_{temp}$ | °C | Real |
| Temperature setpoint | | °C | Real |
| Cold air flow from the cooler into the room | $Qdot$ | J/h | Real |
| Temperature of cold air from the cooler | $TAC$ | °C | Real |
| Air mass flow rate through the cooler | $Mdot$ | kg/h | Real |
| Thermal capacity of air at constant pressure | $c$ | J/kg K | Real |
| Mass of air inside the room | $M_{air}$ | kg | Real |
| Equivalent thermal resistance of the room | $R_{eq}$ | K/W | Real |
| AC power | $Power_{AC}$ | W | Real |
| A power constant | $C_{power}$ | | Real |
| Sampling time | $\Delta t$ | s | Integer |
| Outdoor illumination | | lx | Integer |
| Room illumination | | lx | Integer |
| Illumination setpoint | | % | Integer |
| Lighting power | $Power_{Light}$ | W | Real |
| Luminous flux | $\phi$ | lm | Real |
| Luminous efficacy | $\eta$ | lm/W | Real |
| Load power | | W | Real |
| Number of PV cell in series | $N_S$ | | Integer |
| Number of PV cell in parallel | $N_p$ | | Integer |
| Solar irradiation | $irrad$ | W/m$^2$ | Integer |
| Output current of the PV | $i_{out}$ | A | Real |
| PV voltage | $V_{PV}$ | V | Real |
| State of the charge | $SOC$ | % | Real |
| Charging/discharging current | $I_{chg}$ | A | Real |
| Capacity of battery | $C_{Bat}$ | Ah | Integer |

### 2.2.1. Central Control Agent

The central control agent is the main agent that is responsible to manage the energy in the building by solving the multi-objective optimization problem as described in the following. The objective is to minimize power consumption, while maximizing the user comforts (temperature and lighting). Our multi-objective optimization problem is formulated using four objective functions and four constraints. The objective functions are expressed below

$$Minimize \quad (p_1 + p_2 + p_3) \tag{1}$$

$$Maximize \quad (p_1) \tag{2}$$

$$Maximize \quad (p_2) \tag{3}$$

$$Maximize \quad (p_3) \tag{4}$$

subject to

$$p_{1min} \leq p_1 \leq p_{1max} \tag{5}$$

$$p_{2min} \leq p_2 \leq p_{2max} \tag{6}$$

$$p_{3min} \leq p_3 \leq p_{3max} \tag{7}$$

$$p_1 + p_2 + p_3 - (p_{PV} + p_{Bat}) \leq p_{Gridmax} \tag{8}$$

Equation (1) represents the objective for minimizing the total power consumed by the classroom, the office room and the laboratory room, while Equations (2)–(4) represents the objective for maximizing the user comfort in each room. It is noted here that instead of using the comfort index directly, we use the power consumption to represent user comfort. Therefore maximizing the user comfort could be defined by maximizing the power consumption of each room (Equations (2)–(4)). This approach could be realized due to the fact that when the temperature and the illumination comforts to be increased, the power consumption will increase. The lower user comfort requires lower power consumption. This approach will reduce the number of parameters to be optimized. The objective functions in Equations (1)–(4) only require three variables, i.e., $p_1$, $p_2$, $p_3$ that should be provided in the central control agent. Thus it offers an efficient data exchange between the agents.

The constraints are formulated using the inequalities as expressed by Equations (5)–(8). The constraints in Equations (5)–(7) are the lower and upper bounds of the power consumptions which are used to ensure that the optimized parameters $p_1$, $p_2$, $p_3$ fall in the allowable range of the user comfort. While the constraint in Equation (8) ensures that the power consumption of the building could be supplied by the generator systems (the renewable energy resources and/or the utility grid).

To solve the above multi-objectives optimization problem, we adopt the Multi-Objective Genetic Algorithm (MOGA), more specifically the NSGA-II as proposed by [50]. The MOGA is implemented on the central control agent to find the optimal power required by the building based on the current power consumptions and the generated power as illustrated in Figure 2. As shown in the figure, the inputs of the central control agent are the minimum and maximum power consumptions of the classroom, the office room, and the laboratory room, the power produced by the battery and the PV. Then these values are used by the MOGA to solve the multi-objective optimization as expressed in Equations (1)–(8). The outputs of the central control agent are the optimal values of power required by the classroom, the office room, and the laboratory room which are sent to the respective agents.

The power required by the classroom, the office room, and the laboratory room are the optimal values that should be consumed by the respective loads. Then the respective load agent control its loads to satisfy the power requirement using the strategy as described in the following section.

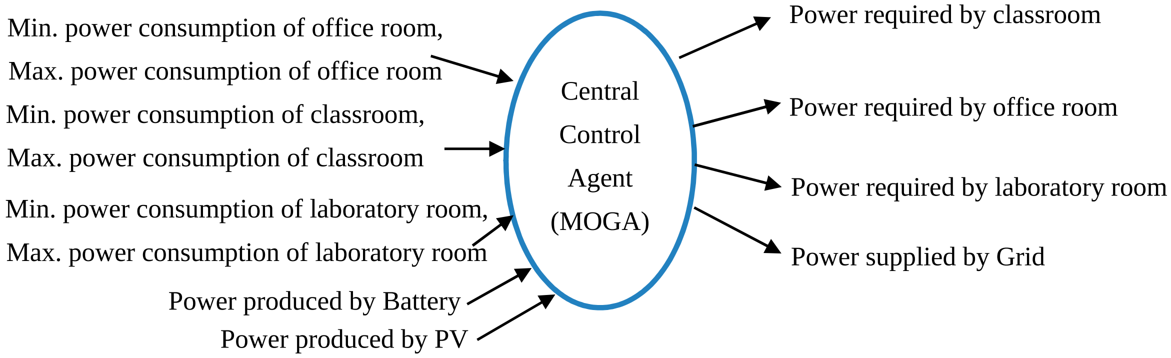


**Figure 2.** Input and output data of central control agent.

### 2.2.2. Load Agent

The load agents in the classroom, the office room and the laboratory room are similar, in the sense of the control function. However in our testbed they have the different device protocols, where the load agent in the classroom communicates with the load devices using the Modbus TCP/IP protocol via the WiFi communication, while the data exchange between the load agents and the devices in the office room and the laboratory room are performed directly in the Wemos module.

Figure 3 illustrates the input and output data of the load agent. As shown in the figure, the inputs are the required power, the outdoor temperature, and the outdoor illumination. These data are used by the fuzzy logic controllers (FLCs) to determine the optimal room temperature and illumination setpoints. There are two FLCs, one for controlling the room temperature setpoint (called as FLC-T), and another one for controlling the room illumination setpoint (called as FLC-I). The inputs of FLC-T are the required power and the outdoor temperature, while the output is the room temperature setpoint. The membership functions of the required power, the outdoor temperature, and the room temperature setpoint are shown in Figure 4, where each variable has three linguistic values, i.e., Low (LOW), Medium (MED), and High (HIGH). The values of the required power (658 W–1137 W), the outdoor temperature (26 °C–30 °C), and the room temperature setpoint (20 °C–25 °C) are normalized to 0–1.

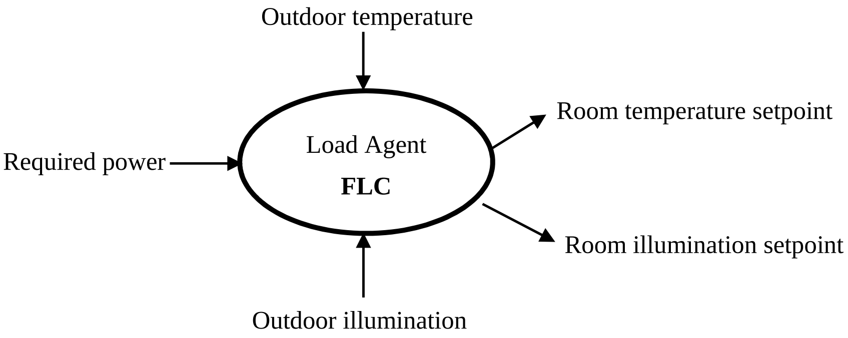
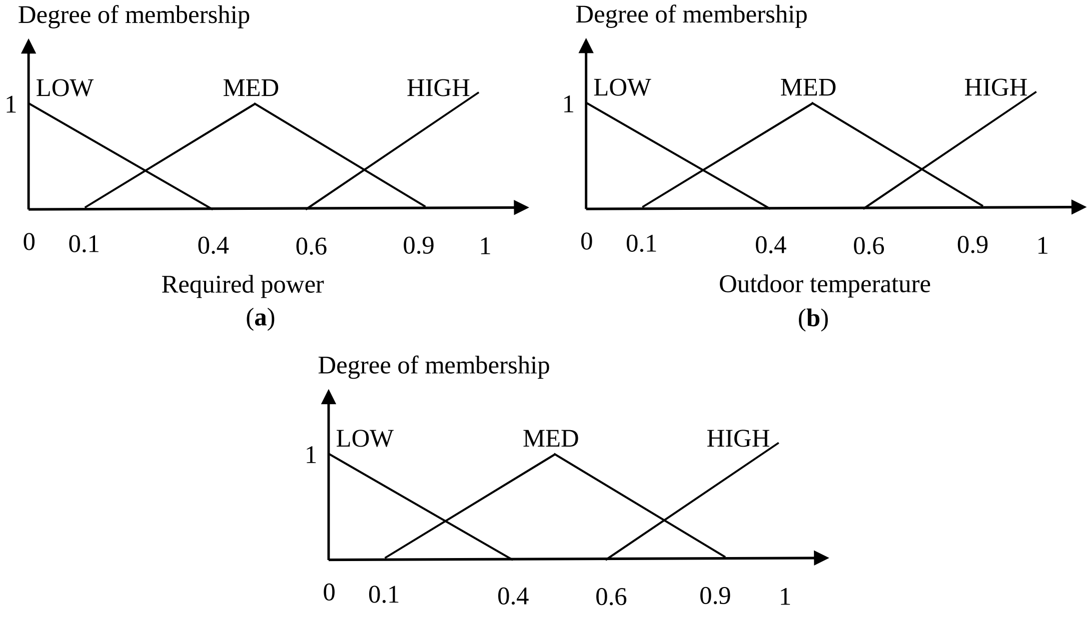


**Figure 3.** Input and output data of the load agent.



(**a**)

(**b**)

(**c**)

**Figure 4.** Membership functions of FLC-T: (**a**) Required power; (**b**) Outdoor temperature; (**c**) Room temperature setpoint.

The fuzzy rules of FLC-T are given in Table 4, where the rules are determined by considering the objectives as follows. It is worthy to note that the AC system discussed here is applicable for the hot season where the AC system is controlled to decrease the outdoor temperature (i.e., the cooling system) to the desired comfortable room temperature. Therefore the consumed power of the AC system will increase when the room temperature setpoint is decreased and vice versa.

- When the required power is low (LOW), then it is better to set the room temperature setpoint follows to the level of the outdoor temperature to minimize the consumed power of the AC. Thus the fuzzy rules given in Table 4 show that when the required power is LOW, the room temperature setpoint is set to LOW when the outdoor temperature is LOW, it is set to MED when the outdoor temperature is MED, and it is set to HIGH when the outdoor temperature is HIGH.
- When the required power is high (HIGH), it allows the AC to consume high power. Thus the room temperature setpoint could be set to LOW for all outdoor temperature conditions.
- When the required power is medium (MED), it is better to set the room temperature setpoint to the medium (MED) regardless of the outdoor temperature conditions.

**Table 4.** Fuzzy rules of FLC-T.

| | | **Outdoor Temperature** | | |
|---|---|---|---|---|
| | | LOW | MED | HIGH |
| **Required Power** | LOW | LOW | MED | HIGH |
| | MED | MED | MED | MED |
| | HIGH | LOW | LOW | LOW |

The inputs of FLC-I is the required power and the outdoor illumination, while the output is the room illumination setpoint. The membership functions of the required power, the outdoor illumination, and the room illumination setpoint are shown in Figure 5, where each variable has three linguistic values, i.e., Low (LOW), Medium (MED), and High (HIGH). The values of the required power (658 W–1137 W), the outdoor illumination (1000 lx–10,000 lx), and the room illumination setpoint (300 lx–500 lx) are normalized to 0–1.

The fuzzy rules of FLC-I are given in Table 5, where the rules are determined by considering the objectives as follows. It is noted that the property of the comfort value of the illumination is the opposite from the one of the temperature, in the sense that the temperature comfort increases when the room temperature setpoint is decreased, while the illumination comfort increases when the room illumination setpoint is increased. Therefore the fuzzy rules of the FLC-I are defined below:

- When the required power is low (LOW), then it is better to set the room illumination setpoint follows to the level of the outdoor illumination to minimize the consumed power of the lighting. Thus the fuzzy rules given in Table 5 show that when the required power is LOW, the room illumination setpoint is set to LOW when the outdoor illumination is LOW, it is set to MED when the outdoor illumination is MED, and it is set to HIGH when the outdoor illumination is HIGH.
- When the required power is high (HIGH), it allows the lighting to consume high power. It means that the room illumination setpoint could be set to the HIGH for all outdoor temperature conditions.
- When the required power is medium (MED), it is better to set the room illumination setpoint to the medium (MED) regardless of the outdoor illumination condition.

