A Review on IoT-Based Carbon Footprint Tracking System for Demand-side Energy Management

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ABSTRACT

Demand for energy management solutions has grown due to global concerns about energy consumption and its environmental impact. The upward trajectory of CO_2 levels in the atmosphere is unsustainable for the near future, potentially leading to a significant increase in average global temperatures and extreme weather conditions like drought, heatwaves and floods. These conditions could further jeopardise food security and affect 30-132 million people's livelihoods. Carbon footprint tracking can help identify areas of high emissions and implement strategies to reduce them. Cloud-based IoT device deployment with real-time data visualisation can improve energy efficiency and cut energy costs by monitoring consumption, remotely controlling energy use, predicting maintenance needs and optimising energy usage. This review analyses the various energy management strategies and the benefits of using an IoT-based carbon footprint tracking system for demand-side energy management, the potential to effectively support the achievement of UN SDG 12 &13 goals within the desired timeframe and the need for further innovation. Carbon footprint is a valid metric and feedback in demand-side energy management for urban settlements (70% of electricity usage), where cost as a metric has proven inefficient. This indicator can significantly influence the behavioural attitudes and changes in electricity usage patterns of all electrical customers.

Keywords: *Carbon Footprint, Cloud Computing, Energy Management, IoT, Machine Learning.*

1. INTRODUCTION

Rapid population growth and technological advancement have increased energy demand, resulting in more fossil fuel power plants and environmental challenges. Cleaner sources like wind, solar, and hydropower are being promoted to reduce impact. The United Nations' sustainable development goals (SDG 12 & 13) aim to ensure global sustainable consumption and production patterns. The irrational and destructive behaviour in producing and consuming goods and services is unsustainable for the environment.

These actions contribute to several environmental problems, including climate change, pollution and loss of biodiversity. Improving energy efficiency and educating consumers about sustainable consumption are some of the actions called by SDG 12.

Others are:

1. Reducing waste and pollution.
2. Promoting the use of renewable energy.
3. Encouraging sustainable agriculture and forestry practices.
4. Supporting fair trade and responsible consumption.

SDG 13 requires immediate action against increasing greenhouse gas emissions, demanding collaboration from governments, businesses, organisations, and individuals worldwide. This necessitates innovative solutions to secure a sustainable future for all generations.

Achieving SDG 13 targets requires reducing greenhouse gas emissions, promoting education and awareness, and facilitating technology transfer to developing nations.

1.1 Significance of Demand-Side Energy Management

Electricity production and demand are responsible for 75% of greenhouse gas emissions (IEA, 2023), which is the leading cause of global warming. The world needs to focus on generating and consuming electricity sustainably to achieve net-zero emissions by mid-century (Bergaentzlé *et al.*, 2014). With temperatures consistently setting new records, as depicted in Figure 1, the urgency for action has never been necessary but now.

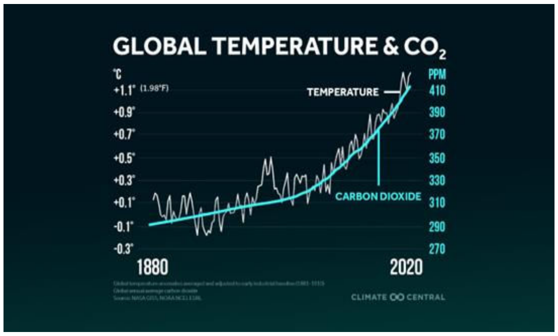

Figure 1: Global Temperature & CO_2 (Globlal, 2020)

Demand-side energy management is the implementation of measures and technologies to control, optimise and reduce energy consumption by end-users (Bergaentzlé *et al.*, 2014). Various studies have enumerated the significance of energy management. The International Energy Agency (IEA) reported that demand-side energy management helps reduce GHG emissions, particularly carbon dioxide (CO_2), the primary contributor to global warming. It estimated that 35% of global energy-related CO_2 emissions in 2019 were caused by households alone. By implementing energy-saving technologies such as clever thermostats, energy-saving appliances, and LED lighting, the energy requirement can be reduced, leading to a decrease in GHG emissions. Perera (2018) focused on the impact of fossil fuel combustion on human health; according to the study, fossil fuel combustion for electricity generation is a major source of air pollution, releasing pollutants such as sulphur dioxide (SO_2), nitrogen oxides (NOx) and particulate matter (PM). Energy efficiency and transition to renewable energy would be the keys to reducing the demand for coal and oil-based electricity due to air pollution and subsequent health implications. Lawrence (2019) highlighted the significance of Californian summer demand response programs, which incentivise consumers to reduce electricity usage during peak demand periods. These programs helped avoid 5-10% of peak demand in California during the summer of 2019, reducing the need for fossil fuel-based generation and associated emissions.

