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Bernergy+: An IoT-Based Approach to Household Energy Waste Reduction

Manuel Rodrigues Casimiro

Master’s in Integrated Decision Support Systems

Supervisor:
Doctor Carlos Eduardo Dias Coutinho, Assistant Professor
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TECNOLOGIAS
E ARQUITETURA

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"I'm not falling behind or running late."

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Resumo

A eficiência energética é uma preocupação cada vez mais significante, considerando os muitos agregados familiares que procuram reduzir o seu impacto ambiental e, ao mesmo tempo, gerir os custos emergentes da energia. Esta tese apresenta a aplicação Bernergy+, uma aplicação para smartphone baseada na Internet das Coisas (IoT) com o objectivo de reduzir o desperdício doméstico de energia com recurso a uma rede de sensores de baixo custo complementados por um sistema de alertas em tempo real quando dispositivos como luzes ou unidades de climatização são deixados ligados desnecessariamente. Ao contrário de soluções automatizadas, o Bernergy+ centra-se na capacitação dos utilizadores para adoptarem comportamentos energeticamente conscientes, ao fornecer dados acionáveis que incentivam a tomada de decisões baseada em dados. De modo a validar a importância da aplicação, foi também efetuada uma análise do impacto financeiro de negligenciar as notificações da aplicação. Para além do descrito acima, este documento estabelece uma ligação entre Unity e IoT - uma área que tem sido notavelmente negligenciada pela comunidade científica. Esta tese espera por isso, contribuir também para corrigir esta lacuna ao apresentar uma pilha tecnológica completa e profunda, pronta a ser adaptada a diversos projetos de IoT. Em conclusão, apesar de permanecer uma prova de conceito, o Bernergy+ demonstrou a sua eficácia no fornecimento de alertas atempados aquando do desperdício de energia na casa do utilizador, promovendo assim hábitos sustentáveis e constituindo um passo imprescindível numa era de aumento drástico das consequências das alterações climáticas e da degradação do meio ambiente.

Palavras-chave: IoT, Unity, Eficiência Energética, Desperdício Energético

Abstract

Energy efficiency is an increasingly critical concern as households seek to reduce their environmental impact while managing rising energy costs. This thesis presents Bernergy+, a proof-of-concept IoT-based smartphone application that aims at reducing household energy consumption by using a network of low-cost sensors to provide real-time alerts when devices such as lights and climate control units are left on unnecessarily. Unlike fully automated solutions, Bernergy+ focuses on empowering users to adopt energy-conscious behaviors by providing actionable data that encourages data-driven decision-making. In order to validate the importance of the app, an analysis of the financial impact of neglecting the app's notifications was also carried out. In addition to the above, this research also establishes a connection between Unity and IoT projects – an area that has been largely overlooked by the broader scientific community. This dissertation therefore hopes to amend this gap by presenting a well-researched and thorough technology stack and solution architecture that can be readily adapted for various IoT projects. Ultimately, although it remains a proof-of-concept, Bernergy+ demonstrated its effectiveness in delivering timely information concerning energy waste in user's homes, thus promoting sustainable habits and being a valuable steppingstone in this age of escalating climate changes and environmental degradation.

Keywords: IoT, Unity, Energy Efficiency, Energy Waste

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Abbreviations

AC	**A**lternating **C**urrent
API	**A**pplication **P**rogramming **I**nterface
AR	**A**ugmented **R**eality
BLE	**B**luetooth **L**ow **E**nergy
DC	**D**irect **C**urrent
DSR	**D**esign **S**cience **R**esearch
HPD	**H**uman **P**resence **D**etector
HTTPS	**H**yper**t**ext **T**ransfer **P**rotocol **S**ecure
IDE	**I**ntegrated **D**evelopment **E**nvironment
IOT	**I**nternet **o**f **T**hings
JSON	**J**avaScript **O**bject **N**otation
LDR	**L**ight **D**ependent **R**esistor
LED	**L**ight **E**mitting **D**iode
MQTT	**M**essage **Q**ueuing **T**elemetry **T**ransport
NoSQL	**N**ot **O**nly **S**tructured **Q**uery **L**anguage
PIR	**P**assive **I**nfra-**R**ed
PQ	**P**ower **Q**uality
QR	**Q**uick **R**esponse
SLR	**S**ystematic **L**iterature **R**eview
VR	**V**irtual **R**eality

CHAPTER 1

Introduction

Energy sustainability is an ever-pressing issue in today’s world. As societal needs arise, inefficiencies in energy consumption lead to significant environmental problems such as contributing to climate change and environmental degradation and destabilization, while also carrying notable economic consequences [1]. The urgency in mitigating energy waste cannot be overstated such that the mission to find plausible and innovative solutions have transcended both the scientific and the technological panorama and have become a moral and global imperative.

On the other hand, as the author of this research, I have always been interested in the automatization and consequent facilitation of day-to-day life by delivering technology that is easy to understand and usable by the general population. It is my unwavering belief that this should be the end point of technology as a whole: enhancing society at a community/personal level, making this the driving factor for this dissertation.

In addition to the broader societal implications, this project offers a unique opportunity to enhance my proficiency in Internet of Things (IoT) systems and applications as well as understanding the intricate relations between software and available hardware in this area. Moreover, the process of conducting rigorous and methodological research in the form of a scientific paper will undoubtedly help me integrate the global scientific community.

1.1. Research Methodology

The Design Science Research (DSR) methodology was chosen for conducting this research. In our exploration of IoT smartphone application development, the choice of the Design Science Research (DSR) methodology stands out due to its ability to prioritize the creation of innovative, practical solutions. The DSR's iterative approach and focus on rigorous evaluation provide a clear advantage over other methodologies, ensuring the development of not only functional, but also secure and user-centric applications. Unlike purely theoretical or quantitative methods, the DSR's adaptability and responsiveness [2] make it an ideal choice for addressing the dynamic nature of IoT technology, ultimately bridging the gap between theory and practice in the development of cutting-edge applications.

The DSR Methodology features four possible entry points, as seen on Figure 1.1.

This dissertation uses a Problem-Centered Initiation as a specific problem has been identified, as detailed earlier in this chapter.

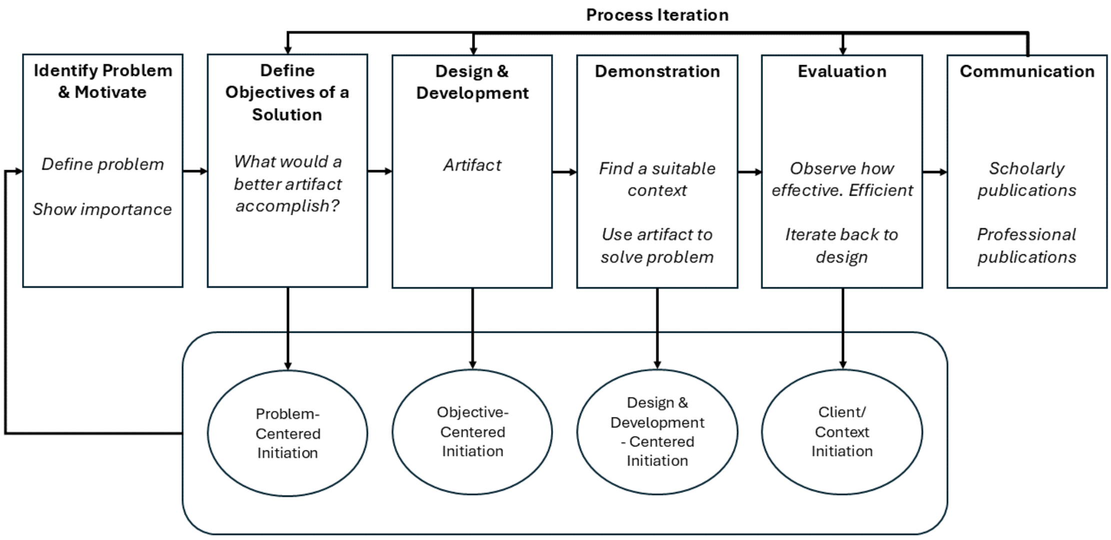

Figure 1.1: DSR Methodology model [2]

Once the problem is defined, the next step lies in establishing the main objective for the proposed solution as well as establishing various hypotheses, which serve as possible avenues for exploration, as presented later in this chapter.

Although not a formal step of the aforementioned methodology, we also conducted a systematic literature review, detailed in Chapter 2, focused on analyzing the available technologies and solutions related to the interaction between IoT and energy conservation. This research not only informed us of the current breakthroughs in this domain but also enlightened us on possible areas of further exploration, all while preparing us for subsequent stages of the DSR methodology.

With the artifact's objectives clearly identified and an overview of the technological landscape into which it integrates, the next step nurtures the creation of said artifact with the purpose of achieving the previously defined objective.

Upon the artifact's development, an analysis of its ability to satisfy the previously defined objective is crucial and composes the centerpiece of the Evaluation stage of development. In addition to this, possible innovations and improvements of existing systems may also be tested during this step. The various iterations our application underwent throughout this process are addressed in Chapter 3.

Lastly, the communication step is represented by this very dissertation and details the approaches, results and conclusions reached during the development cycle. Chapters 4 and 5 address these results and conclusions, respectively.

1.2. Research Question

The main objective of this research is to deliver an application for the general public that allows the user to be notified in real-time if their household is wasting energy. In addition to this, it is imperative that the hardware needed to achieve this is accessible, inexpensive and adjusts to the surrounding environment providing a cheap and effective solution to energy waste at an individual level. Furthermore, this dissertation also aims to bridge the existing gap between Unity [3] and IoT projects through a well-researched and adaptable technology stack and solution architecture.

As such, this dissertation will aim to answer the following research question:

RQ: Can a low-cost sensor-powered Unity application encourage behavioral changes that reduce energy waste in individual households?

1.2.1. Research Hypotheses

The following hypotheses represent possible solutions to the proposed research question:

- H1. Users who are notified by the application when a certain room has achieved the desired temperature will turn off the temperature-control device, thus reducing individual energy waste.
- H2. Users who are notified by the application when a certain room has a light on while being vacant will turn off the light, thus reducing individual energy waste.
- H3: Users who have access to real-time visualizations of the evolution of metrics such as temperature and humidity levels, will be better equipped to make energy-conscious, data-driven decisions.

This work has been validated by the publication and public presentation of the article entitled "Integrating Unity into IoT Solutions" in the conference iSCSi 2024 [4].

CHAPTER 2

Related Work

2.1. Existing Energy Efficiency Solutions using Sensors

Considering that this dissertation's proposed solution revolves around sensors and how they can influence an economically friendly approach to energy-saving, this first subsection delves into existing papers that used sensors in order to achieve energy-efficient solutions. In order to aggregate and select the appropriate papers for this subsection, we led a systematic literature review (SLR) [5] using Scopus [6], having built the following query:

TITLE-ABS ((electricity OR power) AND ("Internet of Things" OR iot) AND sensor AND ("energy efficiency" OR "energy saving" OR "energy management") AND (app OR application) AND NOT ("machine learning"))

As a result, we obtained a total of 446 papers that satisfied the conditions proposed by the query, a number we considered too large for an in-depth analysis of each paper. Table 2.1 describes the subsequent filters applied to the query and the number of papers that remained at each step of the SLR.

