Interconnecting Fog Computing and Microgrids for Greening IoT

Fatemeh Jalali, Arun Vishwanath, Julian de Hoog, Frank Suits
IBM Research
Melbourne, Australia
{fa.jalali, arvishwa, juliandehoog,frankst} @au.ibm.com

Abstract—**The Internet of things (IoT) is hailed as the next big phase in the evolution of the Internet. IoT devices are rapidly proliferating, owing to widespread adoption by industries in various sectors. Unlike security and privacy concerns, the energy consumption of the IoT and its applications has received little attention by the research community. This paper explores different options for deploying energy-efficient IoT applications. Specifically, we evaluate the use of a combination of Fog computing and microgrids for reducing the energy consumption of IoT applications. First, we study the energy consumption of different types of IoT applications (such as IoT applications with differing traffic generation or computation) running from both Fog and Cloud computing. Next, we consider the role of local renewable energy provided by microgrids, and local weather forecasting, along with Fog computing. To evaluate our proposal, energy consumption modeling, practical experiments and measurements were performed. The results indicate that the type of IoT application, the availability of local renewable energy, and weather forecasting all influence how a system makes dynamic decisions in terms of saving energy.**

Keywords— Internet of things (IoT); Fog computing; Edge computing; Microgrids; Energy consumption

I. INTRODUCTION

The Internet of Things (IoT) [1] is one of the major revolutions in information and communication technology (ICT) after computer and Internet inventions. The IoT connects people, machines and devices together and to the Internet to provide bidirectional information transmission and enable real-time decisions. The IoT has been adopted very quickly because of the rapid reduction of sizes and prices of IoT devices as well as advancements in big data and predictive analytics [1, 2]. IoT applications vary from personal usage such as smart homes and wearables, to industrial and business usage such as smart cities, smart grids, and healthcare [1]. As the number of IoT devices and sensors dramatically increases, concerns about security, privacy, data management, and storage management also intensify. These aspects of the IoT have gained considerable research attention; however, there has been less scrutiny on the escalating energy consumption of the IoT. The ever-increasing IoT device sensors require power to collect, transmit, and analyze data. Therefore, the power consumption for the total IoT system is also increasing. Here, we propose a solution to mitigate IoT power consumption growth based on the use of Fog computing [3, 4] and microgrids [5].

Fog computing is an approach for processing, storing and running applications locally rather than sending all data to the Cloud [4]; however, the two are complementary, as Fog computing sends important and necessary updates from the local network to the Cloud [3, 4, 6]. IoT gateways, that is, bridging points between local IoT devices and the Internet, play an important role in Fog computing. Here, we execute various IoT applications using Fog and Cloud computing and examine their energy consumption based on measurements and power consumption modeling. Next, we categorize the IoT applications into two groups based on their energy requirements: energy-efficient using the Fog, or energy-efficient using the Cloud.

Our first categorization involves IoT gateways that are powered by the centralized power grid. The results indicate that IoT applications that require no or low processing and computation are more energy efficient run locally in the Fog, whereas IoT applications with heavy computation consume more energy if run from the Fog. However, this result is altered if the IoT gateway is powered by local smart grids called microgrids with renewable energy sources, and local battery storage. In this case, the IoT applications with heavy computation can be run more efficiently from the Fog. However, when the power generated from the microgrid is not sufficient, power-saving mode is switched on and it would be more energy efficient to send all data and applications to the Cloud for processing and storage. Furthermore, when power-saving mode is on, the IoT gateway could automatically slow the data transmission rate of IoT sensors to reduce the power consumption of data transmission and processing.

This work aims to incorporate two local technologies – local processing, computation, and storage in the IoT (i.e. Fog computing) and local renewable power resources (i.e. microgrids) – to save energy in IoT applications and services. We develop an IoT gateway that is aware of local power and weather forecasts to decide where to most efficiently run IoT applications, the Fog or the Cloud. To the best of our knowledge this paper is the first work that investigate interconnecting Fog computing and microgrid for energy efficient IoT applications. The rest of the paper is organized as follows. Section II surveys the previous studies related to this work. In Section III, the architecture of our proposed idea is discussed. In Section IV, energy consumption modeling and experiments are explained. The paper is concluded in Section V.