1.2 Cloud-Based IoT Devices for Carbon Footprint Tracking

The implementation of IoT technology has become a breakthrough in tracking carbon emissions. The data and the feedback information stimulate climate action from end-users (house owners and professionals) for a sustainable environment. This cutting-edge solution helps end-users access essential information promptly, facilitating prompt mitigation actions and reducing their carbon footprint. The compatibility constraints, data security, and storage with edge technology were resolved using cloud-based technology.

Ming *et al.* (2019) presented a practical and effective approach to environment monitoring, leveraging IoT and cloud computing technologies. It provides valuable insights into carbon dioxide emissions and indoor air quality, benefiting smart home residents and environmental organisations. Integrating IoT and cloud computing enables real-time data visualisation, enhancing the efficiency of analysis and deployment of countermeasures.

A review conducted by (Olatomiwa *et al.*, 2023) highlighted a comprehensive overview of IoT-based visualisation platforms for household Carbon Footprint, their potential and the considerations that need to be considered for effective implementation.

2. RELATED WORKS

Researchers have been exploring various technologies related to demand-side energy management. These techniques have been proven effective in reducing energy consumption, optimising energy systems, and minimising environmental impacts. It is crucial to continue researching, innovating, and adopting these technologies. This review will demonstrate the diverse approaches and solutions for demand-side energy management.

2.1.1 Energy Audits and Energy Management Systems (EMS)

Energy audits involve assessing energy usage and identifying opportunities for improvement in residential, commercial and buildings. On the other hand, an EMS involves using software and hardware systems to monitor, control and optimise energy consumption. (Kluczek and Olszewski, 2017) study investigated the outcomes of energy efficiency improvements and analysed the benefits of various energy efficiency measures from energy audits. The study discussed energy audit structure; new insights into non-energy benefits were defined with very positive outcomes in achieving the reduction of energy consumption and carbon emissions in industrial processes. The results show that the cost-effective and energy conservation potentials represent a reduction in energy consumption up to 70% of the targeted processes used by energy-efficiency investments.

2.1.2 Demand Response Programs

Arias *et al.* (2018) discussed the trend in demand response and how the programs incentivise consumers to reduce electricity usage during periods of high demand or price fluctuations. These programs include time-of-use pricing, critical peak pricing and direct load control. The effectiveness of California's summer demand response programs has been demonstrated in their ability to decrease peak demand and obviate the need for additional electricity derived from fossil fuels (Doudna, 2001).

2.1.3. Smart Grid Technologies and Smart Meters

Zheng *et al.* (2013) outlined some smart meter aspects and functions of smart meters. In addition, radio frequency (RF) and power line carrier (PLC) communication technologies in smart meter systems were discussed. This paper also presents different policies and current statuses, as well as future projects and objectives for developing smart grids (SG) in several countries. Smart meters help consumers track and manage their energy usage, enabling them to make informed decisions regarding reducing energy consumption during peak periods.

2.1.4 Energy-Efficient Appliances and Lighting

Energy-Efficient Appliances and Lighting: Using energy-efficient appliances and lighting technologies, such as ENERGY STAR-certified products and LED lighting, can significantly reduce energy consumption in the residential, commercial and industrial sectors. (Bladh, 2011) demonstrated an empirical analysis of inefficient lighting phase-out in a household. The energy consumption before and after the phase-out was monitored. These technologies have been widely adopted and are supported by various labelling and certification programs.

2.1.5 Building Automation Systems (BAS) and Energy Management Software (EMS)

BAS and EMS allow for centralised control and optimisation of energy-consuming systems within buildings. These systems can monitor and adjust heat, ventilation, air conditioning (HVAC) systems, lighting, and other equipment based on occupancy patterns, weather conditions, and energy demand. Building energy conservation is an important aspect of implementing the sustainable development strategy and realising the goal of a "low-carbon city (Zhang and Yue, 2021).

2.1.6 Behavioural Change and Energy Conservation Programs

Tyagi *et al.* (2020) showed that behavioural change plays a crucial role in energy consumption patterns. Human intervention has a strong role in achieving sustainable energy goals. Renewable energy sources, prioritising energy-efficient practices, and adopting clean energy technologies and infrastructure remain the most viable options for businesses to effectively transition to an affordable, reliable and sustainable energy system.

2.1.7 Distributed Energy Resources (DERs) and Microgrids

DERs, including rooftop solar panels, wind turbines and battery storage systems, can be integrated into the energy grid to supply clean and decentralised energy. Muhtadi *et al.* (2021) their report presented simulations to investigate the impacts of DER sources, electric vehicles (EV), and energy storage systems (ESS) on DER-based microgrids' resilient operation. The simulation results of past works on the effects of solar and wind energy sources, ESS and EVs on the microgrid frequency response were verified.