Table 2.1. SLR's filtering conditions and subsequent number of energy-related papers.

Filter	Retrieved Papers
Initial Query	446
Release Date: Post-2021	215
Subject Areas: Energy or Environmental Science	32
Document Type: Article or Conference Paper	31
Keywords: “Internet of Things”, “Internet of Things (IOT)” or “IoT”	26

Having obtained 26 papers, we consider this an acceptable number to conduct an individual review of each of these, thus concluding our SLR.

The approach explored by Chiradeja et al. [7] aimed at reducing energy wasting within the public-lights system with the help of automatic lights. The research begins with a simulation of the developed smart public lighting system which was then compared to Thailand's public lighting required standards to ensure the solution was applicable to a real situation. It was followed by the design of the automatic lights system which fluctuates the brightness level of a given light depending on the amount of movement near that same light. In addition to this, a mobile application was also developed which allowed the user to consult and control the system using an internet connection. Finally, each lamppost was furnished with additional features such as air quality detection and a camera-powered security system, having this data also available in the aforementioned mobile application.

The solution achieved by Chiradeja et al. can in fact lead to a substantial reduction in energy wasting if applied to a considerable scale such as a large city. However, it is important to note that a failure in the system could lead to extremely dangerous situations to both pedestrians and the drivers of motorized vehicles due to the resulting poor lighting conditions as the proposed system is considerably more complex than a non-automated public lighting system which increases the chance of a system malfunction. Nevertheless, this solution is an ambitious and healthy contribution to the IoT landscape being studied in this paper.

The paper researched by Rao et al. [8] brings a smart energy management solution for utility sources and solar power systems to the IoT energy landscape. Through the use of a varied sensor array composed of a current sensor, a voltage sensor and a temperature sensor connected to a solar panel, the study sought to collect, aggregate and analyze data from the aforementioned array with the objective of anticipating and estimating 'power generation possibilities, revenue production and other factors' while also facilitating and improving 'recorded data analysis, decrease intervention and monitoring time, streamline network administration' and bypass the required routine system maintenance. It is also of note that such a solution could be highly impactful in the case of the solar panel developing a defect.

Although this solution presents a way to monitor and analyze the performance of a solar panel, it is quite limited in its capabilities, given it only aids the user's energy-related decision-making process in case of a malfunction in the solar panel device since the user cannot, in any way, alter the electricity being generated by the solar panel device in question. Additionally, another feature that accentuates this constraint, is the fact that a large majority of European households do not have solar panels installed, amounting to only 9.1% of total European electricity generation in 2023 [9].

Alternating our focus to household-level applications, a paper by Shan et al. [10] details a similar approach to our own for saving energy detailing a system where appliances are turned on/off depending on the activity levels in that specific room. The solution's communication is reliant on Bluetooth Low Energy (BLE) technology due to it being, as the authors put it, a "low-power, low-cost and short-range communication technology". The paper engages this technology with the user's mobile phone (serving as the receiver for the BLE device's broadcast signal), alongside different power switches installed in different appliances, allowing the application to remotely turn on and off said appliances, and lastly, sensors, used to detect temperature, humidity and brightness. All these instruments culminate in a responsive and intelligent indoor localization-based energy management system. Lastly, the researchers performed simulations in order to evaluate how such a solution could impact energy-saving on a household-level, revealing lower consumption levels across all tests.

Although the described paper connected different technologies to reach, according to the simulations, a very interesting and successful solution, it is important to note that no real-life tests were conducted and so, the sharpness of the test's parameters are highly indicative of this apparent success. The researchers assumed "that the user forgets to turn off the power once in each room", a condition that is not truthful to reality, possibly skewing the overwhelmingly positive results achieved. Additionally, although the solution utilizes the user's mobile phone, there is no way for the user to monitor and analyze the captured data, thus providing no incentives for the user to change energetically wasteful habits.

The paper by Nageye et al. [11] presents another approach very similar to our own but applied to a commercial building. The researchers developed a mobile application which granted users access to real-time data from temperature, humidity and motion sensors as well as remote control over several appliances within the building. The application also allowed the users to select specific floors as well as schedule an automatic power cut-off, allowing the building to drastically save power during non-working hours. This system was then tested and validated in a modern building in Mogadishu, Somalia having yielded substantial reductions in electricity consumption in a period of 6 months: a decrease of over 40%, resulting in almost 9,000$ saved for the building's administration.

Being a similar project to our own, the paper by Nageye et al. proves that such an application can be extremely impactful in reducing energy consumption which opens the door for our own research guideline: can a similar solution be scaled down to an individual/household level and be able to replicate substantial energy reductions alongside it?

However, one substantial difference splits the two projects. The researchers of [11] opted for an automated solution for reducing power, something logical due it being designed for large commercial buildings. However, in our solution, designed for the household-level, such automation will not be employed as we are conscious of the possibility that relying solely on automation could inadvertently perpetuate existing energetically wasteful habits rather than encouraging users to adopt more sustainable practices. This would not be a concern if the majority of European households were "smart homes", this is homes equipped with automation devices such as automatic lights, which is far from the truth, for according to [12], smart homes in Europe constitute around 27.1% of all European households, a number that despite presenting a upwards trend, is still considerably low.

Based on our expertise within this landscape, we opted to incorporate additional papers beyond the scope of our SLR in this subsection in order to provide additional technological context of the IoT Energy-Saving landscape explored in this dissertation.

One approach to dampening energy waste using IoT devices was researched by Chenyan et al. [13] and focused on the usage of sensors under the context of Internet of Building Energy Systems (iBES). This paper explains this concept as the employment of a diverse array of sensors to continuously monitor real-time energy consumption data within buildings while also being complemented by an automated and intelligent energy management system. In addition to this, the paper also delves into the different layers of IoT, and a real-world study conducted in an international college, being an important agent in their objective of creating a low-carbon campus. Finally, the paper concludes that "buildings equipped with intelligent control electric heating and ventilation systems will reduce about 50% of the energy consumption", demonstrating the importance of exploration and investigation efforts into the correlation of IoT and energy efficiency.

Concerning the real-life application in this paper, it demonstrated how well-constructed IoT solutions in this area can be profoundly impactful. Additionally, the concept of IoT layers used in our dissertation, will be based heavily on those studied in [13]: a perception layer, a network layer and finally, an application layer focused on real-time data gathering, data communication and data analysis and presentation, respectively. However, a major limitation emerges when translating the proposed system to our artifact: the solution presented in the paper is not suitable for individual/household energy monitoring and is more useful in a larger project. Additionally, those who consume electricity in the aforementioned college campus don't have access to the captured data, something we believe is a missed opportunity for incentivizing the intervening actors to save energy.

A separate paper presented by Shinde et al. [14] conjures a simple IoT solution for measuring temperature, humidity and carbon dioxide levels within an indoor environment. The sensor used for the latter measurements was the MQ135 model, suitable for detecting the presence of various gases in a given environment. Our focus, however, lays with the temperature and humidity sensor utilized in this solution: the DHT22 model, a low-cost, high precision digital sensor which will also be used in our artifact for those same reasons. The researchers opted to develop a Node-RED dashboard, a flow-based programming environment allowing the researchers to easily display the obtained data in real-time, having the transmission of data between the sensors and the dashboard entrusted to a Raspberry Pi board due to its low-cost and variable computational capability.

Despite this research’s simplicity and, at times, superficial nature, there is an extremely insightful decision. Giving the solution not only the ability to be reliant on solar energy while being in a bright room but also allow its microcontroller to oscillate between hibernation states, not only prolongs the device’s battery life but also contributes to an energetically conscious solution. Although the required materials for this exploration, such as solar panels, were unavailable for our own research, this remains a highly promising concept that we would have been eager to implement and explore. Furthermore, although Node-RED is capable of displaying data, our primary focus will be leveraging its functionality as a pivotal 'messenger' within our network layer, entrusting our data visualization predominantly to Unity, recognizing its significantly greater versatility in this regard.

Another approach at the household-level explored by Angrisani et al. [15] involved augmented reality (AR) technology alongside low-cost sensor nodes culminating in a mobile application, aimed at identifying different appliances and projecting the corresponding power consumption in real-time within the user’s environment, both of which made use of the user’s mobile phone’s camera. The aforementioned sensor nodes were built to serve as a ’broker’ between the power supply and a given appliance, monitoring the voltage as well as the current in that environment. This data was then sent through the Message Queuing Telemetry Transport (MQTT) protocol, in detention of the Hypertext Transfer Protocol Secure (HTTPS) protocol, given the latter is considered a ‘heavy’ protocol for the IoT perception layer. Communication from this layer is powered by a Lopy4 board, a device based on the Espressif ESP32 board, a flexible, low-cost board that, being an industry standard, will be used in our own research. Finally, the HTTPS protocol is only used for communication between the application layer (the mobile app) and the server where the perception layer’s data is stored, seeing as this layer is not restrained by the lightweight features of IoT devices.

The solution presented in the aforementioned paper delves once more into the realm of IoT solutions alongside personal applications with the objective of lowering household power consumption, demonstrating how diverse this landscape is. However, despite being technologically impressive, we believe the presented solution has some flaws that deter from the intended household-level usage. Firstly, given the delicate positioning and complex electrical connections of the ‘broker’ system detailed previously, this solution presents a high level of complexity to set up, making it unsuitable for the majority of the public to take advantage of it. In addition to this, while displaying the voltage and current values of household appliances is interesting, these values don’t translate to actionable metrics for the large percentage of the population that aren’t familiar with these electric parameters. While the first problem is much harder to improve on, the second problem could be dampened by creating guidelines for certain intervals of current/voltage for certain appliances, tagging them from “Highly wasteful” to “Highly efficient” for example.

Another paper in this landscape was researched by Sunarko et al. [16] and leveraged electrical current sensors, motion sensors alongside light sensors to achieve a smart home solution capable of remotely controlling the state of lights as well as an array of fans for temperature control, dependent on the data collected by the aforenamed sensors. The selected motion sensors were Passive Infrared (PIR) sensors which allow the detection of movement within a given environment for a considerably low monetary cost, making them suitable for our own solution. The chosen light sensors also follow this monetary guideline being a Light Dependent Resistor (LDR) sensor, this is, a device whose potentiometer’s resistance varies depending on the degree of incident light thus, once again, becoming a consideration target for our own solution. The solution also incorporated a mobile phone app, developed to lend the users an accessible way to examine and visualize the collected data, something our solution will also guarantee, having concluded that a smart home complemented by this solution could achieve monthly energy savings of 21.29%.

The biggest difference between our study and the one developed by Sunarko et al. is, once again, the automatization or lack-there-off in regard to the automatic light system, a decision we explored upon our analysis of [11]. Additionally, the researchers opted to turn on this system whenever motion was detected in a given room or simply if no sunlight was detected on the outside of the house. This second condition is, in our opinion, a considerable oversight since there is no valid reason for a light to be turned on when no one is in the room even if there is no sunlight outside. Additionally, this solution features another massive oversight.