II. Related work

Increasing energy consumption in ICT has become a major concern in recent years [7] across a wide range of sectors, from data centers and infrastructure networks to end-user devices [7-10]. In many cases, systems and networks are implemented without consideration of energy consumption, and then at some point energy needs become a constraint. The same scenario may be applied to the IoT, as it is currently attracting myriad uses with little regard for the energy requirements of running applications and services. A small number of studies [11, 6, 12] on the energy consumption of different access networks of IoT gateways provide some insight into the energy efficiency of various access network technologies. We consider an energy-efficient access network (i.e. the Ethernet) in this work; however, we study the challenge of energy consumption in IoT applications more broadly to examine how IoT applications can be deployed to consume less energy.

Comparisons between the energy demands of Cloud computing applications and Fog computing applications in [6] indicate that applications generating data locally (such as IoT applications) are good candidates to be run on the Fog for saving energy. However, as the focus of [6] is not only IoT applications, the type of IoT applications is not specified in detail whereas we cover it in the current paper. In addition, the role of microgrid and local weather forecast is not studied in [6].

Connecting the Cloud and data centers with smart grids has already been undertaken to exploit renewable energy to optimize energy management in distributed Clouds [13, 14]; however, there has been no discussion on how IoT applications or Fog computing could be integrated into these types of system.

One study [15] introduced an energy management method of Fog computing for microgrids in which Fog computing and the IoT provided a platform to control the power generation and consumption of residential microgrids. However, the use of microgrids in Fog computing and IoT has not been studied [15].

A number of other studies [16-18] have investigated the efficacy of the IoT in industrial energy applications, such as attaching sensors to smart grids, microgrids, and IoT devices to provide information, connectivity and awareness throughout the infrastructure. In contrast, here we merge Fog computing and microgrids to optimize IoT energy consumption. Although the applicability of the IoT in saving energy is celebrated, the energy consumed by IoT applications and services is generally ignored.

To the best of our knowledge, it is the first work that aims to help IoT consume less energy by exploiting microgrids capability along with Fog computing.

III. System Architecture

Here, we describe Fog computing and microgrids, two main components of our proposed system. Then the architecture of IoT gateways connected to the Fog, Cloud and microgrids are discussed.

A. Fog Computing

Fog computing [4, 19] performs a substantial amount of computation, data processing, storage, and filtering at the edge of a local network and close to the source of data (i.e. sensors and IoT devices), rather than sending all information to Cloud data centers. However, Fog computing is not disconnected from the Cloud and sends important updates for synchronization. Therefore, Fog computing is complementary to Cloud computing and can serve some applications that are not delivered efficiently by Cloud computing. Applications sensitive to bandwidth, delay, and privacy can be particularly suitable for the Fog computing approach.

Fog computing was born to deal with the demands of the ever-increasing number of Internet-connected devices in the IoT and big data [4]. IoT devices can be directly connected to the Internet via a 3G/4G connection or they can be connected to the Internet via a gateway that provides a bridging point between IoT devices, networks, and the Internet (Fig. 1). Communication between IoT devices and the gateway is usually through short-range wireless technology such as Bluetooth or ZigBee. The gateway can be connected to the Internet via Ethernet, PON, 3G, or other access technologies.

B. Microgrids

Traditional power grids transfer electricity from centralized power generators (for instance, coal plants or hydroelectric facilities) to home, business, and industry consumers. This system is based on a hierarchical platform, which includes power generators, transmission networks, distribution networks, and consumers. The idea of placing power generation (especially renewables) closer to the point of use emerged at the end of the 20th century [5].