2.1.8 Electric Vehicles (EVs) and Vehicle-to-Grid (V2G) Technology

The electrification of transportation through EVs presents opportunities for demand-side energy management. V2G technology allows EVs to supply excess energy to the grid during peak demand periods, reducing the strain on the grid and enabling grid stabilisation. Mwasilu *et al.* (2014) presented a comprehensive review of the smart grid consisting of V2G technology. Various EV smart charging technologies are also extensively examined from the perspective of their potential, impacts, and limitations under the V2G. In their report, Noel *et al.* (2018) analysed the benefits of EV and V2G beyond carbon emission reduction and economics as noise pollution reduction, vehicle-to-home and solar integration, as well as more novel benefits, like vehicle-to-telescope and emergency power backup. Figure 2 gives a typical connection of V2G technology. The smart meter is between the grid and the vehicle to evaluate the net energy supply to the grid.

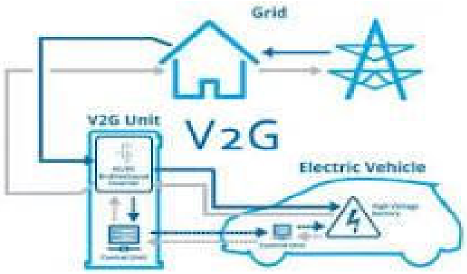

Fig 2: Vehicle to Grid (AbiResearch, 2022)

2.2 Role of IoT in Energy conservation and carbon footprint reduction

The role of IoT in energy conservation and carbon footprint reduction is a topic of interest for many researchers and practitioners. IoT, being the network of devices that can communicate and exchange data over the internet, enables various applications and services. IoT can help reduce energy consumption and carbon emissions by enabling smart technologies that optimise the use of resources, monitor environmental conditions and support renewable energy sources. Other areas where IoT can be used are:

a) Enhance the integration of renewable energy sources, such as solar and wind, into the power grid by using smart meters, inverters and storage devices to balance the load and supply of electricity (Blanco *et al.*, 2018; Zafar *et al.*, 2013; Zhong and Hornik, 2012).

b) Enable the creation of smart cities that leverage IoT to provide sustainable solutions for urban challenges such as waste management, air quality and water supply (Ahad *et al.*, 2020; Bibri, 2018).

3. DEPLOYMENT FRAMEWORK AND METHODOLOGY

3.1 Cloud-Based IoT Infrastructure for Carbon Footprint Tracking

Cloud-based IoT infrastructure provides optimisation and scalability solutions. The shared resources with other cloud-based services (security, storage and data analysis) promote ease of deployment and scalability (Alam, 2021). Cloud-based Internet of Things (IoT) infrastructure enables efficient and scalable carbon footprint tracking solutions. Below is a detailed explanation of the components and benefits of a cloud-based IoT infrastructure for carbon footprint tracking. Figure 3.0 depicts the conceptualisation of the IoT framework for system integration and embedded components.

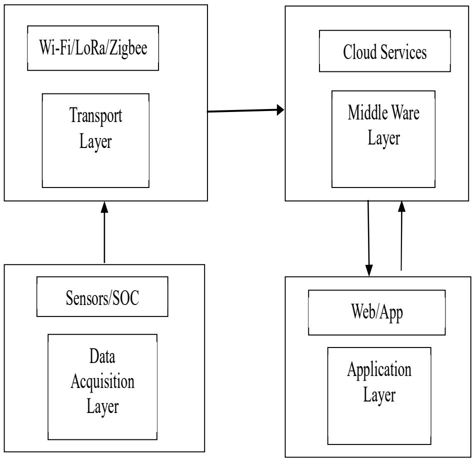

Figure 3: Conceptualisation IoT Framework

3.1.1 Device Connectivity

IoT devices, such as sensors and meters, are deployed to collect relevant carbon emissions data from various sources, such as energy consumption, transportation and waste management (Alam, 2021; Gopika and Goerge, 2021). These devices are connected to the cloud infrastructure through the transport layer using wireless communication technologies like Wi-Fi, cellular networks (e.g., 4G, LTE) or Low-Power Wide-Area Networks (LPWAN) like LoRa WAN or NB-IoT (Choi *et al.*, 2018). This connectivity allows real-time data transmission from the devices to the cloud, ensuring continuous monitoring and tracking of carbon emissions.

3.1.2 Data Aggregation and Processing

The collected data from different IoT devices is transmitted to the cloud for aggregation, visualisation and processing. The cloud-based IoT infrastructure acts as a central hub for collecting vast amounts of data from multiple devices and sources, ensuring that data is efficiently managed, validated, processed and transformed into meaningful insights (Ebiesuwa *et al.*, 2022).

3.1.3 Cloud Storage and Management

The collected and processed IoT data is securely stored in the cloud-based storage infrastructure. Cloud storage services provide scalability, reliability and data redundancy, ensuring that data is always available and protected (Alam, 2021; Mani *et al.*, 2017). Additionally, the cloud infrastructure offers backup and disaster recovery capabilities, safeguarding the collected carbon footprint data.