The incorporation of automatic fans into the system directly contrasts with the purpose of the solution: reduce energy spending. The researchers opted to have the electric fans turn on every time movement is detected in a given room which can lead to massive energy waste, especially in the colder months of the year where such refrigeration is not needed, much less desired. This problem could be solved inexpensively by employing temperature sensors in a way where the fans would only be activated in case of high-temperature readings.

The penultimate solution we will evaluate in this subsection was researched by Rokonuzzaman et al. [17] and revolved around a smart control system intertwined with a 'Smart Socket' and a mobile application powered by MATLAB, allowing for user-defined inputs in the application's simulations. The smart control system itself is composed of various IoT sensors namely, a temperature and humidity sensor and a LDR sensor (similar to those used in [14] and [16], respectively) and, contrary to what has been used in every other paper showcased here, a Human Presence Detector (HPD) as opposed to an infra-red motion sensor.

The use of an HPD reveals an interesting conflict within the choice of presence-detecting sensors. While an HPD would be preferred as it is not our intention for non-human presence to trigger notifications within our application, these sensors typically require more power, something that may not be suitable for an IoT solution. Furthermore, PIR sensors are traditionally cheaper than HPD thus revealing why they are significantly more common in IoT solutions than the latter. The researchers also note that while machine learning algorithms can very easily detect human presence by analyzing video footage, such computational power is not suitable for an IoT solution nor is using cameras in a household environment adequate. The smart socket itself stems from the problem of conversion between Alternating current (AC) and Direct current (DC) which leads to distribution losses which in turn, lead to energy waste. The amassed data is then stored in a cloud server, powered by ThingsSpeak,[18] an extremely common IoT platform. Lastly, the mobile application allows the users to visualize and analyze the obtained data as well as control the smart sockets remotely.

This study presents an approach to energy-wasting and IoT very different to our own: instead of attempting to change human behavioral patterns, it instead opts to reduce energy waste at its core. In addition to this posing the same problems as those we outlined in the analysis of [11], this approach is quite complicated and not suitable for the general public, something our mobile application will attempt to achieve.

Before we conclude this subsection, we believe it is important to highlight the research by Verma et al. [19] on the current issues and challenges within the Intelligent Energy Management System. Amongst these the researchers highlight several trends such as IoT and Big Data Integration. With IoT solutions and integrations displaying an upwards trend in usage, the result is a significant amount of data being generated and while cloud computing is often relied upon within the IoT panorama, it does not handle 'big data' effectively and so, alternatives and industry-wide norms must be adapted to this wave of newfound data. Another worrying issue is that of security, both in terms of user's privacy and the risk of data loss. The researchers concluded that consumers are largely dissatisfied with the lack of privacy protections offered by IoT devices as this is one of the compromises that allow IoT solutions to be economically inexpensive. Additionally, risk of data loss, either due to a network error or due to a malicious attack (such as hacking), restrains IoT from being applied to nationally significant projects (for example, the paper in [7]). The final challenge documented by the researchers refers to the inherent complexity between connecting various devices (e.g. sensors, wearables and systems), something that is intrinsic to the IoT landscape in general but must be improved upon as the world inches ever closer to a fully intertwined network.

In summary, this subsection highlighted several advancements in the sensor-based energy-efficiency landscape. These solutions have demonstrated significant potential in both large-scale projects and household applications, achieving promising results by delivering actionable real-time data directly to users and offering opportunities for data-driven decision-making.

For this dissertation, several key discoveries and takeaways stood out.

Firstly, the commonly adopted three-layered architecture for IoT solutions was found to be reliable, compact, and adaptable, making it a suitable framework for this project.

Secondly, several projects demonstrated successful results despite low monetary costs – an approach we aim to replicate in our own solution, further supported by the confidence gained through these findings.

Lastly a critical observation across several reviewed studies was the over-reliance on automation, which in our opinion, risks fostering user dependency on technology while neglecting the promotion of energy-conscious behaviors, something we believe is of the upmost importance.

In conclusion, it is our goal to leverage these findings to develop an IoT solution that strikes a balance between automation and user input, ensuring that it remains both effective and accessible to the general public.

2.2. Existing Sensor-Reliant Solutions using Unity

Our dissertation, in addition to aiming to construct a helpful, general-public-level application which strives to tackle energy waste in the user's household, also aims to showcase the potential of the platform Unity and the innovative possibilities it can unlock when combined with IoT.

In our previous work within the IoT landscape, we observed signs of stagnation, with investigators often adhering to established industry-wide practices. This is where our enthusiasm for Unity drove us to pursue change and an evolution of the IoT landscape. While Unity is predominantly associated with game development, we believe its broader adoption could open numerous avenues of exploration currently absent in the IoT field, such as virtual and augmented reality experiences and advanced data analysis tools. Motivated by this conviction, we selected Unity as the cornerstone of our end-user application. With this objective in mind, we curated the papers discussed in this subsection by conducting a second systematic literature review, which resulted in the following query:

TITLE-ABS ((unity) AND ("Internet of Things" OR iot) AND sensor AND NOT ("machine learning"))

Consequently, we retrieved a total of 36 papers who then underwent a subsequent filtering process, resulting in the results shown in Table 2.2.

Table 2.2. SLR's filtering conditions and subsequent number of Unity-related papers

Filter	Retrieved Papers
Initial Query	36
Release Date: Post-2016	33
Subject Areas: Engineering, Energy or Environmental Science	16

Given the manageable number of retrieved papers, we concluded our SLR and proceeded to conduct an individual review of the results.

The solution proposed by Shah et al. [20] presents an innovative way to monitor potted plants, reduce waterlogging, mud cracks and enhance plant growth. This solution merges a DHT11 sensor, similar to the sensor discussed in [14] with Augmented Reality (AR), powered by the Unity platform. The researchers developed a mobile application that showcases a given plant's temperature and humidity in real-time, within the plant's surroundings. The researchers also highlight the cost-effectiveness of the solution as well as its wireless nature, which allows for facilitated handling and installation.

Given the cost-effective facet of the solution, we consider it acceptable for the solution to offer the modest list of features described above. However, the solution contains two vulnerabilities the researchers may not have accounted for. Firstly, the DHT11 sensor is significantly inferior to its DHT22 counterpart despite both sensors carrying a similar price point [21]. Secondly, in the proposed solution, the sensor must be placed within the soil of the potted plant in question, making it liable to water-damage, leading to an affordable although unreliable solution. However, the data transmission technique displayed here, between the sensor and the Unity platform, is worthy of note and will be taken into consideration in the solution presented in this dissertation.

A similar solution was proposed by Tisza et al. [22], also employing IoT sensors and communication to a mobile application to ensure and improve plant growth. In addition to temperature and humidity receptors, this solution improves on the previous solution by adding carbon dioxide measurements, furthering the system's depth and utility. Communication between the application layer and the perception layer is, similar to [15], entrusted to MQTT, ensuring a stable and lightweight way to communicate sensor data in real time.

The researchers opted to have a Quick Response (QR) code placed within the user's environment upon where the 3D model, accompanied by the corresponding sensor readings, is instantiated in Augmented Reality, something we consider was executed better on the previous solution due to it avoiding added costs and the necessity for physical objects to function.

Another solution employing Unity's AR capabilities alongside sensors was developed by Dash et al. [23] and compiled the use of different sensors, such as temperature, humidity and pressure sensors, with 3D visualization in real-time displaying the gathered data alongside the appropriate 3D model within a mobile application e.g. if pressure sensors were installed on the wheels of a motorized vehicle, the application would display a 3D model of an automobile with the corresponding sensor data over the appropriate wheel.

As detailed above, the solution is focused on the dynamic display of data, lending the user an intuitive and simple way to interpret and monitor said data but does not provide ways to analyze it, something we consider to be a considerable flaw in the design. Nonetheless, similarly to the paper explored in [20], the data transmission structure between the IoT layer and the Unity platform is deployed effectively and will be taken into account under our solution.

The article developed by Neves et al. [24] presents a novel solution to physical rehabilitation, combining a gamified environment, powered by Unity's Virtual Reality (VR) capabilities, with the capture and analysis of captured data from a Smart Glove device. The application, aimed at patients who sustained injuries to their upper extremities, utilizes a VR game to obtain data regarding variables such as applied force per finger, finger flexion and acceleration and rotation of the upper limbs. The obtained data is then aggregated and stored in an online database, allowing the researchers to analyze and visualize it. Finally, the researchers compared data from a patient who sustained injuries to their upper extremities to that of a healthy patient and determined that the proposed solution could effectively determine the state of a patient's recovery as well as help the patient's physiotherapist's decision-making process.

The solution developed by my colleagues presents an insightful and beneficial approach to the physical therapy-IoT landscape and showcases how IoT can deviate from traditional sensors to achieve truly advantageous solutions. However, during our analysis of the solution we encountered a possible detriment in the solution's architecture: the glove itself. While the glove is suitable for most injuries in the upper extremities, for the cases of injuries that cause increased sensitivity in the patient's hands (such as serious burns), less intrusive devices should have been explored further as these injuries could prevent innumerable patients from taking advantage of the solution.

Concluding this subsection, the paper researched by Vera-Coca et al. [25] represents a steppingstone for our own research: a Unity-powered mobile application aimed at reducing energy through human-led decision-making. The researchers opted to focus on voltage anomalies namely 'voltage sags', a temporary drop in voltage levels in an electrical power system which can severely impact electrical equipment and machinery, potentially precipitating industrial malfunctions or even consequential damage to the equipment. The application allows the users not only consult voltage anomalies by the date of the occurrence but also, real-time data collected by the sensor in question: a Power Quality (PQ) sensor, allowing the solution to correctly identify the voltage anomalies in question.

Despite providing a solution with a similar end goal to our own, the aforementioned approach is more suitable to an industrial setting, due to the fact that voltage anomalies are not a relevant metric for the general public since they do not present the user with an accessible and/or straightforward way of improving and/or fixing the problem. In addition, we believe the interface of the developed application is quite unpleasant and something that could have been explored further, given the capabilities of the Unity software.

In summary, despite the relatively small number of papers employing Unity in the IoT panorama, several translatable takeaways can be applied to our solution.

For instance, the work presented in [20] highlights once more the adoption of the MQTT protocol, further reinforcing our position to utilize it in the communication processes of our own architecture. Moreover, the paper in [25] underscores the importance of designing user-centric applications that encourage behavior-driven solutions, accentuating the necessity for intuitive interfaces and data-analysis tools, all while utilizing Unity to achieve these objectives.

Ultimately, this subsection has demonstrated that Unity is beginning to expand beyond its origins in game development, though its adoption within the scientific community remains in its early stages. However, albeit the solutions discussed here emphasize its potential for creating innovative data visualization methods and highlight positive advancements within the field, Unity in this context remains, in our opinion, severely underutilized, a gap we aim to address through the investigations detailed in the following chapters as well as in future research endeavors.

