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Fuzzy Logic-based Power Management System for Self-Powered Green IoT Edge Devices

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ABSTRACT

The Internet of Things or IoT refers to the billions of devices that are connected to the Internet for intercommunication between each other, allowing Machine to Machine communication. As the IoT is capable of offering many convenient solutions, this paradigm is becoming so much popular creating a huge boom all around the world. Owing to the billions of devices that connect our daily life with the cyber-physical world, powering up these IoT solutions is becoming a big challenge, whereas self-powered IoT devices are becoming a viable solution in which researchers are currently working on. In this regard, many researchers have researched; to power up these IoT devices with renewable energy sources, where solar power is considered to be the key solution that is majorly accepted worldwide. However due to the cyclic variation of the receiving light intensity throughout the day and the unexpected interruptions due to weather conditions are becoming some of the major unresolved challenges pertained to these solar-powered IoT devices, where it requires a backup power source for solar-powered IoT devices with the need of continuous data harvesting throughout a long period of time. The environmental effects raised by removing batteries which is used as key the backup power source in IoT devices will become a major problem in the near future. Hence, in order to address this challenge and to offer a green solution that lowers the effects to the environment, we are presenting a fuzzy logic-based power management system in the context of Green IoT (GIoT).

Key Terms: IoT, Internet of Things, Fuzzy Logic, Green IoT, Renewable Energy

Introduction

The Internet of Things (IoT) is one of the most significant technological revolutions of the twenty-first century, transforming every physical thing into an information source and revolutionizing how we interact with our environment [1]. Its goal is to build a connected object ecosystem and enable pervasive connectivity amongst trillions of Internet-connected devices. While recent advances in the miniaturization of devices with higher computational capabilities and ultra-low power communication technologies have enabled the widespread deployment of sensors and actuators, such an evolution necessitates fundamental changes in hardware design, software, network architecture, data analytics, data storage, and power sources [2]-[4].

In the current context, self-powered IoT devices are becoming a popular solution for the energy demand stress created by the parallel operation of a large number of IoT devices into the grid [1],[2]. It is evident that researchers have tried to power up the IoT devices using renewable power sources like solar energy, thermal energy, vibration, wind,

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and so on as a viable solution. In light of all these renewable energy sources, solar-powered devices are the most admired renewable power source by the majority, among other sorts of energy sources. However, the cyclic variation of the receiving light intensity throughout the day and the unexpected interruptions due to weather conditions are major challenges for solar-powered IoT devices as we have noted in the literature, which researchers are currently working on. Thus, the requirement for a backup power source for solar-powered IoT devices is an essential need for continuous data harvesting throughout a long period [5]-[7].

In this regard, the most reliable secondary power device for solar-powered devices is batteries, as we have noted through the latest research [1],[8],[9]. When it comes to GIoT, the usage of batteries for self-powered devices is a major bottleneck that needs to be addressed, considering the damage they may create upon the surrounding environment. Further owing to the environmental pollution caused by removing batteries, using batteries as the second power source for clear powered IoT devices is still questionable. On the other hand, the impact that can be brought regarding environmental pollution is a major issue with the exponentially increasing IoT devices all around the world in the upcoming years, as already the use of IoT is becoming a mega hype [10].

Further, the possibilities for extending the lifetime of the batteries and utilizing the battery capacity at its maximum level can bring considerable relief for the rapid replacement of batteries from off-grid IoT devices [11],[12]. The purpose of maximizing battery life without compromising the performance of the device is a challenging task when it comes to solar-powered devices. The irregular pattern of power generation due to various factors can easily put a significant amount of stress on the battery in the absence of a proper power management system, which may hinder the adoption of solar power.

Thus, in order to solve this problem and successfully and intelligently manage and control the supplied solar power to the self-powered IoT device, we are proposing a fuzzy-logic controller to intelligently manage the generated power by the solar panel to maximize the lifespan of the battery in solar-powered IoT devices.

Contributions of the study

In order to successfully and intelligently manage and control the supplied solar power to the self-powered IoT device, we are proposing a fuzzy-logic controller to intelligently manage the generated power by the solar panel to maximize the lifespan of the batteries. In this regard, the following contributions have been made. First, a brief overview is presented in terms of self-powered IoT devices. Next, we offer a brief literature review of related work, summarizing the previous work. Afterward, we present our proposed model highlighting the fuzzy controller for determining the power source; then fuzzy controller for determining the operating mode when powered with solar power, and fuzzy controller for determining the operating mode when powered with battery power. Finally, the experimental results are highlighted to prove the validity and significance of our work.

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Outline of the study

Following the introduction, in the second chapter in order to provide a better overview for our readers, we are providing a brief literature review for their understanding. In the third chapter, our proposed model is highlighted. Model evaluation and validation are discussed in the fourth chapter and finally, the conclusions are highlighted in the last chapter, also highlighting future work.