**Table 5.** Fuzzy rules of FLC-I.

| | | **Outdoor Illumination** | | |
|---|---|---|---|---|
| | | LOW | MED | HIGH |
| **Required Power** | LOW | LOW | MED | HIGH |
| | MED | MED | MED | MED |
| | HIGH | HIGH | HIGH | HIGH |

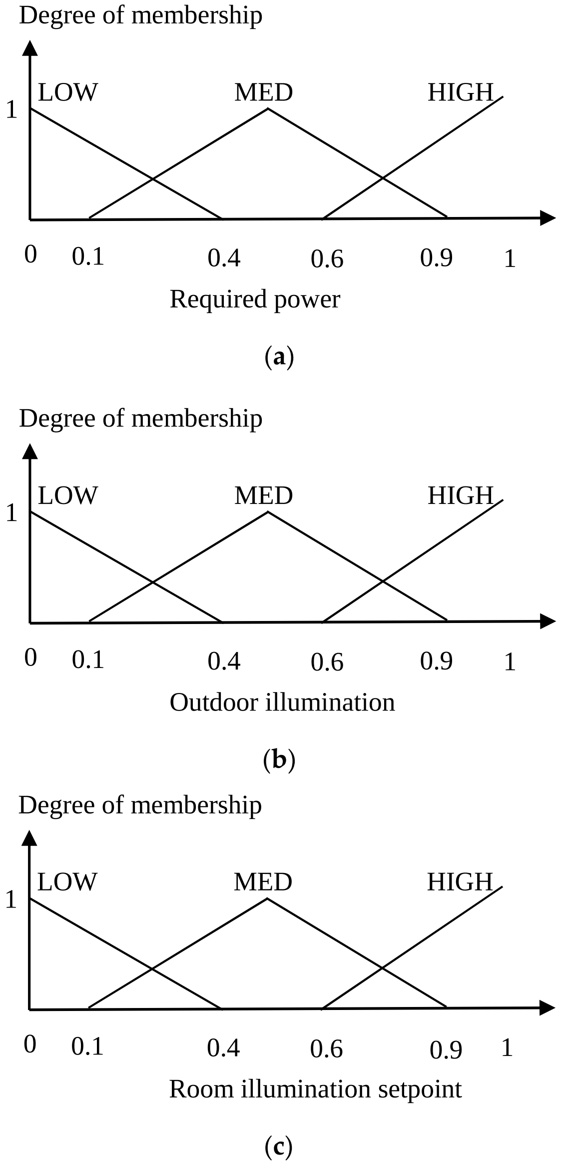


**Figure 5.** Membership functions of FLC-I: (**a**) Required power; (**b**) Outdoor illumination; (**c**) Room illumination setpoint.

### 2.2.3. Generator Agent

The generator agent is used to manage the battery charging/discharging according to the state of charge (SOC) of the battery as illustrated in Figure 6. Besides controlling the battery, the generator agent receives the generated power from the PV-battery system and sends the data to the central control agent as shown in Figure 1.

The battery charging/discharging is controlled using the simple strategy as expressed by Equations (9)–(11). Using these rules, the battery could be effectively operated to supply the load (discharging) and/or saving the PV power based-on the SOC of the battery. Equation (9) is used to prevent the over-discharge, while Equation (11) is used to prevent the over-charge. Equation (10) is used to operate the battery in both charging and discharging modes

$$\text{IF SOC} < 0.3 \text{ THEN Charging is ON and Discharging is OFF} \tag{9}$$

$$\text{IF } 0.3 \leq \text{SOC} \leq 0.7 \text{ THEN Charging is ON and Discharging is ON} \tag{10}$$

$$\text{IF SOC} > 0.7 \text{ THEN Charging is OFF and Discharging is ON} \tag{11}$$

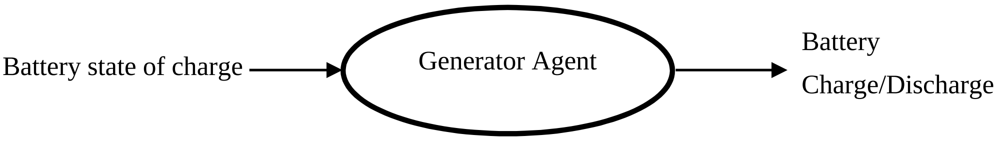


**Figure 6.** Input and output data of the generator agent.

## *2.3. Load and Generator Simulators*

### 2.3.1. AC Simulator

The model of an air conditioning (AC) system is a modified version of the model in [51]. Since the model in [51] is the heater system, we modify it to become the cooling system to fulfill with our proposed system. The important contribution of our work is that the model is simulated in the embedded system (Wemos module) for real-time implementation, especially for the electronic/communication aspects. The AC simulator consists of two models: the AC (cooling system) and the thermodynamic model of a room. The AC system is expressed by Equation (12), while the thermodynamic model of a room is expressed by Equation (13). The electrical power consumed by the room is simplified by a linear function of the difference between the outdoor temperature and the room temperature as expressed by Equation (14):

$$Qdot(k) = (R_{temp}(k) - TAC)Mdot\ c \tag{12}$$

$$R_{temp}(k+1) = R_{temp}(k) + \frac{\Delta t}{M_{air}c}\left(\frac{Out_{temp}(k) - R_{temp}(k)}{R_{eq}} - Qdot(k)\right) \tag{13}$$

$$Power_{AC}(k) = C_{power}(Out_{temp}(k) - R_{temp}(k)) \tag{14}$$

The block diagram of AC simulator is illustrated in Figure 7, where it has two inputs, i.e., the outdoor temperature which is predefined data stored in the Wemos module, and the room temperature setpoint which is received from the load agent (see Figure 1). The AC simulator sends the power consumption, the room temperature and the outdoor temperature to the load agent.

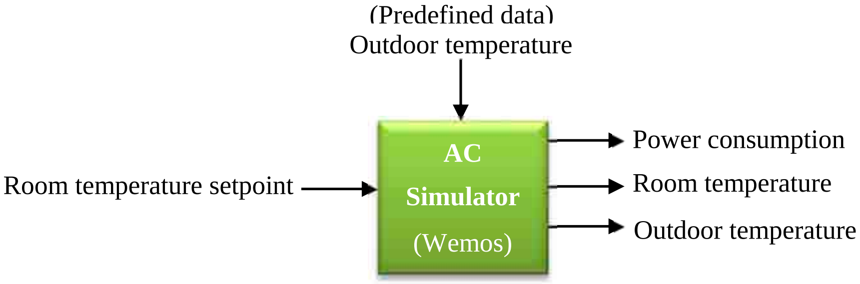


**Figure 7.** Block diagram of the AC simulator.

To provide real-time implementation, we adopt the Modbus TCP/IP protocol for interfacing between the AC simulator and the load agent, where the load agent acts as the master device and the AC simulator is the slave device. The Modbus data such as the register address and the command type are listed in Table 6. To show that the adopted devices are available commercially, the name of the manufacturer is given in the table. As shown in the table, the Modbus data for the AC power consumption is provided by the power meter [52], while Modbus data for the room temperature, the temperature setpoint and the outdoor temperature are provided by the Modbus thermostat device [53].

**Table 6.** Modbus data of the AC simulator.

| IP Address | Register Address | Modbus Command | Variable | Factor (Unit) | Device (Manufacturer Name) |
|---|---|---|---|---|---|
| 192.168.3.2 | 06H | 03H | AC power (LOW) | × 0.1 W | Power meter (Pilot meter SPM91 [52]) |
| | 07H | | AC power (HIGH) | | |
| | 04H | 03H | Room temperature | × 0.01 °C | Thermostat (Neptronic Modbus Thermostat [53]) |
| | 05H | 06H | Temperature setpoint | × 0.1 °C | |
| | 0CH | 03H | Outdoor temperature | × 0.01 °C | |

### 2.3.2. Lighting Simulator

The power consumption of the lighting in the room is calculated by dividing the luminous flux to the luminous efficacy as given in Equation (15):

$$Power_{Light} = \phi / \eta_{power} \tag{15}$$

In the experiment, the LED lamp is used, where the luminous efficacy is 100 lm/W, while the daylight factor (DF) of the room is 2%, which means that the room illumination is 2% of the outdoor illumination.

The block diagram of lighting simulator is illustrated in Figure 8. It has two inputs: the outdoor illumination which is a predefined data stored in the Wemos module, and the room illumination setpoint which is received from the load agent. The lighting simulator sends the data of the power consumption, the room illumination and the outdoor illumination to the load agent.

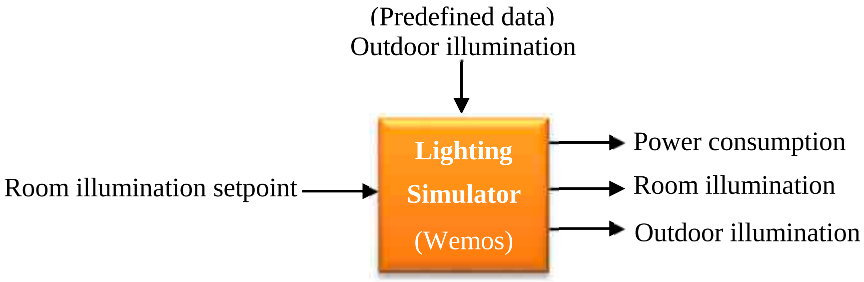


**Figure 8.** Block diagram of lighting simulator.

The Modbus data of the simulator is given in Table 7. Similar to the AC simulator, the Modbus data for the lighting power consumption is provided by the power meter [52]. The Modbus data for the room illumination is provided by the daylight sensor [54]. The LED dimmer [55] provides the Modbus data for the room illumination setpoint. The outdoor light sensor [56] provides the Modbus data for outdoor illumination.

**Table 7.** Modbus data of lighting simulator.

| IP Address | Register Address | Modbus Command | Variable | Factor (Unit) | Device (Manufacturer Name) |
|---|---|---|---|---|---|
| 192.168.3.3 | 06H | 03H | Lighting power (LOW) | × 0.1 W | Power meter (Pilot meter SPM91 [52]) |
| | 07H | | Lighting power (HIGH) | | |
| | 08H | 03H | Room illumination | × 1.0 lx | Daylight sensor (TRANS-MRB-510 series [54]) |
| | 10H | 06H | Room illumination setpoint | × 1.0 (% LED brightness) | LED Dimmer (OPTO 22 NETWORK LED DIMMER [55]) |
| | 3CH | 03H | Outdoor illumination (LOW) | × 1.0 lx | Outdoor light sensor (Li65 + RS485 Modbus Thermokon [56]) |
| | 3DH | | Outdoor illumination (HIGH) | | |

### 2.3.3. Electrical Load Simulator

The block diagram of electrical load simulator is illustrated in Figure 9. The electrical load is modeled with the load profile stored in the Wemos module. The simulator sends the data of power consumption to the load agent using the Modbus data as given in Table 8, where it only contains the power consumption data provided by the power meter [52].

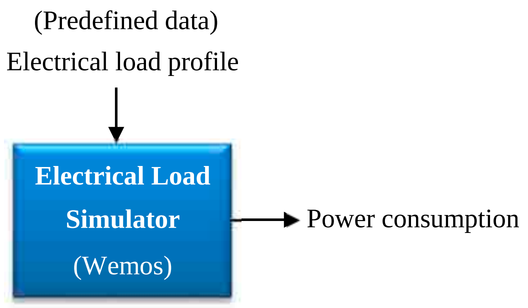


**Figure 9.** Block diagram of the electrical load simulator.

**Table 8.** Modbus data of the electrical load simulator.

| IP Address | Register Address | Modbus Command | Variable | Factor (Unit) | Device (Manufacturer Name) |
|---|---|---|---|---|---|
| 192.168.3.4 | 06H | 03H | Electrical load power (LOW) | × 0.1 W | Power meter (Pilot meter SPM91 [52]) |
| | 07H | | Electrical load power (HIGH) | | |

### 2.3.4. PV-Battery Simulator

The relationship between current and voltage (I-V) of the PV is expressed by Equations (16)–(18) [57], where $N_S = 4$, $N_P = 65$ and $V_{PV} = 48$ V. The battery is modeled by its SOC as expressed by Equation (19) [58]:

$$I_{SC} = irrad\, N_P/1000 \tag{16}$$

$$i_d = N_P e^{-9}\left(e^{((v_{PV}/(36N_S)+0.05 i_{out}/N_P)/26e^{-3})-1)}\right) \tag{17}$$

$$i_{out} = I_{SC} - i_d - v_{PV}(1/(432N_S)) \tag{18}$$

$$\mathrm{SOC}(k) = \mathrm{SOC}(k-1) + \frac{I_{chg}}{C_{Bat}} \tag{19}$$

The block diagram of the PV-battery simulator is illustrated in Figure 10. The PV-battery simulator receives the battery charging/discharging control signal from the generator agent. The predefined data of the solar irradiation is stored in the Wemos module which used to produce the PV power as defined by Equations (16)–(18). Then the PV power, the battery power, and the battery SOC are sent to the generator agent using the Modbus data as given in Table 9. The Modbus data of the PV power is provided by the Gridtie inverter device [59]. The battery power, the battery SOC and the battery charging/discharging control are provided by the battery charger controller [60].