CHAPTER 3

Artifact Design & Development

As stated previously, the main objective of this research project is to design and develop an intuitive smartphone application aimed at reducing household energy waste, all while maintaining a low cost.

In order to support our end-user application, which serves as our primary artifact, a secondary artifact must be developed: a comprehensive architecture that integrates IoT and Unity. This architecture aims to address the previously outlined conviction of creating a bridge between Unity and IoT, thereby facilitating future research into this relationship.

3.1. Artifact 1 – Solution Architecture

3.1.1. Design

The main purpose of this architecture is to capture, communicate, store and display data to an end-user while maintaining a low-cost and reliability. Furthermore, as it is intended to offer the scientific community a ready-to-use framework that integrates Unity and IoT, it must also be adaptable to other solutions focused on similar data processes.

Technology Stack

Taking into consideration the aforementioned objective, the requirements for our solution are:

Data collection:

- Sensor array: A collection of sensors that, altogether, can capture different types of data. The architecture is sensor-agnostic, enhancing its adaptability for integration into diverse projects.
- Integrated Development Environment (IDE): For programming and uploading code to the microcontroller.

Data communication:

- Microcontroller: Able to handle data collection from the aforementioned array as well as communicating that data wirelessly.
- Message Broker: An intermediary messaging agent for reliably ensuring that the data is successfully sent from the perception layer. This component is essential for bridging the protocol differences between these layers, which will be detailed further.

Data storage:

- Database: Able to receive sensor data, store it as well as enable access to it upon request from an authorized source.

Data display:

- Mobile Application: The end-user interface from which the user interacts with the proposed ecosystem.

These requisites collectively establish a cohesive and adaptable data-centric architecture that aligns perfectly with our objectives, guiding the selection of the following technologies to meet each outlined requirement.

- Sensor array: DHT22 sensor, PIR motion sensor & Grove light sensor.

As mentioned previously, affordability is a key feature of this solution, Therefore, the widely adopted sensors DHT22, PIR motion sensor and the Grove light sensor were selected for their cost-effectiveness, reliability, ease of integration and alignment with our application's goal of diminishing household energy waste. By providing real-time temperature and humidity data, these sensors empower users to make informed decisions regarding the operation of climate control devices, ensuring they are only used when absolutely necessary. On the other hand, the motion and light sensors offer insights into the necessity of illumination, allowing users to identify instances where lights remain on unnecessarily, particularly in unoccupied rooms.

Although alternative sensors are available, the DHT22, the PIR motion sensor, and the Grove light sensor were employed in this project due to their immediate accessibility during our research period. Notably, an intriguing avenue for exploration could have involved utilizing a human-presence detector, such as the RCWL-0516 model, as a substitute for the motion sensor employed in this study - a consideration that was unfortunately unfeasible within the time constraints of this dissertation. However, other sensors, such as the Adafruit AHT20 temperature and humidity sensor, or the Adafruit TSL2561 light sensor, could readily substitute any of the corresponding sensors utilized in this project.

- Integrated Development Environment (IDE): Arduino IDE.

The Arduino IDE was selected for its user-friendly interface, extensive community support, and compatibility with a wide range of microcontrollers, including the one chosen for our solution. Its widespread adoption and robust features provide an effective platform for both efficient coding and debugging. One alternative we considered was the PlatformIO IDE, a more powerful and feature-rich development environment that supports a wider range of microcontroller platforms and more advanced features, allowing for more complex projects at the cost of a steeper learning curve [26]. Ultimately, we chose Arduino IDE due to our solution's perception layer being relatively simple, making Arduino IDE well-suited and capable of handling our requirements.

- Microcontroller: ESP-wroom-32.

The ESP-wroom-32 was chosen for its robust processing power, integrated Wi-Fi and Bluetooth connectivity, and low power consumption. This versatile module is well-suited for handling the multiple sensors in our IoT system. Moreover, its popularity and extensive community support provide valuable resources for development and troubleshooting. During the selection process, we evaluated another microcontroller: the Raspberry Pi. The Raspberry Pi microcontroller offers significantly higher processing power (of up to 1.6 GHz) but comes with increased size, higher financial cost and energy requirements [27]. As our solution aims to be a low-cost, energy conscious solution, we have dictated the ESP-wroom32 to be the ideal microcontroller for our solution.

- Message broker: mosquitto & Node-RED.

For our message brokers, we opted for a combination of mosquitto and Node-RED. mosquitto was chosen for its efficient implementation of the MQTT protocol, providing reliable and lightweight communication between IoT devices. Node-RED serves as a versatile platform for testing communication between different layers and enables future expansion of our solution by facilitating access to various Application Programming Interfaces (APIs) and external services. Additionally, since the chosen database only accepts data uploaded via the HTTPS protocol—which we consider too resource-intensive for constant use in the perception layer—Node-RED is responsible for capturing MQTT messages from the perception layer and relaying them to the database using the HTTPS protocol. An alternative to mosquitto that we examined was RabbitMQ.

RabbitMQ, similarly to mosquitto, supports MQTT and message brokering but also provides additional protocol support, enhanced scalability, and more robust messaging features at the cost of being a more resource-intensive message broker. Given that our solution's data flow is relatively lightweight and does not transmit sensitive information through the message broker, mosquitto was deemed sufficient for our requirements.

- Database: Firebase Realtime Database

We chose Firebase Realtime Database due to its ability to provide real-time data synchronization, ensuring that all connected devices receive updates instantly. It offers a straightforward and scalable "not only Structured Query Language" (noSQL) cloud database, simplifying data storage and retrieval. Additionally, its seamless integration with other Firebase services and extensive documentation solidifies this as the ideal choice. One notable alternative identified in our research was the widely adopted MongoDB, which excels in overall performance, offering faster and seamless handling of vast amounts of data, making it suitable for large-scale data management and fast querying responses [28]. However, our application does not require large-scale data management or complex database queries. Therefore, our choice was heavily influenced by the ease of integration between the selected database and our application. Ultimately, Firebase Realtime Database was chosen due to its ready-made Unity packages, significantly reducing development time and meeting our specific requirements.

- Mobile application: Unity

As previously mentioned, Unity was selected as our application development platform due to its potential in IoT solutions and data visualization. Unity offers cross-platform support, powerful 3D visualization, and robust real-time interaction features, making it an ideal choice for creating visually rich and responsive IoT applications. Additionally, its flexibility allows for future expansions, such as integrating augmented reality dioramas or virtual reality features. As it was always our intention to explore innovative IoT applications using Unity, alternatives were not considered.

3.1.2. Development

Following the assembling of our technology stack, we now present the architecture of our IoT solution, which integrates the chosen components detailed above into a cohesive system as seen in Figure 0.1.

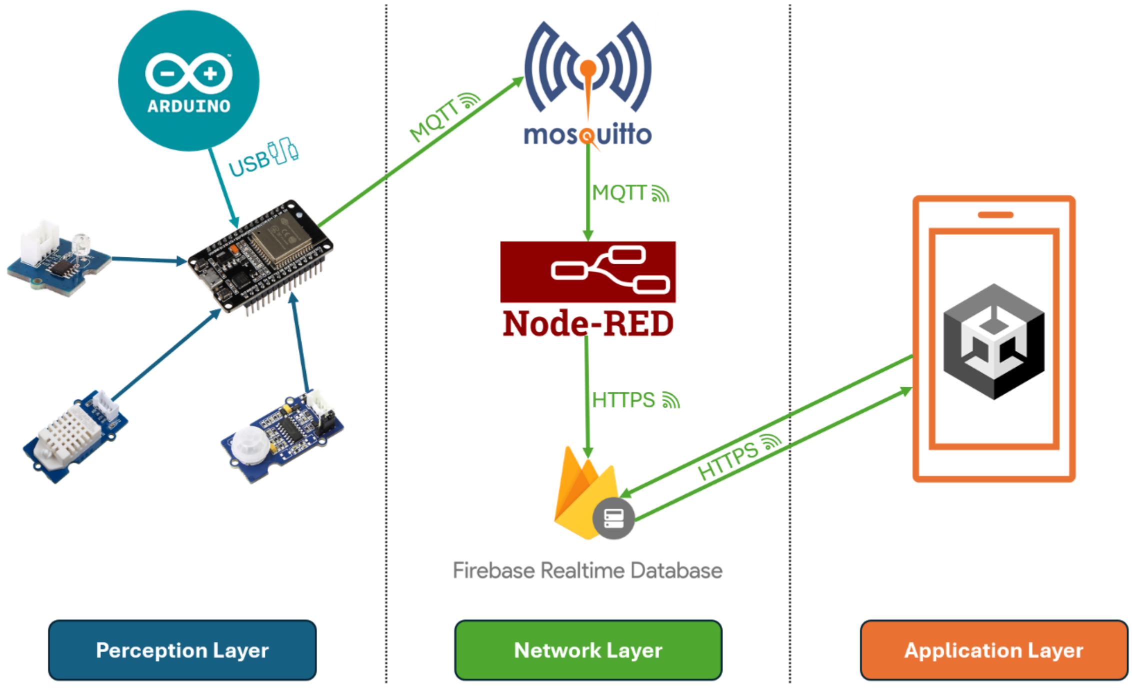

Figure 0.1. Proposed solution architecture

Perception Layer

At the perception layer, our Arduino IDE code is uploaded to the ESP-wroom-32 microcontroller, instructing it on how to handle data received from the DHT22 sensor, the PIR motion sensor, and the Grove light sensor. The microcontroller then prompts the sensors to gather data periodically, which is subsequently transmitted through mosquitto (using the MQTT protocol) to the network layer, the intermediate layer of the proposed architecture. To preserve bandwidth and maintain energy efficiency, the collected data are sent as a single message. Additionally, after the code has been uploaded, the solution has the capability to operate wirelessly, as a physical connection to the Arduino IDE platform is only required during the upload step. A diagram of our perception layer is presented in Figure 0.2.

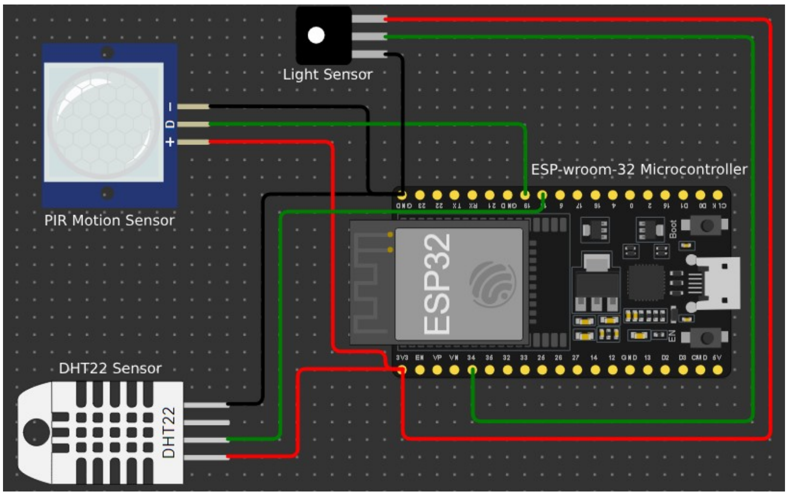

Figure 0.2. Perception layer diagram

Network Layer

Within this layer, mosquitto redirects the data to a locally run Node-RED instance, which enriches the data with the current time and date and formats it into JSON, the required format for our database, before forwarding it to Firebase's Realtime Database as can be seen in Figure 0.3. Additionally, two distinct testing flows were developed to test communication between the network and application layers without requiring a connected sensor array. These flows generated two types of synthetic data: one produced entirely random data, while the other exclusively generated data designed to trigger notifications sent to the user's device, as detailed later in section 0. These testing flows were used exclusively during the development phase to facilitate feature testing by eliminating the variability associated with real-time data.