Background and Related Work

IoT and associated technologies cover a wide range of devices connected to the Internet [1]. These things or items may detect the environment, transport information, and interact with one another in a number of ways. IoT devices, like any other device, require energy to function and run. However, in some circumstances, these devices consume more energy than is required, resulting in energy waste by creating superfluous heat. For the sake of economics and environmental safety, this waste of energy and unneeded heat should be eliminated. The energy consumption for device functioning has grown as a result of recent technology advancements and the exponential expansion of operational IoT devices. As a result, the need for low-power IoT, also known as Green IoT or GIoT, grew. Hence the IoT will play a vital role in reducing climate change in the next years by adjusting to low-energy consumption tactics [13]-[15]. With this in mind, in this research in order to successfully and intelligently manage and control the supplied solar power to the self-powered IoT device, we are proposing a fuzzy-logic controller to intelligently manage the generated power by the solar panel to maximize the lifespan of the batteries, optimize the use of batteries, reducing energy wastage that would have been wasted in the form of heat. Further based on the current context of the research what we have understood is owing to the novelty in the field there is very little research has been done in this area, which necessitates the highest attention to this area. Thus in TABLE 1, we provide a brief summary of related work that has been done by other researchers.

TABLE 1: RELATED WORK IN TERMS SELF POWERED IOT AND GIOT

Reference	Survey	Research	Contributions
[2],2021	✓		A review of Green IoT is presented highlighting what measures can be taken to lessen the environmental damage from IoT
[3],2018		✓	This study shows a proof of concept for a self-powered IoT device that is totally self-sustaining thanks to energy harvesting
[4],2017		✓	A self-powered IoT node with an efficient micro-scale solar power management architecture is presented in this study.
[6],2017		✓	The creation and deployment of a unique, totally autonomous, self-powered wireless sensor for

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			real-time traffic monitoring in smart cities are described in this study.
[7],2020	✓		A review is presented in terms of energy harvesting for IoT.
[8],2019		✓	The researchers investigate the usage of perovskite solar cells to power RF backscatter-based IoT devices in this paper.
[9],2019		✓	The prototype design and testing of a long-range, self-powered IoT device for precision agriculture and aquaponics are presented in this article.
[10],2018	✓		A novel software paradigm is proposed in this research to increase the energy efficiency of edge devices for transient computing using ultra-low energy harvesting power supply.
[12],2018		✓	This research describes a smart self-powered water monitoring system that takes advantage of IoT and cloud computing.
[13],2020		✓	This research describes a self-powered IoT with adaptive power management and feedback for room temperature and humidity monitoring applications.
[14],2018		✓	This study describes a wearable IoT sensor network for safety applications that monitors hazardous environmental conditions.
[15],2017	✓		The researchers address the primary design issues of IoT devices in terms of energy and power in this paper, as well as design considerations for effective self-powered IoT device implementations.

Proposed Model

Having provided a brief overview on background related to the self-powered IoT and Green IoT; in this section, we intended to discuss further on our proposed fuzzy logic power management system. The majority of the self-powered IoT devices that operate on solar power follow a common method to supply power to the system that consists of an energy harvesting device and a battery to store the energy and power up the device. The energy harvesting system only focuses on charging the battery as much as possible throughout the operation. The main disadvantage incorporated with this system is the low

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life span of the battery due to excessive usage and vulnerability to other stresses such as overheating and over-draining during operation. After the completion of charging the battery the generated power from the energy harvesting system becomes unutilized. The purposed system in this paper is capable of utilizing the harvested energy from the energy harvesting system maximumly while keeping the battery condition within the comfort zone.

Our proposed IoT system consists of two power sources including a solar panel and a Li-ion battery that are sufficient enough to power up the system individually. This is one of the major concerns in the system because this specification strengths the capability of the power management system to shift between the power sources frequently to maximize the efficient utilization of resources. In terms of minimizing the battery usage, the fuzzy controller used in this system is mainly oriented to operate using solar power. By minimizing the usage of Li-ion batteries, this system was developed to keep the battery temperature within the lowest possible value when operating in tropical environments. In tropical countries, the environmental temperature rises above 30 °C on a typical day. Under this type of environmental condition, continuous usage of a Li-ion battery encourages to exceed the battery temperature over healthy limits which causes to decrease the lifetime.

When considering the power management system of the IoT setup, firstly the system needs to decide the most suitable power source to operate the IoT device based on the measured parameters. The controlling algorithm of the system was designed with paying a higher percentage of interest to operate the IoT device with solar power rather than using the battery. For the experimental setup, two ESP8266 modules were used for the power management system, along with a cloud-based environmental temperature monitoring system. A DS18B20 temperature sensor was used for taking out temperature measurements.

The process of selecting the power source is based on two inputs.

1. ***Current output from the solar panel***
   For the simplicity of the system, the difference of the voltage at output terminals is considered negligible when compared to the variation of the current. For this experiment, the current supplied from the solar panel was used as an input to the power management system.
2. ***Voltage of the Li-ion battery***
   The variation of the voltage of the Li-ion battery is considered as the main parameter to decide the strength of the power source because the variation of the current supply from the battery is more than 5 times the required value.

Fig 1 illustrates the architecture of the controlling loop embedded in the power management system. On top of this architecture, a closed-loop controller is initiated to decide the power source for the IoT device as the first step. Following the closed-loop controllers' decision, two individual Fuzzy Logic controllers select the operating mode under each selected power source based on its availability and status.