3.1.4. Scalable and Elastic Computing

Cloud computing platforms provide the necessary computing power and resources to handle the large-scale carbon footprint tracking processing requirements. As the number of IoT devices and data streams grows, the cloud infrastructure can easily scale up or down to accommodate the increased workload (Despa *et al.*, 2015). This elasticity allows organisations to handle peak workloads and optimise resource allocation.

3.1.5 Real-time Monitoring and Visualisation

Cloud-based IoT infrastructure enables real-time monitoring of carbon emissions by providing interactive dashboards and visualisation platforms (Giama and Papadopoulos, 2018; Mao *et al.*, 2018; Okafor *et al.*, 2017; Saleem *et al.*, 2022). These dashboards present the collected data as user-friendly, allowing stakeholders to monitor carbon footprint performance, track key metrics, identify inefficiencies and make data-driven decisions towards reducing carbon emissions.

3.1.6 Integration and API-driven Architecture

Cloud-based IoT platforms offer application programming interfaces (APIs) and integration capabilities, allowing seamless integration with other systems, such as enterprise resource planning (ERP) and business intelligence (BI) tools. The API-driven architecture enables the interoperability of different systems, facilitating efficient data exchange and process automation, which further improves carbon footprint tracking and reporting accuracy (Bibri, 2018; Hoffmann *et al.*, 2024; Nasar *et al.*, 2019; Purwania *et al.*, 2020).

3.2 Sensors and Devices Used for Data Collection

In carbon footprint tracking, various sensors and devices are employed to collect relevant data on energy consumption, transportation, waste management and other sources of greenhouse gas emissions. These sensors and devices, along with the cloud-based IoT infrastructure, enable accurate data collection and real-time tracking of carbon emissions, facilitating effective carbon footprint management, counter-measures and reduction strategies. Here is an overview of some commonly used sensors and devices:

3.2.1 Smart Meters

Smart meters are electronic devices used to measure and monitor electricity, gas, and water consumption in real-time. Zheng *et al.* (2013) outline some smart meter's components and functions. In addition, it introduces the recent technologies in the two basic types of smart meter system communication technologies: Radio Frequency (RF) and Power Line Carrier (PLC). It can be connected to the cloud infrastructure via communication protocols, enabling remote monitoring and data collection.

3.2.2 Environmental Sensors

Environmental sensors are deployed to measure parameters like temperature, humidity, air quality, and ambient noise levels. De Paola *et al.* (2012) used a university building as a case study where Wireless Sensor and Actuator Networks (WSAN) were used to monitor and control the environment remotely. These sensors were used to detect the presence of an inhabitant and their environmental preference, like temperature.

3.2.2 GPS Trackers

GPS trackers, commonly used in vehicles, collect location, speed and distance travelled data. Hadwen *et al.* (2017) proposed a novel energy-efficient, small wristband solution integrating LoRa communication and GPS duty cycling technologies. The solution can determine the individual energy consumption of the components in a GPS tracker. Extensive experiments were carried out to verify the prototype communication distance and energy efficiency.

3.2.3 Waste Management Sensors

Waste management sensors, such as fill-level sensors in trash bins or recycling containers, are used to monitor waste generation and optimise waste collection routes. Longhi *et al.* (2012) implemented a remote monitoring solution to improve the waste management process's on-site handling and transfer optimisation. The system has a remote server consisting of sensor nodes and Data Transfer Nodes (DTN) to retrieve data measurements from the garbage bins filling. This solution allowed users to interact with the system using a web browser. By efficiently managing waste collection, these sensors help reduce unnecessary fuel consumption and associated carbon emissions.

3.2.4 Emission Monitoring Systems

Emission monitoring systems are typically used in industrial or commercial settings to collect data on air pollutants and greenhouse gas emissions. Gai *et al.* (2020) proposed alternative monitoring technologies, such as optical and remote sensing instruments and wireless sensors. These systems utilise sensors and analysers to measure emissions of gases like carbon dioxide (CO2), methane (CH4) and nitrogen oxides (NOx), helping organisations track and manage their carbon footprint.

3.3 Analytical Methods Applied to Interpret Collected Data

Several analytical methods can be applied to interpret and utilise the data collected from IoT sensors. These methods help extract valuable insights, identify patterns, and make informed decisions regarding carbon footprint reduction. Here is a description of some commonly used analytical methods:

3.3.1 Data Visualisation

Data visualisation techniques represent data in visual formats like charts, graphs and maps.

3.3.2 Statistical Analysis

Statistical analysis techniques, such as descriptive statistics and inferential statistics, can be applied to extract meaningful information from sensor data.

3.3.3 Machine Learning

Machine learning algorithms can be employed to analyse sensor data and discover patterns or relationships that may not be apparent through traditional statistical methods.

