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EnerMon: IoT Power Monitoring System for Smart Environments

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ISCTE-IUL

Setembro, 2019

Resumo

O presente estudo, realizado no âmbito da tese de mestrado, descreve o desenvolvimento e subsequente validação de EnerMon, um sistema IoT(Internet of Things / Internet das Coisas) LoRa flexível, eficiente e baseado em *edge-computing* capaz de monitorizar consumo de energia em tempo real. Através de processos de análise descritiva é também apresentada uma visão geral sobre o consumo energético ao longo do tempo com a identificação de desperdícios de energia. Neste trabalho o leitor irá tomar conhecimento do processo de desenvolvimento completo do sistema, desde a fase de *design* à fase de testes, criado com o uso de Arduinos, Sensores de transformadores de corrente e Raspberry PIs como servidores aplicacionais, bem como informação relacionada com a comunicação LoRa e o que lhe é expectável.

Esta solução, com a ajuda de analíticas descritivas, permitem a identificação de pegadas energéticas locais, usando materiais de baixo custo por menos de 80€ por sensor de monitorização de três fases. Permite também a fácil instalação sem limitações de alcance e obstáculos na comunicação, simplificando a sua utilização em diferentes ambientes desde edifícios complexos a consumidores energéticos mais pequenos, como caldeiras elétricas ou simplesmente medir a pegada energética de turistas em alojamento local.

Palavras-Chave: Internet das coisas, Monitorização de Energia, Transformadores de corrente, Sensores de Consumo Elétrico, LoRa, Cidades Inteligentes.

Abstract

In this research work, we describe the development and subsequent validation of EnerMon a flexible, efficient, edge-computing based IoT LoRa System to monitor power consumption. This system provides real-time information and a descriptive analytics process to provide a 'big picture' about energy consumption over time and identify energetic waste. The solution is based on Arduinos, Current Transformer Sensors, Raspberry PI as an application server and LoRa communication alongside a description and information on what is to be expected of it. It describes the development process from the Design phase to the Validation phase with all the steps in between. Due to LoRa low debit communication, an edge computing approach was implemented to create a real-time monitoring process based on this technology.

This solution, with the help of descriptive analysis, allows the creation of an energetic local footprint, using a low-cost developed solution for less than 80€ per three-phases monitoring device. It also allows for an easy installation without communication range and obstacles limitations making it easy to be used in a different set of situations from big complex building to smaller consumers, such as electric boilers, or simply to measure the energetic footprint of tourists in a small local tourist apartment.

Keywords: Internet of Things, Power Monitoring, Current Transformer, Power Consumption Sensors, LoRa, Smart Cities.

Acknowledgments

First and foremost I'd like to express my most honest and special thanks of gratitude to my coordinator Professor Doctor João Carlos Ferreira for not only accepting to do this research with me but also proposing the theme and contributing in an indispensable form by, among other contributions, setting up meetings, helping in the research of literature materials, creating a research environment where funds were not an issue and, finally, transmitting the necessary knowledge that led to the development of this work. His contributions were not limited to this work but also to the scientific world in general and my own personal journey by providing means to publish papers based on this research and allowing me the opportunity to transmit the knowledge obtained during the development of this thesis to students during the University's Summer School 2019 – IoT for smart cities as an instructor.

Mr. Rui Miguel da Silva for the special attention provided and guidance when it came to the University's inner workings for the auditoriums and the help provided in setting up the sensors in the electrical boards. To the electrician Mr. Luis Manuel Fernandes that provided us with his time to set up and test the sensors' prototypes in those electrical boards. Without his patience the work in those boards would have been impossible.

Mr. Hugo Silva whose availability, knowledge and help with the sensor's solderings were crucial in the makings of this work. With his help the sensors became solid and capable of placement without the need to worry about movable parts.

Professor Vasco Moreira Rato and Professor Vítor Bastos Fernandes for the availability, amiability, and the overall sharing of knowledge provided that made me want to find out more to further improve this work.

To the pillars of my life. To my parents and brother that allowed me to finish my studies at the university, without their support, this objective would not have been possible. To my girlfriend for the support and unconditional love every step of the way. To all of them for the patience in dealing with my frustrations and listening to my problems.

To my friends for the encouraging words, relaxing moments, and the sharing of knowledge and for simply ever being there to help when needed.

To Mr. Claudio Santos, Mr. Luis Lourenço and Mrs. Joana Gaspar that respectively provided the environment to measure the Agriculture Pump, the Apartment's Electrical Boiler and the Tourist Apartment.

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List of Acronyms

AC	Air Conditioning or Alternating Current
ADC	Analog to Digital Conversion
AES	Advanced Encryption Standard
API	Application programming interface
AREF	Arduino analog reference voltage
BLE	Bluetooth Low Energy
CSS	Chirp Spread Spectrum
CT Sensor	Current Transformer Sensor
ECDHE	Elliptic-curve Diffie–Hellman Exchange
HTTPS	Hypertext Transfer Protocol Secure
HVAC	Heating, ventilation, and air conditioning
IDC	International Data Corporation
IoT	Internet of Things
IT	Information Technologies
LoRa	Long Range
LoRaWAN	Long Range Wide Area Network
LPWAN	Low Power Wide Area Network
LTE	Long Term Evolution
MQTT	Message Queuing Telemetry Transport
NB-IoT	NarrowBand IoT
NFC	Near Field Communications
PTEC	Predictive Thermal and Energy Control System
PU	Processing Units
RSSI	Received Signal Strength Indicator
RTC	Real-Time Clock
TTN	The Things Network
UPS	Uninterruptible Power Sources
RF	Radio Frequency
SF	Spreading Factor
WLAN	Wireless Local Area Network
WPA	Wi-Fi Protected Access
k/T/W/Wh	Kilo/Tera/Watt/Watt-Hour

Chapter 1: Introduction

1.1 Overview

World population has been increasing for years now, and with it comes an increase in resource wasting. This waste of resources comes from several factors including, but not only, the lack of proper rules and standards, the incorrect usage of the existing standards and in some cases the complete disregard for those standards, both in each and some households but also in an enterprise environment. One method used in order to fight these issues was the creation, or manipulation, of sensors and with it, both the communication between them and the analytics that comes with this new information thus creating the Internet of Things (IoT). Nowadays almost every business, from Retail to Healthcare, has already some form of IoT invested. International Data Corporation (IDC) has already concluded that data load, in 2025, will increase to 163 zettabytes, 10 times the data generated in 2016 [1], partially due to these kind of devices. Alongside this values, by that same years, Peter Newman predicts that there will be more than 55 billion IoT devices connected to any form of network and between 2017 to 2025 there is a forecast of nearly $15 trillion in aggregate investments related to IoT [2].

1.2 Motivation

Right now energy generation, displayed below in Figure 1, comes at the cost of the planet. In 2016 over 65.3% of the total electricity generated comes from the burning of fossil fuels into steam generation [3]. The burning of fuels leads to the release of carbon dioxide into the air. This release contributes to negative climatic changes that not only create an impact on us, humanity, but also to natural ecosystems all over the world. These natural ecosystems are already seeing higher rates of insect extinction that are vital for both human survival and nature itself [4].

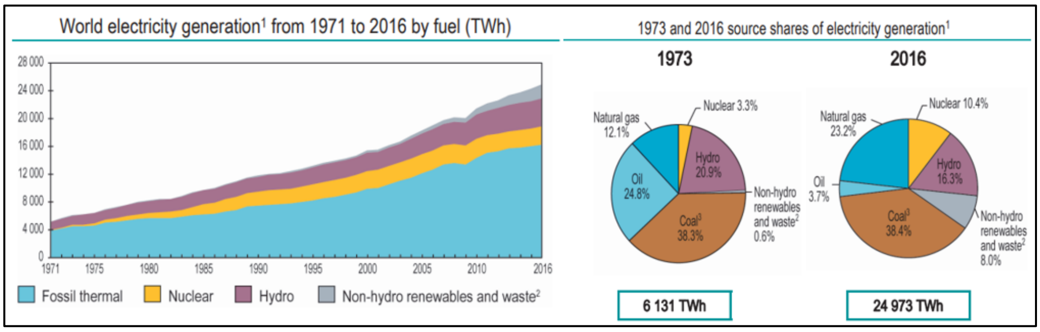

Figure 1 World Electricity Generation by Source [3]

Meanwhile, alternatives such as Nuclear Power and green energies, are hailed as dangerous or expensive. As such, while no better alternatives presented are implemented we need to keep power consumption in check, take care not to waste too much and even when not wasting, trying to keep check on power consumers by finding what we can do to improve them.

1.3 Objective

In this research work, we present a flexible, edge-computing based power monitoring system capable of collecting real-time energy consumption data to a central platform, for data visualization and pattern identification in different environments. The sensors placed on pre-defined electrical board phases send their data using LoRa communication, which in term leads to certain questions:

- How viable is LoRaWAN as the network protocol to send and receive data in and out of power monitoring end-devices?
    - Will the data transference interval limitation and the maximum packet size have a negative impact on the overall performance of this work?
    - Does packet loss interfere with the analysis of the final data?
    - Are we able to apply edge computing approaches in order to mitigate these issues?

The system is developed, mainly, to allow descriptive analytics approaches while also preparing the data and the system to create a predictive service in the near future, when higher data volume allows for it. Based on the descriptive analytics data visualization approach and correlation with external data, we can ask some questions:

- Can we find power consumption waste and identify possible saving solutions?
- Can we relate Power consumption with a different variety of variables (agriculture, heat pumps, boiler efficiency)?
- Can we link power consumptions with other factors such as temperature, classes, seasons, etc?
- Can we find anomalies related to problematic devices, such as inefficient hardware or even broken appliances?

Finally, our main objective with this research is to create a low-cost, flexible and sustainable IoT system that allows for an easy installation process that can be applied from private houses to big complex building like a university campus, with the focused goal being the identification of energetic footprint with descriptive data analytics.

Chapter 2: Background

2.1 Sustainability

Sustainability is not a single process, it is a set of approaches that have an objective of making sure the development of advancement ensures the needs of the present without compromising the needs of future generation:

> *"It ensures that exploitation of resources, direction of investments, orientation of technological development, and institutional change are made consistent with the future as well as present needs."* [5]

Over the times, sustainability has always been defined within three core pillars in development:

- **Economical:** a system that is economically sustainable must be able to produce goods and services on a continuing basis in order to maintain profit [6]. But while profit is important for any business, the economic pillar also includes business management processes such as compliance, proper governance, and risk management [7].
- **Social:** a system socially sustainable must have the support of his employees, stakeholders and consumers/community it operates on. Therefore it must achieve fairness in distribution and opportunity, basically, treating employees the way they should be treated with the social benefits in sectors such as health, education, and equity as well as political accountability and participation [6], [7].
- **Environmental:** focused on reducing waste and maintaining resources, the system must avoid over-exploration of resources both renewable and non-renewable, seeing the former as something that most definitely cannot be depleted. Environmental processes can include the maintenance of biodiversity, atmospheric stability, and other ecosystem functions not ordinarily classed as economic resources [6], [7].

These three pillars while often can work alone they should be used as part of one system working together, so that they can reinforce and help each other in meeting a truly sustainable system such as presented in Figure 2.

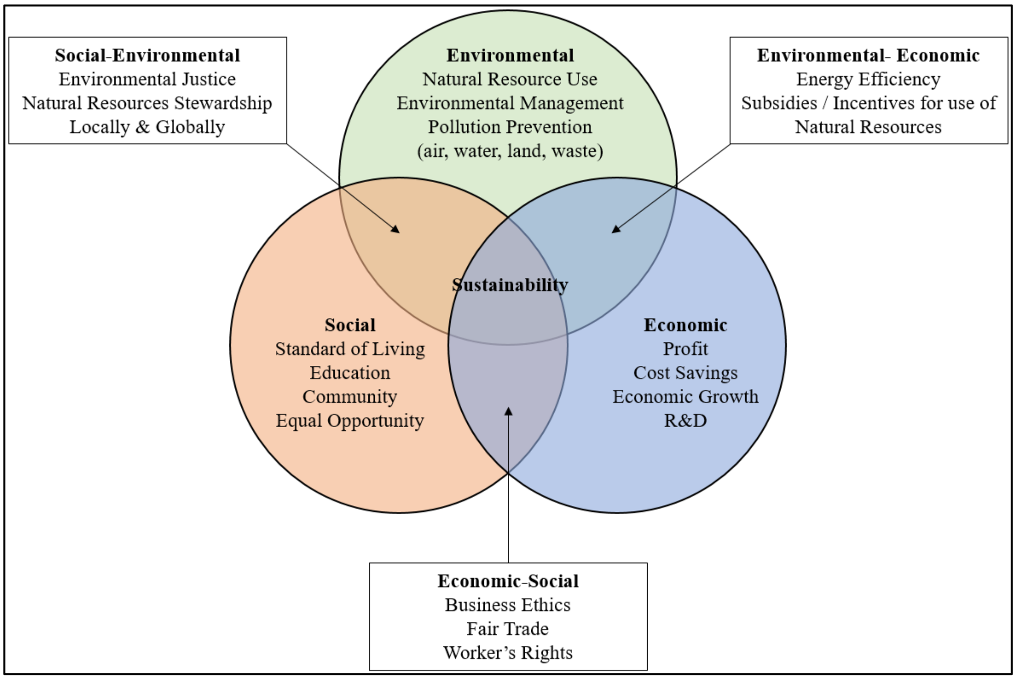

Figure 2 The interlinking pillars that contribute to sustainable development [8]

2.1.1 European Union and Sustainability Programs

Over the last few years, there have been some major concerns when it comes to our planet's well-being. The European Union, especially, has been creating Energy Management directives since 2009 to work on improving energy efficiency in the future. This improvement would show results primarily in increased monetary savings, reducing of reliance on external suppliers of oil and gas, especially when it comes to heating, and, as it's usual, with sustainability projects, to help protect the environment [9].

The most recent directive, known as "Directive (EU) 2018/844 of the European Parliament and of the Council of 30 May 2018 amending Directive 2010/31/EU on the energy performance of buildings and Directive 2012/27/EU on energy efficiency", presents a new regulatory framework [10].

The main objectives this directive sets to achieve can be summarized in a few points:

- The setting of a new renewable energy efficiency target by 2030 of 32% and reduce greenhouse gas emissions by 40%.
- The improvement of sustainability in the use of bioenergy.

"(28), Member States should consider the need for holistic and coherent urban planning as well as the promotion of alternative, safe and sustainable modes of transport and their supporting infrastructure, for example through dedicated parking infrastructure for electric bicycles and for the vehicles of people of reduced mobility." [11]

- Facilitation of delivery and the reduction of administrative procedures.

  "(23), Member States should provide for measures to simplify the deployment of recharging infrastructure with a view to addressing barriers such as split incentives and administrative complications which individual owners encounter when trying to install a recharging point on their parking space."

  "(34), The current independent control systems for energy performance certificates can be used for compliance checking and should be strengthened to ensure certificates are of good quality."[11]

- Creation of a sustainable environment with equal access to everyone. Focusing not only in the end goal but also affordability and cost-effectiveness when it comes to renovations of older buildings, along with a focus on techniques that would reduce energy consumption for heating or cooling such as proper insulation.
- To make use of new sensorial technologies, such as sensors auto-regulating room temperature, not only creates more efficient management of resources, thus being both a cost-effective and significant energy-saving technology, but also they're proven to be a proper replacement for inspections.
- Creation of infrastructures, in residential and non-residential areas. This facilitates the construction of mechanisms, such as smart charging stations for electric vehicles, therefore encouraging the use of this type of vehicles that represent a considerable share of clean energy. The creation of infrastructure would also decrease the costs of installing recharging points not only for individual owners but for businesses that wish to make use of the service, and provide the right conditions for the rapid deployment of these when needed.
- Creation of a smart readiness indicator that would measure how prepared a building is to accommodate intelligent devices.

  "(30), The smart readiness indicator should be used to measure the capacity of buildings to use information and communication technologies and electronic systems to adapt the operation of buildings to the needs of the occupants and the

grid and to improve the energy efficiency and overall performance of buildings. The smart readiness indicator should raise awareness amongst building owners and occupants of the value behind building automation and electronic monitoring of technical building systems and should give confidence to occupants about the actual savings of those new enhanced-functionalities."[11]

Within these initiatives, GAIA (Green Awareness in Action) [12] is one of the main contexts of this work. GAIA's main objectives focuses on the creation of ICT (Information and Communications Technology) ecosystems specifically for educational buildings that motivate and support citizens' behavioral change to achieve greater energy efficiency in over 24 educational sector buildings in 3 countries covering North, Central and South Europe, leading up to reductions of over 15% on the energy that could be influenced by the end-users [12].

2.2 Power Monitoring

2.2.1 Power consumption baselines in Business and General Public

The growing development of cities includes the development of more advanced technologies, which in most cases will bring an increase in energy consumption. It is also proposed that within 35 years, in 2050, 68% of the world's population will live in cities, as opposed to the, about, 50% that today reside in them [13], not only that but as we know, the world's population has been on an increasing trend. Both of these factors will contribute to the increase in the electricity demand. This electricity can come from both clean/renewable sources and fossil fuel sources and others (nuclear, etc) [14], fossil fuel sources being the most concerning in the actuality.

While electricity consumptions in households hold a significant amount of the total's electricity consumption in OECD countries (Figure 3), we should not forget that offices, schools, hospitals and any other non-residential buildings and services also consume a lot of electricity every hour. As a summative value, in 2017, over 21372 TWh were consumed on known countries, 0.2% higher than the value from 2016, China and the US being the largest consumers of this form of energy [15].

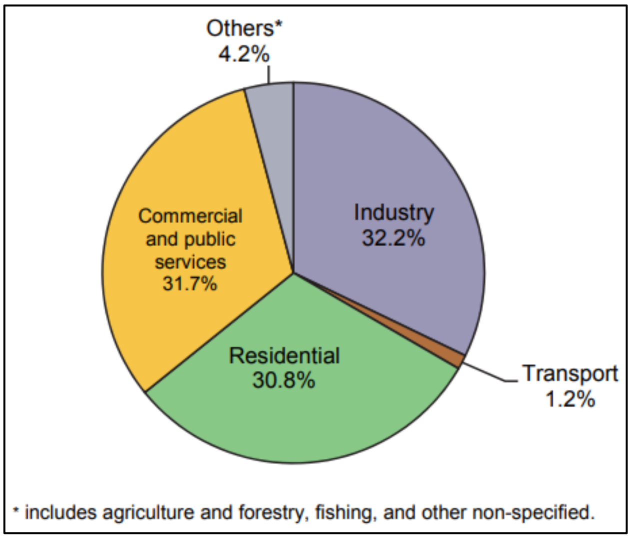

Figure 3 Final electricity consumption by sector in OECD countries in 2017 [15]

When it comes to residential consumption, electricity accounts for over 24% of the total energy consumption in households, and it is one of the main forms of energy used in the European Union. Electricity in households is mainly used for space heating covering 64.1% of the total electricity consumption inside EU-28 countries' houses, as presented in Figure 4. It is also important to note that space cooling in residential buildings has a smaller value than non-residential buildings, the reason for this being that cooling will be done mainly by using Air Conditioning or fans and fans barely use any power, while air conditioning is owned by fewer people [16].

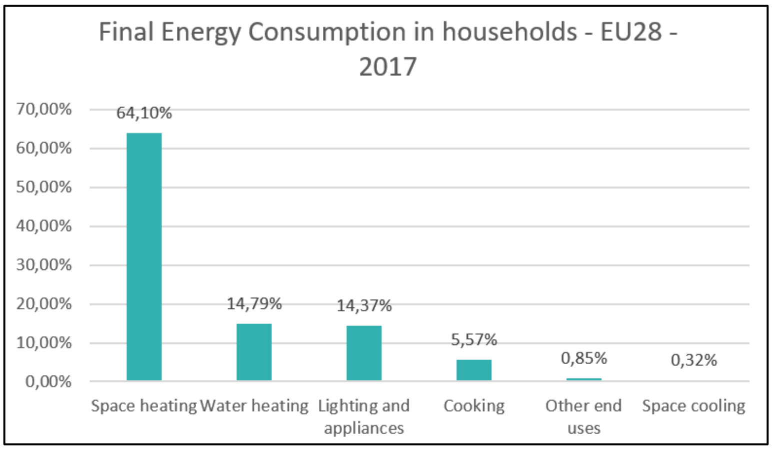

Figure 4 Final electricity consumption in the residential sector [16]

As for the total consumption over a year for every household, it's hard to give a definitive number since some countries might have different averages based on, not only the development level of the country but also what is their norm on power-saving policies.

However, looking at Figure 5, we can safely identify the European Union's countries as developed countries willing to reduce their power consumption over time.