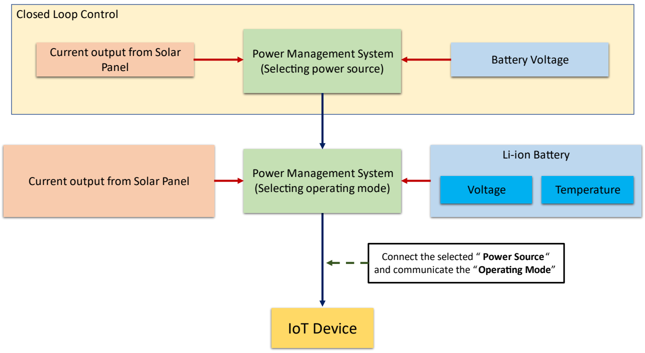

Fig 1. Overview of the Control Architecture for Power Management System

Then the architecture of the IoT device is simplified into two main steps as shown in Fig 2. Firstly, the power management system turns on the IoT device, and then the IoT device initiates the temperature sensor and reads the feedback. At the same time, the power management system communicates the operating mode based on the strength of the power source to the IoT device to complete its task. If the strength of the power source is above the limits, the IoT device will be instructed to connect to the Wi-Fi router and transfer sensor readings to the cloud through the internet.

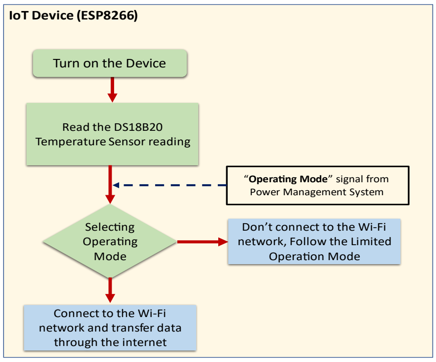

Fig 2. The Overview of IoT Devices' Operation

Fuzzy controller for determining the power source

For the purpose of determining and shifting the power source for the IoT device, a Mandani type Fuzzy Controller is used with 02 inputs and a single output as shown in Fig 3.

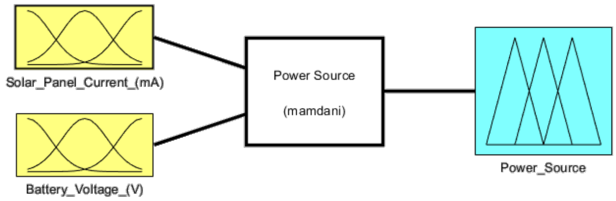

Fig 3. Fuzzy controller for determining the power source

The self-powered IoT device developed in this research consists of two power sources including a solar panel and a Li-ion battery. There should be a well-defined set of rules for deciding the compatibility of solar panel output for operating the IoT device, with the uncertainty of the solar power generation which fluctuates throughout the operation with respect to environmental conditions. For the robustness of the power management system, the design process of membership functions was based on the power consumption of the IoT device under two main different circumstances as described below.

1. Firstly, operating the IoT device with 100% functionality, by reading sensor feedbacks and transferring readings through Wi-Fi connectivity was considered and measured the current demand from the IoT device. Fig 4 illustrates the current demand from the IoT device when it is fully operating under normal conditions under continuous operation mode. In the full operation mode, the IoT device reads the sensor readings and transfer the data through WiFi connectivity.

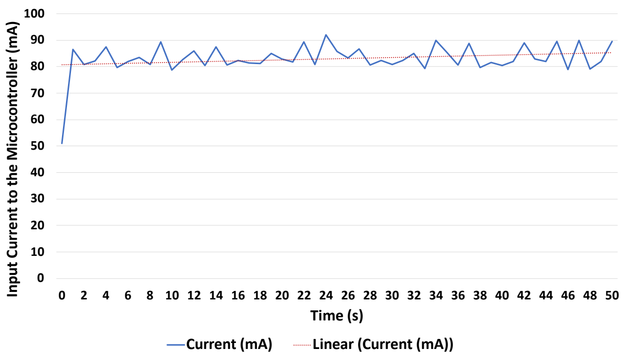

Fig 4. Current Requirement for the IoT Device in Full Operation Mode (Sensor + WiFi Connectivity)

2. Secondly, operating the IoT device with limited functionality, by disabling the WiFi connectivity and only reading the sensor feedbacks was considered and measured the current consumption by the IoT device. Fig 5 illustrates the demand for current by the IoT device that only reads the sensor feedbacks without transferring the data through the Wi-Fi connectivity.

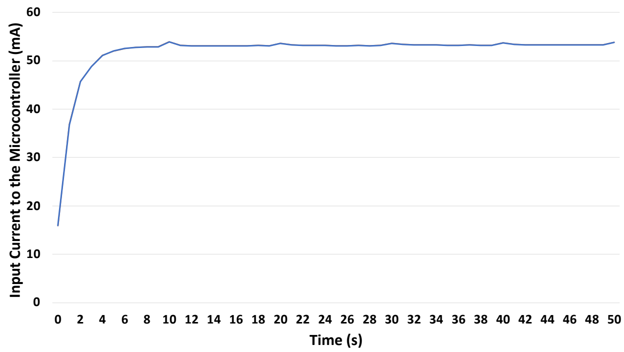

Fig 5. Current Requirement for the IoT Device in Limited Operation Mode (Sensor readings only)

Based on the two conditions described above, membership functions for the solar panel current input were developed as shown in
Fig 6 with five regions to obtain the maximum resolution in the output variable of the fuzzy system.