3.3.4 Time-Series Analysis

Time-series analysis methods are valuable for interpreting IoT sensor data collected over time.

3.3.5 Geospatial Analysis

Geospatial analysis techniques incorporate location information into the analysis of sensor data.

By using analytical methods to interpret the data collected from IoT sensors, individuals can proactively work towards reducing their carbon footprint and positively impacting the environment. This approach empowers individuals to identify areas for improvement and make data-driven decisions, leading to sustainable and eco-friendly practices.

4. CARBON FOOTPRINT TRACKING

Numerous researchers have been studying various technologies related to demand-side energy management. The information from the carbon footprint provides vital feedback and understanding of human activities impact on the planet. By quantifying the amount of greenhouse gas emissions generated by various activities, products, and organisations, we can identify areas where we can make changes to reduce our carbon footprint (Hill *et al.*, 2011; Pandey *et al.*, 2011; West *et al.*, 2016; Wiedmann and Minx, 2008). To help in this process, here are some commonly used metrics that can help individuals track and reduce their carbon footprint (Auger *et al.*, 2021)

4.1.1 CO2 Equivalent (CO2e)

CO2 Equivalent is a metric that represents the amount of carbon dioxide (CO_2) emissions released by a specific activity or product, and it takes into account other greenhouse gases like methane (CH4) and nitrous oxide (N_2O) (Gohar and Shine, 2007). This metric is used to comprehensively assess the total impact of emissions on the environment (Pandey *et al.*, 2011; Wiedmann and Minx, 2008).

4.1.2 Scope Classification

Classifying carbon footprint emissions into three scopes helps identify and understand the sources and activities responsible for greenhouse gas emissions (Olatomiwa *et al.*, 2023). This information can be used to develop effective strategies for reducing carbon footprint and promoting sustainability. (Sprangers, 2011) adopted the scope classification to evaluate the total carbon emission of a university. Scope 1 is direct emissions from sources owned or controlled by the university, such as on-site fuel combustion. The scope is indirect emissions from electricity, heating or cooling purchased and consumed by the university. Scope 3 is Indirect emissions that are not directly owned or controlled by the university but result from its activities. This includes emissions from the supply chain, business travel, and employee and student commuting.

4.1.3 Life Cycle Assessment (LCA)

Life Cycle Assessment is a comprehensive methodology that evaluates the environmental impacts of a product or service throughout its life cycle. It assesses emissions from resource extraction, production, use, end-of-life and disposal stages. (Buberger *et al.*, 2022) offered comprehensive comparisons of the overall greenhouse gas (GHG) emissions generated throughout the entire life cycle of a diverse range of passenger cars with varying powertrains and energy sources.

4.1.4 Energy Consumption

Energy consumption is often used as a parameter to measure carbon footprints, as most energy sources still rely on carbon-intensive fossil fuels. Measuring and analysing the energy consumed provides insights into the associated greenhouse gas emissions. (Oluseyi *et al.*, 2016) used correlation analysis to investigate the interdependence of carbon footprint and energy consumption in hotels in Nigeria. Results showed a significant correlation between energy consumption per unit guest room and the carbon dioxide emission level.

4.1.5 Carbon Intensity

Carbon intensity represents the amount of carbon dioxide emissions per unit of economic output, such as emissions per GDP or emissions per unit of product. It enables the comparison of carbon footprints relative to productive or economic activity. (Transparency, 2020) article showed the fluctuation of carbon intensity of the energy sector in Nigeria over the last three decades.

4.2 How to Track and Interpret Carbon Footprint Data in Real-Time

Energy usage metrics and carbon density provide a framework for quantifying and comparing carbon footprints. The total energy consumption of appliances in a household consisting of always-on appliances and short-time usage appliances can be captured by the smart meter's sensor (rms voltage and rms current). The Wi-Fi capabilities of the on-premise IoT sensors enable connectivity with cloud services for data logging and storage. An internet protocol assigned to the sensors enables seamless communication. Cloud-based information is accessible by end users via an application programming interface designed for Android applications.

The mathematical model expressed below can be used for carbon footprint (CF) computation.

$$CF(kg) = Electricity(kWh) * Carbon\,density(kg/kWh) \qquad (1.20)$$

The end user of energy can leverage the computation above to measure the environmental impact arising from their energy consumption, identify areas for improvement and establish reduction targets. This demand-side energy management approach presents the necessary feedback in real-time and energy usage patterns. This has eliminated the manual meter reading and has also reduced human-prone error in meter reading, among other incentives.