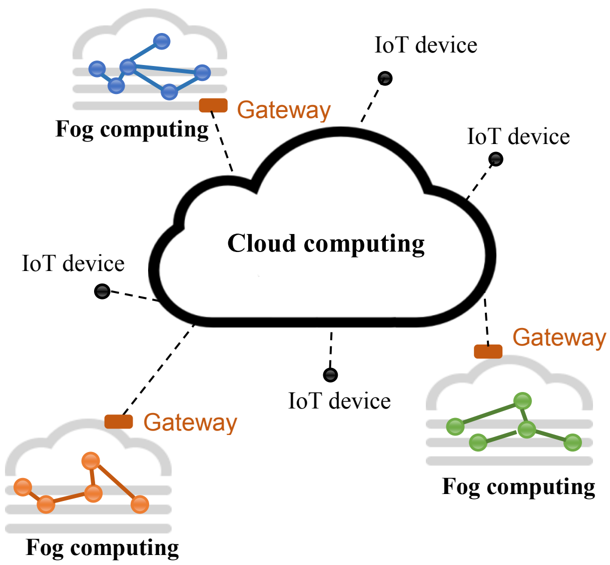

Fig. 1. High level architecture of Fog and Cloud computing

Microgrids are modern, small-scale versions of the traditional centralized electricity grid that comprise distributed power generators, energy storage, and loads. However, microgrids differ from the traditional grid by their closer proximity to demand, resulting in efficiency increases and transmission reductions [5, 13, 16-18]. In fact, microgrids can operate connected to a traditional centralized grid or they can be disconnected from the grid and function autonomously. Microgrids are an ideal way to integrate local renewable resources and local level demand, and also allow direct customer participation in electricity enterprise [5]. Microgrids can provide local, reliable, and affordable energy for urban and rural communities, or for commercial, industrial, and government consumers.

Here, we focus on residential premises powered by microgrids (Fig. 2). In this case, a home or building is equipped with local energy storage that can be recharged by available local renewable energy sources, such as solar or wind power, but also by the grid if the renewable energies are insufficient. A main switch panel monitors the status of the local battery storage and manages the charging of the battery from the local renewable source (i.e. solar panels), or from the traditional grid, or even from electric vehicles that can inject power into the system (as the dashed line from the electric car to the "main switch panel" shows in Fig. 2). The priority is to charge the local battery storage with locally available renewable energy so local demand will be largely met by local battery storage.

Please note that for the sake of simplicity, we did not include AC/DC and DC/AC converters in Fig. 2.

C. Internet of Things (IoT) Gateways Powered by Microgrid and Fog Computing

As explained in Section III-A, IoT devices can be directly connected to the Internet if equipped with access network technologies such as 3G/4G, or they can be connected to a local IoT gateway via short-range wireless technologies such as ZigBee or Bluetooth and from the gateway to the Internet. IoT gateways can be a simple connection that only transmits data to the Internet and takes advantage of Cloud computing for computation, data processing, and storage (Fig. 3). It is possible to allow IoT gateways to carry out multiple functions locally through Fog computing and then send important updates to the Cloud for synchronization.

As shown in Fig. 3, the IoT devices and sensors in our proposed system are connected to an IoT gateway that works on both Cloud computing and Fog computing platforms. The IoT gateway is aware of the local battery status, which is charged through a residential microgrid, and it also has access to the local weather forecast in order to estimate the availability of renewable energies. The IoT gateway can shift a task from the Fog to the Cloud, or vice versa, according to the local battery status and weather forecast to maximize energy efficiency. Furthermore, the IoT gateway can communicate with sensors and decrease their data transmission rate to save energy by receiving and processing less data.

IV. ENERGY CONSUMPTION MODELING AND MEASUREMENTS

In this section, we describe energy consumption models for IoT applications and services provided with Cloud computing and Fog computing.

The energy consumed by an IoT service using Cloud computing can be modeled by splitting it into four components: (a) the energy consumed by IoT gateways to receive data from IoT devices and sensors E_{GW-r}; (b) the energy consumed by IoT gateways to transmit data to the Cloud (E_{GW-t}); (c) the energy consumed by the transport network (aggregation, edge, and core networks) between the IoT gateways and the Cloud (E_{net}); and (d) the energy consumed by the relevant data center including its internal network, storages, and servers (E_{DC}). Therefore, the total energy consumed by an IoT service provided by Cloud computing ($E_{IoT-Cloud}$) can be expressed as:

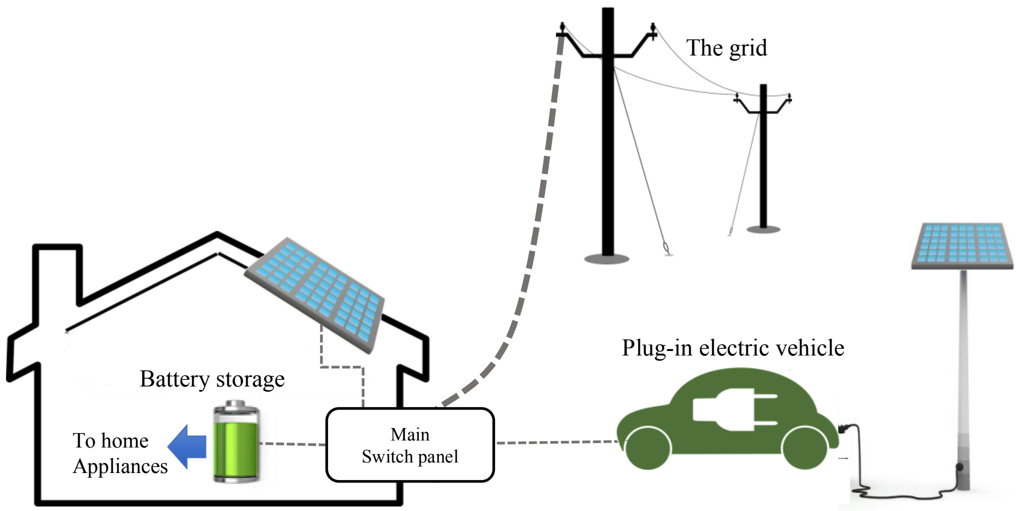

Fig. 2. High level architecture of a home powered by microgrid

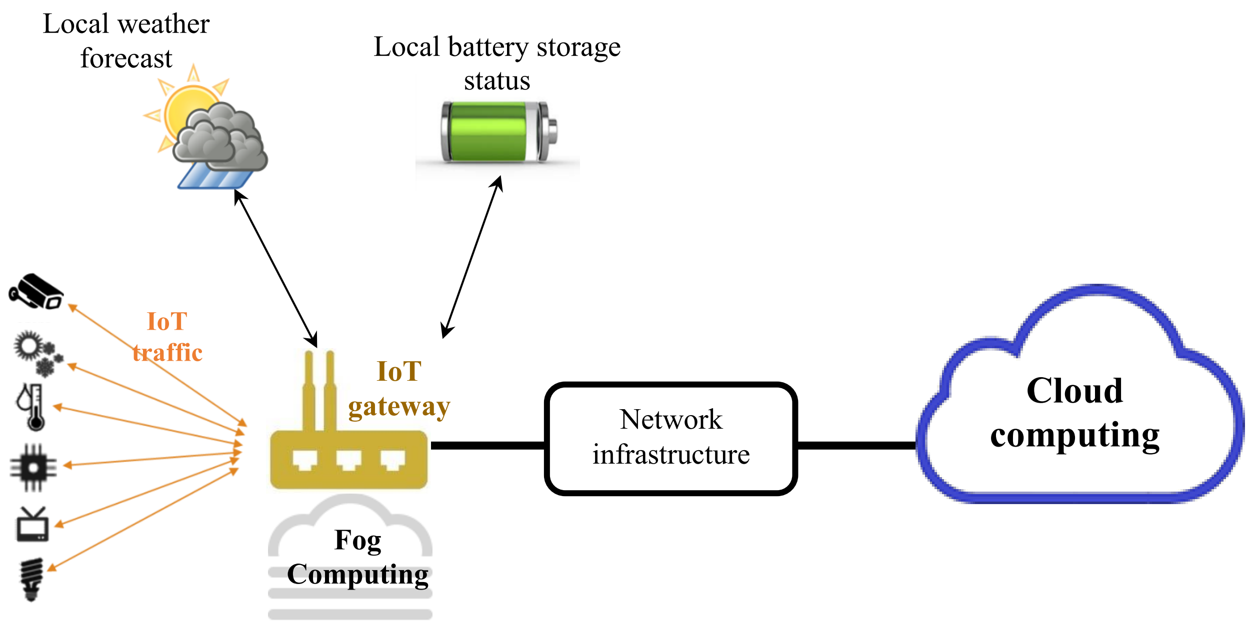

Fig. 3. High level architecture of our proposed system about powering IoT gateways with Fog computing and microgrids

$$E_{IoT-Cloud} = E_{GW-r} + E_{GW-t} + E_{net} + E_{DC} \quad (1)$$

In the case of Fog computing, the energy consumption of an IoT service consists of the following components: (a) the energy consumed by IoT gateways to receive data from IoT devices and sensors (E_{GW-r}); (b) the energy consumed by IoT gateways for local computation and processing (E_{GW-c}); (c) the energy consumed by IoT gateways to transmit updates to the Cloud (E_{GW-t}); (d) the energy consumed by the transport network between the IoT gateways and the Cloud; and (e) the energy consumed by the relevant data center including internal network, storages, and servers (E_{DC}). Hence, the total energy consumed by an IoT service provided by Fog computing ($E_{IoT-Fog}$) can be expressed as:

$$E_{IoT-Fog} = E_{GW-r} + E_{GW-c} + \beta(E_{GW-t} + E_{net} + E_{DC}) \quad (2)$$

where, $\beta = \frac{N_{update}}{N_{receive}}$ is a ratio of the number of updates from the Fog to the Cloud for synchronization (N_{update}) to the total amount of data received from IoT devices for a specific service ($N_{receive}$) and $0 \leq \beta < 1$.