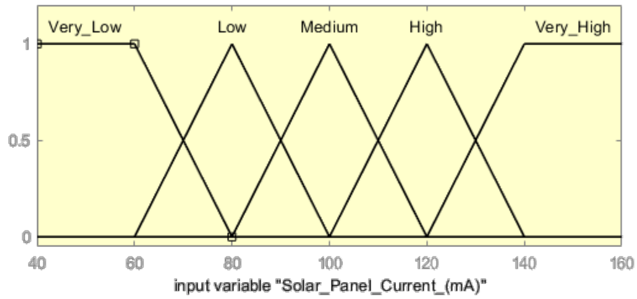

Fig 6. Membership Functions for Solar Panel Current Output Variation

The voltage of the Li-ion battery was considered as the second input for the fuzzy system and the membership functions were organized into four categories based on the voltage supply as shown in
Fig 7.

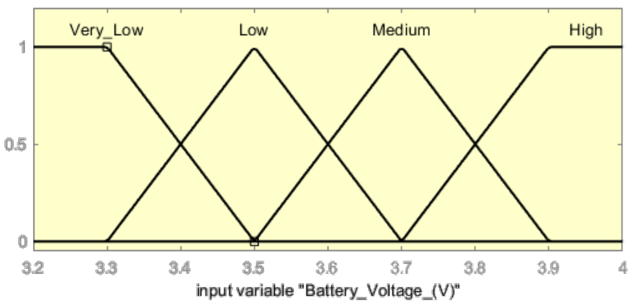

Fig 7. Membership Functions for Battery Voltage Variation

The first fuzzy system was designed as a closed-loop controller because the power generation from the solar panel is totally unpredictable and unstable throughout the

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operating time. The voltage and current sensors embedded in the power management system take measurements every 10 mins to determine the power source to power up the IoT device. Membership functions of the output variable of the first fuzzy controller consist of three options as follows and as shown in
Fig. 8.

a. Operate on Solar Power
b. Operate on Battery Power
c. Go to Deep Sleep for 5 minutes

The third option (option c) was added into the system in order to minimize the conflict situations during an extreme power shortage in both sources. This deep sleep mode was defined at a range where the battery has a considerable capacity to operate the system but to save that energy for the power management system to initiate the startup of the whole process. Without this option, the system will consume the maximum possible energy from the battery and put the total system into not responding mode.

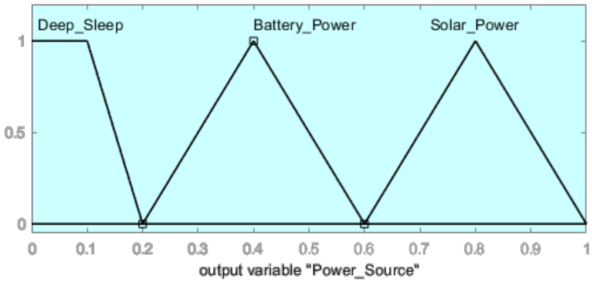

Fig. 8: Membership Functions of Fuzzy Controller Output

As described above, the rules were well defined to save the energy of the battery as much as possible during every circumstance while gaining the maximum benefit from the solar panel. The overview of the fuzzy rules is shown in TABLE 2 and the modes of operation are as follows.

- Solar Power- **S**
- Battery Power – **B**
- Deep Sleep for 5 minutes- **DS**

TABLE 2: FUZZY RULES FOR POWER SOURCE SELECTION

		Solar Panel Current (mA)				
		Very Low	**Low**	**Medium**	**High**	**Very High**
Battery Voltage (V)	**Very Low**	DS	S	S	S	S
	Low	B	S	S	S	S
	Medium	B	B	S	S	S
	High	B	B	B	S	S

Fig 9 illustrates the overview of the fuzzy logic system and it's clearly visible that the system is designed in a way in which the major portion of the operation is powered by solar power.

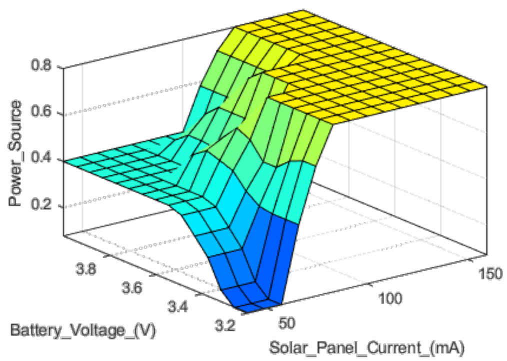

Fig 9. Surface View of the Fuzzy Controller

Fuzzy controller for determining the operating mode when powered with solar power

The first step of the power management system is to determine the power source based on its strength. Once selected the power source, the management system further analyzes the capability of the source to run the IoT device without interruptions. When the IoT device operates with solar power the process of determining the mode of operation is straightforward. The fuzzy system for the solar-powered operation mode consists of single input and single output arrangement having four membership functions for the output as shown in Fig 10. Each output mode has its own instruction set to align the operation of the IoT device as illustrated below.