4.3 The Effectiveness of the Carbon Footprint Tracking System

Recently, various researches have been carried out on the effectiveness of carbon footprint tracking with increasing human activity and energy use (Auger *et al.*, 2021; Harangozo and Szigeti, 2017; Pandey *et al.*, 2011). These researches were carried out on different sectors of human activities from production to consumption of products. Most energy users are unaware of how their daily consumption choices can significantly impact the environment and climate. Compounding this problem is the lack of understanding surrounding the energy consumption of individual devices and applications. Additionally, most individuals do not recognise the potential for energy savings by scrapping certain devices or transitioning to more energy-efficient appliances. This lack of awareness and knowledge can lead to suboptimal decision-making and potentially harm the environment and climate.

Implementing carbon footprint tracking systems has proven effective in various sectors and industries, enabling individuals and organisations to identify emission sources, set targets and implement measures to reduce their carbon footprints (Oluseyi *et al.*, 2016; Sam-Amobi *et al.*, 2019). Carbon footprint calculators (CFCs) provide consumers with feedback about their consumption and lifestyle carbon emissions. Salo *et al.* (2019) used interview-based studies to track individual carbon footprints. The findings show that knowledge-intensive calculators are designed to support a rational reflection of lifestyle and activities from an environmental perspective. Hoffmann *et al.* (2024) discovered that comparing feedback on individual carbon footprint could act as eco-pride or eco-guilt, which may foster action toward a sustainable environment. (Marckmann *et al.*, 2012) also discovered that feedback from individual actions could further motivate the individual for further commitment and behavioural change. In conclusion, carbon footprint tracking can raise individual knowledge of the impact of consumers' actions toward climate change (Olatomiwa *et al.*, 2023).

5. CLOUD-BASED IOT DEVICES

Cloud service providers such as Amazon Web Services (AWS), Microsoft Azure, Google Cloud Platform (GCP), ThinkSpeak, Firebase, IBM Watson, Thingsboard and Ubidots offer dedicated IoT platforms and services. They provide a wide range of tools, services and application programming interfaces (API) designed explicitly for managing and leveraging the potential of IoT devices in the cloud (Chooruang and Meekul, 2018; Mani *et al.*, 2017; Shrivastava *et al.*, 2023)

The cloud infrastructure supporting IoT devices refers to the network of servers, storage, software and other resources necessary to manage and process data generated by IoT devices (Olatomiwa *et al.*, 2023). This infrastructure enables the seamless integration, monitoring and control of IoT devices on a large scale. The cloud infrastructure supports IoT devices in the following areas:

I. Data Collection and Integration: IoT devices generate vast amounts of data. Cloud platforms offer various protocols and APIs (Application Programming Interfaces) to connect and communicate with many IoT devices. (Chooruang and Meekul, 2018), in their report, they used a Pzem004t sensor integrated with a CT sensor, SD3004 electric energy measurement chip and ESP8266 Wemos D1 mini microcontroller to retrieve data from sensor nodes and send data to a cloud via internet connectivity.

II. Data Processing and Analytics: Cloud infrastructure offers the computational power required for processing and analysing the massive amount of data generated by IoT devices (Olatomiwa *et al.*, 2023).

III. Storage and Data Management: Cloud storage is used to store and manage the data collected from IoT devices securely. It provides scalable options that can handle the increasing volume of data generated by IoT devices. This made the deployment of IoT architecture seamless and scalable (Olatomiwa *et al.*, 2023).

IV. Device Management and Control: Cloud platforms allow centralised management and control of IoT devices. They offer features such as remote device monitoring, firmware updates, and configuration management (Okafor *et al.*, 2017; Olatomiwa *et al.*, 2023)

V. Security and Privacy: Cloud infrastructure incorporates robust security measures to protect the data and infrastructure from unauthorised access and cyber threats (Alam, 2021).

VI. Scalability and Availability: Cloud infrastructure is designed to scale according to the needs of IoT deployments. It provides elastic resources to accommodate the increasing number of connected devices and the data they generate (Alam, 2021).

5.1 IoT Devices Communication, Storage and Data Processing

Devices communicate, store and process data in the cloud through various steps and protocols. Below is the description of the process of how IoT devices communicate:

i. Device Communication: IoT devices communicate with the cloud through different connectivity options such as Wi-Fi, cellular networks, Bluetooth, or LPWAN (Low-Power Wide-Area Networks). They use protocols like MQTT (Message Queuing Telemetry Transport) or HTTP (Hypertext Transfer Protocol) to transmit data securely to the cloud (Choi *et al.*, 2018; Chooruang and Meekul, 2018; Mani *et al.*, 2017; Shrivastava *et al.*, 2023).

ii. Data Ingestion: The cloud infrastructure receives the data from IoT devices through gateways or directly from the devices themselves (Alam, 2021).