To examine the value of the defined parameters in (1) and (2), we used flow-based and time-based energy consumption models [6]. The time-based modeling and direct power consumption measurements (explained further in Section IV-A) are applied to the IoT to obtain E_{GW-r}, E_{GW-t}, and E_{GW-c}. The flow-based modeling is applied to the equipment in the transport network and data center to examine E_{net} and E_{dc}. In this model, energy consumption of a service (in the transport network or data center) is calculated based on energy consumption per bit (in the transport network or data center) multiplied by the number of exchanged bits ($E_{service} = E_{bit} \times N_{bit}$). E_{bit} of the transport network includes aceess, edge, and core networks [6] and N_{bit} is a metric that we obtained for our IoT applications through practical experiments and traffic measurements.

More details about flow-based and time-based modelings are explained in [6].

A. *Practical Experiments and Measurements*

To examine and demonstrate the energy consumption variations of Fog computing and Cloud computing, a set of practical experiments and measurements were conducted. Temperature sensors, motion (PIR) sensors, and cameras were connected to a Raspberry Pi acts as an IoT gateway. Then, we connected the Raspberry Pi to an IBM Watson IoT Platform (as a cloud, as an example) through Ethernet. Upon receiving the sensor readings, the Raspberry Pi gateway had two options: (1) publishing the same to Watson IoT Platform, or (2) carrying out all tasks locally in the Fog instead of sending the tasks to the Watson IoT Platform. In all scenarios, power consumption of Raspberry Pi was measured using a Powermate power meter with a resolution of 10 mW. In addition, the volume of traffic exchanged between the IoT gateway (Raspberry Pi) and IBM Watson IoT Platform was measured using a packet analyzer (Wireshark) running on the end-user device.

B. *Findings from the Models and Measurements*

The energy consumption of various scenarios was examined using models defined by (1) and (2) as well as direct power and traffic measurements. The first scenario considered IoT applications that generate data with no or very low processing and computation. Examples of this kind of application include (i) a temperature sensor that takes a measure every second to regulate a thermostat, and (ii) a surveillance camera that continuously stores photos (or video) without any processing. In a comparison of the energy consumption of this type of application running from the Cloud using (1) and the Fog using (2), Fog computing will consume less energy. The reason is that the energy consumption of IoT gateways for computation is zero ($E_{GW-c} \approx 0$) and there is no need to send continuous updates to the Cloud ($\beta \approx 0$). Fig. 4 depicts energy consumption of IoT applications (with no computation) versus the amount of data transmitted from IoT devices to the IoT gateway.

We also calculated energy consumption variations in this type of IoT application (with no processing or computation) as the data transmission between IoT devices and an IoT gateway increases. The energy consumption of IoT applications using the Fog was less than the energy consumption of the same applications using the Cloud (Fig. 4). Although the data transmission increases, because there is no need for data processing, the IoT applications can be served using a low-power local IoT gateway instead of being sent to the transport network and then to a pool of servers within data centers. The stepped curve in the Fog scenario (Fig. 4, blue dotted line) was due to increases of idle power consumption as more Raspberry Pi gateways were added to serve heavier traffic. It should be noted that as information on power consumption of servers within data centers and associated networks is not publicly available, we developed estimates for data center energy consumption in the range of 4–20 µJ [6]. The estimated data center range is highlighted in orange in all figures.

The second scenario concerns IoT applications that do require data processing and computation, such as face detection and recognition of photos or videos recorded by a surveillance camera. We investigated the energy consumption of IoT applications that require low, medium, or heavy data processing. As the processing demand increases in Fog computing, more powerful devices are added to the IoT gateway to serve the application. Therefore, more idle power is consumed to run the IoT applications locally on the Fog. Cloud computing consumes less energy for heavy processing IoT applications due to sharing idle power consumption of powerful servers among many users and services (Fig. 5).