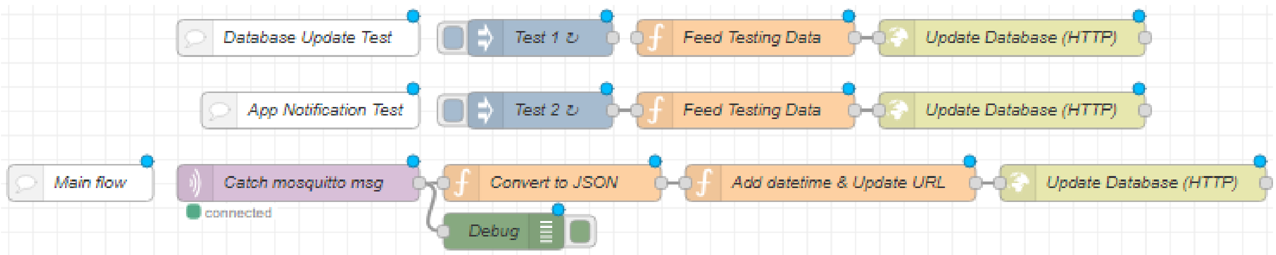

Figure 0.3. Node-RED flows

The database, which features a NoSQL schema i.e. does not conform to a traditional relational database model, can be accessed through HTPPS requests, allowing for efficient retrieval and management of the data. The decision to utilize a NoSQL database schema was motivated by its versatility and potential for reuse in other IoT projects. Unlike traditional SQL-based databases, which would require investigators to design and implement specific relational models, the NoSQL schema offers a more adaptable, ready-to-use architecture. This choice not only simplifies integration but also strengthens the database's role as a bridge between Unity and the IoT ecosystem, highlighting its capacity to support diverse applications with minimal customization. The injected timestamp described previously serves as the identifier for the database nodes, ensuring each data entry node is unique and stored in real-time. An example of a data node is shown in Figure 0.4. Another noteworthy aspect of our database that can be seen in Figure 0.4 is that, despite being based on a JSON format, it is not a human-readable, a characteristic for which JSON databases are typically valued [29]. This, however, was done intentionally considering the potential sensitivity of the captured data. By implementing these measures, we ensure that even if bad actors intercept our communication, they are unable to extract any sensitive information about the user’s household.

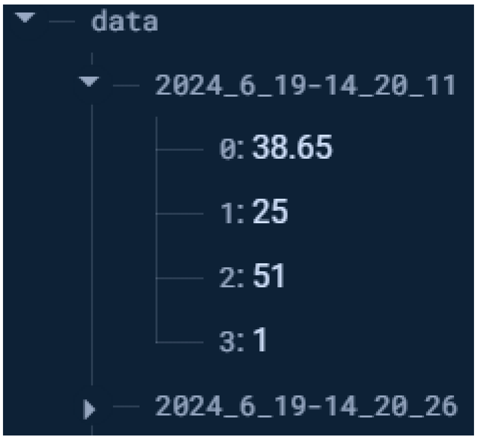

Figure 0.4. Database node example

Application Layer

Finally, our Unity application periodically exchanges HTTPS requests with our database, retrieving the latest data and updating the application interface with the most recent values. The iterations the application underwent are detailed in section 0.

3.2. Artifact 2 – Unity End-User Application

With the backend planning phase of our project complete, we will now delve into the iterations our end-user application, Bernergy+, underwent, carefully detailing the steps of the DSR methodology followed to achieve each version.

3.2.1. First Iteration

Design & Development

In the first iteration, the Design & Development phase prioritized ensuring the end-user application could effectively display updated data. To achieve this, we began by creating a low-fidelity prototype that met this core requirement, as illustrated in Figure 0.5. Following the prototyping stage, the chosen design was implemented as a functional application using Unity, as depicted in Figure 0.6. The first iteration refrained from implementing additional features, prioritizing the validation of the developed architecture's ability to manage the data load within the ecosystem before further advancements.

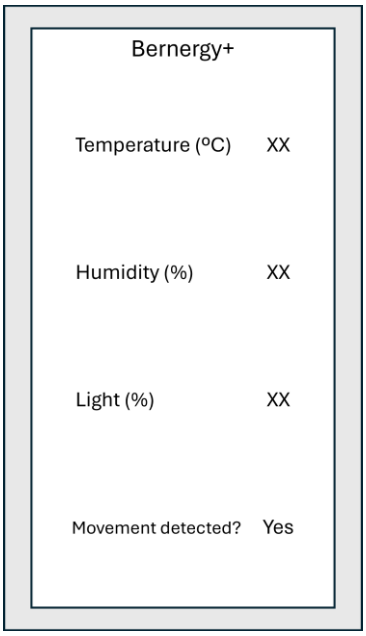

Figure 0.5. Low fidelity prototype (first iteration)

Demonstration

In order to evaluate the stability and performance of the proposed architecture - the main objective of this iteration - we deployed the app to a personal-use smartphone and began transmitting data from our sensor array, comparing the data displayed on the application's interface with that present on our database as well as the raw data transmitted by our sensor array, the latter being accessed through a debug node within our Node-RED flow.

Evaluation

Following our first demonstration phase, we observed the data was consistently transmitted through the layers, with no recorded instances of incorrect or lost data, and the application successfully showed up-to-date data in its interface.

While the overwhelming success of the chosen architecture showed the importance and benefits of a well-researched technology stack, several problems became apparent in relation to this dissertation's research question.

Firstly, although the application correctly displayed data on the percentage level of light presence within a room, this metric did not provide actionable information to the end-user, as it is not a commonly used metric compared to, for example, temperature values.

Secondly, with no way to view the evolution of data (i.e. whether each metric increased or decreased since the last update) additional strain was put on the user's decision-making ability, forcing them to memorize previous values to determine how to proceed and whether any action was needed.

Finally, the application's reliance on users having the app open to access actionable metrics significantly diminished its usefulness and, most critically, failed to warn users to energy waste if the application was not actively running.

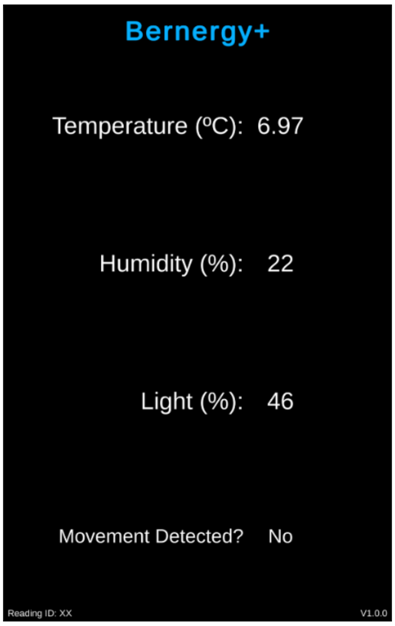

Figure 0.6. First iteration interface

3.2.2. Second Iteration

Design & Development

Taking into consideration the findings of the previous iteration, we returned to the Design & Development stage of the DSR methodology, with the intent of improving upon the problems of the previous iteration. The main focus of this iteration was to alleviate strain on the end-user and enhance decision-making by providing improved data formats and data disambiguation, for which a second low-fidelity prototype was developed, as shown in Figure 0.7.

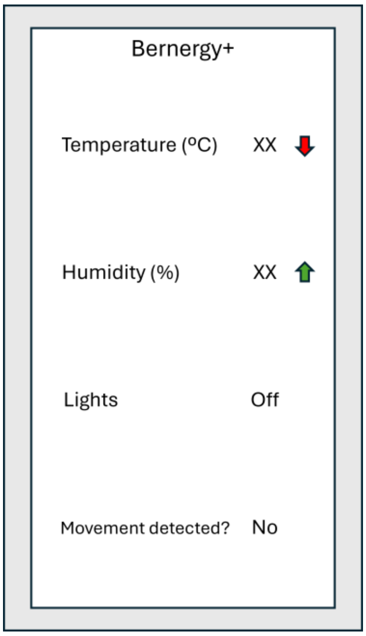

Figure 0.7. Low fidelity prototype (second iteration)

To resolve the first issue referred to previously, the light presence percentage data was simplified to an “On/Off” system. For the second issue, colored arrows were introduced to indicate changes in each data point relative to its prior value.

The third issue was tackled by implementing the notification system referred to in both hypothesis one (H1) and hypothesis two (H2).

These changes are depicted in Figure 0.8 and Figure 0.9, respectively.

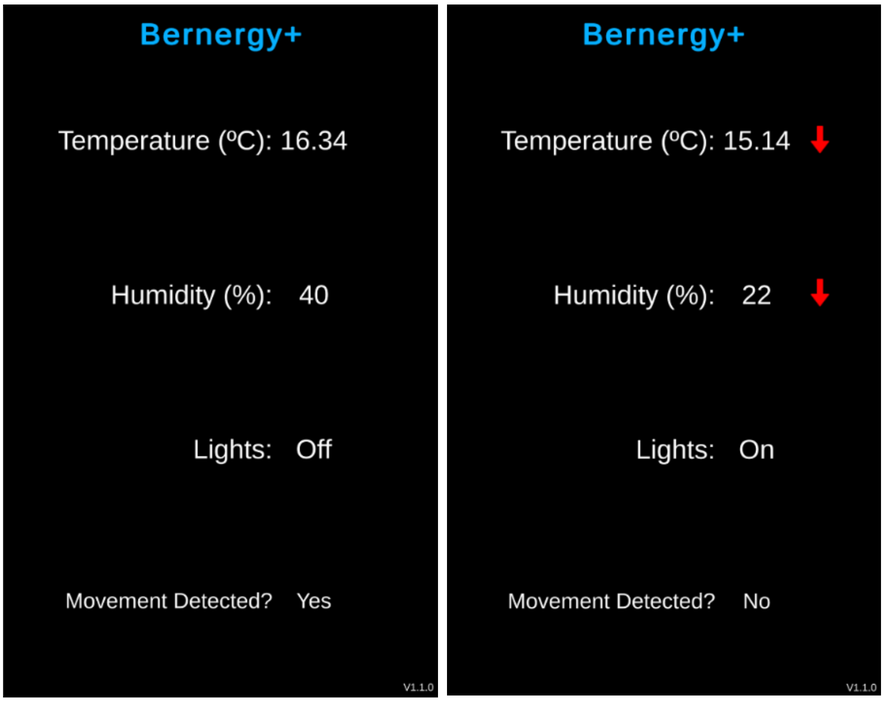

Figure 0.8. Second iteration interface - before and after the data update

Demonstration

After deploying the application to a personal-use smartphone once more, we conducted similar tests as those used in the previous iteration. Additionally, we also used the previously detailed testing-flows within Node-RED to produce synthetic data instead of real-time data with the objective of testing if our notification system was successfully implemented. This approach allowed us to manually trigger notifications and simulate seasonal-dependent scenarios, such as temperature alerts for colder months.