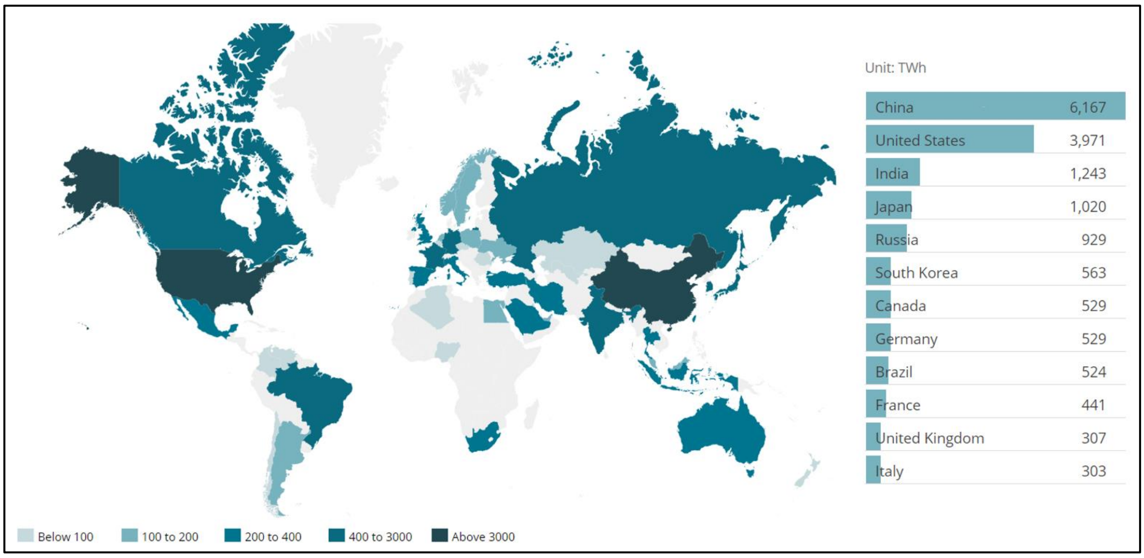

Figure 5 Domestic Power Consumption per Year [17]

Non-residential buildings, on the other hand, have different needs, overall the electricity consumption for Illumination is one of the main focuses but, depending on the months, cooling or heating may be necessary to keep a comfortable working environment. Researchers created a study, in a library (Figure 6), where over the course of several months in one year, they monitored power consumption on a daily basis. As said before, space cooling in these sorts of buildings will see an increase in consumption since they tend to have and make use of air conditioning systems. Overall the total energy consumption over the year reached 2491 MWh in this particular library [18].

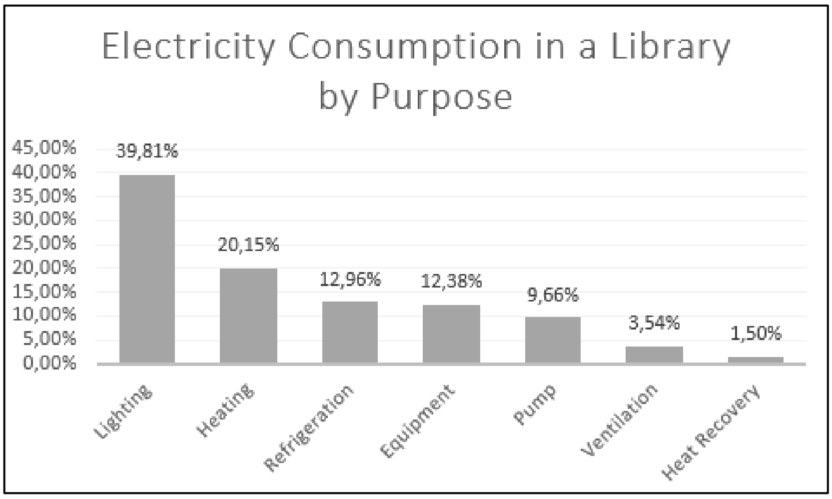

Figure 6 Example of electricity consumption in the business sector [17]

2.2.2 State of the Art in Power Monitoring Systems

The increase in demand for the use of more clean energy leads to an increase in demand for suitable IoT projects and infrastructures in order to create more efficient energy management inside the buildings.

Of course, in some cases, energy consumption monitoring can have its difficulties. The work presented in [19] is an example of the increasing demand for energy consumption and efficiency-measuring platforms for HVACs (Heating, Ventilation and Air Conditioning). However, it is also one example of how the lack of proper infrastructure caused by unreliable networks, where the interference from nearby RF equipment leads to an increasing packet loss. In turn, this caused real-time desynchronization between nodes, leading to improper results in power consumption. Another obstacle that researchers face is the lack of a standard in data created by energy monitoring solutions. Brick [20], is one of the proposed uniform schemas defining a concrete ontology for sensors, subsystems, and relationships among them, which would enable portable applications.

Edge computing is described in [21] as a networking paradigm focused on bringing computing processes as close to the source of data as possible. This, in some cases, could mean the sensor itself is yet another solution to problems caused by finite resources such as bandwidth, server resources and the costs caused by cloud processing. All while reducing latency and adding functionality thus creating a more aware system that can create alerts in a timely manner. An example of this would be a camera sensor, that instead of sending entire videos directly to a cloud server, it could, possibly, only send the most critical parts of the video, or, for more powerful sensors, even process that video and only send the said results of that processing to the server.

In [22], the authors present the design and evaluation of the system PTEC (Predictive Thermal and Energy Control System), a thermal and energy control prediction system in a data center. The focus of the study was to verify if the PTEC could efficiently perform monitoring of the data center with a low cost in the use of power. The system collects data from both the server fans and the air conditioner and checks whether the information on both temperature and power consumption is within a margin of safety for the data center. The evaluation of the system is carried out by means of simulation to verify the efficiency and reliability of the PTEC. The PTEC evaluation has shown that it can reduce cooling and circulation energy consumption by up to 34% and 30% [22]. Temperature and Humidity Sensors alongside cloud management of Air Conditioners can also improve supportive infrastructure by controlling the, sometimes, wasteful cooling procedures. This allows a margin to increase the load by IT servers, increasing performance while maintaining proper temperatures and also reducing energy consumption [23].

Research done in [24] presents a low-cost solution for implementing energy consumption and environmental monitoring using an open-source IoT infrastructure, whose aim was similar to one of this thesis case studies, the monitoring in educational buildings. With the use of XBee devices, moreover, it provides insights derived from initial results which concerns a deployment inside a university building. Meanwhile, in [25] a different approach to energy savings is presented by using occupancy sensors in large commercial buildings to determine the occupancy patterns in certain areas. This creates a more efficient HVAC schedule pattern that can create reductions of up to 38% energy consumption while maintaining thermal comfort.

When it comes to energy monitoring using commercial devices, we can present three of the most common ones available in the market:

- Smart Energy by Develco Products [26] focus on overall building energy monitoring, provides not only tools to measure energy consumption, through intrusive means, but also energy generation such as monitoring of photovoltaics with the use of several communication standards such as Zigbee, Z-Wave, WLAN, Wireless M-Bus, and Bluetooth Low Energy.
- Sense: Home Energy [27] works in a different way from other, more intrusive, sensors. The main particularity of this sensor is that it uses Amperage Clamps or current transformers, such as this work, to measure power consumption.
- Engage: Efergy [28] is yet another home energy consumption monitoring solution that uses current transformers to measure energy with the possibility to mix with future energy plugs, thus allowing for both an intrusive and non-intrusive experience.

In this document, we describe a similar solution that uses current transformers and an Arduino MKR 1300 to send power consumption data to an open-sourced server. This, in turn, allows for visualization and descriptive data analytics on Microsoft’s PowerBI.

To put the more relevant systems in perspective, the following Table 1 was created:

Table 1 Related Works table

System	Source	Sensor Type	Communication	Main Use	Commercial
EnerMon (This document)	Open	**Non-Intrusive:** Current Transformer	LoRa	Any Power Source	No
PTEC[22]	Closed	**Intrusive:** Power Meter **Non-Intrusive:** Temperature Sensor	IEEE 802.15.4 Ethernet	Data Center Cooling	No
Open-source IoT meter devices for smart and energy-efficient school buildings[24]	Open	**Non-Intrusive:** Current Transformer	IEEE 802.15.4	Educational Buildings / Any Power Source	No
Non-Intrusive Techniques for Establishing Occupancy Related Energy Savings in Commercial Buildings [25]	Closed	**Non-Intrusive:** Occupancy Sensor	Not specified	HVAC	No
Smart Energy by Develco Products [26]	Closed	**Intrusive:** Plugs, Meter Interface	Zigbee, Z-Wave, WLAN, Wireless M-Bus, BLE	Any Power Source	Yes
Sense: Home Energy [27]	Closed	**Non-Intrusive:** Current Transformer	Wi-Fi	Any Power Source	Yes
Engage: Efergy [28]	Closed	**Non-Intrusive:** Current Transformer **Intrusive:** Power Plug (Future)	Not specified	Any Power Source	Yes

WLAN: Wireless Lan, BLE: Bluetooth Low Energy, HVAC: Heating, Ventilation and Air Conditioning,

2.3 State of the Art in Communication Protocols

For this thesis, our focus was LoRaWAN, which is described in detail below at the network section (Section 3.3.3). When it comes to long-range communication technologies besides LoRa, two others are described below:

- **SigFox**, as a long-range network technology, presents an important alternative. It is cheaper when compared to LoRa and NB-IoT (Narrowband IoT) but has certain limitations such as the lack of global deployment and the link budget for downlinks is limited, therefore it can sometimes be hard for downlinks to reach the end device.

- **NB-IoT**, another long-range technology, based on 4G (cellular network variant) coverage which means it has a decent coverage range and also allows to send large payloads with faster response times than LoRa. However, this also means that it can consume more battery life than LoRa. As a 4G coverage network, while it performs better than LoRa in Urban areas, it will perform worse in rural areas. LoRa devices also tend to be cheaper but they require a gateway in case there's none nearby, which, with NB-IoT, that is not a requirement.

ZigBee, **Bluetooth Low Energy** or **Z-Wave** can be used for devices that do not require big data packets, don't consume a lot of energy, and are close to each other (small range). **NFC (Near Field Communication)** is another different type of IoT network that is defined by its very short range and small payload length which has its own particular set of use cases with more focus on authentication and real-time interaction systems.

Finally, as a norm, we have to mention the **Wi-Fi** network (Figure 7).

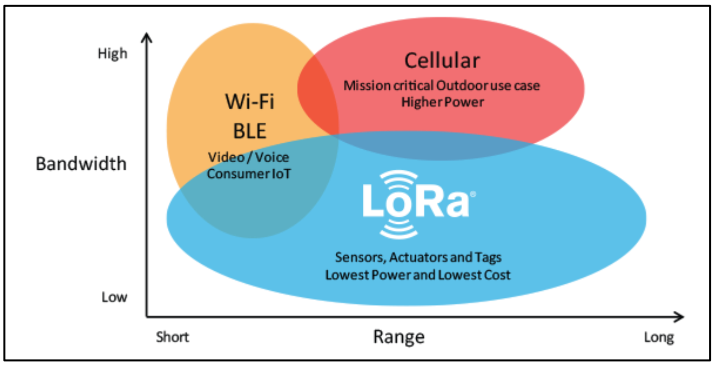

Figure 7 Comparison between LoRa, Wi-Fi and Cellular networks [29]

Wi-Fi, one of the most used networks, has several issues when it comes to IoT devices:

- **Range**, Wi-Fi range can only vary between 1 to 100m.
- **Power Consumption,** for starters the device must be kept active to scan for nearby networks, and also, during the power-saving mode, the device must become active regularly to check if the access point has the need to send any packets [30]. There are, however, low power Wi-Fi microchips available that solve this issue at the cost of bandwidth and data size, however, the range still remains the same [31].

Table 2 shows a more compact view of the several common IoT communication standards that can be used, alongside their specific characteristics that make them an advantage for different types of situations.

Table 2 Overview of Common IoT Communication Standards

Wireless Technology	Data Rate	Max Payload Length	Communication Range	Security	Strengths	Ref
LoRaWAN (This thesis)	50kb/s	243 Bytes	~5km Urban ~15km – 20km Rural	128bit AES	(1) Low Power Consumption (2) Long Communication Range (3) Low Cost (4) Secure (5) Availability	[32] [33] [34]
Sigfox	100 b/s	12 Bytes	~10km Urban ~40km Rural	No Encryption or Adaptable for each case	(1) Long Communication Range (2) Low Power Consumption	[34]
NB-IoT	200 kb/s	1600 Bytes	~1km Urban ~10km Rural	LTE encryption	(1) Large Maximum payload length (4G coverage) (2) Secure	[34]
Wi-Fi	Top 1Gb/s - IEEE 802.11ac	2034 bytes	1-100m	WPA/WPA2	(1) High Speed (2) Advanced/Mature Standard	[35] [33]
ZigBee	250kb/s@2.4 Ghz 40kb/s@915 MHz 20kb/s@868 MHz	255 Bytes	10-300m Direct Line Sight 75 – 100m Indoor	128 bit AES	(1) Low Cost (2) Low Power Consumption (3) Large number of nodes (up to 65000 nodes) (4) Secure	[36] [37] [38]
Bluetooth 5	2 Mb/s 500 kb/s (Long Range S = 2) 125 kb/s (Long Range S = 7	255 Bytes	Up to 200m +200m (BLE)	L1 – No security L2 – AES 128 L3 – AES and Pairing L4 – ECDHE	(1) Ease of access and setup (2) Simple Hardware (3) Secure (4) Low power consumption (BLE)	[39]
Z-Wave	100 kb/s	64 Bytes	~100m (May vary depending on the number of nodes) (Up to 4 hops)	Security 2 (S2) (Include AES-128, ECDHE, secure TLS tunnel)	(1) Low power consumption (2) Simple installation (3) Secure (4) Interoperability between devices of different manufacturers (Standardization)	[40] [41]
NFC	424 kb/s	$2^{32}-1$ Byte	< 20 cm	Short Range	(1) Continuous evolution (2) Stable technology for short range devices	[42]

AES: Advanced Encryption Standard, WPA: Wi-Fi Protected Access, BLE: Bluetooth Low Energy,

ECDHE: Elliptic-curve Diffie–Hellman Exchange, LTE: Long Term Evolution

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Chapter 3: EnerMon IoT System

Since the goal is the development of an IoT System, we follow the typical IoT methodology:

1. Identification of requirements.
2. Design of the System.
3. System development.
4. Testing.
5. Validation and examples of implementation.

3.1 Requirements Identification

Our system proposal can be applied from small houses to big buildings. So in this phase, a set of interviews were performed in several locations such as ISCTE's sustainability and maintenance office and individual house owners. From this initial work, a set of general requirements were identified for EnerMon:

- **Problem**: Pattern identification is important in order to check power consumers that might be having problems.
  - **Requirement**: Real-Time Monitoring of Power Consumption, which requires a Low Data Sending Interval, makes it easier to test for problematic devices.
- **Problem:** It is also important to have, for each month/week, a general vision of how each power consumer is working.
  - **Requirement**: Aggregate Monitoring of Power Consumption with filters based on different attributes.
- **Problem:** Different environments can have several consumers that branch out, so not only the devices must be cheap so many can be made, but they also need to be easy to install in case there's the need to change their location.
  - **Requirement**: Ease of Installation for changeability within different environments.
  - **Requirement**: Low-Cost but accurate (in our case 3% accuracy).
- **Problem**: Power consumption monitoring generates summative values, so it's important to reduce failures to a minimum while always keeping the interval between reads within the same time frame.

    - **Requirement**: Robustness to failures and errors, in order to keep a near 100% uptime.
    - **Requirement**: Real-time device synchronization.
- **Problem:** With different environments comes different network infrastructures. In most cases, the available infrastructure would be Wi-Fi, which can have multiple issues, such as low-range or signal strength loss when crossing walls.
    - **Requirement:** Wide area network with low frequency.

3.2 System Design

The design is based on regular IoT system's architecture and has 4 main components shown below in Figure 8:

1. **Device Layer - LoRa End Device:** The end devices use edge-computing approaches to collect data. It then sends the data to the LoRa gateway without any need for a nearby, small-range communication network (e.g., Wi-Fi).
2. **Communication Layer - LoRa Gateway and LoRa Server:** Receives Uplinks from end Devices and redirects that data to one or more application servers, while, also, sending Downlinks to End Devices, in case there is a need to send a command.
3. **Data Layer - Application Server and Databases:** Receives data from the Gateways, processes that data and stores it in a database while communicating with the End-Device through the LoRa gateway.
4. **Information Layer – Dashboard and Analysis:** The data collected is used to create a dashboard that presents information in the form of detailed graphics alongside proper filters. The analysis is done using PowerBi's dashboard alongside python in order to better understand the data.

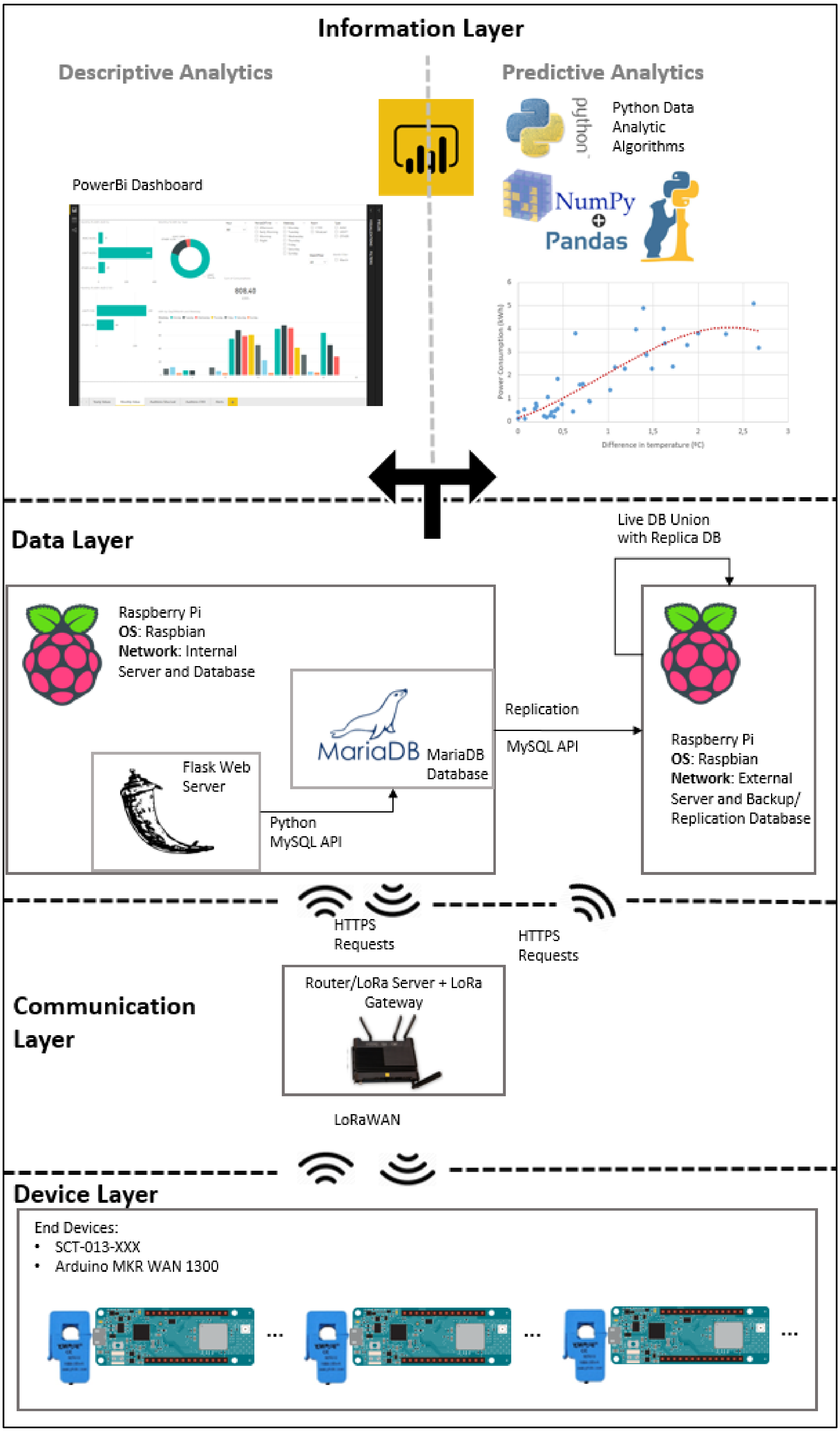

Figure 8 System Design

3.3 Development of the Design

3.3.1 EnerMon Summary

End Devices: Edge Computing based Power Consumption Sensors. Several of the power consumption sensors were placed in different environments formed either by 3-phased power distribution or single-phase power distribution. These prototypes use an Arduino MKR 1300 connected to current Transformers sensor with accuracies that vary depending on the power consumption passing through the main cable at the time:

- With values close to the expected rating of the current transformer, we can expect ∓ a 3% error [43].
- When measuring values that are very close to zero, we can see errors up to 10% [43].
- However, if we go above the expected maximum rating of the transformer by a large factor, we risk obtaining a multitude of accuracy error results up to 70% deviation due to saturation [43].

Each sensor is able to connect to three-phases simultaneously, read each phase individually, and sum the values (kWh per reading interval) received from the phases. The sensor sums the value with each read and resets that sum every time it sends the data (as long as the data was received by the server), while also waiting to receive any message from the server. One LoRa limitation comes from the fact that it can only receive messages right after sending data to the server due to the board's LoRa class A. The type of message this sensor can receive can come in two forms:

- A Feedback acknowledgment from the LoRa server, indicating that the LoRa server received a message, sent automatically for each data uplink received by the LoRa server.
- A corrective message, sent automatically by the Application server when it detects the end-devices clock has gone out of sync, which forces the board's clock to re-sync.

The LoRa gateway connected to a router and a LoRa Server allows us to communicate between the end-devices and the server using two different protocols:

- The LoRaWAN protocol is used to establish a connection between the end-devices and the LoRa gateway.
- HTTPS connects the router to the WebServer/Application Server.

Actility and TTN (The Things Network), are worldwide projects with a myriad of interconnected gateways, focused on creating a secure IoT network based on LoRa technology and LoRaWAN protocol [44][45]. Each sensor is added to the network using the Actility or TTN console that provides a user-friendly interface to make device management as easy as possible. It also allows the integration of a variety of services such as HTTP, MQTT, and cloud services such as Azure or AWS. The Application server in this work bidirectionally communicates with a management server using HTTPS.