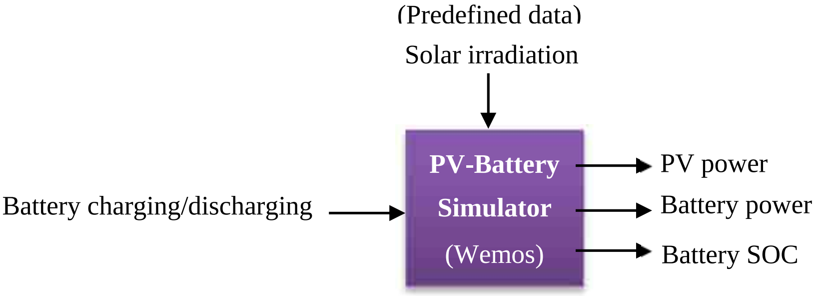


**Figure 10.** Block diagram of the PV-battery simulator.

**Table 9.** Modbus data of the PV-battery simulator.

| IP Address | Register Address | Modbus Command | Variable | Factor (Unit) | Device (Manufacturer Name) |
|---|---|---|---|---|---|
| 192.168.5.2 | 004CH | 03H | PV power (LOW) | × 1 W | Gridtie inverter (Schneider Gridtie device [59]) |
| | 004DH | | PV power (HIGH) | | |
| | 310EH | 04H | Battery power (LOW) | × 0.01 W | Battery charger controller (EPEVER Battery Charger [60]) |
| | 310FH | | Battery power (HIGH) | | |
| | 311AH | 04H | SOC | × 0.01% | |
| | 00H | 05H | Charging on/off | 1 = on,<br>0 = off | |
| | 02H | | Discharging on/off | 1 = on,<br>0 = off | |

### 2.4. Communication Protocol

As described in the previous section, the MQTT protocol is adopted as the communication protocol between the central control agent and the other agents (the load agents and the generator agent). MQTT is lightweight messaging protocol that runs on the Transmission Control Protocol/Internet Protocol (TCP/IP). It works based on the publish-subscribe mechanism, where the MQTT broker is required to establish a connection between the publisher and the subscriber.

The configuration of MQTT protocol is illustrated in Figure 11. In the system, the MQTT broker and the central control agent are installed on same Raspberry Pi module. Thus the central control agent communicates with the broker via a localhost connection. As shown in the figure, each agent publishes and subscribes the specific topics as described in the following.

In Figure 11, an arrow with "Publish-C2CC" means that the load agent in the classroom publishes the "C2CC" topics, while an arrow with "Subscribe-CC2C" means the load agent subscribes the "CC2C" topics. The list of the topics is given in Table 10. As shown in the table, all topics that are published by the load agents and the generator agent are subscribed by the central control agent, thus all data sent by the load agents and the generator agent will be received by the central control agent. Meanwhile, the topics that are subscribed by load agents and the generator agent are published by the central control agent, thus the data that is required by the load agents and the generator agent will be provided by the central control agent.

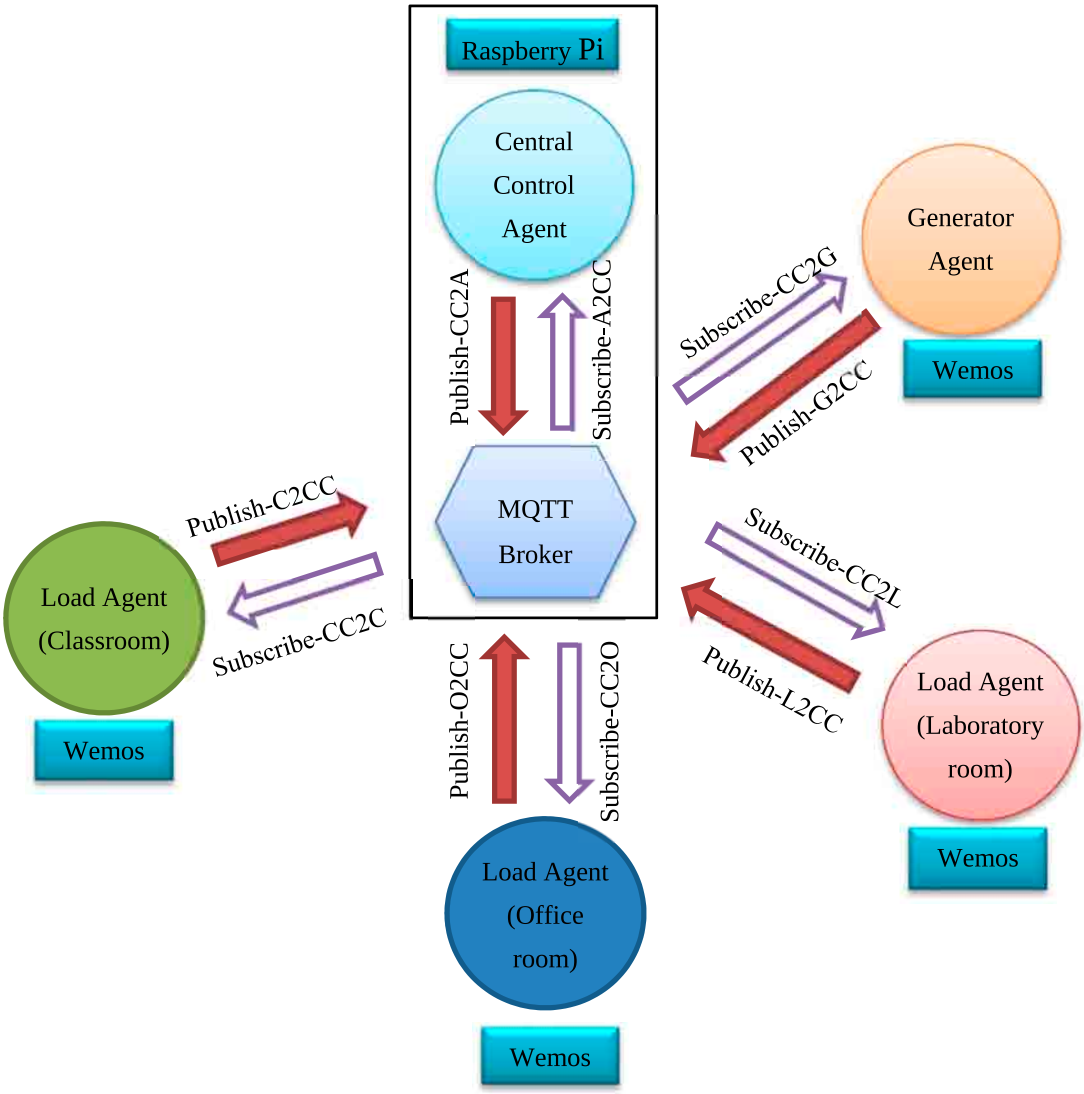


**Figure 11.** MQTT protocol configuration.

**Table 10.** Published and subscribed topics by the agents.

| **Agent Name** | **Topic** | | **Remark** |
|---|---|---|---|
| | **Publish** | **Subscribe** | |
| Load Agent (Classroom) | 1. Classroom-Power<br>2. Min-Classroom-Power<br>3. Max-Classroom-Power | | C2CC |
| | | 1. Classroom-Required-Power | CC2C |
| Load Agent (Office room) | 1. Office-Power<br>2. Min-Office-Power<br>3. Max-Office -Power | | O2CC |
| | | 1. Office-Required-Power | CC2O |

**Table 10.** *Cont.*

| Agent Name | Topic | | Remark |
|---|---|---|---|
| | **Publish** | **Subscribe** | |
| Load Agent (Laboratory room) | 1. Laboratory-Power | | L2CC |
| | 2. Min-Laboratory-Power | | |
| | 3. Max-Laboratory-Power | | |
| | | 1. Laboratory-Required-Power | CC2L |
| Generator Agent | 1. PV-Power | | G2CC |
| | 2. Battery-Power | | |
| | | 1. Grid-Required-Power | CC2G |
| Central Control Agent | 1. Classroom-Required-Power | | CC2A |
| | 2. Office-Required-Power | | |
| | 3. Laboratory-Required-Power | | |
| | 4. Grid-Required-Power | | |
| | | 1. Classroom-Power | A2CC |
| | | 2. Min-Classroom-Power | |
| | | 3. Max-Classroom-Power | |
| | | 4. Office-Power | |
| | | 5. Min-Office-Power | |
| | | 6. Max-Office-Power | |
| | | 7. Laboratory-Power | |
| | | 8. Min- Laboratory -Power | |
| | | 9. Max- Laboratory -Power | |
| | | 10. PV-Power | |
| | | 11. Battery-Power | |

## 3. Experimental Results and Discussion

### 3.1. Model Validation

To verify our proposed model, we evaluate the functionality of the proposed embedded simulators and conduct the sensitivity analysis of the FLC model. To evaluate the AC simulator in the classroom, we record the data of room temperature setpoint, the outdoor temperature, the room temperature, and the power consumption during the simulation into the Wemos memory. The recorded data is illustrated in Figure 12. The time sampling of the simulator is one second, and the hourly data is simulated in one-minute interval. It is noted here that from 0 to 59 seconds and from 300 to 359 seconds, the classroom is not occupied and the AC is switched off. Therefore during these time intervals, the power consumptions are zero and the room temperature is the same as the outdoor temperature. As shown in the figure, the AC simulator works properly, in the sense that the room temperature follows the temperature setpoint, and the power consumption changes proportionally to the difference between the outdoor temperature and the temperature setpoint. The power consumption increases when the difference between the outdoor temperature and the temperature is increased.

The profile of illumination and power consumption of the lighting simulator is illustrated in Figure 13. Similarly to the AC simulator, the lighting system is switched-off during 0 to 59 seconds and 300 to 359 seconds. In the figure, the natural illumination is the room illumination which is caused by the outdoor lighting (sunshine). As shown in the figure, the room illumination is able to follow the illumination setpoint, except at the time during the previous periods. Further, the power consumption shows the proper behavior, i.e., it increases when the difference between the illumination setpoint and the natural illumination is increased.

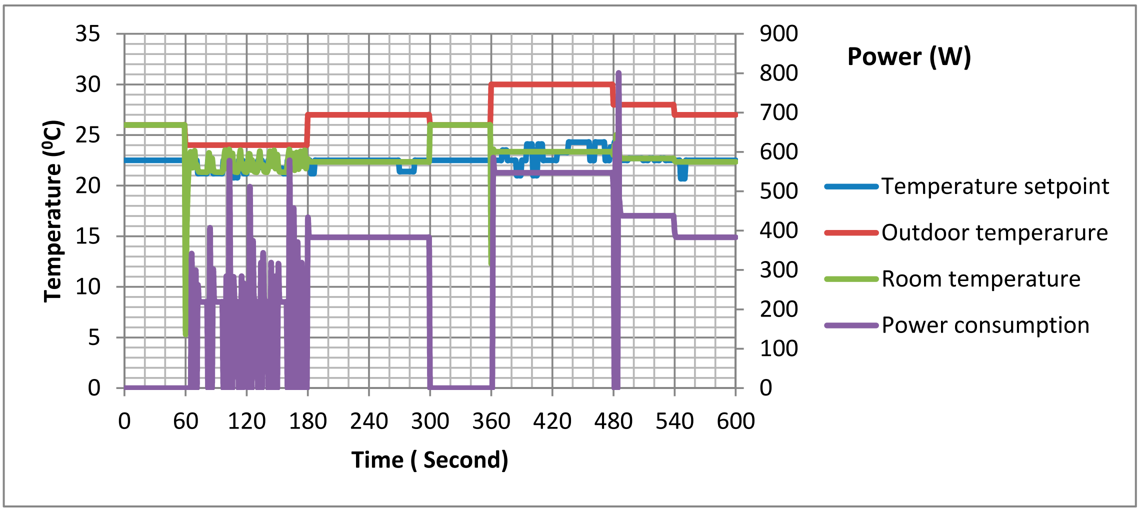


**Figure 12.** Profile of temperatures and power consumption of the AC simulator.

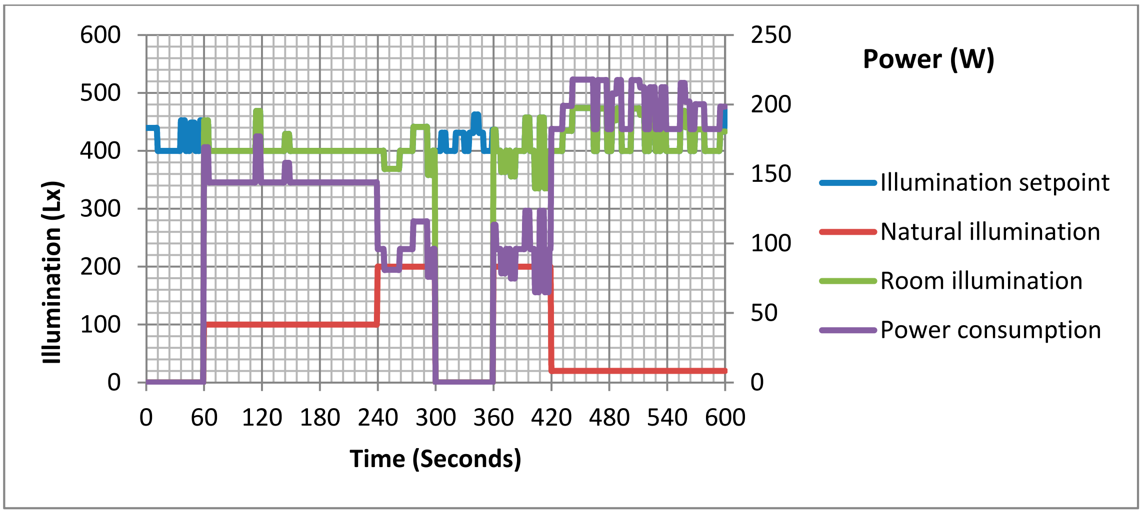
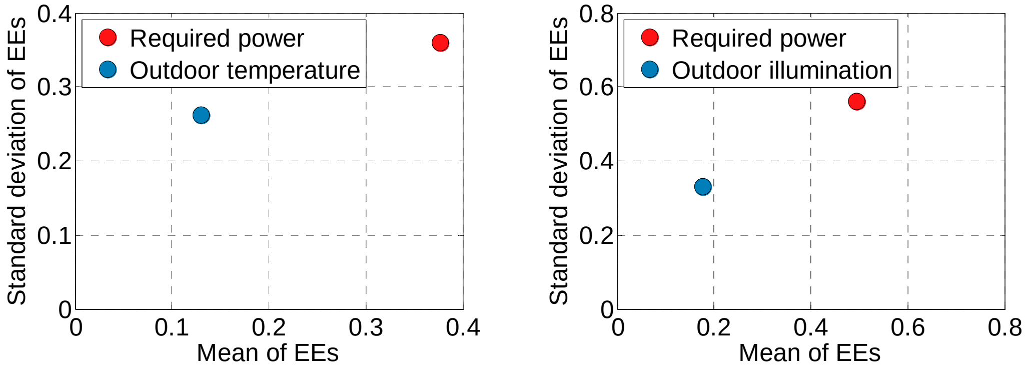


**Figure 13.** Profile of illumination and power consumption of the lighting simulator.

To assess the sensitivity of the parameters of our proposed FLC, we conduct the sensitivity analysis as described in the following. Two sensitivity analysis methods, i.e., the elementary effect (EE) method [61], and the Fourier Amplitude Sensitivity Testing (FAST) method [62] are employed. The EE method is used to find the influential parameters of the model, while the FAST method is used to find the sensitivity indices of the parameters. The EE and FAST methods are calculated using the SAFE, a Matlab Toolbox for global sensitivity analysis provided by [63].