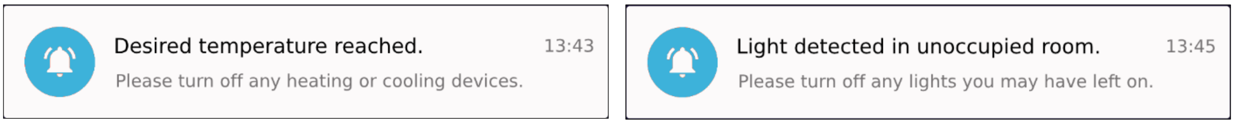

Figure 0.9. Types of developed notifications

Evaluation

This iteration yielded promising results, once again.

Regarding the light presence percentage data, the shift to the revamped system delivered clearer information by eliminating the ambiguity over whether a certain percentage indicated that a light was "On" or "Off" thus providing a better environment for informed decision-making capabilities.

The implementation of directional arrows, though simple, significantly streamlined the user experience by providing clear metrics on data trends and removing the cognitive load of remembering previous values.

Additionally, the implementation of a notification system effectively addressed a significant limitation identified in the first iteration. In the updated version, the application no longer requires the user to have the app or smartphone actively open to receive timely alerts regarding energy waste in their household. Instead, notifications are pushed directly to the user's device, providing an opportunity to promptly intervene and mitigate energy waste as soon as it is detected. Two types of notifications were introduced: (1) a notification pertaining to the presence of light in an unoccupied room, prompting the user to turn off any lights that may have been left on, and (2) a notification that alerts the user when a room has hit a comfortable temperature, suggesting the deactivation of climate control devices. Notifications regarding the presence of light in an unoccupied room were restricted to nighttime, as the light sensor used in our artifact cannot distinguish between natural and artificial light.

However, despite the success of this iteration, additional problems were detected during this Evaluation step. For one, while the change to a binary "On/Off" light presence system was largely successful, it became clear that a predefined percentage cannot be universally applied to all household environments and rooms. This is particularly unsatisfactory when it leads to incorrect readings where the system persistently showed lights as "On", even when they were off, resulting in a flood of inaccurate notifications.

On the subject of data evolution, the arrow system is effective, but we believe it has potential for further development by lending the end-user additional data points thus helping them make more informed decisions.

Lastly, a new problem arose due to the influx of new features. While no performance issues were reported on the mid-range smartphone used for testing, frequent server communication, data updates and notification sending while the app is running in the operating system's background could cause performance issues on lower-end devices, something we need to address in the next iteration as our previously defined goal is to include as many individuals in the general public as possible in the global effort towards energy conservation.

3.2.3. Third Iteration

Design & Development

Based on the insights gained from the previous iteration, we revisited the Design & Development stage of the DSR methodology once again, with the aim of addressing the identified issues. This iteration focuses on enhancing the previously mentioned features based on our evaluations, with the goal of finalizing the application and improving the end-user experience. A third low fidelity prototype was developed for this iteration as can be seen in Figure 0.10.

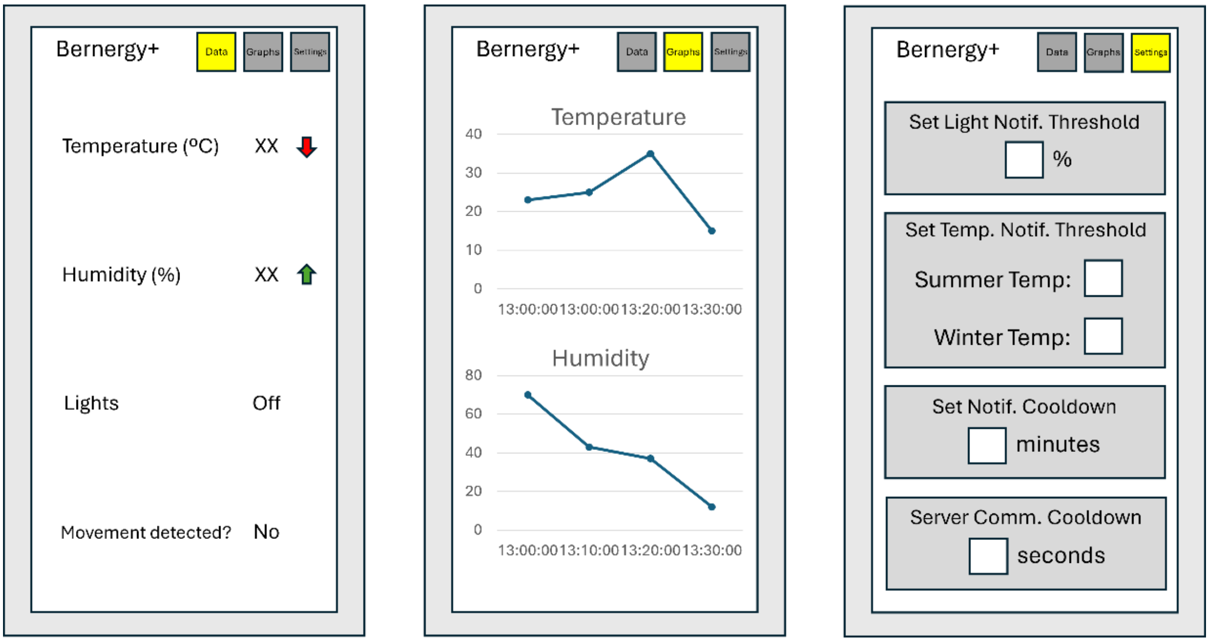

Figure 0.10. Low fidelity prototype (third iteration)

One of the main breakthroughs of this iteration was the creation of a settings panel, aimed at solving some of the problems raised previously, as seen in Figure 0.11. Namely, the light presence percentage threshold can now be adjusted by the end-user, making the application more adaptable. Additionally, the settings panel also allows users to modify the notification cooldown and the server communication interval to better suit the user's personal device and needs. Furthermore, the introduction of a temperature threshold panel provides additional customization, enabling users to customize their preferred temperature for both cold and warm months.

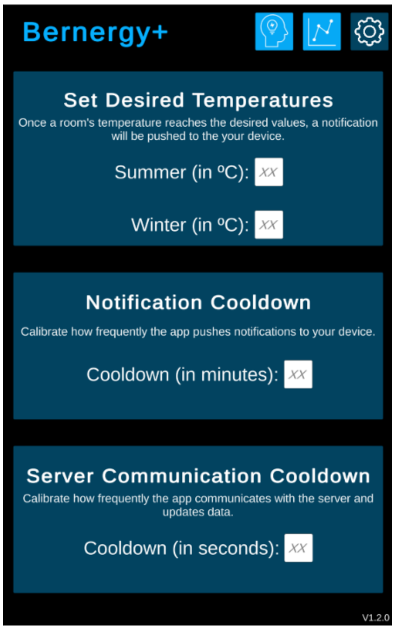

Figure 0.11. Third iteration interface – settings panel

Lastly, as mentioned in the previous evaluation subsection, an additional panel was also developed to display time-series data for both temperature and humidity, as shown in Figure 0.12, using plots through the XCharts Unity package [30]. For these graphs, it was concluded that four plot points per graph represented the optimal balance to ensure clarity and maintain the readability of both axes as including additional plot points resulted in truncated values, particularly on the horizontal axis.

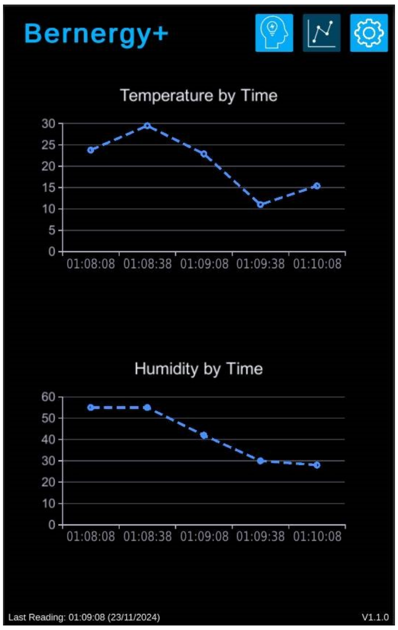

Figure 0.12. Third iteration interface – temporal data evolution panel

Demonstration

Similarly to the previous iterations, we redeployed the newest version of the application and conducted similar testing to that on previous iterations: comparing the data displayed by the application to that captured and transmitted by our sensor array. Furthermore, we also utilized the aforementioned testing flows to verify the functionality of both temperature thresholds, noting the challenges associated with testing the winter temperature threshold at the time of writing this dissertation.

Evaluation

Upon testing this version of the application, it became evident that this iteration improved on every feature of the end-user experience. It provided better context for data evolution and increased user customization, all while maintaining a streamlined interface composed of only three buttons located in the top left corner: one for displaying the most recent values transmitted through the ecosystem (leftmost button), one for accessing temporal data evolution (middle button) and one for accessing the settings where the user can adjust the app's metrics according to their needs.

While additional features could be developed alongside redesigns of current systems, this iteration already boasts several key functionalities and is prepared for proof-of-concept testing, which is detailed in Chapter 4. Further development paths are discussed in Chapter 5.

CHAPTER 4

Results

With the development stage complete, we will now delve into how the developed application, even at this early stage, can deeply impact the energetical footprint of its users.

While ideally, we would be able to quantify the effectiveness of our application, achieving this is quite challenging due to two key behavioral variables that are inseparable from the end-user's personal experience: (1) how frequently the user leaves a device turned on in an empty room, and (2) how frequently the user would return to said room to turn off the device upon receiving a notification from the app. Addressing these variables would require a large-scale survey and extensive data analysis, which is beyond the scope of this project. Instead, seeing as the application functions smoothly, we will instead focus on estimating the financial impact of ignoring the application's notifications alongside a smaller-scale proof-of-concept test designed to demonstrate its functionality and underlying logic.

4.1. Financial Impact Analysis

In this subsection of our research, we will consider four of the most commonly used devices in scenarios where the developed application's notifications would be triggered: Light emitting diodes (LED'S) and incandescent bulbs in relation to the light notification and an air conditioner unit and an electrical heater for the temperature-related notification. This section will consider the annual average for electricity prices in Portugal at the time of writing [31].

4.1.1. Illumination Devices

In this subsection, we will focus on the financial impact of the aforementioned illumination devices: light-emitting diodes (LEDs) and incandescent light bulbs aiming at calculating the cost incurred from neglecting notifications triggered by a light on in a vacant room.

According to [32], a standard 60W incandescent light bulb consumes 0.06kWh (kilowatt-hour) of electricity while an equivalent LED light bulb uses approximately 0.01kWh.