The application server is responsible for receiving the data from the LoRa server and processing it. For this purpose, a Raspberry PI, with Raspbian operating system, was configured to run a full-time Web server using the Flash Web framework written in Python programming language. The reason for Flask is due to its simplicity and optimized framework that is both lightweight and powerful for the task at hand. This server has the function of processing the incoming HTTPS messages with the UPLINK data packets from the end-devices. It then creates the corresponding objects according to the sensor's type and sends them to a database located on the same Raspberry Pi. This server also has the means to detect when any defined end-device has its real-time out of sync and send correction messages to the end-device in order to correct its clock. The data collected by the sensors is structured into individual tables in a SQL database for further analysis, consultation, and export. The power consumption sensors provide kWh per interval of time alongside generated information from the server such as date values (Week, Month, semester, working days, etc.), time, location, classroom occupancy, etc.

Dashboard and Python Analysis. PowerBI is a business analytics software from and for Windows. It provides not only interactive visualization but also a simple way to create flexible filters based on how prepared the database is for business intelligence with its data warehouse capabilities. While it is mostly used for non-real-time business indicators, it provides means to connect to several different APIs and web services. It also allows the programming of scripts in several languages such as R or python. PowerBI connects to a local MySQL database where all the data is stored. Temperature, power consumption and other variables for each classroom are acquired and stored locally and allow data extraction alongside the displaying of gathered information from the data we get from the end-devices using gauges, bar, line, and circular charts. Meanwhile, Python, using numpy and Pandas were used to, not only, clean the data but also to prepare predictive analytics solutions that can be used when higher data volume overtime is available. Python is also used to aggregate other data types to present it in a form PowerBI did not have available.

3.3.2 Device Layer: LoRa End Device

The end-devices were created using two principal components, the CT (Current Transformer) sensor, and the Arduino (Figure 9). The sensor reads the current from the wire and then feeds that information into the Arduino. The Arduino applies edge computing approaches by processing that information and saving it in memory. Then on a set Interval, sends the data to the LoRa server. Both the device and the servers make sure the data is never lost in case of network failure and receive messages to correct the end-device's own timer based on information that comes from the application server.

The device is also sustainable, as in, besides having very low power consumption on data sending, since it uses LoRa, it also requires very little human interaction over time. Right now, the only mandatory interaction required are rebooting when power outages occur due to its need to be power by electric plugs.

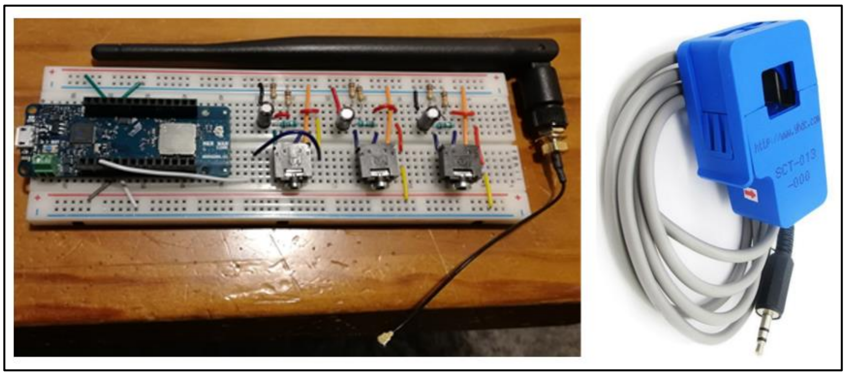

Figure 9 Three-Phase LoRa Current Sensor and Current Transformer Sensor

3.3.2.1 Current Transformer Sensor

Current Transformer Sensors measure Alternating Current (AC). This type of sensor is based on current clamps, which in turn use Current Transformers. Like a current clamp, the sensor has a ring of ferrite, with a wire coil around it forming a secondary winding. A primary current wire is then placed between the ferrite ring which carries the current we want to measure, the primary conductor.

As the example in Figure 10 shows, when an alternating current passes through the primary conductor, the secondary wiring generates an alternating current, whose values are much smaller but also proportional to the current that we want to measure [46].

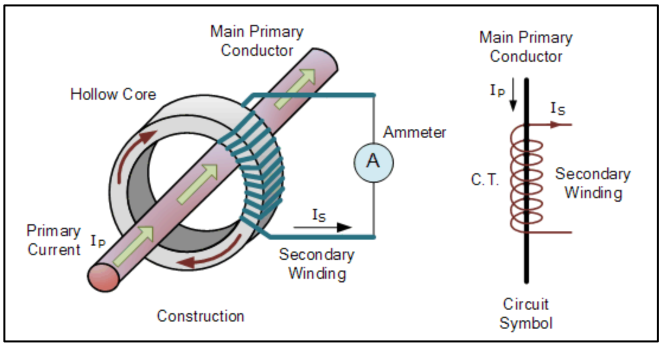

Figure 10 Current Transformer

CT sensors, also, have different secondary ratings. Ratings are the values of current or voltage the sensor provides when a certain primary current is being passed.

Example:

- A sensor whose rating is 100A:50mA, means that when 100A is passing through the primary conductor, the current value that this sensor outputs is 50mA without any control to the voltage.
- A sensor whose rating is 100A:1V, means that when 100A is passing through the primary conductor, the voltage value that this sensor outputs is 1V without any control to the current.

The Arduino then reads the resulting Voltage that this CT sensor outputs. In cases like 100A:50mA, where the output signal is a Current without a normalized voltage, there is the need to add a burden resistor outside of the CT sensor (i.e. in a breadboard), so that the electric flow meets the requirements of the Arduino analog input, 0v to the ADC (Analog to Digital) reference voltage. This reference voltage depends either on the input voltage from the Arduino or the maximum value that Arduino can handle. In this case, the burden resistor needs to be calculated based on the maximum Current the CT sensor can measure, and the Arduino power source input voltage.

On the other hand, some CT sensors output a normalized voltage and present us with ratings such as 100A:1V, this means that inside the CT sensor exists a burden resistor, so there is no need for one outside of it.

Three types of CT sensors were used in this work:

- SCT-013-000 - 100A:50mA

- SCT-013-030 – 30A:1V
- SCT-013-100 – 100A:1V

The particular reason for the choice of the current transformer SCT-013-XXX was due to costs, the cable length, and the output/input (audio jack).
The size of the current transformer was also one of the main parameters when choosing this transformer because in most cases the electrical boards are not properly prepared to receive sensors and the spacing between wires can create complications in the installation. Finally, it is also important to refer to the fact that it is Split-coil, which means it can be opened and installed around the wire which is a must for this type of work since we want to make installation as easy as possible.

Below, Table 3 shows split-coil transformers, with accuracies relatively close, that could have been used in this work. Letters in red show several reasons why they were not selected in the end.

Table 3 List of Split Coil Transformers in the Market

Model	**Max Input (Range of possibilities)**	**Price**	**Size**	**Opening Size**	**Observations**
SCT-013-XXX	30-150A	3.50€/ea	5.7 x 3.2 x 2.2cm	13 x 13mm	Most widely used for IoT works.
KCT38	50-600A	5.30€/ea	8.6 x 9.7 x 2.6 cm	38 x 38mm	Can only be closed with screws
BH-066-XXX	10-400A	2.54€/ea	8.0 x 6.0 x 3.7cm	20x20mm (minimum)	No wire, no known projects
PZCT-02	100A	4.63€/ea	3.1 x 2.9 x 4.7cm	Unknown	-
BZCT30AL	50 and 100A	7.20€/ea	7.8 x 6.2 2.4 cm	30x30mm	-

For each Arduino three CT sensors of the same type were used, thus creating a Three-Phase sensor (Figure 11), to connect the Sensor and the Arduino, breadboards with electrical components were used, based on specifications used by previous researches:

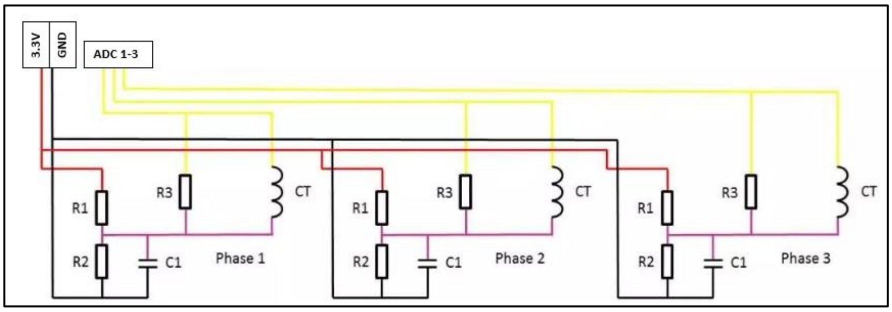

Figure 11 Three Phase Energy Meter [47][48]

- **R1 and R2** are voltage dividers. The main use for these resistors is energy consumption reduction and generating safe voltages for both the CT sensor and the Arduino to use. In our case, we use a power source instead of batteries so the value can be anything from 10k Ohm to 470k Ohm as long as both are of the same value. For batteries, the recommended value is 470k Ohm, which provides less energetic consumption by the sensor.
- **C1**, usually 10 µF, the capacitor provides a path for the alternating current to bypass the resistor. It is a decoupling capacitor to reduce noise.
- **R3**, the burden resistor, mandatory on sensors with a Current output signal, unneeded on sensors with a Voltage output signal. This resistor creates safe voltage values to be used by the ADC (Analog to Digital Converter) inputs on the Arduino while also creating a Voltage proportional to the value we want to measure (usually the Primary Max peak current returns a 1V value when connected to the burden resistor, as in 100A:50mA becomes 100A:1V). The resistor value can be calculated using the following formula:
  - $Ideal\ Burden\ Resistance = \frac{\frac{AREF}{2}}{Secondary\ Peak\ Current}$
    - AREF: Arduino analog reference voltage
    - $Secondary\ Peak\ Current = \frac{Primary\ Peak\ Current}{N^{o}\ of\ turns}$
      - $Primary\ Peak\ Current = Max\ Sensor\ Current\ \times \sqrt{2}$
  - **Example** for SCT-013-00 100A:50mA.
    - AREF, in this case, the Arduino output to feed the electrical components, equals 3.3V.
    - Nº of turns in this particular sensor is approximately 2000.
    - Max Sensor Current: 100A.

- $IBR = \frac{3.3A \times 2000}{2\sqrt{2} \times 100A} = 23.3\ \Omega$
- Since there are no 23.3 resistors, the closest one would be 22 Ω ± 1% or 18 Ω ± 1% is also acceptable as long as proper calibration procedures are followed.

- **CT** is the current transformer sensor whose output connects to the ADC inputs of the Arduino.

As mentioned before, the current Transformers sensor offers accuracies that vary depending on the power consumption passing through the main cable at the time:

- With values close to the expected rating of the current transformer, we can expect ∓ a 3% error [43].
- When measuring values that are very close to zero, we can see errors up to 10% [43].
- However, if we go above the expected maximum rating by a large factor, we risk error results up to 70% due to saturation [43]. In Figure 12 we can see the problem that occurs when too much current is measured using a 100A:50mA CT. Up until 100A, we see the linearity between the voltage we are going to, send into the Arduino and the primary wire current using a 22-ohm resistor. After the 100A that linearity is gone, so the values presented using the usual formulas will be wrong.

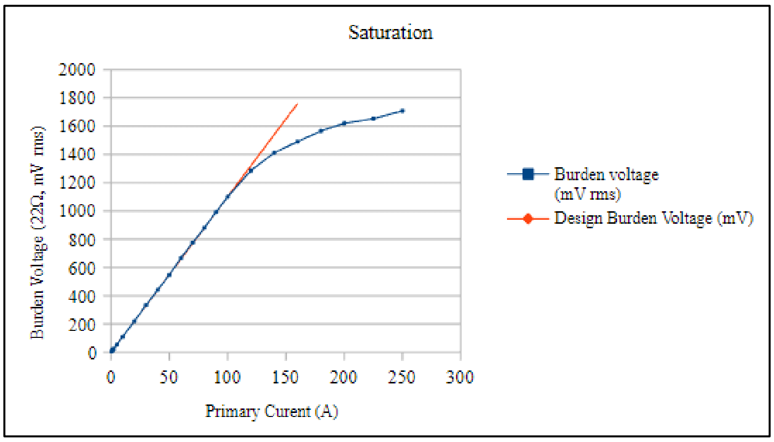

Figure 12 Voltage deviation due to saturation

3.3.2.2 Arduino MKR 1300 WAN

The Arduino is the main communicator with the servers. It receives data fed by the current transformers, making it into kWh per data Read interval, summing it to a total value and then, at a data Send interval, send that value through a LoRa Network to a LoRa gateway. It is also able to receive messages from the application server when needed.

The main characteristics of this board are the following:

- Microcontroller SAMD21, along with an RTC (Real-Time Clock), allows us to use a library called RTCZero, which controls the Arduino's RTC enabling the creation of alarms.
- Circuit Operating Voltage of 3.3V, which is the maximum voltage we can apply to this board both through source input or ADC input, although by using a power supply through micro-USB (5V) we can bypass this limitation on the source input.
- Carrier Frequency of 433/868/915 Mhz, frequency used by LoRa.

Three fundamental libraries are necessary:

- **MKRWAN**
    - This library provides an API that uses the built-in LoRa chipset to receive and send messages through LoRa networks.
    - With this library, there is the possibility to define keys and get the Device EUI from our device to then create an agreement with the nearest gateway.
    - After an agreement is created, data can be sent through a LoRa network, and each time a message is sent, two types of messages can be received from the LoRa server.
        - The first message is the feedback acknowledgment from the LoRa server, indicating that the LoRa server received a message, sent automatically for each data uplink received by the LoRa server.
        - The second message that can be received from the server are messages that serve as commands that permit the board's RTC to calibrate itself in case there is an issue with the timings. These downlink messages are sent by the application server and are put on the queue at the LoRa server waiting for a new data uplink (Class A, explained below).

- **RTCZero**
  - This library provides an API to use the built-in RTC in the SAMD boards.
  - Real-time clocks provide a means of creating alarms and defining the board's real-time in the necessary instant.
  - RTC works in a parallel frequency to the normal clock frequency of the Arduino, so it keeps running, even, while the Arduino is in sleep mode.
  - RTC requires re-synchronization from time to time so that it doesn't become unsynchronized with the actual real-time.

- **EmonLib** (Arduino Energy Monitoring Library)
  - This library provides an easy way to transform the input voltage from the ADC into a readable Current value that can be calibrated.
  - For each reading, we can define the number of samples for the library to calculate, the bigger the number of samples the longer the method it takes to calculate the Current.
  - The library uses the Root Mean Square to calculate the current:
    - Supposing N equals the number of samples, and u(n) being the voltage sample that we get from the ADC:
      - $Urms = \sqrt{\frac{\sum_{n=0}^{N-1} u^2(n)}{N}}$ (1)
    - This (1) Urms value is then multiplied by the calibration coefficients, based on the value we define at the beginning for each ADC input, which results in a Current Value which we call $Irms$.
    - With the $Irms$ we calculate the Apparent Power by multiplying it with a voltage constant.
  - Each phase calculates his own Apparent Power in kWh/Interval (kilowatt-hour per data Read Interval), which is then summed into a total kWh/interval value that is kept in the Arduino's memory until it is sent as a message. The message is only considered "sent" when feedback from the LoRa server is received, and only then the

sequence number is advanced, and the total kWh/Interval value resets to zero.

- **Calibration:**
  - The calibration of the sensors is done for each ADC input.
  - Calibration has theoretical value based on the CT sensor rating and the burden resistor used:
    - $CalValue = \frac{CT\ Ratio}{BurdenResis}$
    - $i.e: 100A: 50mA \rightarrow \frac{100/_{0.05}}{18} = 111.1$
  - Theoretical values, however, do not account for hardware error variations so the calculated value should be used as a baseline and then adapted using real value comparisons.
    - Errors can come from several factors, such as:
      - CT materials.
      - Burden Resistor ± 1%.
      - Arduino Analog Reference.
      - Power Source.
    - To provide real values, an Amperometric Clamp Uni-T UT202 was used for comparison in real-time calibration.

3.3.2.3 Arduino MKR 1300 WAN: Workflow

Finally, in Figure 13, we can see the general workflow for the algorithm used in this board and the overall workflow used to measure power consumption with Arduinos. On the annex, a written version of this workflow is mentioned (Annex 2).

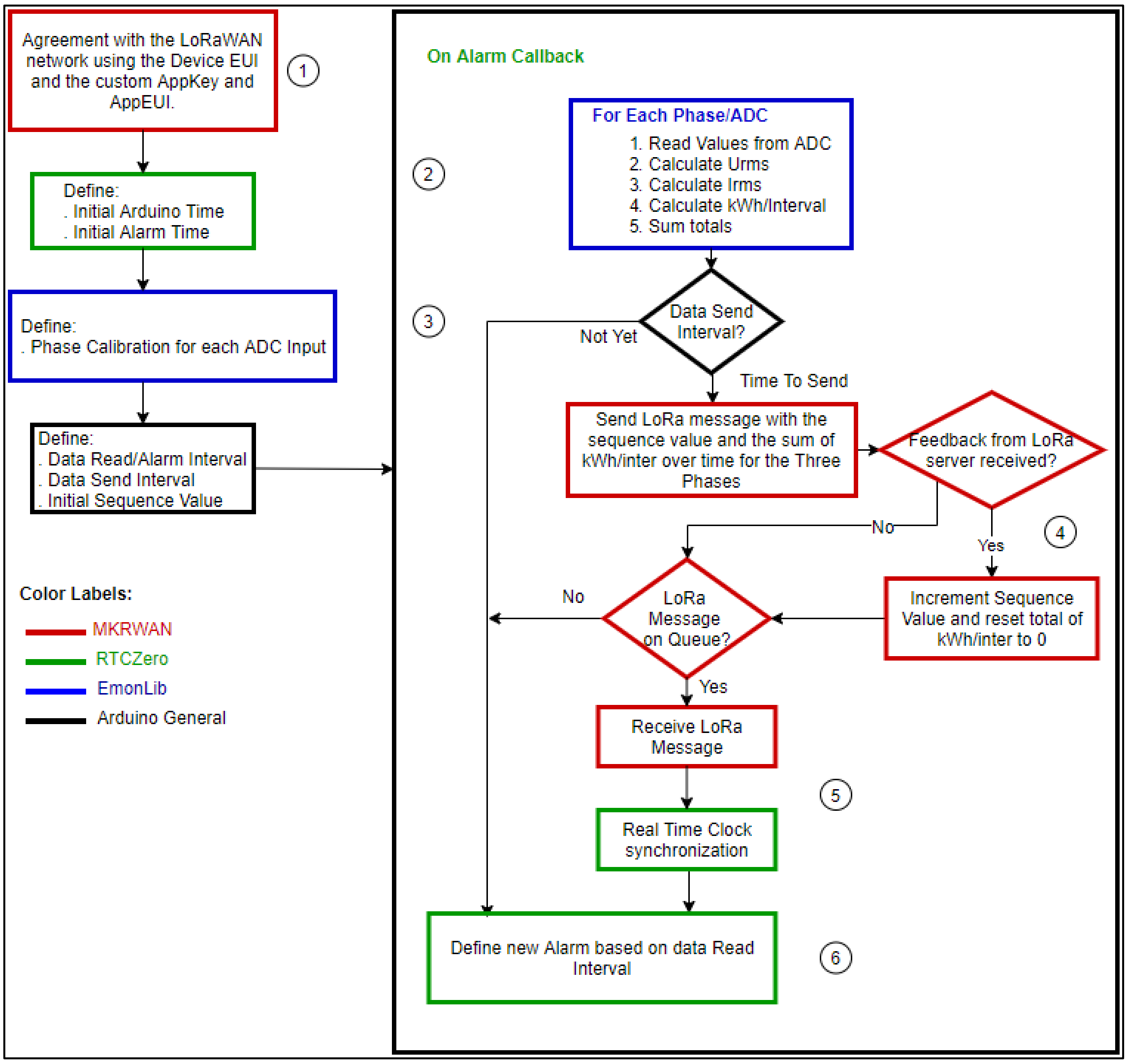

Figure 13 Arduino Workflow

3.3.3 Communications Layer: LoRaWAN

LoRa is a spread spectrum modulation technique derived from chirp spread spectrum (CSS) technology with Long Range, low power wireless chipset whose aim of it was to resolve challenges such as energy management, natural resource reduction, pollution control, infrastructure efficiency, and disaster prevention. Operates on the LoRaWAN standard maintained by LoRa Alliance whose ecosystem consists of over 500 members and includes over 100 public network operators with service in 51 countries [29]

The key principles of LoRa are the following [29]:

- **Security**. *"Features end-to-end AES128 encryption, mutual authentication, integrity protection, and confidentiality."*
- **Low Power.** *"Requires minimal energy, with a prolonged battery lifetime of up to 10 years, minimizing battery replacement costs."*
- **Long Range.** *"Connects devices up to 30 miles apart in rural areas and penetrates dense urban or deep indoor environments."*
- **Low Cost.** **"***Reduces infrastructure investment, battery replacement expense, and ultimately operating expenses.***"**
- **Mobile.** *"Maintains communication with devices in motion without strain on power consumption."*
- **High Capacity.** *"Supports millions of messages per base station, meeting the needs of public network operators serving large markets."*
- **Standardized.** *"Offers device interoperability and global availability of LoRaWAN networks for speedy deployment of IoT applications anywhere."*

While LoRa technology is the lower physical layer of the network, LoRaWAN defines the protocol that occupies the upper layers and acts as the network layer to manage communications between LPWAN (Low Power Wide Area Network) gateways and the LoRa end devices as a protocol for routing with provided security [49].

The reason we choose LoRa for this research work was the need for a network that could work in several environments without the need for a nearby gateway and was partially unfazed by most obstacles. We choose LoRa for the following reasons:

- A Wi-Fi network is low range, and it loses a lot of strength between walls so in areas with only one Wi-Fi Router it would complicate the process since the Routers and the electrical boards aren't usually right next to each other.