The mean and standard deviation of EEs of the FLC inputs of the FLC-T and the FLC-I are illustrated in Figure 14a,b respectively. In Figure 14a, the red dot and the blue dot represent the normalized required power and the normalized outdoor temperature respectively. As shown in the figure, the mean and the standard deviation of the required power are higher than the outdoor temperature. Thus it could be concluded that the required power input is more influential than the outdoor temperature input. This result could be understood from the observation of the fuzzy rules of FLC-T shown in Table 4, where the changes of linguistic values (LOW, MED, HIGH) of the outdoor temperature do not change the output when the linguistic values of required power is MED or HIGH.

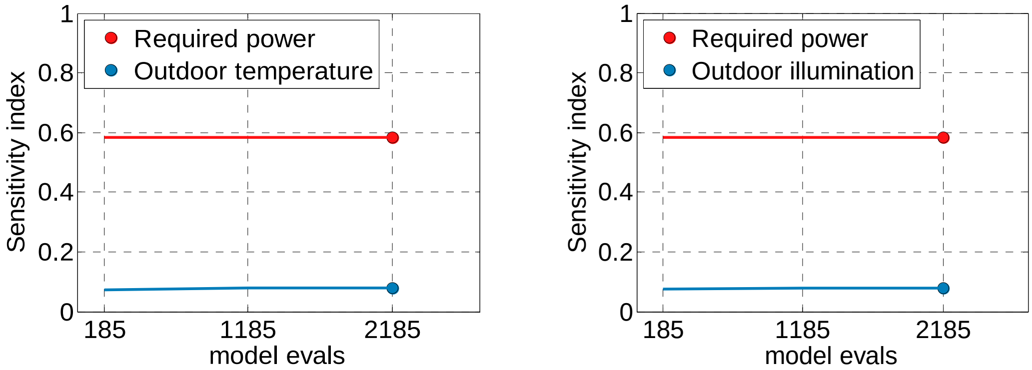
The changes of the outdoor temperature affect the output, only when the value of required power is LOW. Therefore it is clearly shown that the influential effect of the required power is higher than the outdoor illumination. In Figure 14b, the red dot and the blue dot represent the normalized required power and the normalized outdoor illumination respectively. As shown in the figure, the mean and the standard deviation of the required power are higher than the illumination. Thus the required power input is more influential than the outdoor illumination input. Similar to the FLC-T discussed previously, the result could understood from the examination of fuzzy rules of FLC-I shown in Table 5.



(**a**) (**b**)

**Figure 14.** Mean and standard deviation of EEs of FLC inputs: (**a**) Normalized required power and outdoor temperature of FLC-T; (**b**) Normalized required power and outdoor illumination of FLC-I.

The sensitivity indices calculated using the FAST method are shown in Figure 15, where Figure 15a shows the sensitivity indices of the FLC-T inputs, i.e., the normalized required power and the normalized outdoor temperature, while Figure 15b shows the sensitivity indices of the FLC-I inputs, i.e., the normalized required power and the normalized outdoor illumination.



(**a**) (**b**)

**Figure 15.** Sensitivity index of FLC inputs: (**a**) Normalized required power and outdoor temperature of FLC-T; (**b**) Normalized required power and outdoor illumination of FLC-I.

Both figures show that the sensitivity index of the required power input is higher than the outdoor temperature input and the outdoor illumination input. These results conform to the previous EE analysis. The sensitivity analysis results show that it is reasonable to select the required power, the outdoor temperature, and the outdoor illumination as the inputs of the proposed FLCs, even though the last two inputs have a less influential effect compared to the required power input.

### 3.2. Performance of Real-Time Implementation

Since the objective of the proposed testbed is for testing the real-time implementation of the building energy management system, we conduct several experiments to verify our method in the term of the real-time implementation such as the execution time of the algorithm, the sampling time of the agents, and the efficiency of the optimization technique.

The execution times of FLCs which are implemented on the Wemos modules are given in Table 11. As shown in the table, the execution time of FLC is about 10 to 12 ms. Thus to execute both FLC-T and FLC-I on a Wemos module, it requires about 22 ms. The results verify that the proposed embedded agent using Wemos is suitable for a real-time implementation of the FLC algorithm. Since the sampling time of an agent is determined by the execution time of the algorithm and the transmission time of the communication protocol employed, we examine the sampling time of each agent as given in Table 11. Since the data communication between the load agents in the office room and the laboratory room with the simulators are performed directly, the sampling times of these load agents are quite fast, i.e., about 1.25 ms. Meanwhile, the sampling times of the agents with the Modbus protocol, i.e., the load agent in the classroom and the generator agent are 6.59 s and 2.63 s respectively. These results indicate that the sampling time is very affected by the transmission time of the Modbus protocol. Further, since the number of the Modbus slave devices in the classroom is higher than the generator agent, the sampling time is longer due to the fact that the master must poll the slaves.

The sampling times of the load agent in the classroom and the load agent in the office room are illustrated in Figures 16 and 17, respectively. In the figures, the profiles of room temperature setpoints against time are shown, where the updated data are indicated with the marks on the graphs. Figure 16 shows that the room temperature setpoints in the classroom are updated in an average time of 6 s, while Figure 17 shows that the room temperature setpoints in the office room are updated in an average time of 1 s.

**Table 11.** Execution time and sampling time.

| Location | Parameter | Average Value |
|---|---|---|
| Classroom | Execution time of FLC-T | 12.13 ms |
| | Execution time of FLC-I | 12.02 ms |
| | Sampling time of Load Agent | 6.59 s |
| Office room | Execution time of FLC-T | 11.01 ms |
| | Execution time of FLC-I | 10.99 ms |
| | Sampling time of Load Agent | 1.25 s |
| Laboratory room | Execution time of FLC-T | 12.10 ms |
| | Execution time of FLC-I | 12.01 ms |
| | Sampling time of Load Agent | 1.25 s |
| Generator Agent | Sampling time of Generator Agent | 2.63 s |
| Central Control Agent | Execution time of GA | 14.25 s |
| | Sampling time of Central Control Agent | 16.60 s |

The main contribution of our proposed system in the real-time implementation of the optimization technique using GA is shown in Table 11, where the execution time of GA on the Raspberry Pi module is 14.25 s (the number of population is 100 and the number of iteration is 30). While the sampling time of the central control agent is 16.60 s. The result implies that the communication task performed by the MQTT protocol only contributes a small portion of the time. Most of the time is consumed by the GA. It also suggests that the lightweight protocols such as the MQTT and the LWM2M protocols are the effective communication protocols between the agents in the MAS. Relying on the sampling time of the central control agent which is lower than one minute, we may conclude that our proposed testbed is suitable for implementing the BEMS, where the updating process is done in hourly basis even every minute.

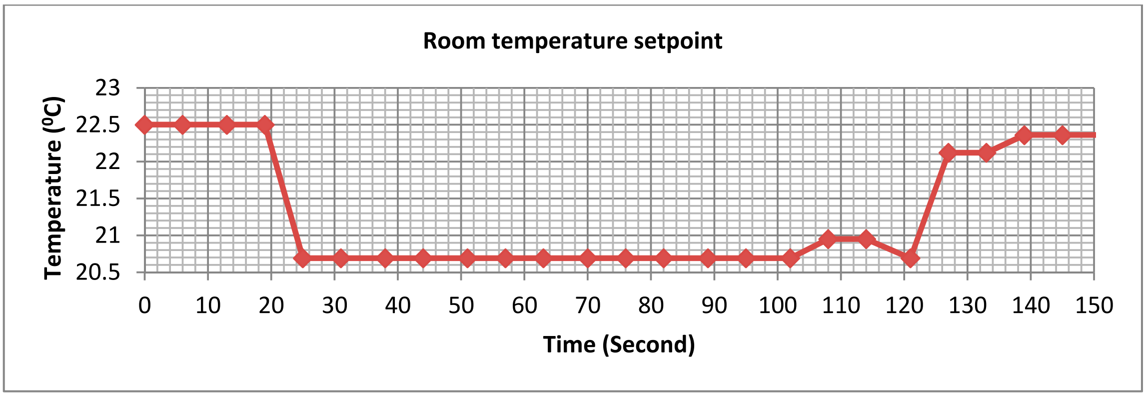


**Figure 16.** Sampling time of the load agent in the classroom.

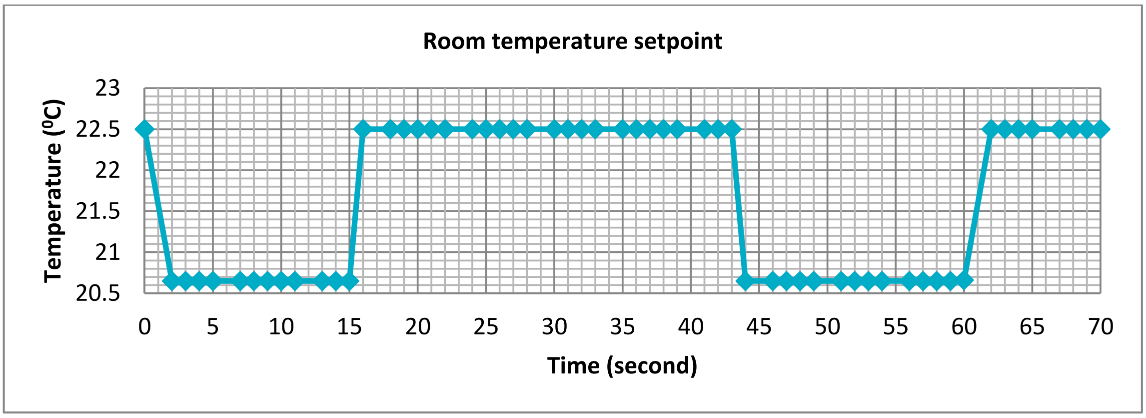


**Figure 17.** Sampling time of the load agent in the office room.

### 3.3. Effectiveness of Optimization Technique

To verify the effectiveness of the proposed optimization technique, we evaluate the comfort index and the energy extracted from the grid. The objective is to maximize the comfort index while minimizing the energy extracted from the grid. The temperature comfort index (CIT) and the illumination comfort index (CII) are defined based on [64] as follows:

$$\mathrm{CIT} = 1 - \left(\frac{Temp_{opt} - Temp_{min}}{Temp_{max} - Temp_{min}}\right)^2 \tag{20}$$

$$\mathrm{CII} = 1 - \left(\frac{Illum_{max} - Illum_{opt}}{Illum_{max} - Illum_{min}}\right)^2 \tag{21}$$

where $Temp_{opt}$, $Temp_{min}$, $Temp_{max}$ is the optimized room temperature, the allowed minimum and maximum room temperatures respectively, $Illum_{opt}$, $Illum_{min}$, $Illum_{max}$ is the optimized room illumination, the allowed minimum and maximum room illuminations respectively. From Equations (20) and (21), the maximum comfort is achieved when the value of CIT or CII is 1, and the minimum comfort is achieved when the value is 0.

In the experiments, we compare our proposed method that adjusts the temperature and the illumination setpoints to the existing method proposed by [2] (called as EXT), the fixed setpoint methods, i.e., the setpoint is set to the minimum comfort (called as Min-comfort), the setpoint is set to the middle comfort (called as Mid-comfort), and the setpoint is set to the maximum comfort (called as Max-comfort). The EXT [2] employs the FLC to adjust the temperature. The difference with our approach is described briefly in the following. Instead of using the required power and the outdoor temperature as the fuzzy inputs, the EXT uses the electricity price and the outdoor temperature. In this case, the electricity price has two linguistic values (PEAK, MD), whose membership functions are shown in Figure 18. As shown in the figure, the electricity price is expressed in respect to the time of use, which is adopted from [2]. While the membership function of the outdoor temperature and the temperature setpoint are the same with our proposed method. The fuzzy rules are given in Table 12.