Taking an electricity price yearly average of 51.95€/MWh [31], the cost per hour of operation for an incandescent light bulb is 0.31 cents (0.0031€) whereas for an LED light bulb, it is 0.026 cents (0.00026€).

4.1.2. Climate Control Devices

Following our analysis of the financial impact of ignoring the aforementioned notification, we will now turn our attention to climate control systems. This subsection will examine the financial impact of ignoring notifications triggered when a room reaches a desired temperature.

As reported by [33], an average electrical heater requires 1.2kWh to function, leading to a financial impact of 6.24 cents (0.0624€) per hour.

In the case of the air conditioner unit, an average household device, according to [34], has a consumption of 3kWh. Assuming the electricity price disclosed previously, this leads to a financial impact of approximately 16 cents (0.1558€) per hour.

4.1.3. Financial Impact Overview

To facilitate comparison and analysis, the values obtained in the previous subsection are summarized in Table 3.1.

Table 3.1. Average hourly energy consumption and corresponding cost by device

	Device	Average Hourly Energy Consumption (kWh)	Hourly running cost (€)
Light Notification Triggering Devices	Incandescent Light Bulb	0.06	0.0031
	LED Light Bulb	0.01	0.00026
Temperature Notification Triggering Devices	Electrical Heater	1.20	0.0624
	Air Conditioning Unit	3.00	0.1558

As we can see in Table 3.1, the financial impact of the light notification is minimal, particularly for LED light bulbs, with an hourly cost of less than a tenth of a cent. In contrast, the financial impact of climatization devices is significantly higher, reaching up to 15 cents per hour for an average air conditioning unit.

Further insights from this subsection are discussed in Section 4.3, as the results presented here form the basis for the financial analysis conducted in our proof-of-concept testing.

4.2. Proof-of-Concept Testing

As mentioned at the beginning of this chapter, quantifying the effectiveness of our application depends on two key behavioral variables that are deeply intertwined with the end-user's personal experience and so, achieving accurate quantification would require a large-scale survey, extensive data analysis, and comprehensive usability testing. However, due to time constraints, such an approach is beyond the scope of this dissertation, leading us to conduct a smaller-scale proof-of-concept test. This test is intended to demonstrate the fundamental viability and utility of the application, albeit in a limited context.

For this test, we conducted an 18-hour observation of a single user's interaction with the application, starting at 6:00 AM and concluding at midnight. During this period, data on one room of the household were collected with this subsection looking to analyze it in relation to the application's functionalities and the user's behavior. A plot comprising the collected temperature data is shown in Figure 3.1 while a plot comprising collected light presence/movement data is shown in Figure 3.2. All data was collected concurrently.

4.2.1. Temperature Data Analysis

As stated previously, the graph presented in Figure 3.1. illustrates the temperature variation over a single day within a room in the user's household. The blue line represents the ambient temperature within the room, while the orange dashed line denotes the desired temperature set by the user, which in this case is 25°C. Three critical data points were identified during the analysis and are highlighted in Figure 3.1.

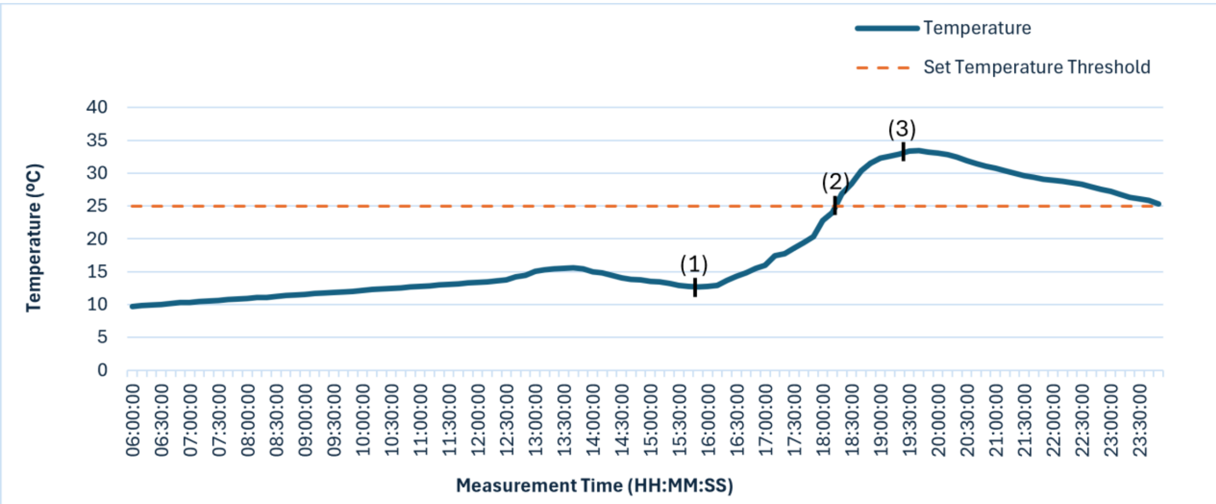

Figure 3.1. Proof-of-concept testing - temperature variation over time

At the start of the test, a slight increase in temperature was observed, which can be attributed to the rise in external temperatures as the morning progressed. This gradual increase culminated in a peak temperature of 15.51°C at approximately 1:40 PM.

Subsequently, the temperature readings began to decline until point (1), where a significant increase was recorded over approximately four hours, indicating that a climate control device had been activated by the user. Once the temperature surpassed the threshold set by the user, the application sent a push notification to their device, alerting them that the desired temperature had been achieved. This event, marked as point (2), occurred at approximately 6:20 PM. The climate control device remained on until around 7:30 PM, corresponding to point (3), implying that the application's notification was ignored by the user. Taking into account the calculations presented in the previous subsection, it can be determined that, on average, the user incurred a loss of approximately 7 cents during this brief period, noting that this cost would have more than doubled if a similar situation had involved the use of a cooling device, such as a standard air conditioning unit.

4.2.2. Light Presence and Movement Data Analysis

Following the analysis of the captured temperature data, we now direct our attention to the graph presented in Figure 3.2. which presents the variation in light presence percentage and movement data over the same period as the previous plot. The green series represents the light presence percentage recorded at a given time within the user's room, while the pink area highlights intervals where movement was detected. Additionally, the brown dashed line marks the light presence threshold defined by the user. This threshold specifies the percentage of light intensity at which the user considers their room to be adequately illuminated. In this case, the user designated a threshold of 30%.

Throughout the analysis, six key data points were identified and highlighted on Figure 3.2.

During the initial hours of the experiment, while temperature changes were recorded, no significant light presence or movement variations were detected. This is likely due to the user being either asleep or not present in the room. At approximately 11:00 AM, corresponding to data point (1), movement was detected alongside a sharp increase in light presence. This activity persisted for approximately ninety minutes, during which variations in light levels were observed, strongly suggesting that the source of the light was not constant, such as an electronic device, but instead dynamic and potentially attributable to natural light conditions influenced by fluctuating climatic factors.

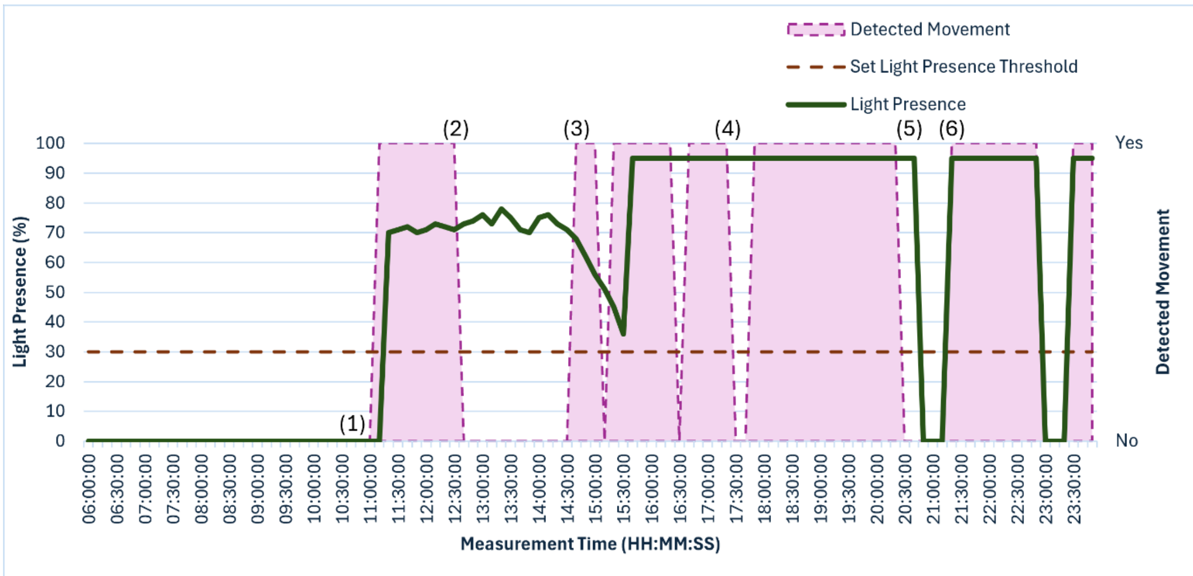

Figure 3.2. Proof-of-concept testing – light presence and detected movement over time

At data point (2), recorded at approximately 12:40 PM, the cessation of detected movement indicated that the user exited the room. Concurrently, the light intensity experienced a decline, which was notably consistent with a drop in temperature recorded in Figure 3.1. This correlation strongly supports the hypothesis that the light source during this period was external and uncontrolled, likely originating from natural sunlight, which may have been increasingly obscured by cloud cover as the day progressed thus resulting in diminishing temperatures.

By 2:30 PM, corresponding to data point (3), movement was once again detected within the room, even as the light intensity continued to decline steadily until approximately 3:30 PM. At this point, a sharp and abrupt increase in light intensity was recorded. Given that no corresponding rise in temperature occurred—a phenomenon typically associated with exposure to direct sunlight—it is reasonable to infer that the user activated an artificial illumination device, contributing to the observed spike in light levels.

During the afternoon, the user was observed leaving the room on several occasions, including a prolonged absence of approximately ten minutes at around 5:30 PM, during which the lights were left on. It is important to note, however, that the application did not issue a notification during this specific interval. This limitation stems from the nature of the light sensor employed in the study, which is unable to differentiate between natural sunlight and artificial lighting. Consequently, the notification system is designed to issue light-related alerts only during nighttime, when the absence of natural sunlight ensures that any detected light originates form an electricity-dependent source.

At data point (5) however, a notification was in fact triggered after the user left the room, presumably for dinner, seeing as the lights were left on and it being considered nighttime by the application. Shortly after the notification was sent, the captured data indicated that the lights were turned off, suggesting that the user obliged to the application's alert. It is important to clarify that, although no movement was detected during this interval, it is plausible that the user turned off the lights during the gaps between the predefined data collection events. Given that the system captures data at discrete intervals, such as every thirty seconds, it is entirely reasonable to infer that the user performed this action during one of these intervals.