- In the university experiments, we noticed the Wi-Fi network was protected with authentication that required both a user and a password. Most IoT boards do not allow for this kind of authentication, so we needed a way to circumvent this.
- In the near future (not on the scope of this work) the solution is going to be upgraded from being powered through the power plug to being powered by batteries and LoRa is perfect for that.

3.3.3.1 LoRa network topology

For the network's topology (Figure 14), we can look at it the same way we look at our system's architecture. We have the end-nodes that are the **LoRa devices** that send data to a **LoRa gateway**. That LoRa gateway is connected directly to **a regular router** that connects to a LoRa network server. This network server routes the packets right into their preferred **application servers** by using the defined integrations.

All of this is secured end to end using AES-128 encryption.

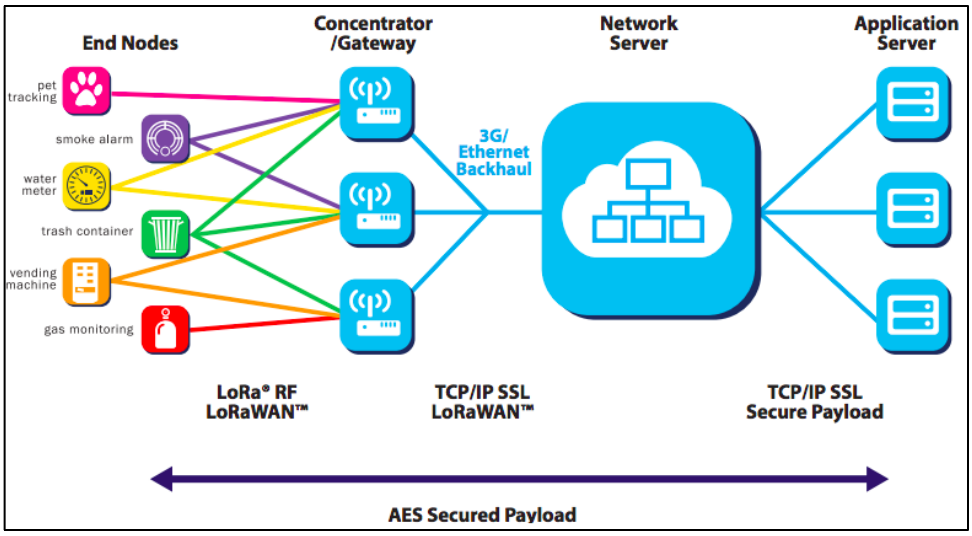

Figure 14 LoRa Network Topology [29]

3.3.3.2 LoRa Device Bi-directional Communication Classes

LoRa applies three different types of classes, these classes exist for one main purpose, the battery saving capability, being class A the class that enables a "10 year-long battery autonomy", class B, the middle ground and class C the one that should be powered using a power source. When it comes to battery autonomy, the developer should also care to limit its payload since larger payloads mean more energy consumption when sending data [50].

Class A. LoRa Class A devices are kept in sleep mode unless they need to transmit something. Only after an uplink transmission by the end-device into the LoRa server, the server will schedule a downlink transmission with the device. As shown in Figure 15 once an uplink is finished the device opens up two receive windows (1st second, Rx1 and 2nd second, Rx2 after the uplink) if the server does not respond after those windows, the next chance to receive the downlink will be on the next uplink [51].

The devices used in this work uses this same principle, the difference being the sleep time is cut off because the device needs to measure power consumption when not sending data.

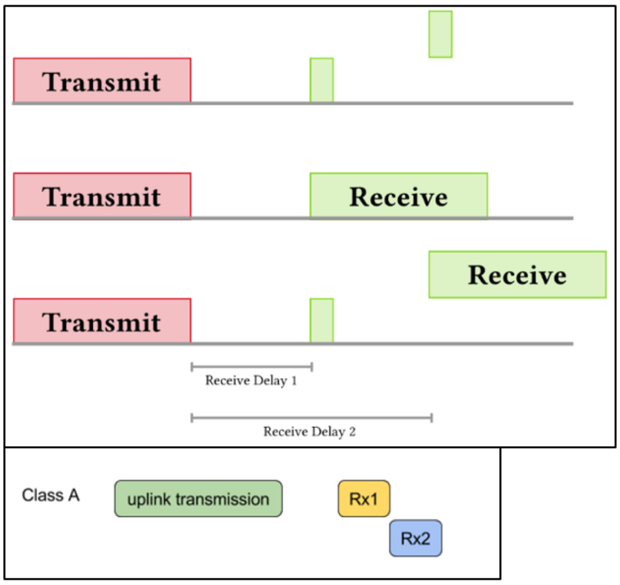

Figure 15 Class A Downlink Windows [47]

Class B. LoRa class B (Figure 16) is an extension of class A that opens receive windows periodically using time-synchronized beacon frames transmitted by the gateway, which means the gateway defines those transmit windows, not the device [51].

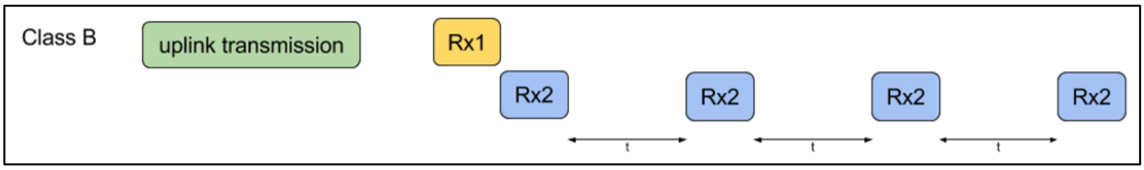

Figure 16 Class B Downlink Windows [47]

Class C. LoRa Class C (Figure 17) keeps the transmission window completely open unless an uplink is being performed. While this considerably reduces bi-directional communication latency, it also consumes a lot more energy.

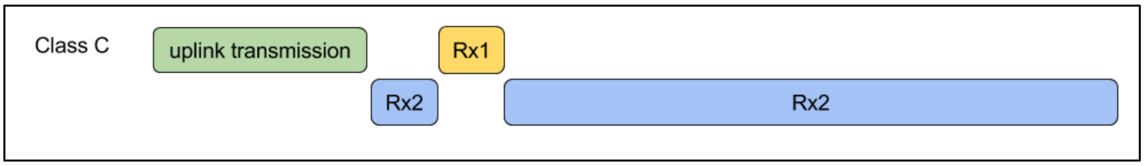

Figure 17 Class C Downlink Windows [45]

In summary, each device must be picked depending on the conditions of the surrounding area keeping in mind the factors shown in Figure 18.

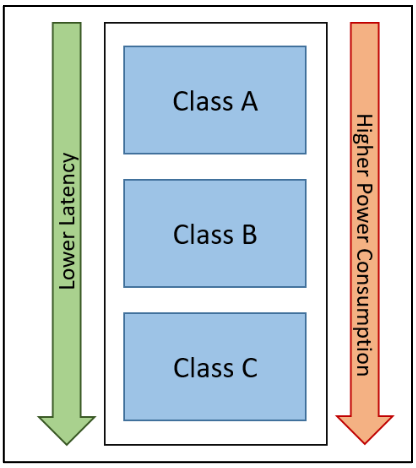

Figure 18 Device Classes Summary

3.3.3.3 LoRa Limitations

Before delving into limitations, we need first to understand that between different end-devices, LoRa spreads its communications between different channels and frequencies. This happens because end-devices can have different communication qualities such as range, message size that affects duration, materials between the device and the gateway, and so on. So for each end-device, they are assigned an SF (Spreading Factor) based on the quality of the communication. Each spreading factor has different rates has seen in Figure 19 [52].

Spreading Factor	Bandwidth [kHz]	Spreading Factor [chips/symbol]	Bit rate of the signal [bits/sec]	Chip rate [chips/sec]	Time per symbol [sec/symbol]
SF7	**125**	128	5469	125000	0,001024
SF8	**125**	256	3125	125000	0,002048
SF9	**125**	512	1758	125000	0,004096
SF10	**125**	1024	977	125000	0,008192
SF11	**125**	2048	537	125000	0,016384
SF12	**125**	4096	293	125000	0,032768

Figure 19 Spreading Factors Attributes [52]

In this work, we are using LoRa as a means to communicate in near real-time with the server. However, LoRa, as a network is not the best candidate for critical real-time solutions due to its latency limitations even at lower spreading factors (SF = 7) and sending data of 10 Bytes, may even lead to delays of 400ms. This limited nature of the network also means that the bigger the packet and the lengthier the range, the more time this packet will stay on the air, as seen in Figure 20 [32].

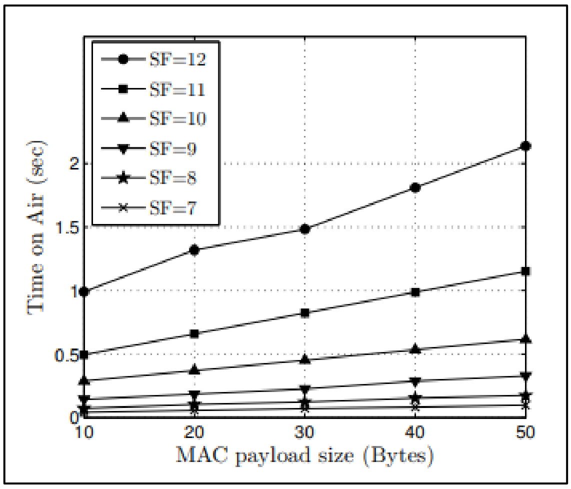

Figure 20 Time on Air of LoRaWAN with code rate 4/5 and a 125 kHz bandwidth [32]

When it comes to reliability LoRaWAN uses acknowledgments of frames in the downlink on the receive windows, devices should actually try and minimize the request for acknowledgments to avoid reaching a capacity limit. Acknowledgments also cause significant battery drain since they are using the communication windows [32].

RSSI (Received Signal Strength Indicator) meanwhile, aggregates all these factors and returns a single value, an estimated measure of strength level that a radio frequency client (in this case the LoRA device) device is receiving from a gateway. A weaker signal means slower data rates.

3.3.3.4 University LoRa Experiment Reliability Results

End-Devices in one of the experiments (University experiment, Chapter 4) were placed both in an underground auditorium and in an auditorium that could be described as being ground level, shown in Figure 21. The difference in both these devices was noticeable, not only in the receiving of acknowledgments but also in a number of delayed packets. In Table 4, we can see the main difference between both groups of devices.

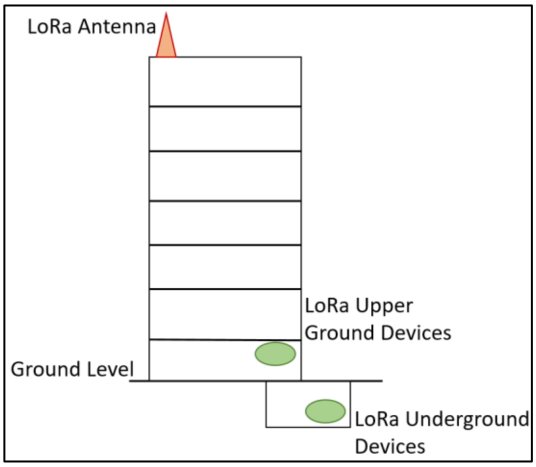

Figure 21 Lora devices in auditoriums

Table 4 Comparison of reliability between devices above ground and devices underground

Device	Ground Level Devices	Underground Devices
Spreading Factor	SF7	SF8/SF9
Channel Rotation	Channel 1-3	Channel 1-8
RSSI (average)	-73	-117
Delays (+1 minute)	1,1%	2,6%
Average Delay (minutes)	0m:54s	1m:26s
Missing Acknowledges	3.2%	7,1%

RSSI: Received Signal Strength Indicator (Higher is better)

Missing Acknowledges were detected on the Application server using an algorithm (explained on 3.3.4.4) that tracks these issues based on the sequence value received from the end-device. With the delays, there was no need for an algorithm since every device is set to send on a defined time interval and the sensor's time is synchronized with real-time with the help of the application server. So any delay is easy to calculate based, simply, on when the message reached the application server.

As we see in Table 4, we noticed that a significant number of ack downlinks are lost in the air, due to the small receive windows of Class A devices and a connection that is not completely optimal. No lost data uplinks were detected during the experiments.

In all the other cases (Chapter 4) done in this research, a LoRa gateway was created and placed in a nearby area with an internet connection. Therefore, all connections were performed in SF7 with barely any network issues.

3.3.4 Data Layer: Web/Application Server and Database

The application server, running on a Raspberry PI, has four main functions:

- Receive reading data, treat and analyze that data, and store it in MariaDB.
- Calibration of each end-device's real-time clock.
- Correction of issues caused by missing uplinks and downlinks.
- Replication and Union of databases' tables into one live database.

Raspberry PI was chosen as the hardware for this server for the following reasons:

- Low Power Consumption
- Unix based OS (Debian/Raspbian), which means it's open-source and, as such, free and, to some degree, safe.
    - Acceptable hardware specifications compared to some **free** cloud options in the market.
- The easy portability of both the hardware and software.
- Ease of use.
- Low-cost and durable.

The HTTPS application server was created using Flask, a microframework based on Werkzeug and Jinja 2. The reason this framework was picked can be seen as the same reasons his creators called it "micro" framework:

- Ease of use but also easily extensible.
- Databases in use are up to the application developer.
- Default options are easy to change, and the framework can easily handle multiple libraries.

The application server also uses an OpenWeatherMaps API to obtain outdoors temperature that is then used for further analysis. OWM API is completely free and does not have monthly limitations on its base model, unlike some competitors.

3.3.4.1 Database

The server connects to a MariaDB database. This database server is completely free and open-source with a great variety of features while also maintaining backward compatibility with MySQL.

The database schema (Figure 22) used for this work contains five main tables:

- **Reading**: the main table and connector to all other tables.
- **Date and Time**: both these tables present information based on temporal marks that simplify the analysis of the Reading entries.
- **Device:** contains information about the sensors, the locations they are placed, and what they are measuring. It is used both to feed sensor information to the application server and to help the consumption analysis.
    - *Active* attribute tells the server if it should expect data uplinks from a certain sensor.
    - *Correction* attribute tells the server what the proper time it should expect from the sensor is, and it also serves as an indicator as to whether that sensor requires correction or not.
    - *DevType*, indicates the type of sensor, Arduino (made in this work) or Third-party.
    - *Margin* acts as a lower limit to values, to remove outliers caused by small reading errors.
- **Alert:** This table, not connected to any other table, is used to present alerts when it comes to the communication layer's error like delays or missing acknowledgments. When an error is found a new entry is added to the database, where the description tells us the type of error and the value tells us the degree of that error.
- **Other Tables based on the Implementation (Optional):** tables that can be added to the database based on where the solution is being used (example: Class, for university implementation, shown in Figure 22).

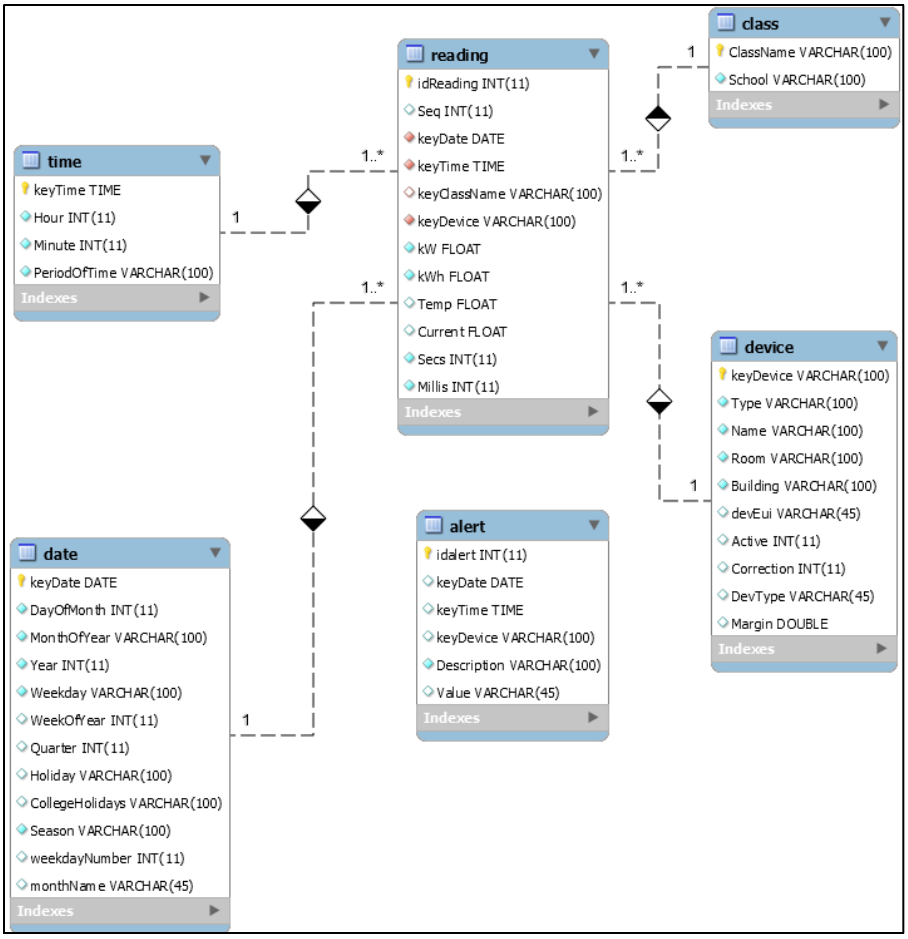

Figure 22 Database Entity-Relationship Model

As we can see from Figure 22, this database is based on a Star Schema model used in data marts, although, most of the rules for the creation of star schemas were not used. The decision for this type of model came from two main factors:

- Simplicity
  - If each "dimension" table (the tables around Reading) have pre-defined values, those values can easily be called when inserting a Reading entry, and then easily queried when the analysis is required.
  - Simple queries create performance gains.
- Storage efficiency (less space occupied overall) and, therefore, increase performance when using queries.

3.3.4.2 Application server: Data Treatment

Before adding data from the readings into the database, we need to treat that data and generate information based on the attributes we have at work. The server generates data based on the readings it gets from the sensors. There are two main approaches to obtain data using this application server:

- Directly from the sensors and into the database.
- Derived from sensor reading data.
    - Data that uses readings from sensors to generate new data.
    - Derived data is important because sometimes, due to the way electrical boards were made, there is either no space between wires to add a current transformer or the phases are all mixed up.
    - **Example**:
        - Let's say that $\text{Total\_Current}_{\text{Room1}}$ is one current measurement from a sensor.
        - $HVAC_{\text{Room1}}$ is another current measurement.
        - $LIGHTS_{\text{Room1}}$ is yet another current measurement.
        - From these 3 current measurements that come from the sensor, we can derive the following data:
            - $Other_{\text{Room1}} = \text{Total\_Current}_{\text{Room1}} - HVAC_{\text{Room1}} - LIGHTS_{\text{Room1}}$
            - $Other_{\text{Room1}}$ is the electrical plugs derived data that is, also, added to the database.

Before the server initializes, there are a few procedures it must follow:

- (Optional) Every 30 minutes, the server, by using OpenWeatherMaps API, updates the temperature value from the outside, so this thread (programming thread) must be started before the first reading arrives.
- Obtain a list of active devices. This list of active devices is obtained from the database and consists of pairs of key:values where the key belongs to the device devEUI and the value is the deviceID on the database.
    - **Example**: A8640A31703C7313 : HVAC_ROOM1
        - The devEUI above belongs to the current sensor measuring HVAC in Room 1.
- Obtain, from an outside JSON, a list of derived Reading calculation sheet, which allows an algorithm to calculate derived data the moment every

necessary reading from the end-device arrives. An example of the Json file can be seen in Annex 1 of this work.

Once the server is ready to start data is allowed to be received:

- End-Device's Reading Data gets generated by the end-device and is then sent through a LoRaWAN network where it gets received in the LoRa gateway.
- The LoRa gateway then places it on a LoRa Server, and that server generates an HTTPS POST request to any URL the developer previously defined.

1. The Application receives this POST request, and then uses it to creates a small dictionary line shown in Table 5 below.
2. For each data posted a verifier worker checks for **Derived reading data**, to verify if all the required entries to generate that Derived reading data are complete. In case it gets completed, a new dictionary line is generated too.
    - **Example**: The flowchart below (Figure 23) exemplifies how the Derived data $Other_{\mathrm{Room1}}$ would be formed like:
    - $Other_{\mathrm{Room1}} = Total\_Current_{\mathrm{Room1}} - HVAC_{Room1}$
  - **Derived Data Issue:** In case, reading from a sensor gets lost during transmission, all the values forward would be wrong.
    - **Solution:** At a set interval where all messages are supposed to be received, all values in memory are reset to -1, the same as if all values were received, as shown in Figure 23.