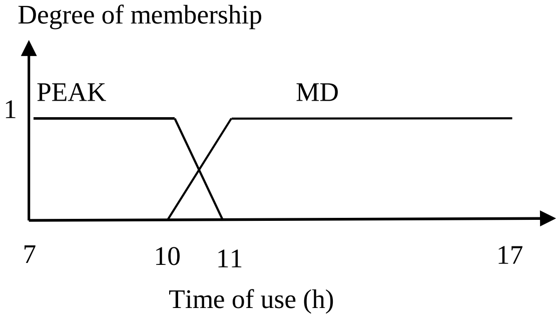


**Figure 18.** Membership function of electricity price in the EXT.

**Table 12.** Fuzzy rules of EXT.

| | | **Outdoor Illumination** | | |
|---|---|---|---|---|
| | | LOW | MED | HIGH |
| **Electricity Price** | PEAK | HIGH | HIGH | HIGH |
| | MD | LOW | MED | HIGH |

The room temperature setpoints for Min-comfort, Mid-comfort, and Max-comfort are set to 25 °C, 22.5 °C, and 20 °C respectively. The room illumination setpoints for Min-comfort, Mid-comfort, and Max-comfort are set to 300, 400 and 500 lx, respectively. The data of solar irradiation, the outdoor temperature, the outdoor illumination, and the electrical load from 7 h to 17 h given in Table 13 are used during comparisons.

**Table 13.** Data inputs used in the experiments.

| **Time (Hour)** | **Solar Irradiation ($W/m^2$)** | **Electrical Load Power (W)** | | | **Outdoor Temperature (°C)** | **Outdoor Illumination (lx)** |
|---|---|---|---|---|---|---|
| | | **Classroom** | **Office Room** | **Laboratory** | | |
| 7 | 400 | 0.0 | 0.0 | 0.0 | 25.5 | 5000 |
| 8 | 500 | 350.0 | 400.0 | 2000.0 | 25.5 | 5000 |
| 9 | 700 | 350.0 | 400.0 | 2000.0 | 25.5 | 5000 |
| 10 | 900 | 350.0 | 400.0 | 2000.0 | 27.0 | 5000 |
| 11 | 1000 | 350.0 | 400.0 | 2000.0 | 27.0 | 10,000 |
| 12 | 800 | 0.0 | 400.0 | 2000.0 | 29.0 | 10,000 |
| 13 | 500 | 350.0 | 400.0 | 2000.0 | 30.0 | 10,000 |
| 14 | 300 | 350.0 | 400.0 | 2000.0 | 30.0 | 1000 |
| 15 | 0 | 350.0 | 400.0 | 2000.0 | 28.0 | 1000 |
| 16 | 0 | 350.0 | 400.0 | 2000.0 | 27.0 | 1000 |
| 17 | 0 | 0.0 | 0.0 | 2000.0 | 27.0 | 0 |

The results of the comfort index and the energy extracted from the grid for five methods (Min-comfort, Mid-comfort, Max-comfort, Proposed, EXT) are given in Table 14. It is clearly shown that the Max-comfort achieves the highest comfort index, however the energy extracted from the grid is also highest. The lowest energy extracted from the grid is achieved by the Min-comfort, however the comfort index is also lowest. The energy extracted from the grid of the EXT is the second lowest, but the comfort index is also the second lowest. Our proposed method optimizes both comfort index and energy extracted from the grid, where it achieves the comfort index of 0.7866, while the energy extracted from the grid is 21,773.06 Wh. These optimized values are better than the ones obtained by setting the setpoint to the middle value (Mid-comfort).

**Table 14.** Comfort index and energy extracted from grid.

| Parameter | | Min-Comfort | Mid-Comfort | Max-Comfort | EXT | Proposed |
|---|---|---|---|---|---|---|
| Classroom | CIT | 0.0961 | 0.7325 | 0.7409 | 0.3144 | 0.7376 |
| | CII | 0 | 0.7500 | 1 | 0.7780 | 0.7780 |
| Laboratory room | CIT | 0.1720 | 0.7246 | 0.7340 | 0.3714 | 0.7279 |
| | CII | 0 | 0.7500 | 1 | 0.8240 | 0.8240 |
| Office room | CIT | 0.1630 | 0.7638 | 0.9480 | 0.3614 | 0.8288 |
| | CII | 0 | 0.7500 | 1 | 0.8230 | 0.8230 |
| Average CIT | | 0.1437 | 0.7403 | 0.8076 | 0.3491 | 0.7648 |
| Average CII | | 0 | 0.7500 | 1 | 0.8083 | 0.8083 |
| Average Comfort index | | 0.0719 | 0.7452 | 0.9038 | 0.5787 | 0.7866 |
| Energy extracted from grid (Wh) | | 15,664.60 | 22,988.09 | 23,130.34 | 19,964.84 | 21,773.06 |

By comparing our proposed method with the EXT, we may examine that the since the EXT adjusts the temperature setpoint according to the time of use (the electricity price) and the outdoor temperature, and due to the fact that the electricity price only changes twice, i.e., in the morning and the afternoon (see Figure 18), the EXT fails to adjust the temperature setpoint, where the outdoor temperature fluctuates hourly. Furthermore, the FLC in the EXT tends to optimize the energy cost only as shown with the lower energy extracted from the grid. Contrary, our proposed method considers the required power to adjust the temperature setpoint. The required power is the power that should be consumed to achieve the optimal values of the energy cost and the user comfort. Thus the resulted temperature setpoint accommodates both parameters. Therefore the energy extracted from the grid and the comfort index of our proposed method is the optimal values.

Figures 19–21 illustrate the comparison of temperature comfort index, the illumination comfort index in the office room, and the energy extracted from the grid of five methods. Figure 19 shows that during 8 h to 17 h, the temperature comfort indices of Min-comfort, Mid-comfort, and EXT oscillate. The oscillation is caused by the thermostat control used for controlling the AC. Meanwhile, the temperature comfort index of our proposed method varies to find the optimal value and at the same time reduces the oscillation effect of the thermostat control. The figure also shows that the comfort index of the EXT is in the middle between Mid-comfort and the Min-Comfort.

In Figure 20, the profiles of the illumination comfort index do not show the dynamic behavior compared to Figure 19 due to fact the illumination model is simple. Since the EXT does not consider the illumination comfort index, it is not shown in Figure 20. By observing Figures 19 and 20, the profile of temperature comfort index of our proposed method is similar to the illumination comfort index of or proposed method. This result could be understood from the fact that both FLC controller (FLC-T and FLC-I) have similar membership functions and the fuzzy rules.

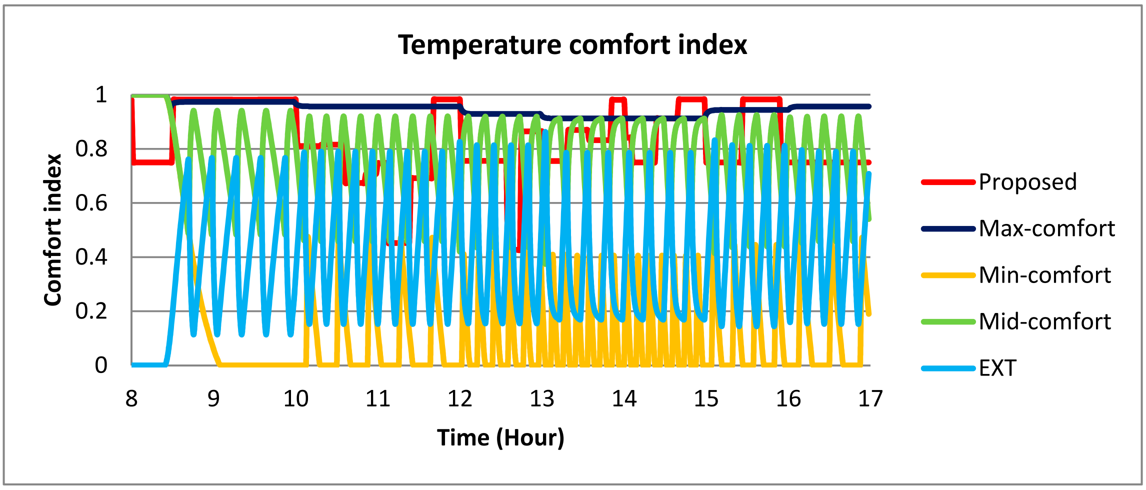


**Figure 19.** Temperature comfort index in the office room.

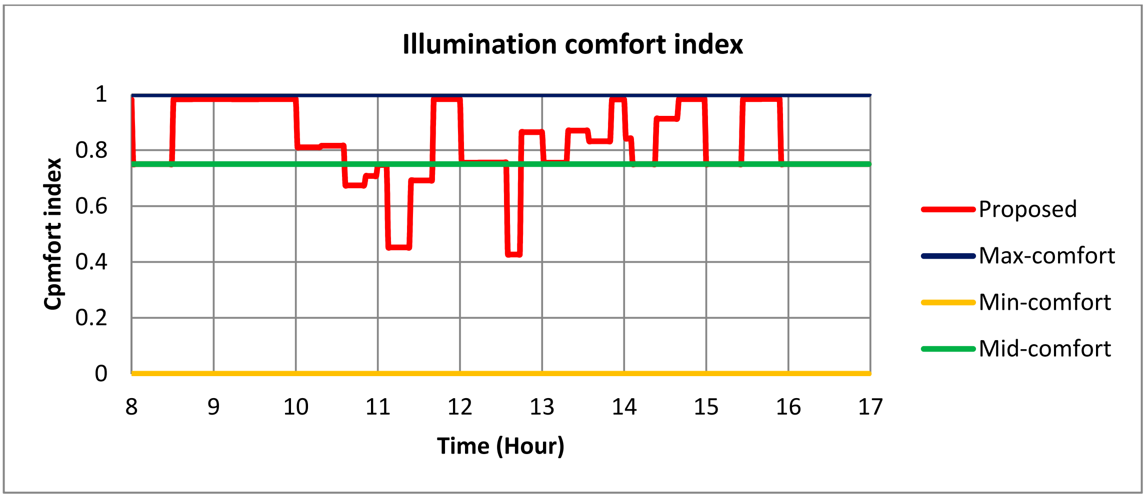


**Figure 20.** Illumination comfort index in the office room.

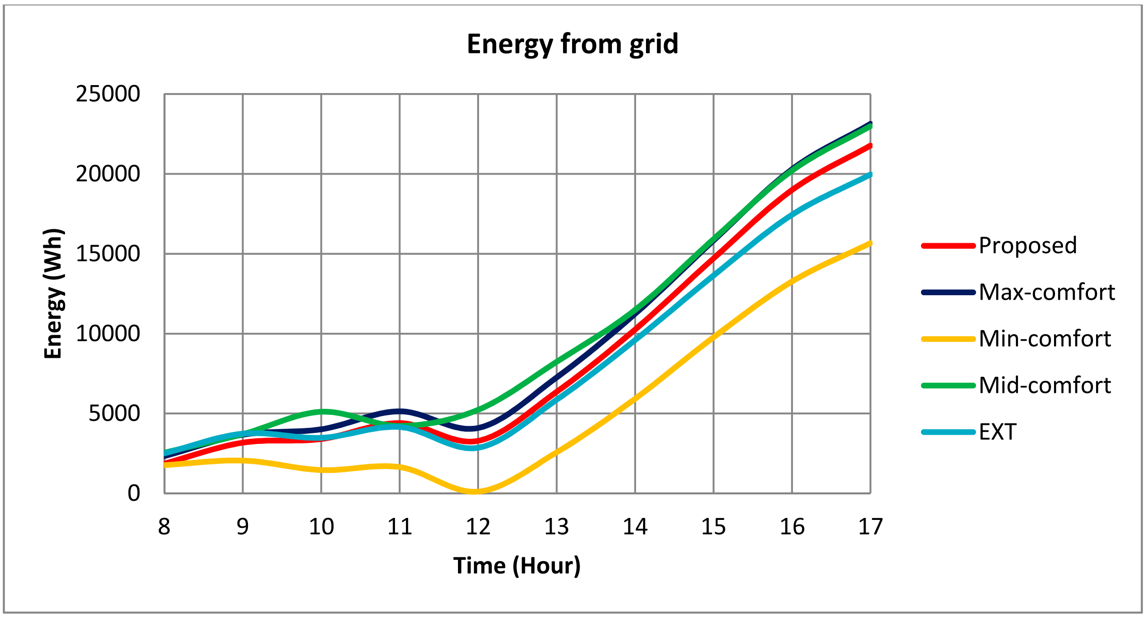


**Figure 21.** Energy extracted from the grid.

Figure 21 shows that the energy extracted from the grid of Min-comfort is always the lowest one, however since its comfort indices as shown in Figures 19 and 20 are also the lowest ones, we could not adopt this method. The same results are also achieved by the EXT, where as shown in the Figure 21, the energy extracted from the grid is lower than our proposed method, however the comfort index is also lower.

It is worth noting that compared to Max-comfort and Mid-comfort, the energy profile extracted from the grid of our proposed method is lower than both methods. Therefore the effectiveness of our proposed in optimizing the comfort index and energy extracted from the grid is verified.