Full - Sensor + WiFi connectivity
Limited - Sensor + Limited WiFi connectivity
Highly **L**imited - Sensor + Highly limited WiFi connectivity
Deep **S**leep - Turn on Deep Sleep for 5 mins

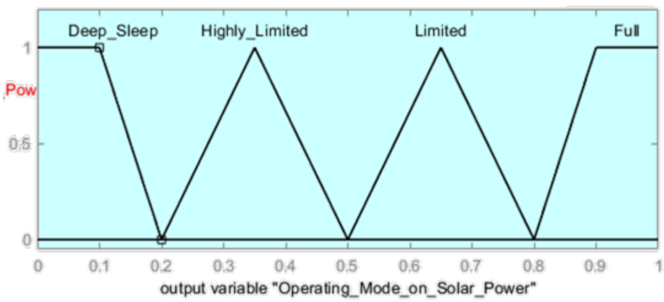

Fig 10. Membership Functions for Operation Mode Under Solar Power

An overview of the fuzzy rules for the solar-powered operating mode is shown in Fig 11.

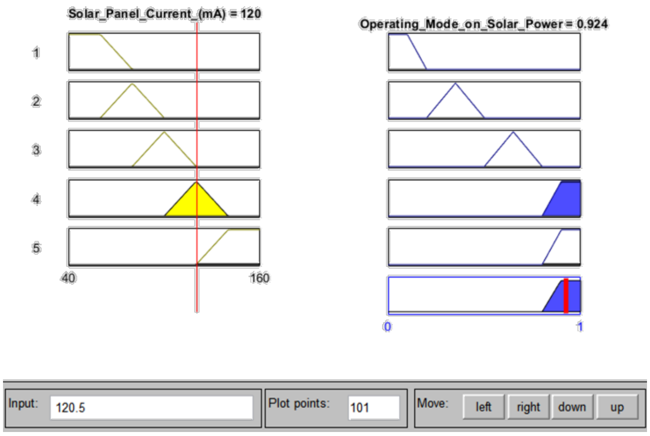

Fig 11. Fuzzy Rules for Operation Mode Under Solar Power

As described above, the process of determining the operating mode is straightforward which is based only on single input as shown in the surface view of Fig 12.

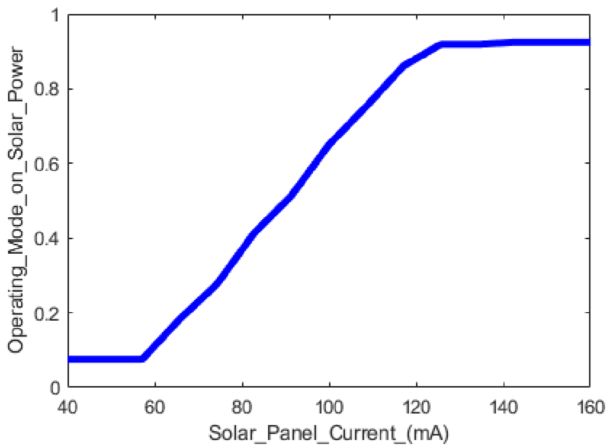

Fig 12. Surface View of the Fuzzy Controller for Solar Power

Fuzzy controller for determining the operating mode when powered with battery power

There is a significant difference between the factors related to the health of the power source when working with solar panels and Li-ion batteries. Solar panels are more reliable and robust to environmental condition changes and can operate for long periods without any major concern. But Li-ion batteries are sensitive to temperature and if operated

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in higher temperatures battery lifetime and capacity will be reduced. For standalone self-powered IoT devices, the health of the battery is one of the major concerns that determine its lifetime and performance. In this experimental setup, we have considered two main factors to determine the health condition of the battery, voltage, and temperature. The controller is designed in a way that always manages the stress acting on the Li-ion battery at a minimum level to maximize the life span.

The fuzzy controller of the battery-powered mode has two inputs to sharpen the decision-making process. One input for the fuzzy system is the temperature of the battery, as the temperature of the Li-ion batteries plays a vital role in the lifespan. Also, the voltage is considered as the second input for the fuzzy system as shown in Fig 13.

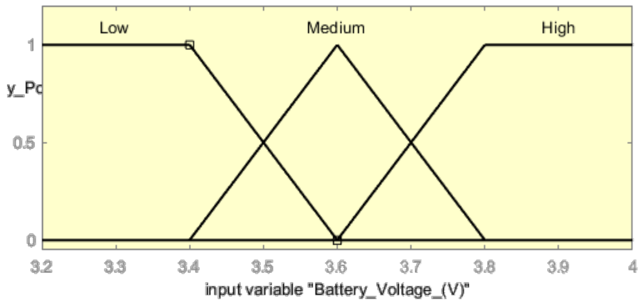

Fig 13. Membership Functions for Li-ion Battery Voltage

As mentioned above, the temperature of the Li-ion battery feeds into the fuzzy controller using 05 membership functions to limit the usage under temperature regions that may be harmful to the battery life. The membership functions of the battery temperature input are shown in Fig 14.