At approximately 9:10 PM, corresponding to data point (6), the user returned to the room and turned the lights back on. Notably, from this point onward, each time the user exited the room, as indicated by the cessation of movement detection, they consistently turned off the lights.

4.3. Results Discussion

With both the financial analysis and proof-of-concept testing completed, we will now turn to a discussion of the achieved results.

Despite being a small-scale test, we observed the user ignored a notification, identified as (2) in Figure 3.1, but afterwards obliged to one, identified as (5) in Figure 3.2. This behavioral shift demonstrates the application's potential to effectively encourage energy-conscious habits in its users, particularly through the combination of real-time monitoring and targeted notifications. However, it is essential to emphasize that the proof-of-concept test conducted in this study primarily focused on evaluating the effectiveness of the notification system in influencing user behavior, particularly in scenarios where the user might not actively consult the application. It is equally important to recognize that engaging directly with the application's data can further promote energy-conscious behavior by enabling users to act preemptively, even before notifications are triggered. For instance, users can monitor real-time temperature and humidity data to proactively adjust temperature thresholds or review in-application plots to anticipate temperature trends, allowing them to deactivate climate control devices or take other energy-saving actions ahead of time, thereby enabling more effective and timely energy-conscious efforts. For users who may prefer not to consult the application frequently or who are unable to do so, the notification system serves as an effective safety net, reinforcing positive behavioral changes and supporting sustainable energy use.

We must note, however, that despite the promising results achieved, this was a small-scale test focused around a single user that hinges on two behavioral variables, which might not translate to others. This is, while the user in this case followed the notifications occasionally and left the light on almost always, others might, for example, never leave lights on or always oblige by the notifications. The test showcased here may not be a reflection of our application's power to influence users, something we are conscious of and will delve into more detail in the future work section.

Another important takeaway from our testing is the total financial impact incurred by the user as a result of ignoring the application's notifications. As previously mentioned, the financial consequence of disregarding the temperature-related notification amounted to 7 cents, while the consequence associated with the light-related notification being less than one-tenth of a cent.

While these costs may have considerable relevance for lower-income households, their impact on average-income and higher-income households is likely to be less significant, as these groups may not place the same level of importance on such expenses. Nonetheless, even when users are capable of accommodating these costs, it is imperative to acknowledge that the objective of energy conservation extends beyond mere financial savings. The core focus should instead be on its broader implications for the global energy ecosystem. Even seemingly insignificant amounts of energy waste, when accumulated across millions of households, can result in substantial increases in overall demand, thereby contributing to heightened environmental strain, resource depletion, and the intensification of climate-related challenges.

4.3.1. Implications

The conducted exploration and its consequent results not only demonstrate the feasibility of integrating Unity into IoT solutions but also pave the way for further research. The proposed architecture is highly adaptable and capable of transmitting and storing various types of data, with Unity serving as an exceptionally versatile end-user platform, placing itself as an interesting research subject for the broader scientific community. Additionally, the concept of exploring alternative platforms for IoT development can be extended to other underrepresented platforms within the IoT landscape.

Furthermore, our end-user application, although still in its early stages, already shows promise in encouraging behavioral changes among its users—a topic that will be further explored in the Future Work section.

4.3.2. Limitations

Despite the success of our proof-of-concept application, several challenges emerged during its development, which warrant further discussion. Firstly, as our project pioneers the use of Unity as a prominent IoT end-user development platform, the available literature on this specific integration was sparse, offering few precedents or frameworks to draw upon. This lack of prior work necessitated significant effort on our part to address and resolve numerous challenges independently, which ultimately delayed the development process. For instance, we encountered an issue with Firebase’s premade Unity packages, which were incompatible from the outset due to a conflict involving the application’s cache. This incompatibility caused the application to display incorrect data that did not exist within the database, requiring a thorough investigation and resolution.

Time constraints imposed by the dissertation timeline constituted another significant limitation, as they restricted our ability to conduct extensive and rigorous end-user testing, which would have provided valuable insights into the application's performance and usability.

In terms of the proposed solution itself, several specific limitations were identified. For example, the sensor array requires a power source, leading to potential downtime while the array is charging. If the array is configured to gather data continuously, it must remain connected to a power source, which partially undermines the energy-saving goals of the solution. Furthermore, the current implementation is limited to a single room within the user’s household. Scaling the application to monitor multiple rooms would require separate sensor arrays, each paired with distinct end-user applications. This lack of scalability is addressed in the Future Work section, where potential solutions for unifying the application are explored.

Additional technical challenges were encountered with Unity’s native notification system, which led us to adopt a community-created package to manage notifications. While functional, this workaround raises concerns about future compatibility, necessitating redevelopment of the notification system using Unity’s native features for long-term reliability.

Moreover, the proof-of-concept testing relied on a Node-RED flow hosted locally. For broader public testing and deployment, this flow would need to transition to a cloud-based solution. Similarly, the sensor array was programmed to operate exclusively with the testing facility’s Wi-Fi network. Addressing this limitation would involve enabling the system to retrieve Wi-Fi credentials from the user’s smartphone and integrating this functionality into the architecture to support backward communication. These enhancements, while feasible, would require additional time and resources to implement effectively.

CHAPTER 5

Conclusion

5.1. Conclusions

The main objective for this project was to develop an intuitive smartphone application aimed at reducing household energy waste by leveraging sensor-based Internet of Things (IoT) technologies. Through careful research, design and iterative development, a fully functional proof-of-concept artifact was produced, aimed at addressing our previously formulated research question:

RQ: Can a low-cost sensor-powered Unity application encourage behavioral changes that reduce energy waste in individual households?

This artifact, designed to notify when energy waste is occurring - whether through unattended lightning or climate control devices – effectively demonstrated its capacity to stimulate more energy-conscious behaviors all while employing low-cost, easily obtainable sensors. Through these notifications, users are given the opportunity to make immediate adjustments, such as turning off unnecessary devices, thus contributing to reducing household energy consumption and addressing our research question. Additionally, the artifact incorporated all features proposed in the hypotheses, thereby increasing its reliability and utility with each implementation.

In terms of our second artifact, our solution architecture, it not only proved the feasibility of integrating Unity into IoT solutions but also opened the door for further exploration of this relationship by the scientific community. One promising avenue for such exploration is the now-facilitated implementation of gamification in IoT solutions—a core functionality of Unity that many other IoT platforms lack which can directly lead to more active and rewarding interactions between IoT applications and its users. This represents a future objective for our first artifact, which is discussed further in the future work section.

In reflecting on this research, while it is clear that energy conservation is one of the biggest technological challenges of the 21st century, it is important to note that it is also a behavioral one. Our solution acknowledges this by placing the user at the core of the process, empowering them to make informed decisions and adopt energy-conscious habits.

As the world faces escalating environmental challenges and governing bodies remain slow to act, solutions that promote individual responsibility and sustainable practices are more vital than ever. This project offers a small but significant step towards a future where energy efficiency is woven into daily life, reminding us that, together, we can build towards a better world.

5.2. Contributions

Through this project, two main contributions were made to the broader scientific community:

- An adaptable, reliable and ready-to-use solution architecture that connects IoT to Unity.
- An end-user ready mobile application that focuses on reducing household energy waste.
- A publication regarding the implementation of Unity within an Internet of Things architecture and its benefits: Casimiro M.; Coutinho C.; Integrating Unity into IoT solutions.

5.3. Future Work

Despite the success of our project, the developed artifact remains a proof-of-concept, with countless avenues of improvement and exploration. As stated in chapter 2, Unity is largely uncharted territory within the IoT landscape, especially when considering its capabilities for VR and AR integration, making it a worthy object of further research. Building upon this project's well-researched and thorough technology stack, researchers can leverage our work to focus on innovative breakthroughs without the need to address the underlying complexities of the application's perception and network layers.

With respect to the application itself, its current state offers immense potential for improvement and expansion, given its early-stage development. While it has already demonstrated its ability to encourage behavioral changes, the next logical steps involve refining and extending its capabilities to create a solution ready for real-world deployment. The first phase of these improvements, as highlighted in the Limitations section, would involve enhancing the application's architecture to ensure seamless functionality in actual households. This would include implementing backward compatibility, enabling the sensor array to connect to any network via the user's mobile device, and transitioning the Node-RED flow from a locally hosted system to a cloud-based one accessible by multiple devices.

Once these foundational upgrades are complete, large-scale, user-centered usability testing would be the next crucial step. The goal of such testing would be to gather meaningful data on the application's effectiveness in promoting energy-saving behaviors and to identify areas for improvement. Feedback from these tests would inform subsequent iterations, with a particular focus on enhancing the application's user interface and overall ease of use—areas that were intentionally deprioritized during the proof-of-concept stage. This iterative cycle of user feedback and application refinement would continue until the application achieves an optimal balance of functionality and usability, satisfying both developers and users alike. It is also at this stage that we would conduct color studies, which were not undertaken during the proof-of-concept phase, as the primary objective was to test and validate the application's functionality and utility before moving forward. These color studies, combined with a comprehensive user interface overhaul, will ensure that the brand and application present a cohesive and visually appealing design.

Following successful user testing and feedback-driven refinements, the application could be expanded to incorporate more advanced features and address challenges identified in Chapter 2. One such enhancement would be the ability to manage and analyze data from more complex sensor arrays, allowing simultaneous support for multiple rooms and their respective sensor arrays. This development would create a more comprehensive energy management solution, offering users room-specific notifications such as, "Desired temperature reached in the kitchen." Additionally, incorporating solar power into the sensor array could enhance the artifact's energy-conscious design by reducing reliance on traditional charging methods.

Another area for post-testing exploration involves addressing data security and storage. Advanced data security measures could protect sensitive user information, while improved data storage techniques would enable efficient handling of obsolete data. Enhancements to data visualization tools could also be explored, for example, exploring the utilized package to display the horizontal axis legends vertically, thus enabling more data points to be displayed without sacrificing legibility. Additionally, leveraging Unity's built-in augmented reality (AR) capabilities to provide users with intuitive and engaging ways to interpret energy usage data, deepening their understanding of consumption habits.

In terms of future development paths, there is significant potential for innovation. Recognizing that environmental degradation alone may not serve as a sufficient motivator for all users, the application could introduce, as stated before, gamification elements to increase engagement by rewarding energy-conscious behaviors. Although still in the conceptual stage, this system is projected to reward players for energy-conscious actions, such as responding to notifications by turning off a device or using the app to identify and turn off devices consuming electricity. However, even at this conceptual stage, potential challenges have been identified. For example, users might attempt to exploit the gamification system by deliberately leaving energy-wasting devices on to generate notifications and earn rewards. Addressing this issue would necessitate the integration of artificial intelligence into the system, allowing for the development of a behavioral analysis model. Such a model could evaluate user actions to distinguish between genuine efforts to save energy and attempts to game the system, ensuring the integrity of the application's objectives.

In conclusion, Bernergy+ is a promising proof-of-concept application with the potential to evolve into a transformative tool for reducing energy waste. By building upon the work presented in this dissertation and incorporating additional innovations, the application is well-positioned to drive meaningful change and contribute to a greener, more sustainable future.

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