## 4. Conclusions

An embedded platform for implementing the multi agent system (MAS) in the building energy management is proposed. The proposed MAS consists of the load agent, the generator agent, and the central control agent. The genetic algorithm (GA) is implemented on the central control agent to find the optimal power required by the load agents based on the availability of the PV-battery power and the requirement of the user comforts. The proposed objective functions require a few parameters, thus the data exchange between the agents could be performed efficiently. To provide a flexible implementation in the existing building infrastructure and to integrate with the state of the art IoT technology, our testbed employs the industrial Modbus protocol and the MQTT protocol, which are implemented on the low cost embedded platform. In the experiments, the execution time, the communication protocols and the sampling time of the embedded testbed are evaluated. The experiments results show that our proposed testbed is able to maximize the temperature and illumination comforts while minimizing the energy in a real-time manner. Further, the effectiveness of the optimization technique to optimize the energy cost and the user comfort of the building is verified.

In future, the testbed system will be extended to cope with the complex building energy management by employing the complex models and advanced optimization algorithms. Further, the electrical system will be considered in the tested.

**Author Contributions:** A.S. proposed and implemented the whole system and wrote the paper; Y.I.N. shared the idea about the electrical system; C.S. shared the idea about the energy management.

**Funding:** This work was supported by the Research Grant, Excellent Basic Research on Higher Institution scheme from the Directorate General of Higher Education, Ministry of Research and Technology and Higher Education, Republic of Indonesia (No.: 079/SP2H/LT/MONO/L7/2019).

**Conflicts of Interest:** The authors declare no conflict of interest.

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Dokumen pendukung luaran Wajib #1

Luaran dijanjikan: Prosiding dalam pertemuan ilmiah Internasional

Target: sudah terbit/sudah dilaksanakan
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Dokumen wajib diunggah:
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Dokumen belum diunggah:
-

Peran penulis: first author
Nama Konferensi/Seminar: IEEE International Conference on Mechatronics and Automation (ICMA)
Lembaga penyelenggara: IEEE Robotics and Automation Society
Tempat penyelenggara: Tianjin, Cina
Tgl penyelenggaraan mulai: 4 Agustus 2019 | Tgl selesai: 7 Agustus 2019
ISBN/ISSN: 978-1-7281-1697-6
Lembaga pengindeks: IEEEXPLORE/SCOPUS
URL website: http://2019.ieee-icma.org/
Judul artikel: Intelligent Multi Agent System for Energy Management in the Classrooms with Grid Connected PV

Proceedings of 2019 IEEE
International Conference on Mechatronics and Automation
August 4 - 7, Tianjin, China

# Intelligent Multi Agent System for Energy Management in the Classrooms with Grid Connected PV

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*Abstract* - **This paper presents an application of the Multi Agent System (MAS) in the Building Energy Management System, more specifically to manage the energy in the classrooms of a university. The grid connected photovoltaic (PV) is used as the electrical generation system to supply the loads in the classrooms. The objective is to minimize the electricity cost while maintaining user comfort. The MAS consists of the PV Agent, the Utility Agent, the Load Agent and the Central Control Agent. In addition, the Course Scheduler Unit is employed to inform the utilization or occupancy of the classrooms. The proposed system provides a new method to manage the energy usage from the PV by changing the temperature set-point of the air conditioner system using the Fuzzy Logic Controller. The simulation results show that the proposed system provides the highest performance index of 0.9902 in the optimization of the electricity cost and temperature comfort compared to the conventional method using a fixed temperature set-point.**

***Index Terms – Multi agent, energy management, grid connected PV.***

## I. INTRODUCTION

An Intelligent Multi Agent System (MAS) is widely adopted in the distributed control systems [1]. An intelligent agent (or agent) is an autonomous system that acts in the environment to achieve its goal. An agent receives the information from the environment and takes a decision to response the changes according to the goal. In the MAS, several agents collaborate with each other to meet the global objective.

Nowadays, the development of electrical power system increases rapidly in the framework of smart grid technology. The distributed generation becomes popular due to the high penetration of renewable energy resources. Another aspect in the smart grid that attracts the attention is the energy management system. The MAS is adopted in both applications, such as for the microgrid operations [2,3], the renewable energy generation [4], the energy management in smart homes [5-7] and the buildings [8-13].

The MAS was employed to schedule smart devices in multiple smart homes [5]. The objective is to minimize the cost and peak load. In [6], the MAS was proposed to optimize energy usage in a smart home. The multi agents consist of the Management Agents, the Electrical Supply System Agents, and the Home Appliance Agents. There are three agents in the Management Agents, i.e. the Supply Side Management Agent, which is used to manage the power from the supply systems; the Demand Side Management Agent, which is used to manage the power to the loads; and the Home Energy Management Agent, which is used to manage both Supply Side Management Agent and Demand Side Management Agent. The MAS in [7] used the Fuzzy Logic Controller (FLC) which is embedded in each agent of the home appliance. The system was developed to minimize the electricity cost while maintaining the user comfort level.

A four-layer agent consisted of the Switch Agent, the Central Coordinator Agent, the Local Controller Agent, and the Load Agent was proposed in [8] to manage energy in the commercial building. The Local Controller Agent controls the lighting and temperature of the rooms using the FLC. The Central Coordinator Agent coordinates the Switch Agent, the Local Controller Agent, and the Load Agent.

In [11] the MAS was employed in the Building Energy Management System (BEMS). The building is divided into several zones which are controlled by the agents. The agents consist of the Local Zone Agent, the Zone Agent, the On-site Generation Agent, and the Building Agent. The Local Zone Agent controls the environment at the local zone (room), which is composed of the H-agent (heating system), the V-agent (ventilation system), the C-agent (cooling system), the E-agent (lighting and electrical systems) and the U-agent (occupancy level).

Three agents namely the Generation Agent, the Load Agent, and the Storage Agent were proposed to manage the energy operation in the self-sustainable building [12]. The Generation Agent performs the following tasks: analyze and acquire the historical and weather data, control the electrical output, and power conditioning. The Load Agent optimizes the usage of loads of building by performing several tasks, such as load forecasting, appliance management, metering, and load scheduling. The Storage Agent controls the charging/discharging of the battery storage based on the state of charge (SOC) and the charging/discharging rate.

As discussed previously, the MAS in the BEMS is usually divided into the generation agents (and the storage agents), the load agents and the control agents. The loads discussed previously are the general loads in the common building such as the air conditioner, the lighting, etc. In this paper, we deal

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with the BEMS in a university building, more specifically the lecture rooms or the classrooms. The building is powered by the grid connected PV system. One unique characteristic of our proposed system is that the occupancy of the classroom is well defined by the course schedule. The main contribution of our paper is in the application of MAS to optimize the energy consumed by the classrooms by maximizing the energy from the PV resources while satisfying the temperature comfort in the classrooms. It is conducted by employing the FLC to set the temperature set-point of the classroom according to the power availability of the PV system and the outdoor temperature.

The rest of paper is organized as follows. Section 2 presents the proposed system. Section 3 discusses the simulation results. The conclusion is covered in Section 4.

## II. PROPOSED SYSTEM

### A. *System Overview*

The configuration of the electrical system is depicted in Fig. 1, where the arrow indicates the electrical flow. As shown in the figure, the electrical power to the loads in the classrooms is supplied by the PV system and the electric utility.

In this research, to simplify the discussion, only five classrooms are considered. However, the proposed system could be extended to cope with a large number of classrooms accordingly. In each classroom, there are three kinds of loads, i.e. the air conditioner (AC), the LCD projector, and the lamps. The LCD projector and the lamps are controlled by on/off mode according to the class utilization. While the AC is a thermostat controlled, in which the temperature set-point is determined by the MAS as described in the next section.

The configuration of MAS to manage the energy consumption in the classroom is depicted in Fig. 2. The Load Agent (LA) is used to control the loads in a classroom. It sets the temperature set-point for operating the AC and switches on/off the lamps and the LCD projector based on the information from the Central Control Agent (CCA) and the Course Scheduler (CSCH). The CCA sends information about the available power of renewable resources. The Course Scheduler (CSCH) is an information system that manages the utilization of classrooms, i.e. the time schedule of the course.

The PV Agent (PVA) is an agent that is responsible to manage the power from the PV. The PVA sends the information about its power to the CCA and gets the control signal related to its power flow from the CCA. The UA is basically a simple agent to control the connection of the utility to the grid according to the signal control sent by the CCA.

CCA is the main control of the whole system. It manages the operation of the loads, the PV system and the utility. The CCA employs the FLC to generate the signal controls to the respective agents. The main objective is to maximize the power while maintaining the user comfort.

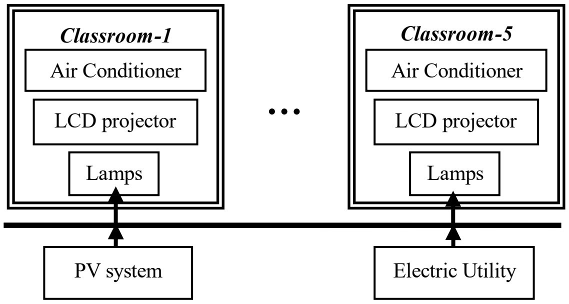

Fig. 1 Configuration of electrical system.

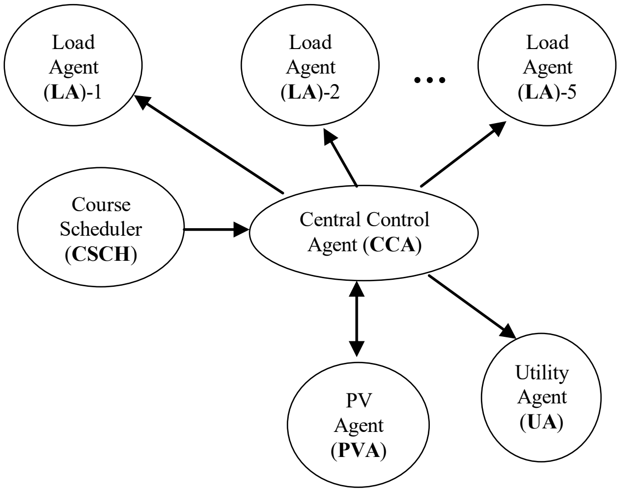

Fig. 2 Configuration of MAS.

### B. *Multi Agent System*

The configuration of the Load Agent (LA) is depicted in Fig. 3. All three loads (AC, lamps, LCD projector) are operated when the classroom is occupied, i.e. there is a course conducted in the classroom. The occupancy information is obtained from the CSCH.

In the current research, the operation of the Lamps and the LCD projector is just switched on/off. While the AC is operated using the thermostat control, i.e. the temperature of the classroom should follow the temperature set-point of AC. By varying the temperature set-point, the energy consumed by the AC could be managed respectively.

As shown in the figure, the agent controls the operation of the loads based on the occupancy of the classroom, the outdoor temperature and the level of renewable energy resources (RES_LEV). The RES_LEV data is sent by the CCA. The RES_LEV is a value that indicates the level of availability of renewable energy resources. This value will be used by the FLC in the LA to set the temperature set-point as discussed in the next section.

The configuration of the PV Agent (PVA) is depicted in Fig. 4. PVA has two main tasks. The first task is to read the weather information and send the predicted PV power to the CCA. The second task is to read the control signal from the CCA and generate a switching signal to the power switch.

The switching signal is used to select the power flow from the PV as follows:

- Grid connection: the PV is connected to the grid
- Disconnected: the PV is disconnected from the system.

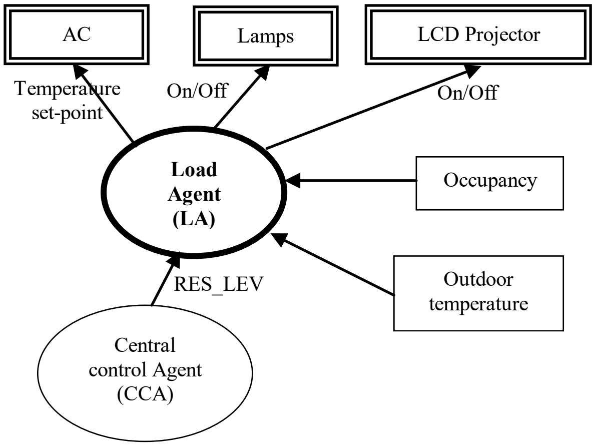

Fig. 3 Configuration of the Load Agent.

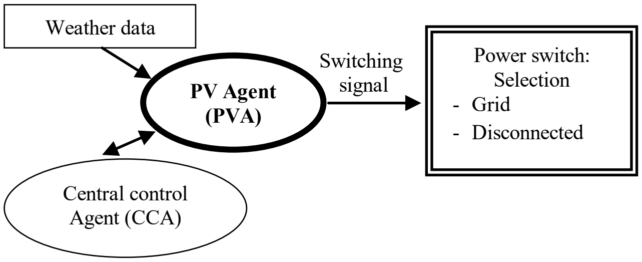

Fig. 4 Configuration of the PV Agent.

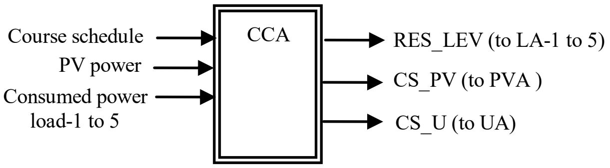

Fig. 5.The input and output of the Central Control Agent.

The CCA generates the control signals to the other agents as depicted in Fig. 5. The control signal to PVA and UA are CS_PV and CS_U, which are used to connect or connect the PV and the utility to the grid.

The control signal to the LA is RES_LEV which is determined by the FLC as described in the following section.