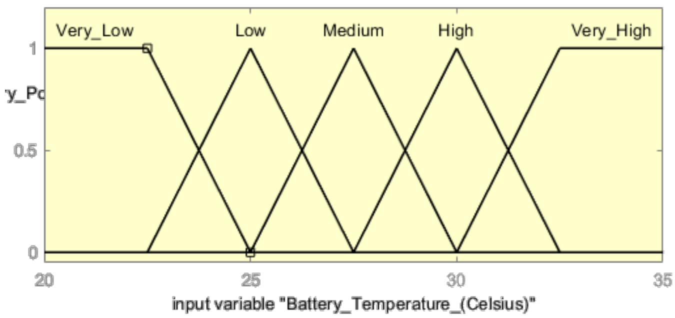

Fig 14. Membership Functions for Li-ion Battery Temperature

Based on the two input variables, the power management system maps the operating mode into four output membership functions as illustrated in Fig 15.

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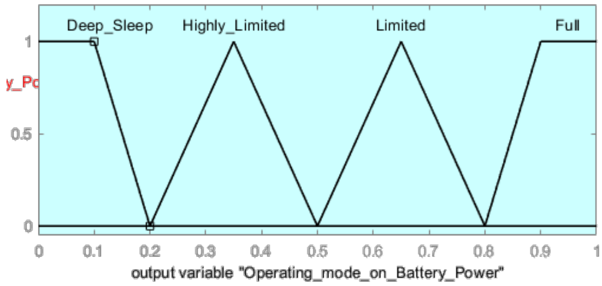

Fig 15. Membership Functions for Operation Modes on Battery Power

Inside the fuzzy controller, a well-defined rule set is defined as summarized in TABLE 3.

TABLE 3: FUZZY RULES FOR OPERATION MODE SELECTION ON BATTERY POWER

		Battery Temperature (Celsius)				
		Very Low	**Low**	**Medium**	**High**	**Very High**
Battery Voltage (V)	**Low**	HL	HL	HL	DS	DS
	Medium	F	F	L	HL	DS
	High	F	F	F	L	DS

The overall surface view of the fuzzy controller that was developed to determine the operating mode under battery power is shown in Fig 16. In the fuzzy surface view graph, it is clearly shown that the operating mode tends to move towards limited and finally into deep sleep mode when the Li-ion battery temperature rise.

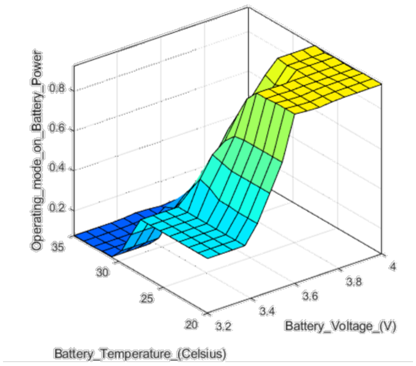

Fig 16. Surface View of the Fuzzy Controller for Operation Modes on Battery Power

Evaluation and Validation

The Fuzzy Controllers for the 03 main decision-making stages were simulated in MATLAB and confirmed their performance under extreme conditions before implementing the control algorithm with microcontrollers. For the implementation process, two ESP8266

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microcontrollers were used for the power management system and IoT device. To measure the Li-ion battery temperature and environmental temperature for the IoT device, two DS18B20 temperature probes were used. The solar panel was selected considering the current demand of the IoT device shown in Fig 4 and Fig 5 to power up the device under moderate sunlight. A solar panel with 6V and 160mA rating was used considering the power demand. For the purpose of supplying the rated voltage to the ESP8266, a DC-DC Buck Converter was used to step down the supply voltage to 3.5V. Specifications of the main components in the setup are shown in TABLE 4.

TABLE 4: SPECIFICATIONS OF MAIN COMPONENTS IN EXPERIMENTAL SETUP

Component	**Specifications**
ESP8266 Wi-Fi Module	2.4 GHz Wi-Fi (802.11 b/g/n, supporting WPA/WPA2) Input voltage 3.0 – 3.5 V
DS18B20 Temperature Sensor	Input Voltage 3.2 - 40V Measuing range - 10°C to +85°C
Solar Panel	Open Circuit Voltage 6v Short Circuit Current 165mA
Battery	18650 Rechargeable Li-ion 1800mAh 3.7V

The experimental setup used to validate the purposed fuzzy logic controller and obtain the fluctuation of parameters is shown in Fig 17.

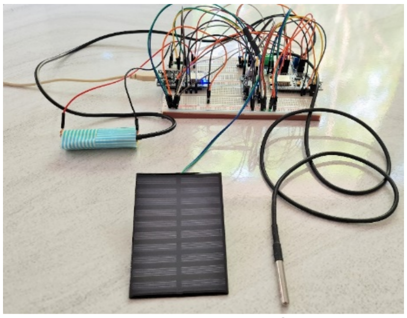

Fig 17. Experimental Setup

The pattern of current output received from the solar panel throughout a typical day is shown in Fig 18. From the experimental data, it is evident that more than 50% of the daytime solar panel is capable of producing enough current to operate the IoT device (more than 110 mA) with full capacity (sensor readings + Wi-Fi connectivity). Further, the unexpected weather situations that occurred around 11:00 in the graph show the unpredictability of solar energy even in the middle of a sunny day. This graph clearly shows the capability of solar energy to run the device and the necessity of a backup power plan

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when it comes to continuous data harvesting from an IoT device.