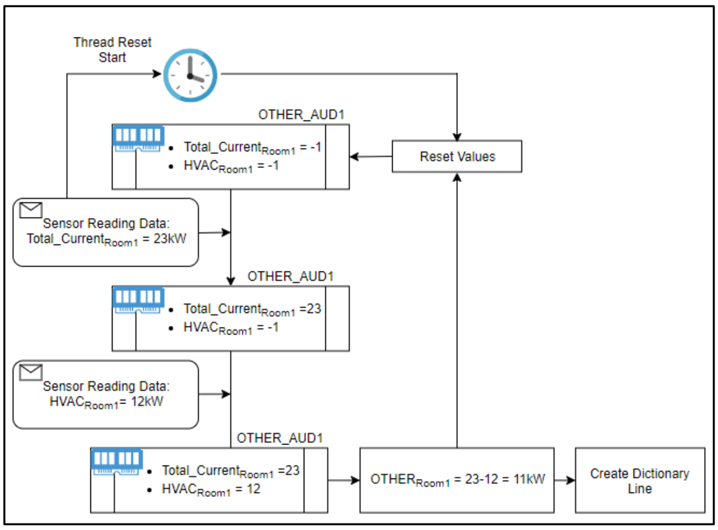

Figure 23 Derived Data Workflow

Table 5 Facilitator Dictionary Line

Key	**Data Type**	**Objective**	**Example**
Time	Datetime	Server time that is used to generate information for the tables Date and Time on the database	'2019-01-30T17:00:31.003876+00:00'
Internal	Integer/ Boolean	Tells the server if this message was generated by a sensor or if it is derived.	1 or 0
kWh	Float	Kilowatt-hour/interval value, the minimum value is defined by the attribute *Margin* in the Device Table	45,67
ID	String	Device ID obtained from the list of devices in memory loaded initially.	'AVAC_ROOM1'
Alerts	List of Dict	If any communication error is detected the description and value are appended to this list	[{“Delay”:1 Min},{“Repeated Sequence”: “No Value”}]

3. This dictionary line from Table 5 is then sent to another module called Reading. This module is the link between the server and the database. It reads this dictionary line and generates information based on it, creating a new Reading entry with the proper foreign keys:

- **Date and Time:** Verifies if the requested date and time already exists in the database's tables. In case it does exist, it simply adds a Foreign Key to the Reading entry. In case it doesn't it generates all the information necessary for the tables Date and Time on the database, insert that information into the database and then on the Reading entry add the foreign key.
- **Device:** Verifies if the device exists in the database. If it doesn't, it discards the Reading entry, in case it does it adds the Foreign Key. Due to their nature, devices need to be inserted manually in the database.
- **Reading:** Reading is the main entry and the link between all tables, it contains foreign keys to all other tables, consumption information, and outdoors temperature information.
- **Other Informations Table:** Adds any other relevant information based on the implementation that is being used

3.3.4.3 Application server: Calibration of End-Device Sensor's Clock

One of the main problems encountered with the MKR Arduino was real-time desynchronization. Over time the Arduino would send the data sooner and sooner, tested by the millisecond, and then after a few hours, it would lose a second. This was an issue that needed to be solved or else over time end-devices would become desynchronized with each other:

- **Example of the problem**:
  - **Sensor 1**, set to send every 5 minutes at minute HH:00, HH:05, HH:10, HH:15.
    1. **Sensor 1** loses 1 second every 3 hours.
    2. After 5 days, **sensor 1** would send data at minutes HH:59, HH:04, HH:09, HH:14.
  - **Sensor 2**, set to send every 5 minutes at minute HH:00, HH:05, HH:10, HH:15.
    1. **Sensor 2** loses 1 second every 2 hours.
    2. After 3 days, **sensor 2** would send data at minutes HH:59, HH:04, HH:09, HH:14.

- Data on the database on day 3
    1. **Sensor 1**, sending data at HH:00, HH:05, HH:10, HH:15.
    2. **Sensor 2**, sending data at HH:59, HH:04, HH:09, HH:14.
    3. Analysis done by the hour would receive data from different time periods for each sensor.
    4. **Sensor 1** would only become synchronized with **Sensor 2** after 2 more days, and between those 2 days, data analysis results could be erroneous.

Time Calibration Solution: Have the application server verify the seconds of the received message and, then, send a message to the end-device in case they start deviating from the normal values. This message indicates that the RTC on the end-device's board must increase or decrease one second.

- **Problem 1:** If there are "delays" caused by the network between the LoRa server and the application server, the application server sends messages to correct those delays every time. Once the "delays" are corrected, the application server has to send more messages to re-calibrate the sensors since they are wrongfully corrected because of the previous network delays.
- **Problem 2**: LoRa messages for this type of Arduino (class A LoRa) can only be received when a message is sent from the Arduino to the server. This means that once the Application Server sends the corrective message, the message is only received on the data send interval. This could cause message loops:
    - **Example:**
        1. Sensor 1, due to a network delay, sends data at second 40 instead of second 30.
        2. Application Server queues message to seconds to the sensor.
        3. Sensor 1, sends another data, this time usually at second 30, but receives queued message to add seconds.
        4. Sensor 1, is now sending data at second 21, so another message must be sent to fix it.
- **Overall** several unnecessary messages had to be sent due to simple Arduino errors. As mentioned before, with LoRaWAN, we need to be careful with unnecessary data traffic.

- **Solution:** Add a chance to send the message to the application server, in this case, a 33% chance to send a message in case it detects a timing error.

To send messages to the LoRa server, there is, also, the need to generate an authentication and authorization token for the server's user the application belongs to. After generating this token, the user is allowed to send messages for a fixed period of time until that token expires and a new token has to be generated. After the program obtains a token it sends a POST request to the LoRa server, through an HTTPS connection, with the corrective message. The LoRa Server then saves the message in a queue and send it the next time the Sensor is ready to receive it.

Workflow for the whole correction process, server-wide, is shown in Figure 24:

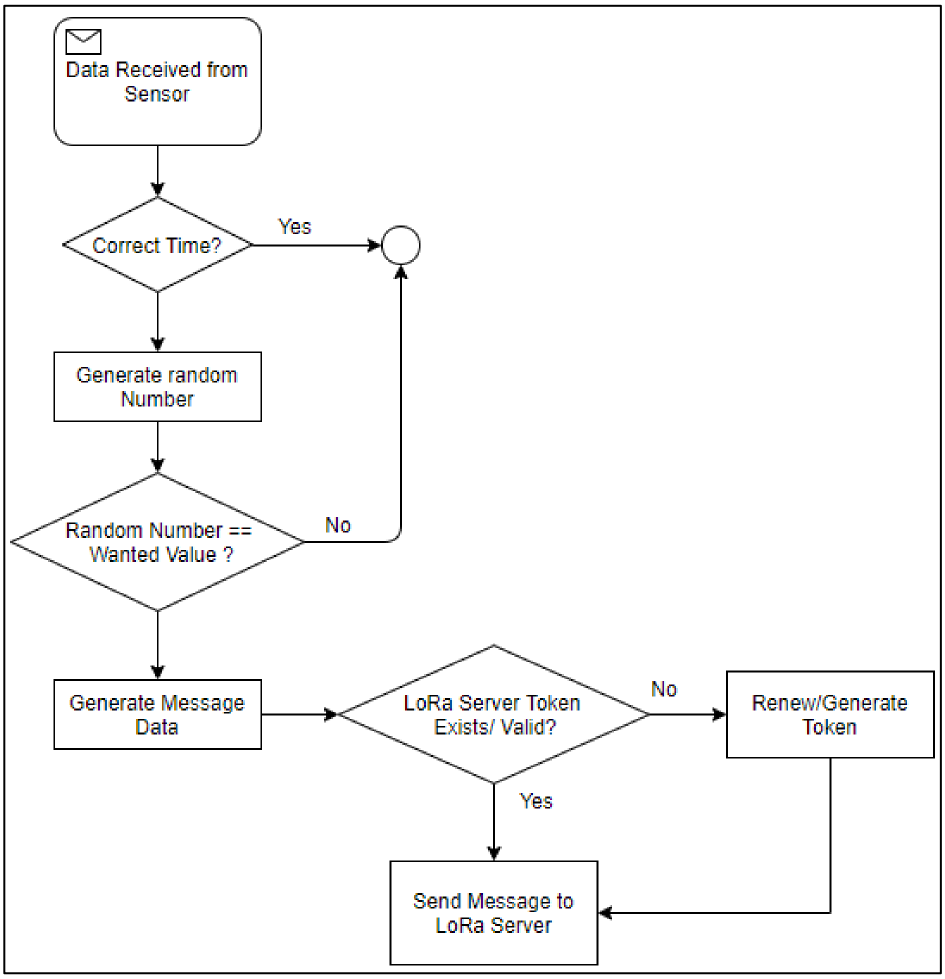

Figure 24 Sensor Correction Workflow

3.3.4.4 Application server: Correction of Missing Packets

To correct missing packets we use Sequence values that are programmed inside the Arduino's code and are only incremented when a feedback message from the LoRa Server is received right after the Arduino sends his data to that server. The data value (sum of kWh /interval) is also only reset to 0 when feedback is received.

There can be three types of missing packets that are problematic:

- **Lost Feedback Acknowledgment from the LoRa Server to the end-device:** In this case, the data has reached the LoRa Server, it is sent to the Application server, but the feedback message to the end-device was lost.
  - **Problem:** The sequence value is not incremented, and the sum of kWh/interval is not reset to 0.
  - **Solution:** The application server always saves the last message received, for each device ID, and then compares the sequence value. If the sequence value is the same as the last one, it means the message was sent, but the feedback was not received. In this case, it just needs to subtract the most recent value with the last value. An alert is then added to the Alerts table.
    - **Example (Messages from same DevEUI):**
      - **Message Received 1** - Time: 10:10:00, Sequence: 330, kW: 0.40 (message saved in memory).
      - kW value saved in database 0.4 kW.
      - **Message Received 2** – Time: 10:15:00, Sequence: 330, kW: 0,81 (New message).
        - **Repeated Sequence warning.**
      - kW value saved in database will be 0.81-0.4 = 0.41 kW.
      - **Message Received 2** saved in memory with value 0.81 kW.
      - **Message Received 3** - Time: 10:20:00, Sequence: 330, kW: 1.51 (New message).
        - **Repeated Sequence warning.**
      - kW value saved in database will be 1.51-0.81 = 0.40 kW.
      - **Message Received 3** saved in memory with value 1.51 kW.
- **Lost Uplink from the end-device to the LoRa Server:** In this case, we won't get the data for that time interval, but then again, no acknowledgment is sent to

the end-device so the next time the sensor sends his next packet the sum of kWh/interval has the values from that last missing packet, so no data is lost.

- **Lost Data HTTPS Post Request from LoRa Server to Application Server:** Sometimes due to Wi-Fi network congestion packets may be lost between the two servers, and this is why the LoRa server was defined to send packets to two application servers, one using the internal network and another using an external network. This two server at a set interval join together both its databases (below at 3.3.4.5).
  - **Problem:** The packet did not reach any of the two servers.
  - **Solution:** None, the data was lost, but we can manually obtain it by checking the LoRa server logs if really needed.

3.3.4.5 Application server: Replication and Union

At a set interval, the database from one internal network replicates itself (Figure 25) on the database of the external network in a backup table on that external database based on the primary key. This backup table also has a trigger that, when a new entry is inserted, adds the entry to a temporary table in the internal database.

The server compares the Time, Date, and device ID on that temporary table and if something is missing from the live table, it adds from that temporary table. In this temporary table, each selected value is then deleted, so it doesn’t fill up.

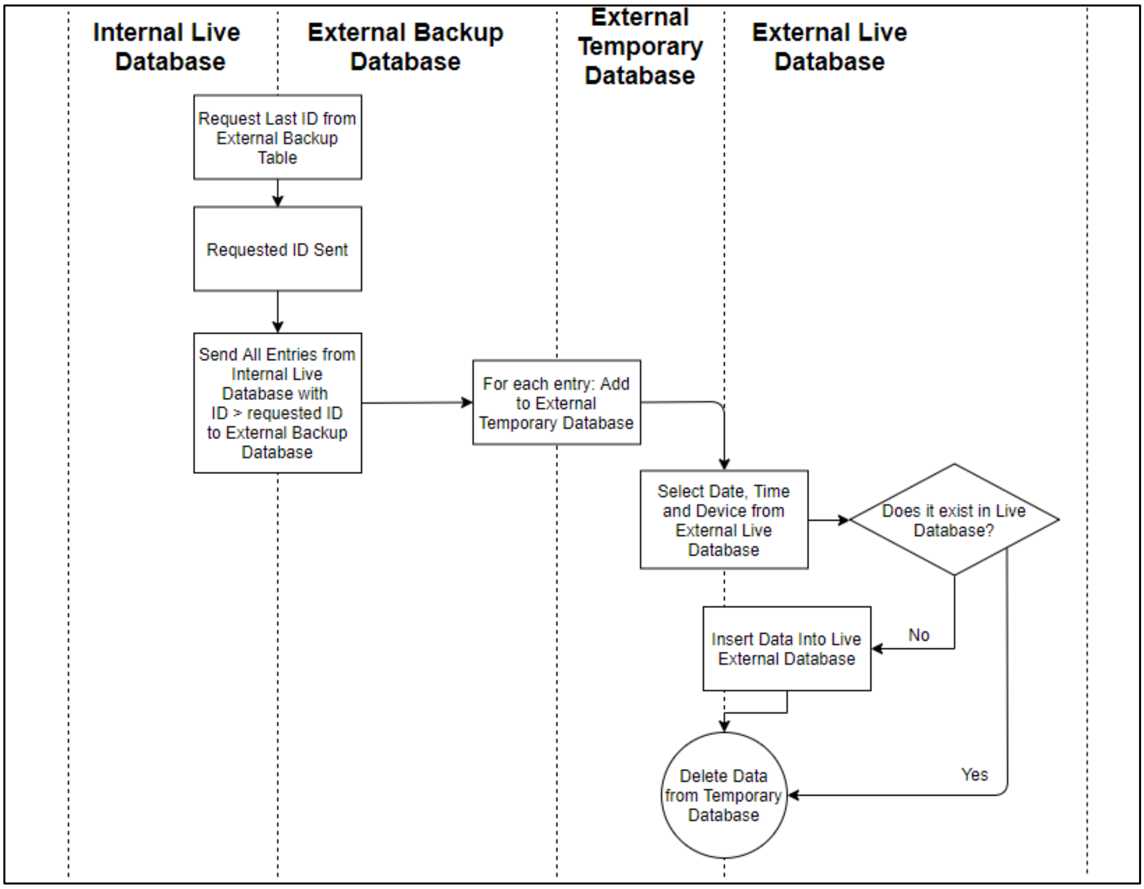

Figure 25 Application Server Backup Routine

The workflow was done this way to avoid errors caused by network congestion/packet losses. In case an export job is interrupted in any of the steps above the data always finds a way to reach the external live database since interrupts in any part of the process can be solved:

- **Interrupt on Internal Live Database to External Backup Database:** For each job the ID requested is the one from the Backup table so if a full backup isn't finished in one iteration the other always gets it. In case there is an interrupt, data is also not placed on the External Temporary Database since the job is done with database triggers.
- **Interrupt on External Temporary Database to External Live Database:** If an interrupt happens, the entry is not deleted from the temporary database and as such it is verified in the next iteration.

3.3.4.6 Application Server Overall Workflow

Finally, as a summary, Figure 26 shows what the entire workflow of the server looks like from a Top point of view.

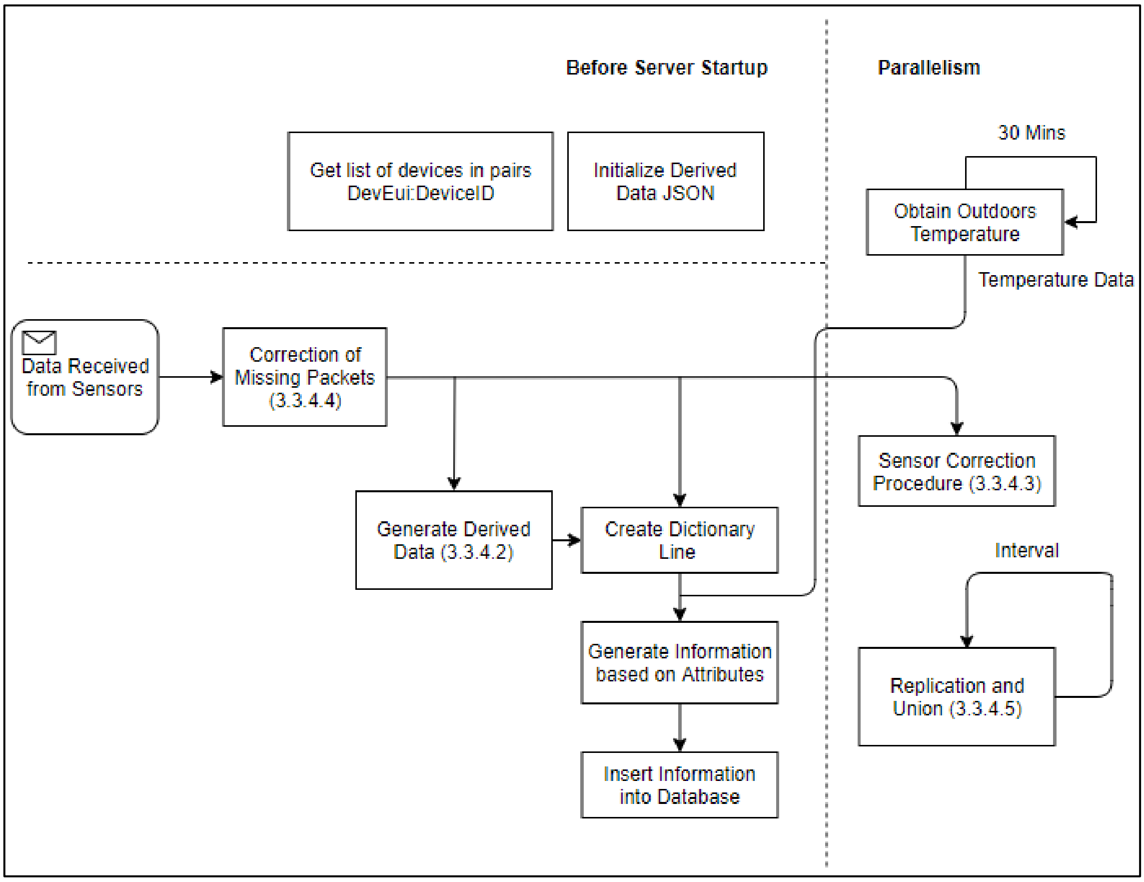

Figure 26 Application Server Workflow

3.3.5 Information Layer: Dashboard and Analysis

The dashboard done in PowerBI provides a means to visualize the data in a timely manner when the users want. Its main objective is to provide day to day information using descriptive analytics that can help in managing the energy consumption of the facilities that are being measured, both in a real-time environment but also in the long term. This type of analytics (descriptive) allows us to understand what is wrong and what is right, with the expected outcome of this part of our system being, to learn from past behaviors and how they can be used to influence the outcome of future events.

The predictive analysis was also considered, and a set of models were tried, however, the focus of this work was not to try and create forecasts on the future. Also, one principal issue encountered when trying to do predictive analytics was the lack of data volume for the timeframe used, which would compromise the results and the outcomes.

Once again, the database we are using is MariaDB/MySQL, which then copies its data in a local PowerBI that contains a database of its own. As for the python scripts, the data is obtained with the help of both the PyMySQL library and the Pandas library, which offers built-in MySQL features.

3.3.5.1 PowerBi Dashboard

PowerBi was chosen as the dashboard software for its free properties. It's a powerful and optimized tool capable of handling, analyzing, and aggregating hundreds of thousands of data at the same time without slowing down. It is also one of the tools with visuals that are pleasing to the eye and allows for easy sharing between computers as long as they run on Windows OS.

To enumerate a few advantages:

- Filters are intuitive and easy to place as long as the database is well organized.
- In-software database replication speeds up the aggregation process.
- Free limitations are not that problematic; 1GB storage is more than enough.
- The software is recent and is being updated constantly.
- Any new device complying with the database can be easily added into this dashboard.
- Visuals are top-notch.

And a few disadvantages:

- With free limitations, data sources are limited, especially if we want a real-time interval of data updates.
- Sharing of the dashboard is complicated, and users need to share the same domain of accounts.
- If the database schema is confusing, it will make the job of the developer a lot harder.

In Figure 27, we can see an example of the monthly report from the University that can be filtered by:

- Year, Month, Day.
- Type of consumption (Light, HVAC, Pool pump, Heater, Boiler, etc.).
- The building's Room (Classroom).
- Weekday, Class (Ongoing or Not Ongoing)
- Period of Time.
- Hour of the day.

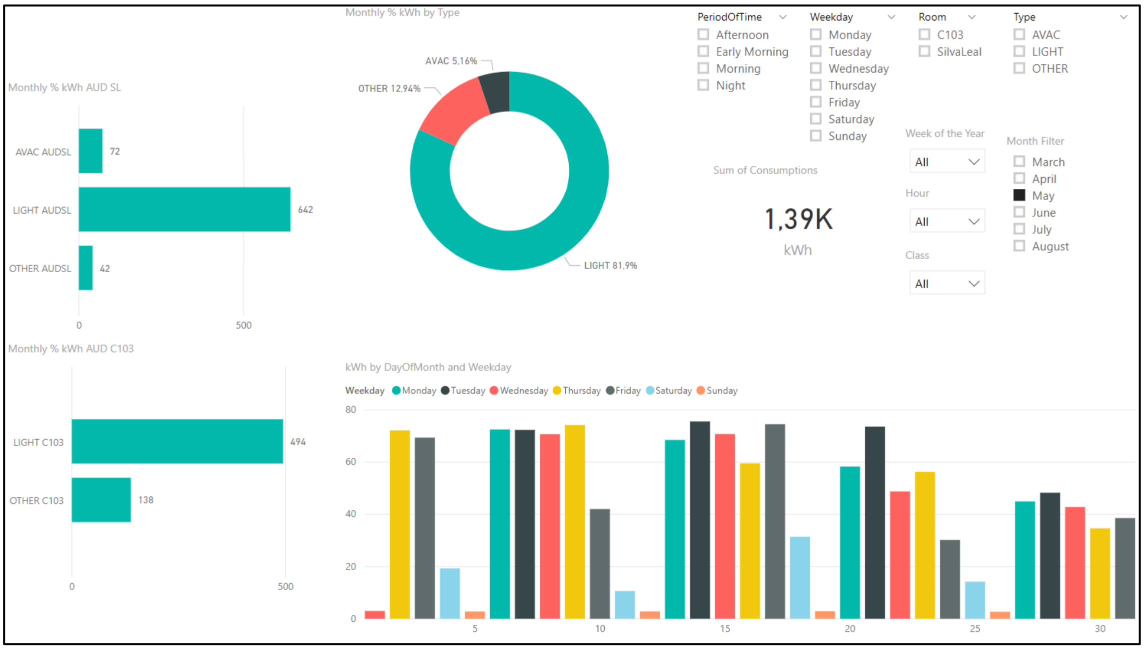

Figure 27 PowerBi Monthly Report

In Figure 28, an example of the reporting for an Auditorium, with device and date filters on the left.