iii. Data Storage: Cloud infrastructure provides scalable storage options to store and manage the data generated by IoT devices (Alam, 2021; Olatomiwa *et al.*, 2023)

iv. Data Processing: Cloud platforms offer various data processing capabilities to analyse and derive insights from IoT data. This includes real-time stream, batch, or event-driven processing using tools like Apache Kafka, Apache Spark, or AWS Lambda. Data is processed to perform tasks such as aggregations, filtering, anomaly detection, or predictive analytics (Ajibade and Adediran, 2016; Diamantoulakis *et al.*, 2015)

v. Machine Learning and AI: Cloud infrastructure also provides tools and frameworks for machine learning and artificial intelligence. These capabilities can be applied to the IoT data for advanced analytics, predictive maintenance, anomaly detection, pattern recognition, or intelligent automation. Platforms like TensorFlow, Azure Machine Learning or AWS Sage Maker enable the development and deployment of machine learning models. ThingSpeak has MATLAB visualisation tools for visualisation and analysis (Alam, 2021; Chen *et al.*, 2014; Najafi *et al.*, 2018; Olatomiwa *et al.*, 2023; Reinhardt and Klemenjak, 2020)

vi. Data Visualisation and Analytics: Cloud platforms offer visualisation tools and dashboards to analyse and represent IoT data in a user-friendly manner. With services like Amazon Quick Sight, Microsoft Power BI or Google Data Studio, data can be transformed into meaningful insights, charts, graphs, and reports. This enables users to monitor, track and make informed decisions based on real-time data(Brewer, 2009; Stusek *et al.*, 2017)

5.2 Scalability and Flexibility of the Cloud-Based IoT Architecture

Scalability and flexibility are key advantages of cloud-based IoT architecture. These have increased the deployment of IoT devices in recent times. Several researchers and developers have explored this innovation. (Alam, 2021) narrated how cloud-based IoT architecture offers inherent scalability, allowing businesses to handle large-scale deployments without infrastructure constraints. In another study (Kumar *et al.*, 2019; Mrabet *et al.*, 2020), the flexibility of cloud-based architecture was also explained, from integrating diverse devices and protocols to accommodating heterogeneous IoT environments. Cloud platforms support various connectivity options such as Wi-Fi, cellular networks, or LPWAN, enabling seamless communication with different devices. Also, in the study conducted by (Cao *et al.*, 2020), an overview of the concept of edge computing, comparison and integration with cloud computing was conducted. Edge computing allows data processing at the network's edge, closer to IoT devices, reducing latency and enhancing real-time decision-making. Cloud providers offer edge computing services that complement their cloud platforms, allowing organisations to balance data processing between the cloud and edge devices.

6. DEMAND-SIDE ENERGY MANAGEMENT STRATEGIES

Demand-side energy management strategies aim to achieve energy efficiency and a sustainable environment. These strategies focus on reducing energy consumption and demand by modifying the behaviour of consumers and businesses.

One of the key demand-side energy management strategies is energy efficiency. This involves implementing various measures to reduce energy waste, such as upgrading insulation, using energy-efficient appliances, and adopting efficient lighting systems. (Khan, 2019) considered Bangladesh and other least-developed economies on the potential of energy-saving behaviour as a DSM strategy. The literature suggests that energy-saving behaviour could reduce energy demand by 21.9%. Energy-efficient technologies lower energy consumption and lead to cost savings for consumers and businesses in the long run.

Vardakas *et al.* (2014) also explored demand response programs as a cost-effective, reliable and important strategy in demand-side energy management. These programs encourage consumers to reduce their electricity consumption during peak demand periods, such as hot summer days when air conditioning demand is high.

Le *et al.* (2016) enumerated the benefits of smart grid technologies and advanced metering infrastructure in demand-side energy management strategies. By providing real-time information on energy consumption, these technologies enable consumers to monitor and manage their electricity usage more effectively. Haney *et al.* (2010) focused on

DSM policies, which include energy conservation and demand-side management. Those strategies are not limited to residential consumers alone but can also be administered by utilities, state agencies or non-profit organisations. Commercial and industrial consumers can also adopt energy-efficient practices, implement demand response programs, and utilise smart grid technologies to reduce their energy consumption and demand. These strategies help businesses optimise operations, reduce energy costs, and contribute to a more sustainable energy future.

In conclusion, demand-side energy management strategies are critical for achieving energy efficiency, reducing demand on the electricity grid, and promoting a sustainable environment.

6.2 Case Studies Showcasing Successful Implementation of IoT

Recent studies have demonstrated successful implementation and a positive impact on carbon emission mitigation. Fay *et al.* (2023) demonstrated the potential of microcontrollers as a sustainable alternative to traditional resource-intensive AIML platforms for real-time event detection. The case studies demonstrated the effectiveness of using low-power microcontroller technology for event detection in carbon-emission reduction, showcasing its efficiency and potential for power savings.

Ming *et al.* (2019) demonstrated the practical implementation of environment monitoring using IoT and cloud computing technologies. The monitoring architecture developed in the research utilises a carbon dioxide sensor, a Wi-Fi module, a cloud storage service and an Android mobile application for data visualisation. The data sampling rate was 30-second intervals for 10 days. Those data were successfully collected and stored for visualisation. The solution presents great potential in creating awareness of indoor air quality for smart home residents and providing valuable insights into carbon dioxide emissions for industries and environmental organisations.