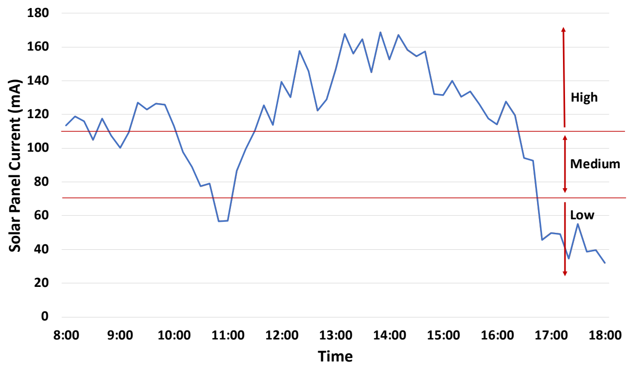

Fig 18. Current Output From the Solar Panel During a Typical Day

To regulate the Li-ion battery voltage supply to the IoT device and charging process using the solar panel output a 1S 3.7V 3A BMS PCM 18650 battery charging protection board was used. During a typical day including some low light situations, the fluctuation of the battery voltage is above the maximum voltage limits. Fig 19 shows the drop in the battery voltage throughout the experiment time and it is clearly shown during low light conditions the controller shifted the power source to the battery and the voltage began to drop during those periods.

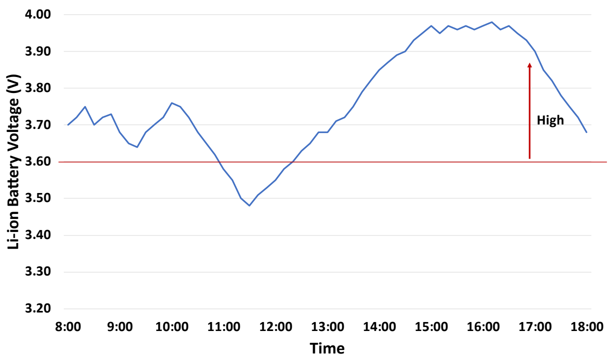

Fig 19. Battery Voltage Variation During a Typical Day

The temperature of the Li-ion battery is one of the key factors that determine the length of the life span of the battery. Sri Lanka is a tropical country that receives a significant amount of solar energy throughout the year. On the other hand, this sunny climate creates unbearable heat during the daytime especially around 12:00 to 14:00 on most of the days. The environmental temperature rises up to 34 °C during a sunny day in most of the places in Sri Lanka. If an IoT device continuously operates in such a situation, the Li-ion batteries will drain fast and the temperature of the batteries will rise drastically which causes to shorten the lifespan causing periodic battery replacements. In this experimental setup, a dedicated temperature sensor was mounted on the battery surface to measure the battery temperature during operation and the temperature variation is

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shown in Fig 20. Also, the third Fuzzy Control was designed to minimize the usage of the battery when its temperature is above the safe region. The controller was well capable of handling the system while reducing the possibilities for dramatic rises in battery temperature. For an application that is not critical, this fuzzy controller can be implemented to maximize the battery life while offering continuous data harvesting.

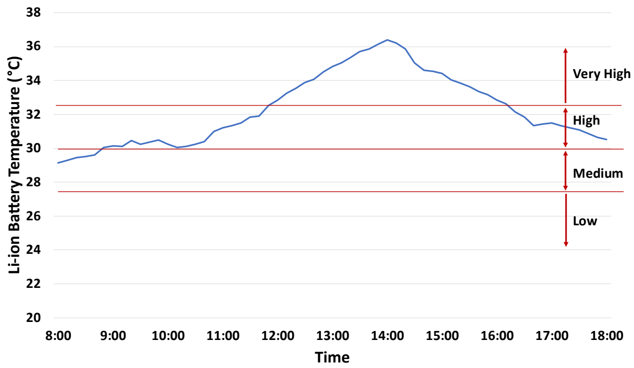

Fig 20. Battery Temperature Variation During a Typical Day

From the viewpoint of GIoT, maximum utilization of solar energy is economical and beneficial. Fig. 21 illustrates the usage of battery power during a typical day for better understanding. With the help of the Fuzzy system, the controller managed to operate the system continuously while reducing the battery usage by 64% and for a sunny day, this value will go over 90% with the constant power generation by the solar panel resulting in better utilization of renewable energy source.

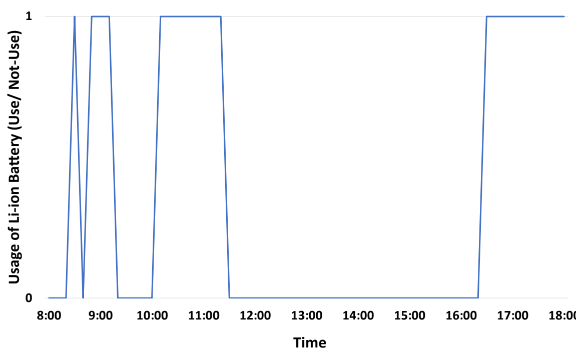

Fig 21. Usage of the Li-ion Battery During a Typical Day

Conclusions and Future work

On account of the main fuzzy approach introduced for the determination of the power source based on the availability, the IoT device was managed to operate stably using a minimum amount of battery power as we expected in this research. Further, the introduced dual fuzzy controllers helped to select the best operation mode and helped the