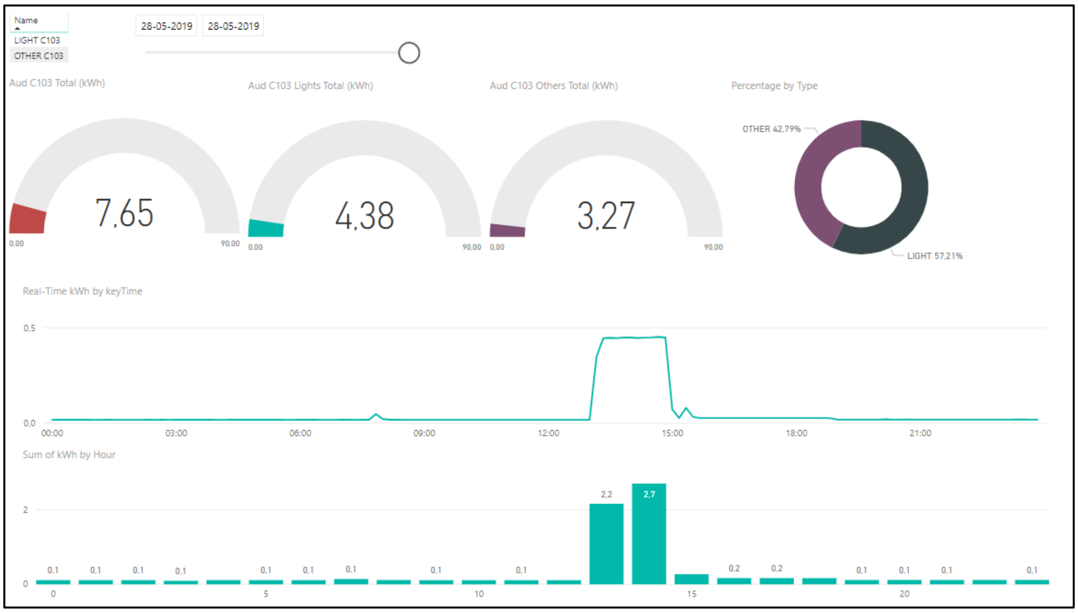

Figure 28 PowerBI Daily Report

3.3.5.2 Descriptive data analysis with Python

Data analysis was done using both the information we obtain from PowerBI and using pandas from python to aggregate and clean the data. The main objective of Pandas was to clean the data, find any new information, and create a path to predictive data analysis in the future and for that, it was used to, between other things:

- Remove outliers created by errors related to installation.
- Removing outliers created by errors when sensors have accuracy problems near-zero values.
- Remove temperature data outliers for HVAC analysis in one of the Auditoriums.
- Generating information such as:
  - Time the HVAC/Boiler/Heaters were turned ON and OFF based on the power consumption.
  - The temperature gradient between the startup of the HVAC and when it was turned off.
  - The minimum and maximum temperatures inside the room.
- Aggregating Data counts and averages within specific Dates.
- Generate Correlations between two or more factors in the data.

3.4 System Testing

In order to make sure the system was working properly before being implemented into real-life situations, this is a non-exhaustive list of some of the tests performed:

3.4.1 Testing: End Device

- For the first calibration (and following calibrations too) an Amperometric clamp was used to find the real value and calibrate the sensor based on those values. Different burden resistors were also used to test the accuracy of the sensor on different environments and see if there were any improvements to be made. Still, on the topic of calibrations, tests were also made using different wires and variable currents being passed through those wires to find any issues that could arise. Subsequent calibrations in real solutions are done using both the theoretical values and the Amperometric clamp and are required for each new device.
- In order to test the network, several sensors were left running for some weeks, this led to the discovery that the Arduino's integrated RTC gets desynchronized with real-time by one second every few hours (hours depend on the board). This meant there was the need to correct the device but since we are using LoRa that posed a challenge because of the Class A limitations. After the solution was implemented, several more days of testing were required.
- Several tests were also run to see if the Arduino board could handle power outages and still keep running when the energy went back on (With WiFi-based Arduinos this is an issue, with LoRa it wasn't).
- LoRa network failures were also simulated in order to see if the device could connect and reconnect without any problems, even in higher Spreading Factors environments.

3.4.2 Testing: Application Server

- As a server, several stress tests were required to run, to see if the server could handle receiving, processing and finally inserting into the database large volumes of data at the same time. As such, 200 different packets were sent to the server every minute for over an hour to verify these issues. The 200 packets were distinct to see if the "Derived Data" and the Correction of missing packets were working properly.

- There was also the need to check for memory leaks and exceptions, so a test consisting of continuous sending of different types of malformed packets were sent.
- It was also important to know how many messages the server could send to the LoRa Server at a given time, so over 200 messages in a minute were sent during a few minutes, to see if the LoRa server itself could handle them.
- In order to test the backup procedures and replication to the database few tests were also performed, for example, by turning off the network interface while a replication job was ongoing to see if the data did not get repeated on the databases, or if all data was sent over the next backup job.

Chapter 4: Implementation, Results, and Discussion

4.1 Implementation

Finally, we needed to implement our solution. One of the biggest difficulties we had when it comes to power consumers using electrical boards was the lack of space on those electrical boards and the fact that most cases phases do, not only, belong to several consumers, but they may also have mixing issues.

Over the course of this entire study, the size of the database reached approximately 42.6 MB when measuring with all the data we collected.

Figure 29 showcases one of the several solutions created:

Figure 29 Final solution ready for Implementation

4.1.1 Auditorium Silva Leal

This auditorium in the university was known for a while as a problematic consumer, so we set out to find any issues with it by measuring the three-phased electrical board that was used to power it. With this auditorium measuring results, a baseline can be created for yet another auditorium that functions the same way as this one, therefore, its consumption habits are similar. Since this auditorium was in a university, meetings had to be planned out in order to place these sensors.

- **Requirements:**
    - Find any anomalies related to power consumption in any of the consumers.
    - Identify waste.
    - Create a general vision for power consumption.
    - Evaluate HVAC efficiency.
- **Data details:**
    - Data from 1st March 2019 up until 31st May 2019.
    - 36918 entries were created for the timeframe above, but in total, 58808 entries were created in the Reading table.
- **Phases measured:**
    - Lighting (3 Phases) (Figure 30 (a)).
    - HVAC (3 Phases) (Figure 30 (a)).
    - Power outlets (3 Phases) (Figure 30 (b)).

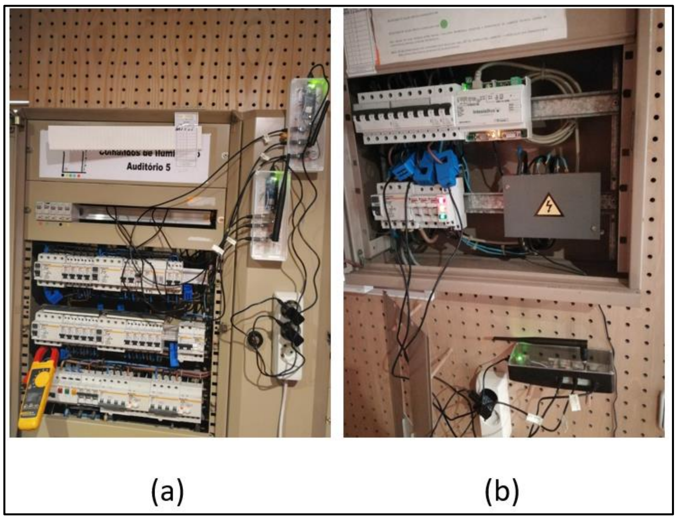

Figure 30 Implementation of the solution in the Silva Leal's Lighting, Power Outlets (a) and HVAC (b) electrical boards

4.1.2 Auditorium C103

This auditorium was to serve as an example to any other auditoriums in the campus since, in most cases, the procedures followed by this auditorium and wirings are similar. HVAC, however, was not measured because in this case we did not have access to it since the electrical board for this room's HVAC belongs to the entire floor and not just this auditorium.

- **Requirements:**
    - Find any anomalies related to power consumption in any of the consumers.
    - Create a general vision for power consumption.
    - Identify waste.
- **Data details**:
    - Data from 1st March 2019 up until 31st May 2019.
    - 24925 entries were created for the timeframe above, but in total, 37430 entries were created in the Reading table.
- **Phases measured:**
    - Lighting (3 Phases) (Figure 31).
    - Power Outlets (3 Phases) (Figure 31).

Figure 31 Implementation of the solution in Auditorium C103

4.1.3 House with Heated Pool

We also wanted to apply this solution to private houses to see if we could find any patterns, so we found the opportunity to apply it to a large house with a heated swimming pool. In order to measure some phases for this part of the work LoRa single-phase sensors had to be created, they works the same way as the 3-phase ones the only difference is that they only have one phase to measure. This type of sensor can be seen, **with a different board**, in Figure 34 (4.1.5) on the Electric boiler Implementation.

- **Requirements:**
    - Find any anomalies related to power consumption in any of the consumers.
    - Create a general vision for power consumption.
    - Identify waste.
    - Identifying patterns based on total power consumption.
- **Data details:**
    - Data from 5th July to 2nd August.
    - 95135 entries were created in the Reading table overall.
- **Phases measured:**
    - With this house, we used a top-down approach of monitoring, where we monitored different parts of the house for different results.
    - Total Power Consumption (3 Phases) (Figure 32 (a)).
        - Pool Heater (3 Phases) (Figure 32 (b)).
        - Pool Pump (Single Phase).
        - Inductive Oven (Single Phase).
        - Dishwasher (Single Phase).

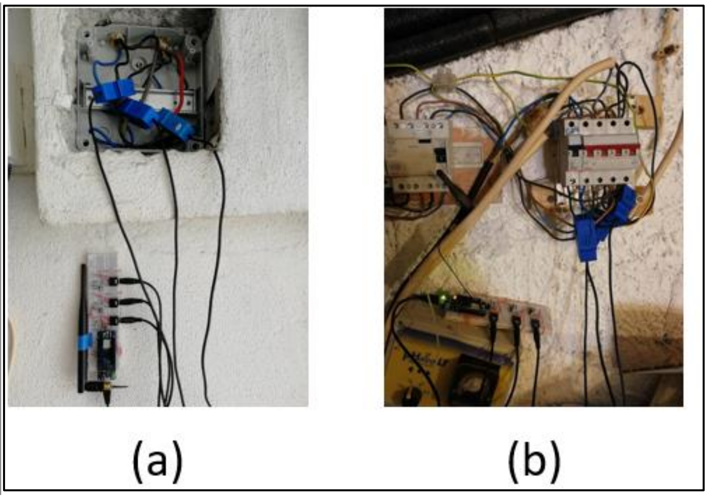

Figure 32 Implementation of the solution in the phases corresponding to the House's Total Consumption (a) and the Pool's Heater (b)

4.1.4 Agriculture Pump in a Farm

We had the opportunity to apply this solution to an agriculture pump. We wanted to see if we could correlate the power consumption with the water that was being spent in agriculture.

- **Requirements:**
  - Find any anomalies related to power consumption in any of the consumers.
  - Create a general vision for power consumption.
  - Identify waste in power consumption and water consumption.
- **Data details:**
  - Data from 13th July to 20th July.
  - 54602 entries were created in the Reading table overall.
- **Phases measured:**
  - Agriculture Pump (3 Phases)(Figure 33).

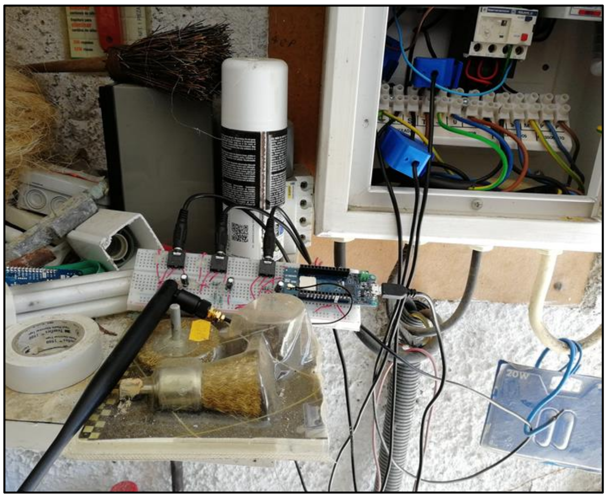

Figure 33 Implementation on the Agriculture Pump

4.1.5 Apartment Electrical Boiler

This small apartment has an electric boiler that is, in fact, the biggest overall consumer of the place and as such, we wanted to see if we could create any correlations or find any sort of issues with the efficiency of this boiler. In this particular case, Wi-Fi was accessible, and there were no more LoRa Boards available, so the decision to use a Wi-Fi board was made. The way the board works is exactly the same. The only difference is that it uses HTTPS and communicates directly with the Application Server.

- **Requirements:**
  - Find any anomalies related to power consumption in any of the consumers.
  - Create a general vision for power consumption.
  - Identify waste.
  - Evaluation of the boiler's efficiency.
- **Data details**:
  - Data from 25th June to 26th July.
  - 39430 entries were created for the timeframe above in the Reading table overall.
- **Phases measured:**
  - Electrical boiler (Single Phase and Wi-Fi) (Figure 34).

Figure 34 Solution Implementation in the Single Phase Electric Boiler's Source

4.1.6 Tourism Apartment

The tourism apartment/ local accommodation was picked because it could be interesting to see the energetic footprint that tourists tend to leave. Once again, yet another LoRa single-phase sensor had to be constructed since the apartment's wirings on the electrical board was single-phased.

- **Requirements:**
    - Find any anomalies related to power consumption in any of the consumers.
    - Create a general vision for power consumption.
    - Identify waste.
    - Evaluation of tourist's electrical footprint.
- **Data details**:
    - Data from 12th July to 9th August.
    - 40137 entries were created for the timeframe above.
- **Phases Measured:**
    - General Consumption (Single Phase).

4.2 Case 1: Auditorium Silva Leal Results

The results for this research were obtained exactly from dates 1 of March 2019 up until 31 of May, and we decided to pick May as our main evaluation month since it was the month with no school holidays. Overall the total power consumption for the 3 months in this evaluated auditorium was 1710 kWh with May consuming 44% of that total, 755kWh. In general, for the month of May, and in all the other months the biggest consumer was, in fact, Lighting, reaching over 85% of the total electricity consumption (see Figure 35 (a)) which corresponds to 642 kWh overall (See Figure 35 (b)).

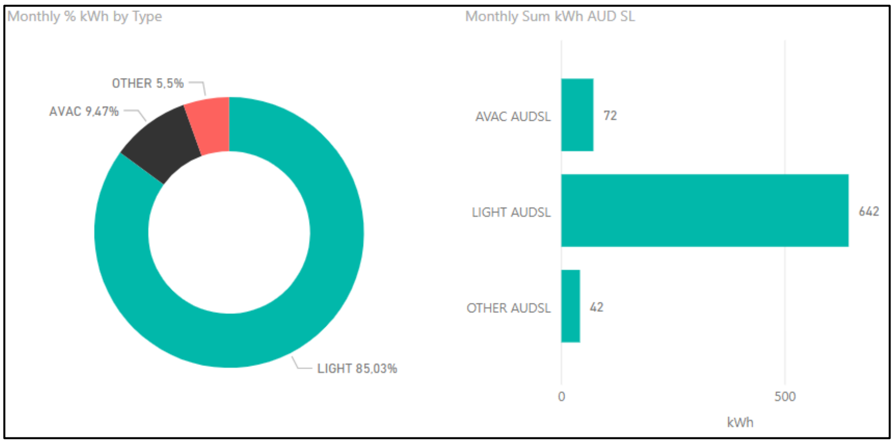

Figure 35 Ratio of the total power consumed per type of device in percentage (a) and the total value consumed in kWh (b)

The main reason for these values is an issue where light switches are in a hard-to-reach location within the auditorium. Therefore the only people allowed to turn that switch ON or OFF are the security guards for the building. This, in turn, leads to heavy power consumption since the security guards won't bother turning the lights off when no classes are occurring in the auditorium / between classes. The automated scheduled classes also have partial blame, since security guards are to be told that classes were going to occur in the auditorium but then no one would show up.

In this auditorium, out of the 642 kWh used for Lighting, over 248kWh was wasted, which is about 38% of the total **Lighting consumption** and 32% of the **overall power consumption** for the month of May only. The best solution for this issue would be to add a new Light switch accessible to all users, which would make sure they would be able to turn the lights ON and OFF when they please. Figure 36 shows the difference between the sum of **wasted** power consumption (kWh) per day in an auditorium with a normal light switch (lower) and this auditorium (upper). The residual daily consumption we see in the second auditorium is related to cleaning schedules that happen every day except Sundays.

Figure 36 Daily difference in the sum of wasted power between the evaluated auditorium with out-of-reach light switches (upper) and one with user-moderated switches (C103) (lower).

Still, on this same topic and already within the values above, we also can see that lights are turned on too early. By which we mean that between 7 AM to 8 AM we have lighting consumptions values of 43.96 kWh in the evaluated auditorium while in the normal auditorium (C103) those values barely reach 8 kWh, which is used for cleaning duties (See Figure 37, highlighted square). In this Figure we also note the difference in hourly variation; while in the evaluated auditorium (a) the values tend to be higher and more close together between each hour with slight variations, the normal auditorium (b) seems to have bigger variations between each hour, which can clearly be seen between lunch hours (12:00h block)

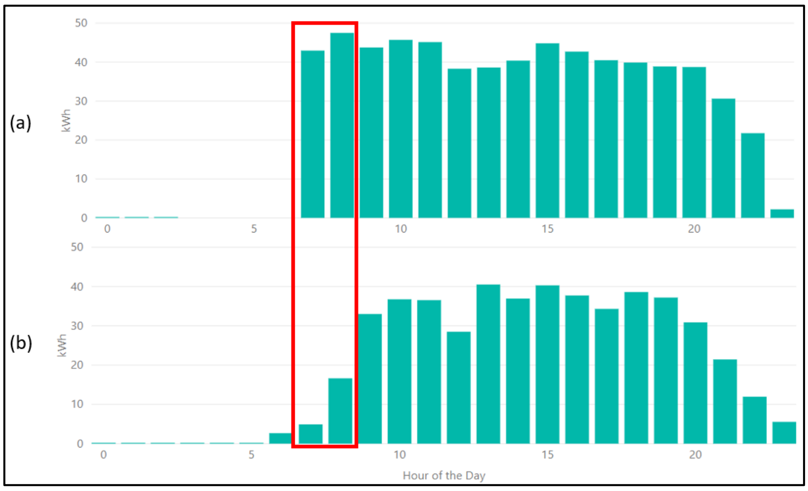

Figure 37 Hourly difference in the sum of daily power consumptions between the evaluated auditorium with out-of-reach light switches (a) and one with user-moderated switches (b). Power consumption within hours 6 AM to 8 AM exclusive marked

As for the auditorium's environment and HVAC efficiency, first, we decided to compare the daily maximum and minimum temperatures inside the auditorium with the outside temperature (See Figure 38). The auditorium temperature was measured using a temperature/humidity sensor created for another work. The data collection started in April and was kept running.

In Figure 38 we see that, while the outside temperature tends to vary quite a bit, the temperature inside the auditoriums is always relatively constant, never below 18ºC but also never above 25ºC, whereas temperatures outside reached less than 13ºC and went over 34ºC.

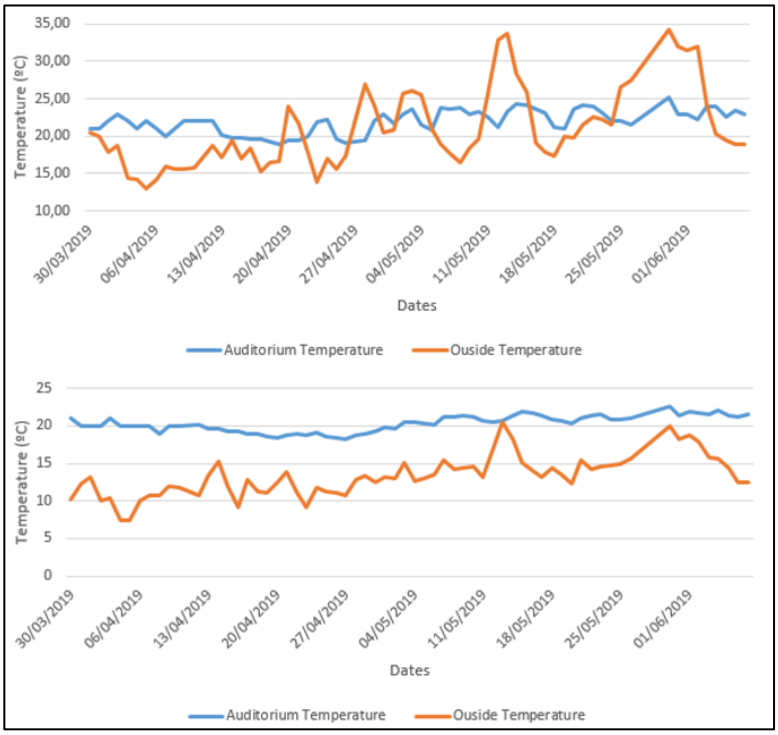

Figure 38 Difference in daily maximum temperatures (Upper) and daily minimum temperatures (Lower) between the outside temperature and the temperature inside the auditorium

In order to analyze how the people feel inside the auditorium we tried to correlate the temperature inside and when the AC is turned ON and how long does it run for, the results can be seen in Figure 39 below.