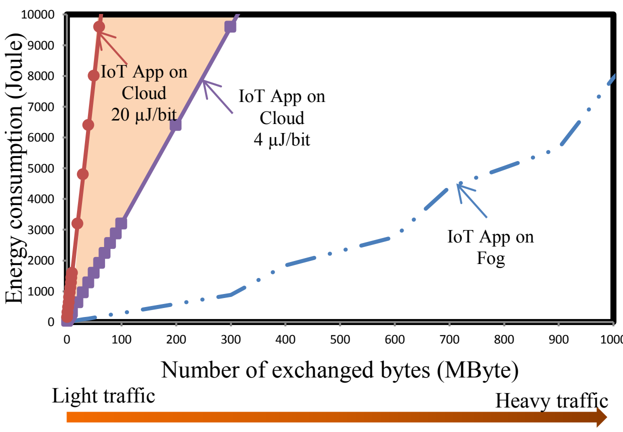

Fig. 4. Energy consumption of IoT applications with no computation provided from the Cloud and the Fog

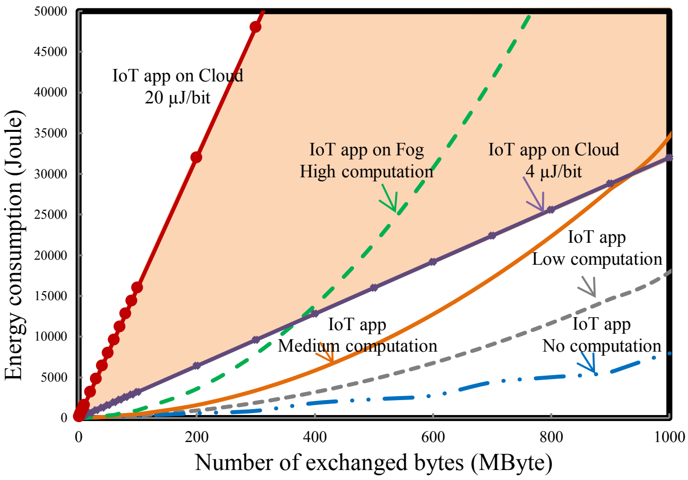

Fig. 5. Energy consumption of IoT applications running from the Cloud and the Fog with various computations

Another way to save energy is avoiding transmitting unnecessary data from IoT sensors to IoT gateways and ultimately to the Cloud. This can be achieved by reducing the data transmission of IoT sensors or by designing the applications to be more efficient in terms of energy usage. For example, instead of sending video continuously, a motion sensor can be installed close to the camera, which only sends data to the Cloud when the motion sensor is active.

In the previous two scenarios, we assumed the Fog equipment was powered by the centralized grid. The third scenario involved IoT applications with heavy computation powered by renewable energy utilized through a microgrid. In this case, the IoT gateway could make real-time decisions based on the availability of local energy. For example, if the IoT gateway identified that the local battery level was high enough, it could wake up a local device (e.g. a laptop or a set of Raspberry Pi's) and assign the heavy-computation IoT application to that device locally. On the other hand, if the IoT gateway noticed a lack of local energy, it could transfer the IoT application to the Cloud and put the local device in sleep mode. In relation to the presence of local renewable energy sources, it makes sense to locate the load and processing close to the generated energy to avoid the energy requirements of transmission and data centers.

The fourth scenario involved IoT applications with no computation when the IoT gateway was powered by a microgrid.

As explained, the Fog platform is very energy efficient for this type of IoT application so it is more energy-wise to avoid sending their data to the Cloud. If the IoT gateway identified a lack of local energy, the best way to deal with the energy consumption of the IoT applications was to decrease the data transmission rate from IoT devices and sensors.

V. Discussion and Future Work

In this work, Fog computing and microgrids are utilized together to reduce energy consumption of IoT applications. A microgrid uses locally distributed energy to reduce the distance between energy production and use. Separately, Fog computing is proposed as a solution to help IoT applications with local processing, computation and storage. Both Fog computing and microgrids deal with localized services and complement each other. Our results indicate that localizing IoT loads and energy sources using interconnected Fog computing and microgrids may allow IoT applications to consume less energy. In addition, a dynamic and real-time energy management strategy based on type of IoT application, local renewable energy, and local weather forecasting is required to switch between the Cloud and the Fog for the most energy-efficient use of IoT applications.

This is the first work to consider connecting Fog computing and microgrids to reduce energy consumption of IoT applications. Therefore, there are a number of factors and parameters that merit further study. In addition, developing smart IoT gateways powered by machine learning for automatic decision-making will be essential to continue exploration of this concept.

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