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power management system to control the IoT device without any interruptions throughout the operation period. The decision-making process was well determined through the rule-based fuzzy system and before the implementations, each scenario was carefully simulated in MATLAB under critical scenarios. The microcontroller was well managed to transfer the temperature data to the cloud continuously throughout the experiment. The temperature rise in the environment around noon is one of the most critical periods for the battery regarding the high operating temperature causes to reduce the lifespan. This purposed system was well performed during that critical period by shifting the power source into the solar panel and proved the capability of reducing the energy stress acting on the battery during sunny weather conditions. On the other hand, this power management system encourages minimizing the required battery capacity for solar-powered IoT applications resulting in better efficiency. Overall, it is evident that the self-powered IoT device can operate with a minimum amount of battery capacity using this method in tropical countries. As for future work we believe, this study can be further extended into a power synchronizing system to reduce the battery capacity further and utilize the solar power at a maximum level. Nevertheless, we believe that this would pave the way towards designing an economical and environment-friendly self-powered IoT infrastructure.

References

1. Priyashan, W. M., & Thilakarathne, N. N. (2020). IIoT framework for sme level injection molding industry in the context of industry 4.0. future, 16, 17.
2. Thilakarathne, N. N., Kagita, M. K., & Priyashan, W. D. (2022). Green Internet of Things: The Next Generation Energy Efficient Internet of Things. In Applied Information Processing Systems (pp. 391-402). Springer, Singapore.
3. Kjellby, R. A., Johnsrud, T. E., Loetveit, S. E., Cenkeramaddi, L. R., Hamid, M., & Beferull-Lozano, B. (2018, January). Self-powered iot device for indoor applications. In 2018 31st International Conference on VLSI Design and 2018 17th International Conference on Embedded Systems (VLSID) (pp. 455-456). IEEE.
4. Mondal, S., & Paily, R. (2017). Efficient solar power management system for self-powered IoT node. IEEE Transactions on Circuits and Systems I: Regular Papers, 64(9), 2359-2369.
5. Klinefelter, A., Roberts, N. E., Shakhsheer, Y., Gonzalez, P., Shrivastava, A., Roy, A., ... & Calhoun, B. H. (2015, February). 21.3 A 6.45 μW self-powered IoT SoC with integrated energy-harvesting power management and ULP asymmetric radios. In 2015 IEEE International Solid-State Circuits Conference-(ISSCC) Digest of Technical Papers (pp. 1-3). IEEE.
6. Balid, W., & Refai, H. H. (2017, October). On the development of self-powered iot sensor for real-time traffic monitoring in smart cities. In 2017 IEEE SENSORS (pp. 1-3). IEEE.
7. Elahi, H., Munir, K., Eugeni, M., Atek, S., & Gaudenzi, P. (2020). Energy harvesting towards self-powered IoT devices. Energies, 13(21), 5528.
8. Kantareddy, S. N. R., Mathews, I., Sun, S., Layurova, M., Thapa, J., Correa-Baena, J. P., ... & Peters, I. M. (2019). Perovskite PV-powered RFID: Enabling low-cost self-powered IoT sensors. IEEE Sensors Journal, 20(1), 471-478.

 [RECEIVED: 26TH APRIL, 2022; REVISED AND ACCEPTED: 20TH SEPTEMBER, 2022]

9. Kjellby, R. A., Cenkeramaddi, L. R., Frøytlog, A., Lozano, B. B., Soumya, J., & Bhange, M. (2019, April). Long-range & self-powered IoT devices for agriculture & aquaponics based on multi-hop topology. In 2019 IEEE 5th World Forum on Internet of Things (WF-IoT) (pp. 545-549). IEEE.
10. Pan, C., Xie, M., & Hu, J. (2018). ENZYME: An energy-efficient transient computing paradigm for ultralow self-powered IoT edge devices. IEEE Transactions on Computer-Aided Design of Integrated Circuits and Systems, 37(11), 2440-2450.
11. Pardue, C. A., Bellaredj, M. L. F., Davis, A. K., Swaminathan, M., Kohl, P., Fujii, T., & Nakazawa, S. (2018). Design and characterization of inductors for self-powered IoT edge devices. IEEE Transactions on Components, Packaging and Manufacturing Technology, 8(7), 1263-1271.
12. Mhaisen, N., Abazeed, O., Al Hariri, Y., Alsalemi, A., & Halabi, O. (2018, August). Self-Powered IoT-Enabled Water Monitoring System. In 2018 International Conference on Computer and Applications (ICCA) (pp. 41-45). IEEE.
13. Aripriharta, A., Firmansah, A., Yazid, M., Wahyono, I. D., & Horng, G. J. (2020, July). Modelling of adaptive power management circuit with feedback for self-powered IoT. In Journal of Physics: Conference Series (Vol. 1595, No. 1, p. 012023). IOP Publishing.
14. Wu, F., Redouté, J. M., & Yuce, M. R. (2018). We-safe: A self-powered wearable iot sensor network for safety applications based on lora. IEEE Access, 6, 40846-40853.
15. Shirvanimoghaddam, M., Shirvanimoghaddam, K., Abolhasani, M. M., Farhangi, M., Barsari, V. Z., Liu, H., ... & Naebe, M. (2017). Paving the path to a green and self-powered internet of things. arXiv preprint arXiv:1712.02277.

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