The first thing we noticed is that the AC is never started up with temperatures below the 20.5ºC (although after being turned on for a while it does reaches temperatures below that level) and while we clearly see that temperatures below 22.5ºC tend to warrant less AC time (Figure 39 orange outline), we also see that most of the times when the AC is on for over 20 minutes the temperatures tend to be above that value, 22.5ºC (Figure 39 Green Outline). The number of times the AC was started up over the course of 2 months (April and May) is also pretty low, only reaching 38 times overall. With this it's pretty safe to say that the auditorium has a good thermal insulation that helps keep the room cool when the outside is hot and vice versa which means, as also presented in Figure 35 (a) (HVAC – 9.47%), that the HVAC's power consumption isn't really an issue.

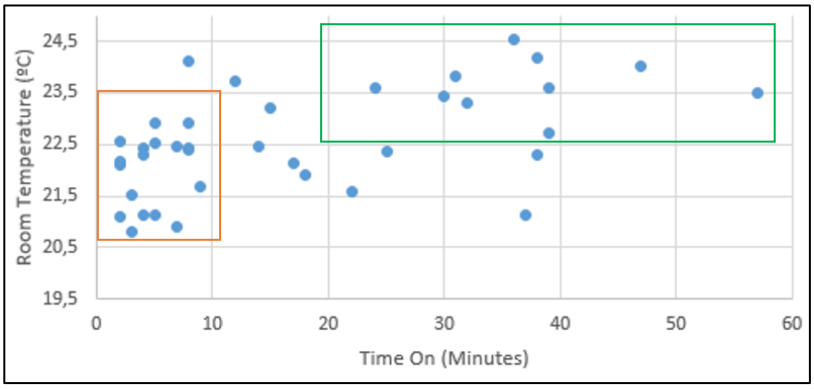

Figure 39 Relation between the temperature inside the auditorium and how much time the AC is turned ON.

In Figure 40 we see how efficient the AC is, the results tell us that in most cases a slight consumption will lead to very small reductions, leaning close to less than 0.5ºC decreases while in order to decrease by at least 1ºC there tends to be a need for at least a 1 kWh consumption in a continuous time period.

However, this data does not account for the number of people in the room, which can increase the consumption required to reduce the temperature.

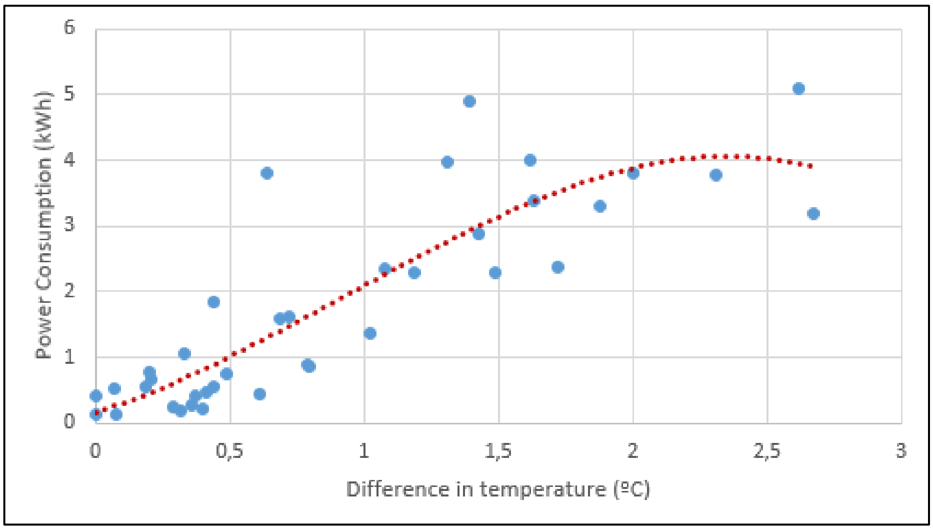

Figure 40 Relation between the decrease in room temperature and the power consumption over time while the AC is turned ON

4.2.1 Auditorium Silva Leal Discussion

According to the graphics seen above the biggest concern is most definitely the lack of a light switch inside the classroom. Professors can't turn the lights ON and OFF when they please, and since security guards do not care enough to switch the lights when needed, as we've seen above, there will always be an unusual amount of waste that should not exist. It is also important to note that there's one more auditorium right next to it with the same issues, so the waste of power can be said to be double. On the topic of lighting, this solution can also be used to find and report when lightbulbs get burned out and need to be replaced, simply by notifying a constant reduction of maximum power consumption when compared to other days, this can be seen on the dashboard or an application could be created for these types of situations.

AC efficiency as we see in Figure 40 could be improved. This improvement could come in the form of proper cleaning of the vents and the condenser since, from what we see here, it takes quite a lot of electrical power to receive a small decrease in temperatures for the auditorium.

As for the power outlets, we did not notice any big issues on these case, as noted in Figure 35 ((a) and (b)).

Besides these issues, another set of problems were also found in the electrical board during the installation of sensors in the Auditorium Silva Leal:

- Phases from the auditorium Silva Leal would join together with the Auditorium Afonso Barros, the unusual high values registered by the sensors, provided a way to find out that the phases for Afonso Barros Illumination were being joined with the Total power phases from the auditorium Silva Leal. That issue was promptly fixed by the electrician.
- A cut neutral cable was also discovered during installation shown by the lack of current being passed through it.
- Based on the current measured while installing the clamps, the HVAC panel for both the auditoriums had the nomenclature switched, and when the HVAC for the Silva Leal was activated on the panel, the Afonso Barros would turn on instead. That was also fixed on the spot by the electrician in order not to skew the results.

4.3 Case 2: Auditorium C103 Results

This specific auditorium was not chosen because it had any particular issues. The reason it was picked was to measure what a usual auditorium would spend on a daily basis in the university. Once again, we picked the month of May for the same reasons as in the case above from Auditorium Silva Leal.

Overall this auditorium, in this month, reached a summative consumption of 637 kWh, 43% of the total consumption over the 3 months (1st March – 31st May), 1470 kWh, with lighting consuming 494 kWh and Power outlets reaching 142kWh during May.

In this particular case, the lighting was not an issue due to light switches being accessible to users, as seen above on case 1 in Figure 36 (lower). However, this auditorium and several others scattered around the university have one solid issue with classroom computers being left ON 100% of the time to avoid loading times. As observed in Figure 41 (a), every single day between the hours of 23:00h and 8:00h there is approximately 1,20kWh waste per day, leading up to 33 kWh per month, while on Sundays, 24 hours, days when there are no classes, consumption reaches 2,75kWh / day on average (Figure 41 (b)).

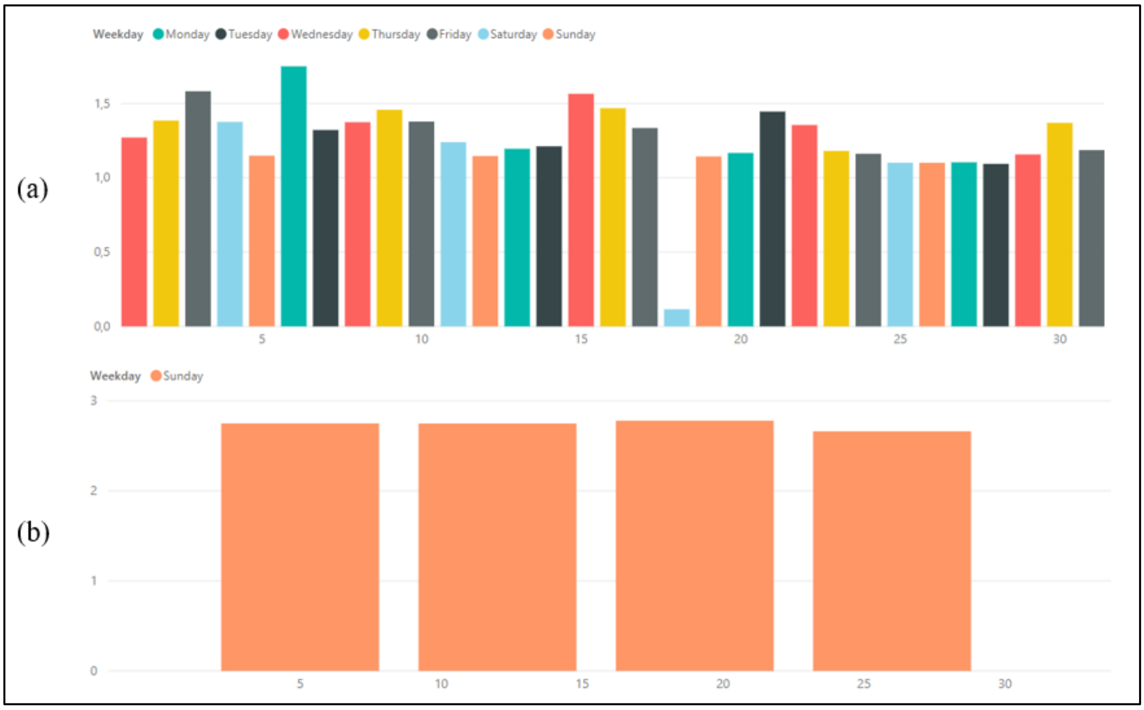

Figure 41 Wasted Power Consumption on turned ON computer during off-hours (23:00h – 08:00h) (a) and full Sunday days(b)

Overall, while using the “Class ongoing” data to see how much the power outlets were consuming during off-class hours, a total of 71,37 kWh was wasted in the month of May as shown in Figure 42. Obviously, in this graphic, we are not only accounting for the computers being left on but also projectors and student’s computer between classes.

In order to obtain the “Class ongoing” data, a mix of both ISCTE’s planning schedulers and when the lights were ON were used so we could have the maximum possible accuracy with the tools available. This values also account for Sundays and off-hours.

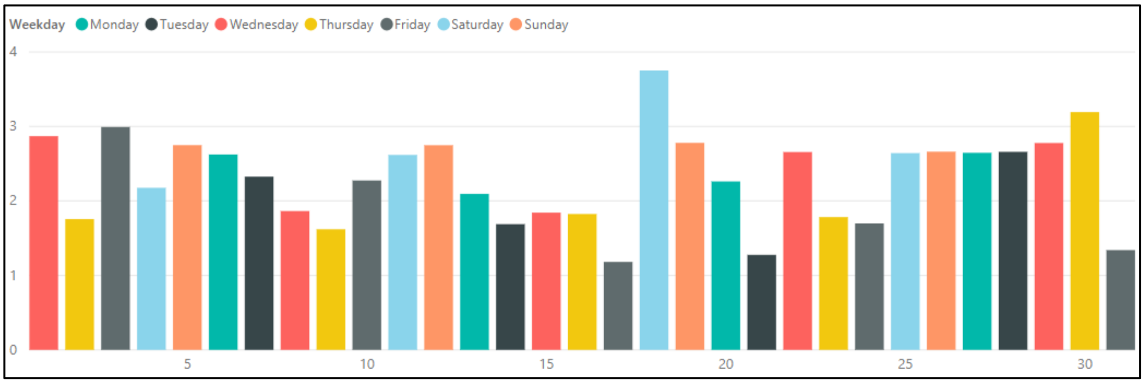

Figure 42 Wasted Power Consumption During Off-classes time

4.3.2 Auditorium C103 Discussion

In this case, we know for a fact that computers are left ON day and night, even on weekends, and this is something that, according to the ones responsible in the university, happens in several other classrooms within this university. The problems seems to be, mainly, because some computers take a long time to load because of the use of Hard Drives, so the easier solution for this would be to replace the Hard Drives with Solid State Drives, decreasing the loading times considerably (average boot-up time for an SSD is around 10-13 seconds while HDD is around 30-40 seconds). If this trend keeps up, in a year, per classroom with issues like this, a reasonable 2.75kWh * 365 = 1003,75kWh/year could be wasted (maximum value possible). Assuming there’re at least 10 classrooms that work like this (and there are), it would mean 10.037,5 kWh per year could be wasted, and that is not only a waste of money but also a waste of resources.

4.4 Case 3: House with Heated Swimming Pool Results

This camp house was measured for a few weeks (5th July – 7th August). We used a top-down approach by first measuring the house’s entire consumption, then for each discovered pattern we created a supposition to what it could be. Finally, we measured phases based on that supposition in order to validate it. In this case, we found out that the biggest consumers were both the Pool Heater and Water Pump.

Several patterns were identified in this case, and each was measured during different times:

- Pool Heater (Figure 43 Red Square) – (1 Week) 24th July to 2nd August.
- Pool Pump (Figure 43 Green Square) – (1 Week) 24th July to 2nd August.
- Induction Oven (Figure 43 Blue Square) – (2 days) 19th and 20th July.
- Dishwasher (Figure 43 Orange Square) – (3 days) 20th July to 23rd July.

The overall Total Consumption was measured for one month (5th July to 2nd August) since it was the base of the consumption. This total consumption was also what was used to evaluate the waste of power consumption caused by the Heater and the Pump.

There are of course several other consumers around the house, but one of the scopes of this case was to see if we could easily identify patterns based on the total consumption and then prove them by measuring them and see if those patterns match.

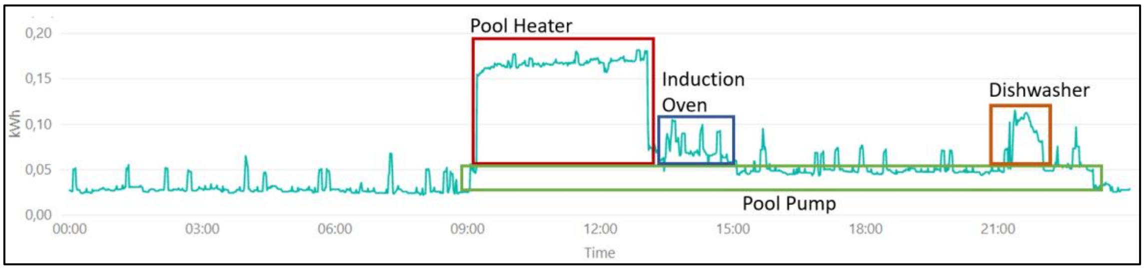

Figure 43 Total Power Consumption on day 16-07-2019

4.4.1 Pattern Recognition

In order to understand the patterns, we first had to reach out to references to understand what each consumer should look like and then measure each of those consumers physically to validate our findings.

The patterns we identified and tested were the following:

- Pool Heater.
- Pool Pump.
- Induction Oven.
- Dishwasher.

The first obvious consumer was the pool's heater, in Figure 44, an image showing what the usual pattern looks like when measured. This heater consumes approximately 5.25 kWh per hour based on our data.

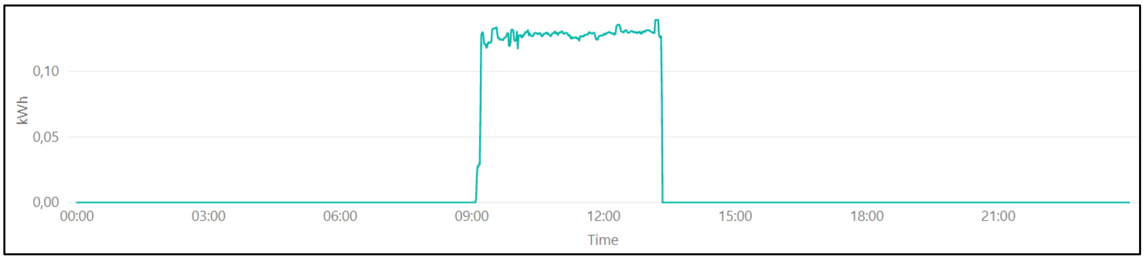

Figure 44 Pool Heater on day 31-07-2019

At the same time, we measured the pool's pump (Figure 45). The pool pump, unlike the heater, seems to run at a fixed schedule, meaning it will be the same every day from 09:00 to 23:00, consuming on a daily basis up to 20.39 kWh.

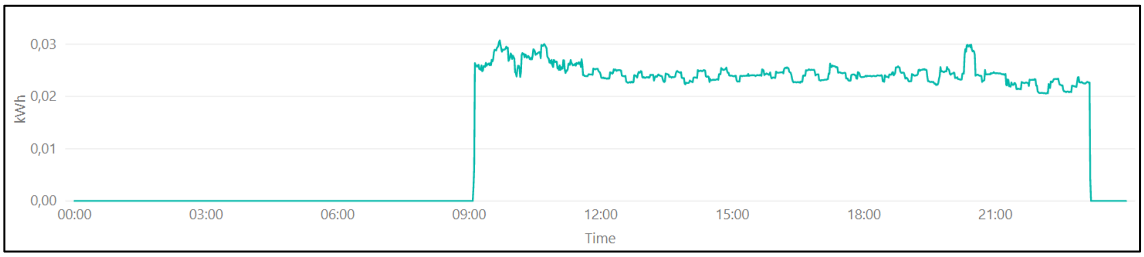

Figure 45 Pool Pump on day 31-07-2019

The induction oven was a little harder to figure out since it always seemed to have a changeable pattern. However, once we measured it, we immediately noticed a recognizable pattern, as seen in Figure 46.

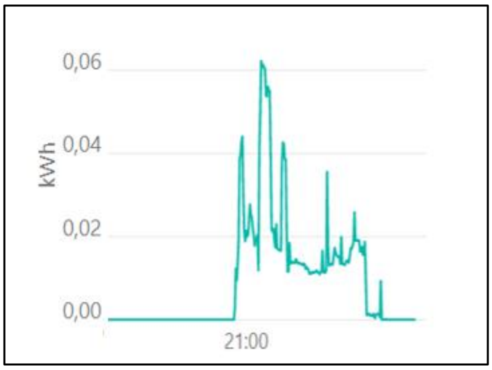

Figure 46 Induction Oven cooking on day 20-07-2019 between 21:03h and 22:37h

Finally, the dishwasher has patterns depending on the setting used. The largest power consuming of the dishwasher is when it has to heat up the water, as shown in Figure 47.

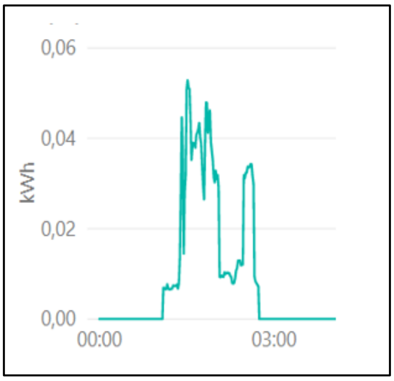

Figure 47 Dishwasher on day 23-07-2019 between 01:42h and 02:51h

4.4.2 Study on Waste and Efficiency

From the overall consumption of the house we know two important things:

- The Pool Heater is one of the biggest consumers.
  - The Pool Heater will always turn on at 09:00h.
  - It will keep running until it reaches water temperature of 28ºC
  - It will restart running when that temperature reaches a lower threshold (unknown).
  - It is turned off completely at 23:00h.
- The pool pump that will transfer the heated water is almost always running. It is turned on at 09:00h and off at 23:00h. Based on the data we have, an approximate value of 20,4 kWh is spent every day just on the pump.

Power consumption in the house usually increases by a wide margin alongside the time the pool's heater is kept on.

This total of consumptions can sometimes even manage to reach almost 100 kWh a day. Taking into account that the total includes all the appliances in house, including the ones mentioned above.

Figure 48 shows one example of the issue with the pool's heater which from time to time turns on and never turns off until 23:00h, this is **not** something that happens every day, but it is recurrent.

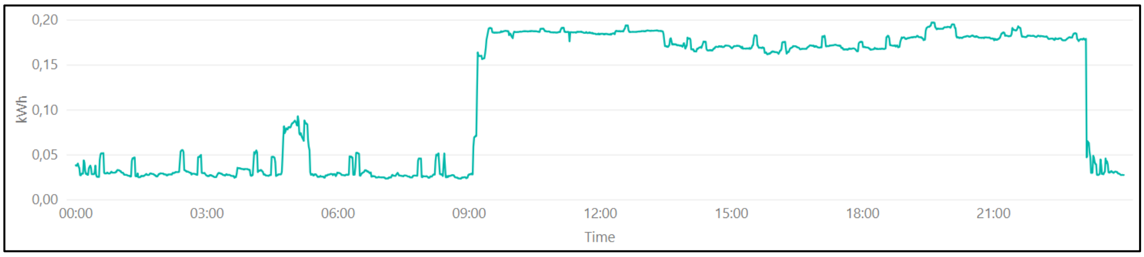

Figure 48 Global consumption shows unusual Pool Heater Functioning on 17-07-2019

This, however, didn't feel like the correct functioning of the pool's heater, because the normal workings of the heater (days where the heater isn't kept ON for 14 hours) over the course of the measured days, the time the heater is kept ON didn't go above 8 hours. So in order to see if there was a correlation between this anomaly and the outside temperature a scatter chart was created that correlated the daily time ON (hours) of the Heater and the maximum temperature reached on that day. Maximum because the Heater is only ON during the day and the average temperature would also count the night time's temperature, which could also get pretty low, thus skewing results since the pump isn't working at that time, so water flow is stopped. Figure 49 shows the result, and as expected the time the Heater is ON varies with the maximum temperature, the higher the temperature, the lower the time seems to be. However, we can also notice that sometimes the Heater is kept ON all day (14 hours) without any apparent reason, therefore, this is an anomaly.