(Ma *et al.*, 2023) used Raspberry Pi minicomputers as a platform for connecting sensors to a blockchain network to provide and analyse real-time indoor environmental quality (IEQ), energy, and carbon intensity data. The infrastructure allows for the evaluation and incentivisation of occupant behaviours related to electric demand flexibility in buildings. It aims to provide grid-responsive support and encourage demand response (DR) participation. The environmental footprints of homeowners were evaluated using Blockchain IoT Network (BIN). It executes novel algorithms as smart contracts on the blockchain network to normalise energy usage and carbon intensity, considering various environmental factors.

7. CHALLENGES AND LIMITATIONS

Cloud-based IoT deployment for carbon footprint tracking and energy management has challenges and limitations; these are the subject of further research and study. The following are the Challenges and limitations:

1. Data Security: Implementing IoT and cloud computing for environment monitoring raises concerns about data security and privacy, as sensitive information is transmitted and stored in the cloud.
2. Reliability and Connectivity: The reliability and connectivity of IoT devices and Wi-Fi modules can pose challenges in ensuring continuous and uninterrupted data collection and transmission.
3. Cost and Scalability: Implementing IoT and cloud computing solutions for environment monitoring may require significant initial investment and ongoing maintenance costs. In

addition, scaling up the system to accommodate a larger number of sensors and data points may present scalability challenges.

4. Data Accuracy and Calibration: Ensuring the accuracy and calibration of carbon dioxide sensors used in the monitoring system is crucial for obtaining reliable and meaningful data. Regular calibration and maintenance of the sensors may be required.
5. Integration and Compatibility: Integrating different components of the monitoring system, such as the sensor, Wi-Fi module, cloud storage service, and visualisation application, may require compatibility and interoperability considerations.

8. CONCLUSION

This review extensively discusses the increasing demand for energy management solutions and the significant role of demand-side energy management in mitigating environmental effects caused by energy consumption. The introduction of Cloud-based Internet of Things (IoT) devices for efficient energy management is attracting more interest from researchers. The review highlights the significance of energy-efficient technologies and practices in reducing energy demand, which can decrease greenhouse gas emissions, improve air quality, and conserve natural resources. The successful deployment of demand-side energy management programs and technologies has proven effective in reducing environmental impacts and should continue to be pursued as a key strategy for achieving sustainable development goals.

Cloud-based IoT solution has the potential to impact demand-side energy management significantly. By leveraging real-time data from IoT devices, the solution can provide insights into energy consumption patterns and enable more effective energy management. This could lead to reduced consumer energy costs and a more efficient energy grid overall. Additionally, the cloud-based nature of the solution could allow for scalability and flexibility, making it easier to implement across a wide range of industries. However, it is important to consider potential privacy and security concerns associated with using IoT devices and cloud-based solutions. The solution has promising potential for improving demand-side energy management, but careful consideration of its implementation and potential risks is necessary.

To unravel the limitations in the implementation of cloud-based IoT devices, the following areas are the subject of further study and research:

a) Data Quality and Validation: Further research is needed to ensure the accuracy and reliability of the collected data, as well as the validation of the sensor readings against established standards and calibration methods.

b) Energy Efficiency: Exploring energy-efficient solutions for IoT devices and Wi-Fi modules can help optimise power consumption and extend the battery life of the monitoring system.

c) Scalability and Interoperability: Developing scalable and interoperable solutions that can accommodate a larger number of sensors and integrate with different IoT platforms and cloud services would enhance the flexibility and usability of the system.

d) Privacy and Security: Addressing privacy and security concerns by implementing robust encryption and authentication mechanisms to protect sensitive data during transmission and storage is crucial.

e) Integration with Other Environmental Parameters: Investigating the integration of carbon dioxide monitoring with other environmental parameters, such as temperature, humidity, and air quality, can provide a more comprehensive understanding of indoor and outdoor environments.

f) Cost-Effectiveness: Exploring cost-effective alternatives for sensors, IoT devices, and cloud storage services can make environment monitoring solutions more accessible and affordable.

Despite the potential benefits, integrating demand response mechanisms with IoT technology faces several challenges, including accurate data collection considering latency and cost-effectiveness, customer participation, communication infrastructure and market design. Future research should focus on developing enhanced communication protocols for data security and streaming and addressing regulatory barriers to enable the widespread adoption of an integrated demand response approach to carbon footprint reduction. Technological advancements are also necessary to overcome existing challenges and promote the widespread adoption of these integrated approaches. Integrating demand response mechanisms with IoT technology can contribute significantly to effective energy management, reduced environmental impacts of energy consumption and a sustainable energy future.