### C. *FLC in the Central Control Agent*

As described previously, the CCA employs the FLC (later on is called as the FLC-CCA) to generate the control signal to the LA, the PVA, and the UA. The architecture of FLC-CCA is depicted in Fig. 6. As shown in the figure, the FLC-CCA has two inputs and one output. The inputs are the available power from the renewable energy resources (RES_PWR=PV power) and the power consumed by the loads (CONS_PWR=Consumed power load-1 to 5). While the output is the level of available power from renewable energy resources (RES_LEV).

The fuzzy membership functions of RES_PWR, CONS_PWR, and RES_LEV are depicted in Fig. 7. Each variable has three linguistic values, i.e. LOW, MED, and HIGH.

Since the objective of MAS is to minimize the electricity cost by maximizing the energy usage from the RES, thus the fuzzy rules are developed in such a way to fulfill that objective. The main idea is to provide information about the availability of RES to the LA. Then the LA uses this information to determine the temperature set-point.

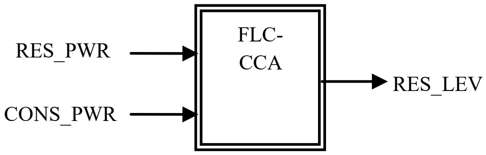

Fig. 6 FLC-CCA architecture.

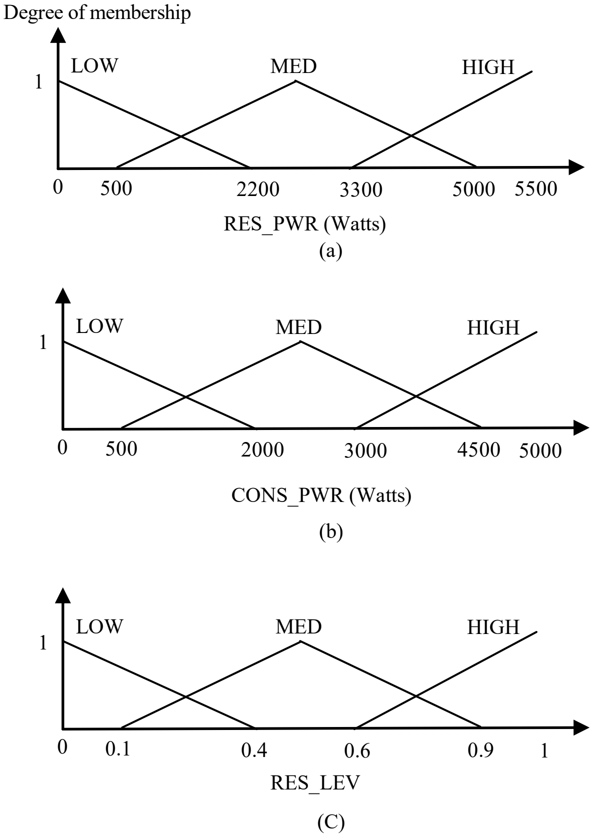

Fig. 7 Membership functions of FLC-CCA: (a) RES_PWR; (b) CONS_PWR; (c) RES_LEV.

TABLE I
FUZZY RULES OF FLC-CCA

| *RES_PWR*<br>*CONS_PWR* | LOW | MED | HIGH |
|---|---|---|---|
| **LOW** | ***MED*** | ***MED*** | ***HIGH*** |
| **MED** | ***LOW*** | ***MED*** | ***HIGH*** |
| **HIGH** | ***LOW*** | ***MED*** | ***MED*** |

The information about the availability of RES is then called as the RES_LEV and determined based on the RES_PWR and CONS_PWR. The fuzzy rules are listed in Table 1. Several rules from the table could be explained as follows:

- IF RES_PWR is HIGH AND CONS_PWR is LOW THEN RES_LEV is HIGH: There is surplus power from RES, thus the RES_LEV is set to a high level.
- IF RES_PWR is LOW AND CONS_PWR is HIGH THEN RES_LEV is LOW: There is not enough power from RES, thus the RES_LEV is set to a low level.
- IF RES_PWR is MED AND CONS_PWR is MED THEN RES_LEV is MED: The availability of power from RES is medium, thus the RES_LEV is set to medium level.

### D. *FLC in the Load Agent*

The FLC in the LA (later on is called FLC-LA) is used to set the temperature set-point of the AC in the classroom as depicted in Fig. 8. This set-point is determined to satisfy two conditions: a) the temperature set-point is in the range of comfortable level; b) the availability power from RES should be extracted as much as possible.

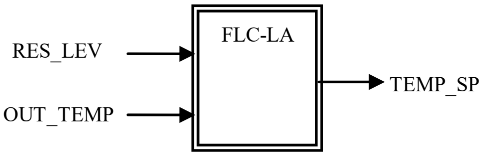

Fig. 8 FLC-LA architecture.

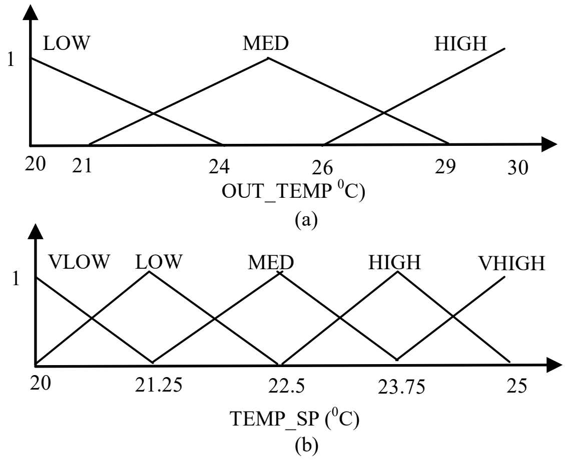

Fig. 9 Membership functions of FLC-LA: (a) OUT_TEMP; (b) TEMP_SP.

TABLE II
FUZZY RULES OF FLC-LA

| *RES_LEV*<br>*OUT_TEMP* | LOW | MED | HIGH |
|---|---|---|---|
| **LOW** | ***VERY HIGH*** | ***MED*** | ***VERY LOW*** |
| **MED** | ***HIGH*** | ***MED*** | ***LOW*** |
| **HIGH** | ***HIGH*** | ***MED*** | ***LOW*** |

As shown in Fig. 8, the inputs of FLC-LA are the RES_LEV and the outdoor temperature (OUT_TEMP). While the output is the temperature set-point (TEMP_SP). The fuzzy membership function of RES_LEV is the one in the FLC-CCA which is shown in Fig. 7(c). The fuzzy membership functions of OUT_TEMP and TEMP_SP are depicted in Fig. 9. It is noted here that the value of TEMP_SP falls in the range of user comfortable, i.e. from 20 $^{0}$C to 25 $^{0}$C.

To achieve the goal of minimizing the electricity cost while allowing the temperature comfort, the fuzzy rules are defined as listed in Table 2. The rules are determined based on the idea that by increasing the temperature set-point, the energy consumed by the AC will decrease. Thus when the RES power is low, it is better to increase the temperature set-point and vice versa.

From the fuzzy rules listed in Table 2, several rules are explained as follows:

- IF RES_LEV is LOW AND OUT_TEMP is LOW THEN TEMP_SP is VERY HIGH: There is a small amount power from RES, and the outdoor temperature is low, thus it is a better to set the temperature set-point to very high value for decreasing the energy consumption.
- IF RES_LEV is HIGH AND OUT_TEMP is HIGH THEN TEMP_SP is VERY LOW: There is surplus power from RES, and the outdoor temperature is low, thus it suggests that the temperature set-point could be set to a very low value.

## III. SIMULATION RESULTS

To verify our proposed system, we model the system using MATLAB-SIMULINK [14]. The PV generator is simulated using the model developed in [15]. The AC and thermal system of the room are modeled based on the example given in the SIMULINK software [14]. The electrical power rating of the PV and the loads in the classroom are given in Table 3. The data for irradiation, outdoor temperature, course schedule (occupancy of the classroom) are given in Table 4.

The simulation results are depicted in Fig. 10 and Fig. 11. In Fig. 10, the profiles of RES_LEV, outdoor temperature, temperature set-point, classroom temperature of classroom-1 are shown. For convenience, the profiles are shown from 06:00 h to 17:00 h when the classrooms are occupied. From the figure, we can see that at 07:00 h, the classroom-1 is occupied and the PV produces a small power.

Therefore the RES_LEV is low and forces the system to set the temperature set-point to the higher value, i.e. 23 $^0$C. At 12:00 h, when there is enough power from the PV and the consumed power is also high, then the RES_LEV will have a medium value, i.e. 0.5. It will set the temperature set-point to the medium value, i.e. 22.5 $^0$C.

Fig. 11 shows the profiles of consumed power of classroom-1 to classroom-5 from 06:00 h to 17:00 h. By observing the top figure, i.e. the consumed power of classroom-1, it is obtained that the consumed power in the morning is lower than the one in the afternoon. This result could be understood by examining Fig. 10 as follows. In the afternoon, the outside temperature is higher than the one in the morning. Since the temperature set-point is about 22.5 $^0$C, the AC will consume more power in the afternoon to reach the set-point.

TABLE III
POWER RATINGS OF GENERATOR AND LOADS

| **Generator and Loads** | **Power rating** |
|---|---|
| PV | 3000 W |
| AC | 450 W (per room) |
| LCD projector | 310 W (per room) |
| Lamps | 240 W (per room) |

TABLE IV
IRRADIATION, OUTDOOR TEMPERATURE, OCCUPANCY OF CLASSROOM-1 TO 5

| **Time (hour)** | **Irradiation (W/m$^2$)** | **Outdoor temperature ($^0$C)** | **Classroom (O=occupied; X=empty)** | | | | |
|---|---|---|---|---|---|---|---|
| | | | **1** | **2** | **3** | **4** | **5** |
| 00:00 | 0 | 21 | X | X | X | X | X |
| 01:00 | 0 | 21 | X | X | X | X | X |
| 02:00 | 0 | 21 | X | X | X | X | X |
| 03:00 | 0 | 21 | X | X | X | X | X |
| 04:00 | 0 | 21 | X | X | X | X | X |
| 05:00 | 0 | 21 | X | X | X | X | X |
| 06:00 | 0 | 22 | X | X | X | X | O |
| 07:00 | 200 | 22 | O | X | X | O | O |
| 08:00 | 300 | 24 | O | O | X | O | O |
| 09:00 | 500 | 25 | O | O | X | O | O |
| 10:00 | 700 | 26 | X | O | O | X | O |
| 11:00 | 900 | 26 | X | O | O | X | O |
| 12:00 | 900 | 26 | O | O | O | X | X |
| 13:00 | 800 | 26 | O | X | O | X | O |
| 14:00 | 600 | 27 | O | X | O | O | O |
| 15:00 | 400 | 27 | X | X | O | O | O |
| 16:00 | 300 | 24 | X | X | X | O | X |
| 17:00 | 0 | 24 | X | X | X | X | X |
| 18:00 | 0 | 24 | X | X | X | X | X |
| 19:00 | 0 | 24 | X | X | X | X | X |
| 20:00 | 0 | 23 | X | X | X | X | X |
| 21:00 | 0 | 23 | X | X | X | X | X |
| 22:00 | 0 | 23 | X | X | X | X | X |
| 23:00 | 0 | 22 | X | X | X | X | X |

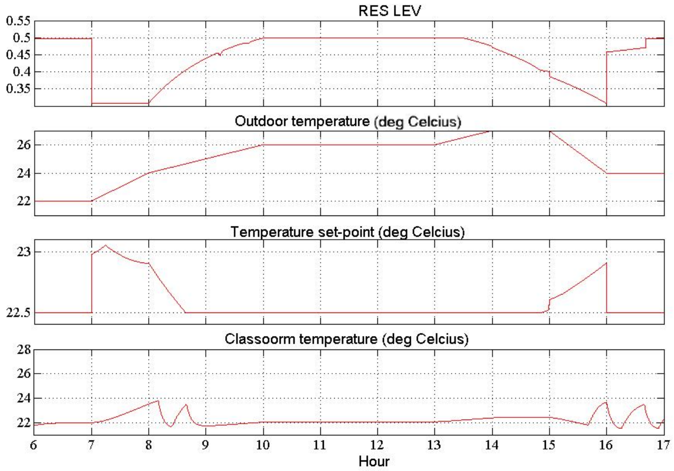

Fig. 10 Profiles of RES_LEV, outdoor temperature, temperature set-point, classroom temperature of classroom-1.

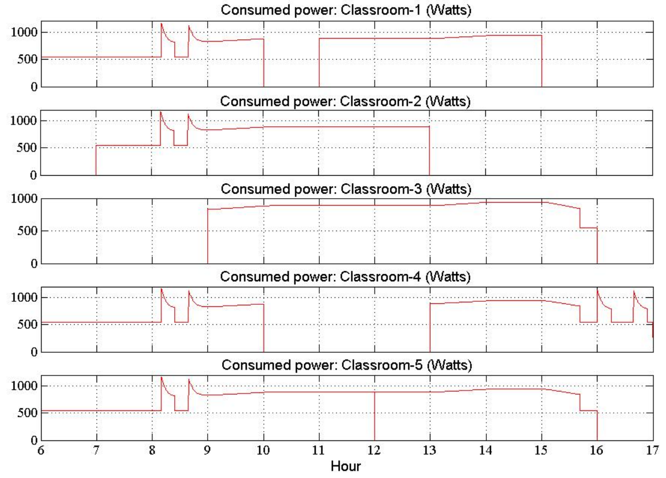

Fig. 11 Profiles of consumed power of classroom-1 to classroom-5.

TABLE V
COMPARISON RESULTS OF PERFORMANCE INDEX

| **Method** | | ***en_lev*** | ***cf_lev*** | ***pi*** |
|---|---|---|---|---|
| Fixed temperature set-point | 21 $^0$C | 0.0039 | 0.8480 | 0.8519 |
| | 22 $^0$C | 0.0498 | 0.9124 | 0.9622 |
| | 23 $^0$C | 0.1475 | 0.8276 | 0.9751 |
| | 24 $^0$C | 0.4317 | 0.3541 | 0.7858 |
| | 25 $^0$C | 0.6358 | 0.0077 | 0.6435 |
| Proposed system | | 0.0989 | 0.8913 | 0.9902 |

To measure the effectiveness of the proposed system in the optimization of the electricity cost and the comfort level, we define the performance index (*pi*) as follows:

$$pi = en\_lev + cf\_lev \quad (1)$$

$$en\_lev = 1 - \sum_{h} (c - p)/\beta) \quad (2)$$

$$cf\_lev = 1 - \sum_{h} \left| st - rt \right| / \gamma) \quad (3)$$

where *en_lev* and *cf_lev* represent the level of electricity cost and the temperature comfort respectively, *c* and *p* are consumed power by the loads and the PV power respectively, *st* and *rt* are the reference temperature and the classroom temperature respectively, *β* and *γ* are the constants for normalization, and *h* represents the hour.

In the simulation, we compare our proposed system, i.e. varying the temperature set-point, with the fixed temperature set-point. The comparison results are given in Table 5. It is clearly shown that the proposed method provides the highest value of the performance index (*pi*). It means that our proposed system achieves the highest performance among the other methods (fixed temperature set-point). The table suggests that our proposed system achieves the high index of the temperature level. It conforms with the idea of the proposed algorithm that determining the temperature set-point according to the availability of power from the PV and the outdoor temperature.

In addition, we test our proposed MAS on the embedded system, especially dealing with the execution time, the implementation cost, and the communication interface. The embedded platform is similar to our previous work [16], i.e. using the low cost WeMos module [17]. The main algorithm of each agent is implemented on the WeMos module, which is communicated with other agents via the WiFi communication. From the experiments, the execution time of the FLC is 13 ms and the transfer time between each agent is 332 ms. The results show that our proposed method is suitable for the real-time implementation, in which the update time of building energy management system is usually on hourly basis.

## IV. CONCLUSION

The MAS is proposed to manage the energy in the classrooms by varying the temperature set-point according to the PV power and the outdoor temperature. The FLC is adopted in the agents to find the optimal temperature set-point. The performance index representing the measurement of the level of electricity saving cost and the user comfortable level is developed which is used to compare the proposed system with the fixed temperature set-point. Using the developed performance index, the proposed system achieves the highest value of 0.9902. Further, the possible implementation in the real-time system is verified by a small embedded platform and shows the promising results, in terms of the fast execution time, i.e. less than one minute, and the low cost implementation of the embedded system.

In future, the system will be extended to cope with more complex building. The advanced algorithms will be adopted accordingly. Further the system will be implemented in the hardware prototype.

## ACKNOWLEDGMENT

This work is supported by the Research Grant, Excellent Basic Research on Higher Institution scheme (PDUPT) from Directorate General of Higher Education, Ministry of Research and Technology and Higher Education, Republic of Indonesia, 2019.

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Dokumen pendukung luaran Wajib #2

Luaran dijanjikan: Buku Hasil Penelitian

Target: sudah terbit
Dicapai: Terbit

Dokumen wajib diunggah:
1.

Dokumen sudah diunggah:
1. Buku hasil penelitian meliputi cover, lembar yg memuat ISBN dan daftar isi

Dokumen belum diunggah:
-

Judul Buku: SISTEM MANAJEMEN ENERGI LISTRIK RUMAH DAN GEDUNG
Nama Penerbit: Dream Litera Buana
Website Penerbit: http://dreamlitera.com/
ISBN: 978-623-7598-05-3
Tahun Terbit: 2019
Jumlah Halaman: 58
URL Buku: http://dreamlitera.com/

# SISTEM MANAJEMEN ENERGI LISTRIK RUMAH DAN GEDUNG

**Oleh:**
**Aryuanto Soetedjo**
**Yusuf Ismail Nakhoda**
**Choirul Saleh**

**Dream Litera Buana**
**Malang 2019**

**Aryuanto Soetedjo**
**Yusuf Ismail Nakhoda**
**Choirul Saleh**

# SISTEM MANAJEMEN
# ENERGI LISTRIK
# RUMAH DAN GEDUNG

**SISTEM MANAJEMEN ENERGI LISTRIK RUMAH DAN GEDUNG**

**Penulis:**
**Aryuanto Soetedjo**
**Yusuf Ismail Nakhoda**
**Choirul Saleh**

Malang 2019
58 halaman, 15,5 x 23 cm

**ISBN: 978-623-7598-05-3**

Diterbitkan oleh:
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Anggota IKAPI No. 158/JTI/2015

Cetakan pertama, Nopember 2019

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Dibiayai Hibah Penelitian Dasar Unggulana Perguruan Tinggi (PDUPT)
Ristekdikti  Tahun 2018-2019

# KATA PENGANTAR

Puji syukur kami ke hadirat Allah SWT atas rahmat dan karunianya sehingga Buku "Sistem Manajemen Energi Listrik Rumah dan Gedung" dapat diselesaikan dengan baik. Buku ini membahas secara singkat contoh sistem manajemen energi listrik di rumah dan gedung.

Sistem manajemen energi yang dibahas dalan buku ini meliputi optimasi pemakaian energi listrik di rumah dan gedung yang dilengkapi dengan pembangkit energi surya. Beberapa teknik optimasi seperti menggunakan pemrograman linier dan logika fuzzy dibahas Selain itu dibahas juga implementasi sistem optimasi energi listrik menggunakan sistem embeded.

Penulis berharap buku ini dapat memberikan gambaran pembaca tentang perkembangan teknologi kelisitrikan, elektronika dan komputer khususnya implementasi sistem manajemen energi listrik di perumahan dan gedung secara nyata.

Akhir kata penulis mengucapkan terima kasih kepada semua pihak yang sudah membantu dalam penerbitan buku ini. Kritik dan saran sangat kami harapkan untuk perbaikan buku ini.

**Malang, Oktober 2019**

**Penulis**

# DAFTAR ISI

dreamlitera

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Kepuharjo, Karangploso
Kabupaten Malang, Jawa Timur
Telp. 0812 3312 8428 / 0856 4663 3407

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## SURAT PERNYATAAN

Nomor : 0155/DL/SP/11/2019

Yang bertanda tangan di bawah ini :

**Nama** : **Geneng Dwi Yoga Isnaini**
**Alamat** : **Perum Griya Sampurna, Blok E7/5. Kepuharjo, Karangploso, Kabupaten Malang**
**Jabatan** : **Direktur CV. Dream Litera Buana (Anggota IKAPI No. 158/JTI/2015)**

Dengan ini menyatakan bahwa buku berjudul: **Sistem Manajemen Energi Listrik Rumah Dan Gedung** penulis (1) **Aryuanto Soetedjo, (2) Yusuf Ismail Nakhoda, (3) Choirul Saleh** dengan jumlah halaman 52 halaman dan ISBN: 978-623-7598-05-3 telah diterbitkan secara nasional oleh penerbit Dreamlitera Buana Malang pada November 2019 sebanyak 30 eksemplar

Demikian surat pernyataan ini dibuat agar dapat dipergunakan sebagaimana mestinya.

Malang, 21 November 2019
Hormat kami

**Geneng Dwi Yoga Isnaini**
*Direktur Dream Litera*

Dokumen pendukung luaran Wajib #3

Luaran dijanjikan: Hak Cipta

Target: granted
Dicapai: Bersertifikat

Dokumen wajib diunggah:
1. Deskripsi dan spesifikasi ciptaan
2. Sertifikat hak cipta

Dokumen sudah diunggah:
1. Deskripsi dan spesifikasi ciptaan
2. Sertifikat hak cipta

Dokumen belum diunggah:
-

Nama Ciptaan: Program Komputer SOLAR PV SIMULATOR (SIMULATOR PANEL SURYA)
Pemegang Hak Cipta: ITN Malang
No Pencatatan: 000163262
Tgl Pencatatan: 9 November 2019

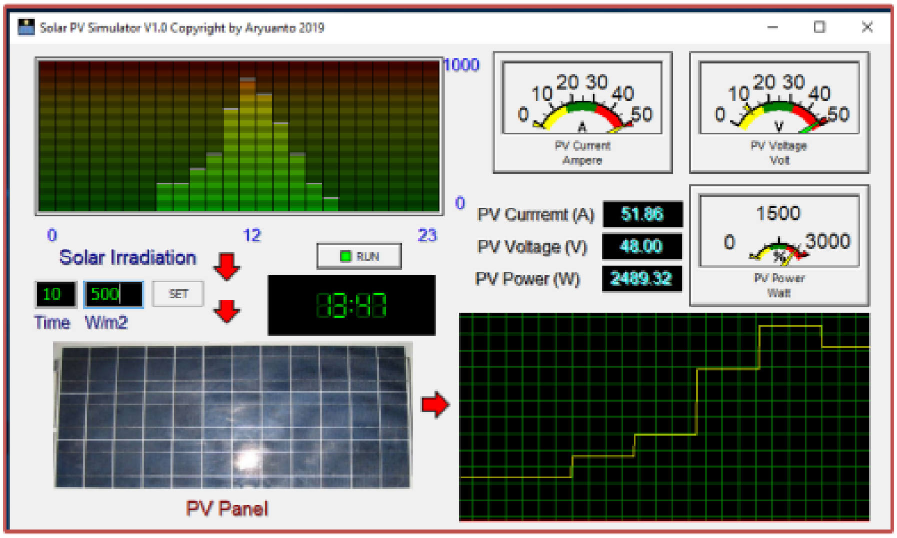
# Deskripsi dan Spesisfikasi Program Solar PV Simulator (Simulator Panel Surya)

Perangkat lunak Solar PV Simulator merupakan sebuah program aplikasi yang digunakan untuk mensimulasikan panel surya. Perangkat lunak ini dilengkapi dengan beberapa fitur seperti:

- ✓ Menampilkan grafik radiasi surya
- ✓ Menampilkan grafik daya listrik panel surya
- ✓ Menampilkan tegangan, arus dan daya listrik panel surya
- ✓ Pengguna dapat mengeset nilai radiasi surya yang diinginkan

Simulasi panel surya dilakukan berdasarkan data masukan radiasi surya yang dapat diset oleh pengguna dari pagi sampai sore dengan interval waktu 1 jam. Ketika program simulasi berjalan, maka tegangan, arus dan daya panel surya dihitung dan ditampilkan baik dalam bentuk angka, tampilan meter dan grafik berjalan selama simulasi berlangsung.

Dengan menggunakan perangkat lunak simulasi ini, hubungan antara besarnya radiasi surya dan daya listrk yang dihasilkan dapat diketahui dan ditampilkan dalam bentuk grafik yang mempermdah pengguna untuk melakukan analisa data terkait dengan karakteristik panel surya.


Solar PV Simulator V1.0 Copyright by Aryuanto 2019

Time: 10
W/m2: 500

PV Curremt (A) 51.86
PV Voltage (V) 48.00
PV Power (W) 2489.32

**REPUBLIK INDONESIA**
**KEMENTERIAN HUKUM DAN HAK ASASI MANUSIA**

# SURAT PENCATATAN CIPTAAN

Dalam rangka pelindungan ciptaan di bidang ilmu pengetahuan, seni dan sastra berdasarkan Undang-Undang Nomor 28 Tahun 2014 tentang Hak Cipta, dengan ini menerangkan:

| | | |
|---|---|---|
| Nomor dan tanggal permohonan | : | EC00201980748, 9 November 2019 |
| **Pencipta** | | |
| Nama | : | **Dr. Eng. Aryuanto Soetedjo, ST., MT.** |
| Alamat | : | Jl. Bendungan Sigura-gura Nomor 2 , Malang, Jawa Timur, 65145 |
| Kewarganegaraan | : | Indonesia |
| **Pemegang Hak Cipta** | | |
| Nama | : | **ITN Malang** |
| Alamat | : | Jl. Bendungan Sigura-gura Nomor 2 , Malang, Jawa Timur, 65145 |
| Kewarganegaraan | : | Indonesia |
| Jenis Ciptaan | : | **Program Komputer** |
| Judul Ciptaan | : | **SOLAR PV SIMULATOR (SIMULATOR PANEL SURYA)** |
| Tanggal dan tempat diumumkan untuk pertama kali di wilayah Indonesia atau di luar wilayah Indonesia | : | 8 November 2019, di Malang |
| Jangka waktu pelindungan | : | Berlaku selama 50 (lima puluh) tahun sejak Ciptaan tersebut pertama kali dilakukan Pengumuman. |
| Nomor pencatatan | : | 000163262 |

adalah benar berdasarkan keterangan yang diberikan oleh Pemohon.
Surat Pencatatan Hak Cipta atau produk Hak terkait ini sesuai dengan Pasal 72 Undang-Undang Nomor 28 Tahun 2014 tentang Hak Cipta.

a.n. MENTERI HUKUM DAN HAK ASASI MANUSIA
DIREKTUR JENDERAL KEKAYAAN INTELEKTUAL

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