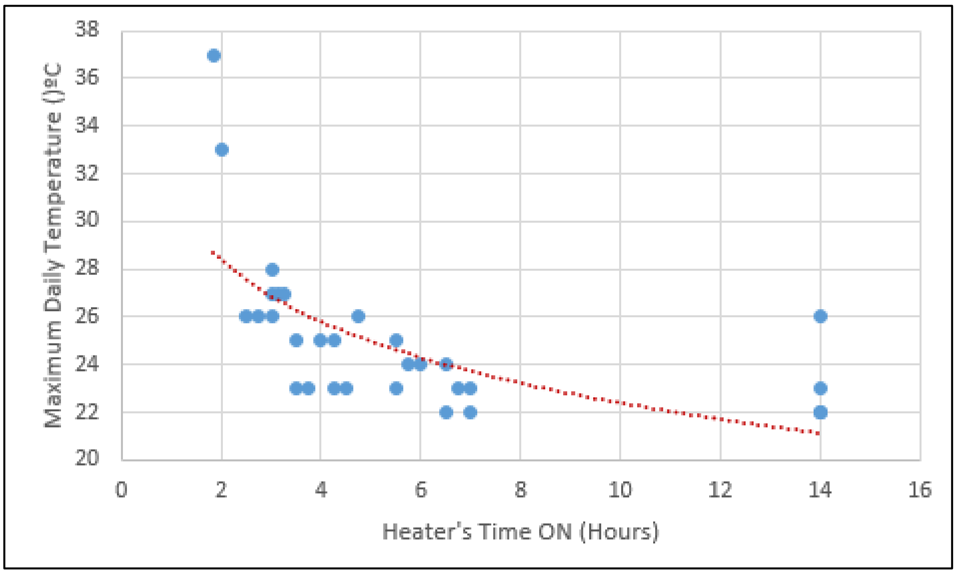

Figure 49 Relation between the Maximum Daily Temperature and the time the Heater is kept functioning

4.4.3 House with Heated Pool Discussion

In this case we had a few difficulties when it came to verifying patterns mostly due to bad unreachable wirings and mixed appliances within phases, so only a very few select appliances managed to be written on this work. However, in our waste study, on Figure 49, we did find out that the pool's heater seems to be having issues that make it work all day while ignoring the water's temperature, this happens in at least 5 days during the 33 days measured. We have also seen that the pool heater plus the pump are the biggest consumers, and they do consume a lot. In days where the heater works for 14 hours, the consumption these two appliances can reach is up to 93.9 kWh in a single day. However, as seen in Figure 44, the pump seems to usually consume 5.25 kWh per hour, therefore even in days where it's ON for only 5 to 7 hours, it will still consume about 26.25 kWh to 36.75 kWh, plus the pump, which is still a high value.

A solution for theses consumptions could be to replace the heater and pump with a pool cover making it an internal pool. Interior Pools, most of the time, do not require heating since the inside of the cover can get heated due to the greenhouse effect. This solution would be the best option to keep the pool heated while reducing power consumption.

However, the problematic anomaly should be verified to see if the heater is really working as intended.

4.5 Case 4: Agriculture Pump in a Farm Results

We were given the opportunity to work with this pump from 13th July to 20th July. Since one of our objectives was to relate power consumption with different factors from different environments we decided to take it to see if we could actually correlate the power consumption with the water consumption used for agriculture.

This pump works the following way:

1. The pump has a "balloon" that holds water.
2. When that "balloon" loses water, the pump will replenish it once that loss reaches a threshold.
3. Depending on how much water it needs to be replenished, the pump will increase or decrease power consumption.

The plant watering mechanism can be manually activated on different settings, meaning it can use up a modifiable amount of water, and that has an effect on the Pump's power consumption.

During a normal day without any plant watering, Figure 50 shows us what is expected of the pump.

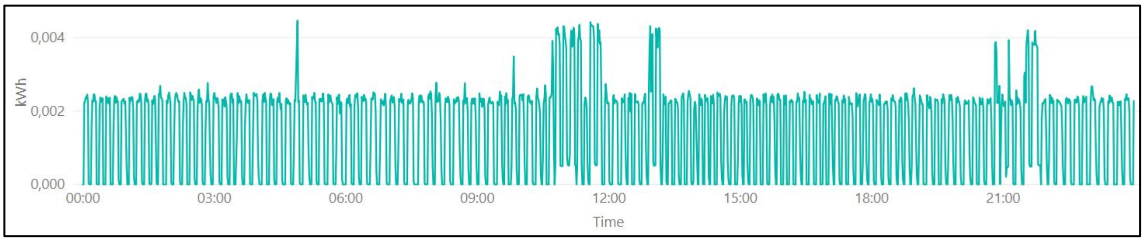

Figure 50 Regular Idle Pump Routine

These peaks shown in Figure 50 should not exist; as said above, the pump only works when there's the need to fill the balloon with water. This means that a set interval the pump is requiring to fill the balloon slightly. The most likely reason for this issue is water leaks that are reaching the threshold for the pump to work. When it comes to regular power consumption, this isn't a big issue, approximately 3,11 kWh in one day were consumed here (Figure 50).

However, every few days, the watering system must be turned on, and this system works with several settings. Using the power consumption system, we can see when each set was applied based on the pattern of the lines, as seen in Figure 51. On setting (a) 20,63 kWh was spent for 5 hours, while on (b), 16,75 kWh were spent, also, during 5 hours. Overall, the consumption depends on how the user defines the settings and for how long.

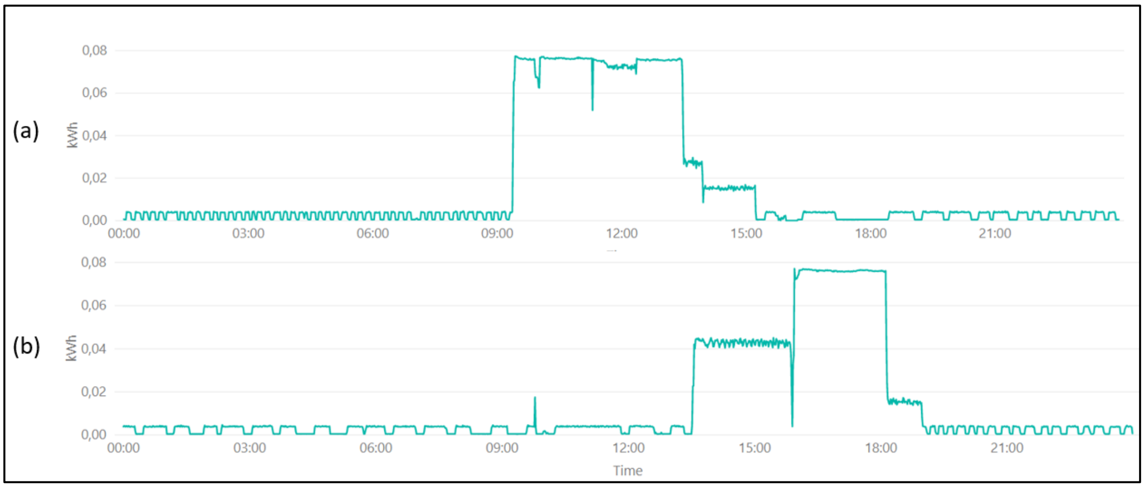

Figure 51 Different Agriculture Pump Settings

4.5.1 Agriculture Pump Discussion

The Agriculture Pump is controlled manually, therefore only creates abundant consumption when the user actually wants it too. However, according to Figure 50, the idle consumption shows that there might be leaks somewhere that should be repaired. That said, the values for the agriculture pump seem a bit too high on this work, as noted in Figure 51, which could be accountable due to an actual problem with the pump, it could be due to a sensor reading error, or, the most likely scenario, the pump just consumes a lot of power overall (2 hp pumps can pull up to 2.4 kWh).

If possible, it's also important for the user to try and use the setting that **consumes more** but **not as many times** since the difference in consumptions seems to be minimal, or even better, try always to use the settings that consume less water, on the same amount of time. Not forgetting, of course, to find the possible water leaks and plug them.

4.6 Case 5: Apartment's Electric Boiler Results

This case presents data from 25th June to 26th July (1 Month). The purpose of this case was to find anything related to the efficiency of the electric boiler.

The environment in this apartment can be described as the following:

- Four people live in the apartment.
- Two people always start their day in the morning.
- One of them goes to school.

- The boiler has a capacity of 100L and works by heating and storing hot water when it's not full.

Overall, during this month 164kWh was consumed, which means that over the course of the 31 days, the average daily consumption was approximately 5.2kWh. As expected, and shown in Figure 52 the hours of bigger consumption were in the morning, between 08:00 and 09:00, when people usually take baths/prepare themselves to work and at around 20:00 and 21:00 when people either take their bath too or do the dishes with hot water.

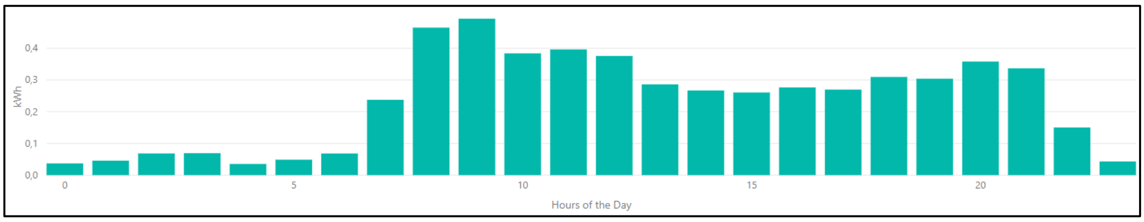

Figure 52 Average Hourly Consumption by the Electric Boiler

In order to figure out how this boiler works a look at the daily consumption had to be taken. In Figure 53, we take a few important assumptions:

- We can make an assumption that more people take baths in the morning, thus spending more water, of course, this must be taken with a grain of salt since some people might take more time during bath time in certain days.
    - In Figure 53 (a) we know for a fact that all the hot water was indeed used in the morning by 3 people. As such, we know that at about 0.8 ~ 0.9 kWh the boiler is going to take approximately 6 hours to completely fill up. This means that **in order to fill the entire boiler**, approximately 4.8 kWh will be used, which translates into 0.048kWh or 48Wh/L at 0.8 kWh.
    - Figure 53 (b) a normal weekday where 2 people took a bath in the morning.
- We can see that from time to time, **the boiler needs to re-heat the water**, so it keeps the same temperature. This value can vary depending on not only the exterior temperature but also the container's temperature. In Figure 53 (c) a day when no one used hot water is shown.
- Based on how the lines look like and the time between those lines, **patterns can be formed** for when water is used for small cleanings such as dishes and when it is used for baths. This obviously could bring privacy concerns to some, but as long as the data remains private and is consented by the users, there is no issue.

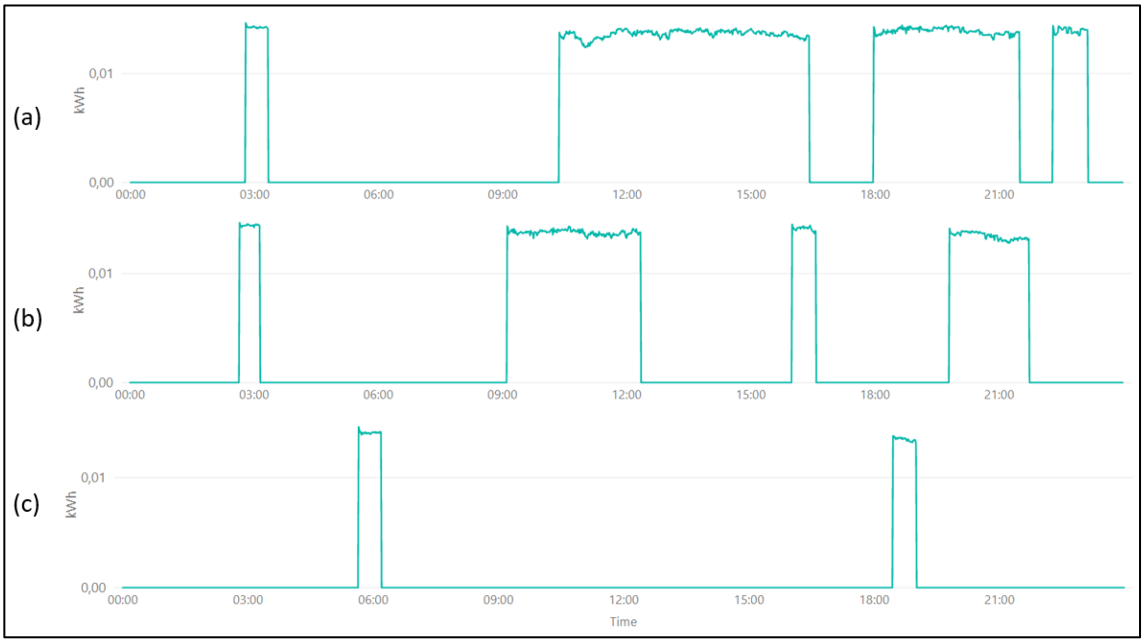

Figure 53 Boiler differences between diverse days, Saturday (a), Thursday (b) and holiday (c).

Finally, we wanted to know what was the average time between each boiler heatings/re-heatings. The value obtained from a simple python script was 5 hours and 19 minutes which surprisingly most of the times re-heating would end up being at around 03:00 in the morning. However, in situations where no one used hot water for a full day the time between re-heats, during the day, could reach almost 12 hours such as in Figure 53 (c). Power consumption for re-heating is approximately at 0.4kWh in 30 minutes, which is not a big consumer.

4.6.1 Apartment's Electric Boiler Discussion

In this case, there is not much to discuss, no exceptional waste was found and the re-heating time between water usages seems to be fine and only tends to work when really needed as shown in Figure 53 (c). It takes 6 hours to completely store 100L of water (Figure 53 (a)), which seems a bit too long. However, consumption is also not that big (4.8kWh in 6 hours). Nonetheless, the boiler is rated to be able to fill the 100L completely in 4 hours, so there might be some issues related to the efficiency of this particular boiler: One thing mentioned was that, while this boiler is 8 years old, it was never really cleaned so a proper cleaning by professionals could, maybe, improve the efficiency.

One obvious thing, in this case, is related to the privacy and security of the household owners. Someone with access to this data is able to know when the homeowners are at home and when they are not (Holidays) by simply looking at the data trends, so while in this case we were given permission to store the data and keep it in a moderately secure manner, it is important that when a production solution is implemented the data is kept safe using the standardized measures.

4.7 Case 6: Tourism Apartment Results

This case came to be because of a favor asked by a coworker that owns a local remodeled lodging/tourism apartment in the middle of Lisbon. The apartment was recently renovated with brand new wiring/appliances. The decision, however, to use this as an, yet another, example of a use case for this solution was ours.

The values shown below represent the summative values of the Power Outlets, the Lighting, the oven, and the AC, while, the fridge and hot water boiler were not added into this electrical single-phase. The AC itself is lightweight, and the consumer with the largest potency is definitely the induction oven.

Over the course of approximately one month (12th July to 9th August) only 33kWh were spent, an average of 1.17kWh per day over 28 days. In those 28 days, only 3 days had no guests whatsoever. In Figure 54 we see that the time when most electricity was consumed was between 09:00 and 13:00 since not every tourist enjoys eating out so both the oven and the AC (since it's summer) might be working. Other devices such as the toaster or the microwave are also big power consumers that work for a short time, but with this data, we can't really discern which ones would be each device.

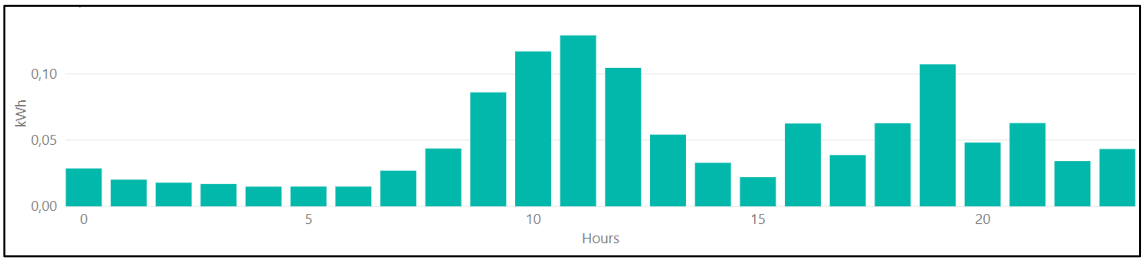

Figure 54 Average Hourly Power Consumption in the Tourism Apartment

We can, however, try to discern certain patterns, for example in Figure 55 in the red square we see a continuous usage of power consumption. The only appliance capable of producing that much potency for that period of time would be the AC or the oven but there is doubt that the oven would be left on for over 3 hours, and the temperature on this day (03/08) was pretty high for Portugal nowadays, so we can safely say that this is the

AC. Either way, the best way to discern patterns here would be to simply ask the tenant to allows us to test each device, and then we would have a baseline on what to expect.

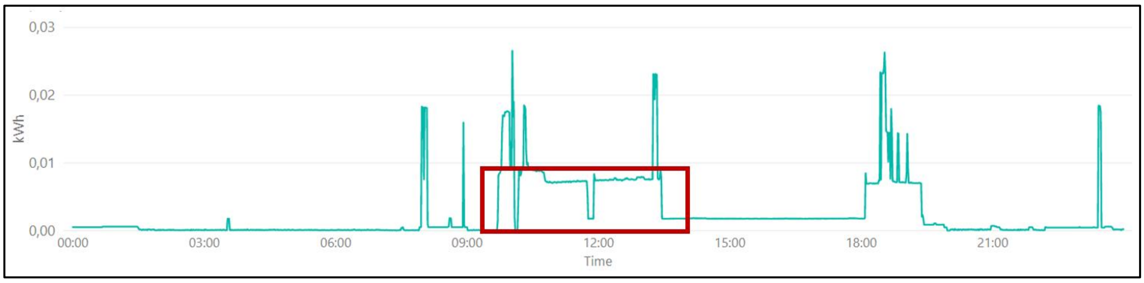

Figure 55 Usual Power Consumption when tourists occupy the apartment

It is also important to note that when no guests are using the apartment, power consumption of about 0.10 ~ 0.13 kWh/day is still present with small anomalous spikes of consumption as shown in Figure 56. In this Figure 56, the consumption showed between 19:30 and 21:00 seems to be lighting, but as said before, these are just assumptions and should be taken as such.

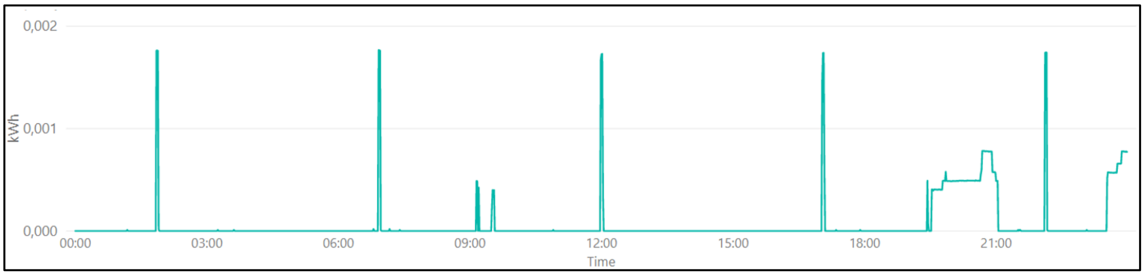

Figure 56 Day without any guests showing small anomalies every few hours

4.7.1 Tourism Apartment Discussion

Once again not much is there to be told about this case; as noted above, at an average of 1.17 kWh/day the apartment is extremely efficient mostly due to the eco-friendly lights. Either that or the tourists take care not to waste too much electricity which is also a viable assumption. The oven, while a big consumer overall, is left on for almost no time at all, meaning that it never takes long to cook something. As for the AC it doesn't seem that it's turned on regularly, one reason for this, and one thing we noticed when installing the solution is that the apartment never gets very hot (although to actually confirm this we would need temperature sensors). Portugal, during the timeframe used in the experiment, also hadn't reached any extreme temperatures so guests might've not felt the need to turn the AC on.

Chapter 5: Conclusion

In this work, we set out to create EnerMon a flexible, sustainable and efficient Power Monitoring IoT system, capable of measuring any sort of electrical phase in different environments and use cases while applying edge computing capabilities to find anomalies, patterns, and overall waste.
This work was applied in auditoriums, farm, pools, and apartments and as such proved itself to be flexible enough to call it a success while also finding several anomalies in each case that proved that the system is working as intended. Six installation processes were performed, using the developed system, where the device's hardware, the data layer, and the information layer did not require any modification at all for the different cases.

In the auditoriums, the lack of a proper lighting management system leads to a massive waste of power every month. This research also helped when it comes to HVAC disaster management and reporting, i.e., usage of power but no noticeable temperature reduction overall, or simply prepare the auditoriums to improve the comfort of the students with technologies such as AC automation. In the house with a pool, the lack of maintenance and control of the pool's heaters leads to extremely large wastes every month. The monitoring of the power consumption in a pump used for Agriculture led to the belief that leaks are a recurrent problem while the pump itself is not a big spender. In the apartment's boiler, the only case where a small modification was done on the hardware side (Wi-Fi), there is a doubt that the boiler is working as it should since it takes more time to completely fill up its entirety than the rated time of the boiler. In the Tourism apartment, aside from small anomalies, no actual issues were found but an evaluation of the energetic efficiency was done, and it was proven that it's in an excellent place mostly due to innovative remodelling focused in eco-friendly procedures.

LoRa as the chosen communications technology did not prove to be an issue since the data is kept safeguarded by the end-device's memory when the LoRa packets are not received by the server. However, if we are going for pattern recognition it might be better to try and keep the sending interval as low as available with LoRa, which might be hard to find the perfect "sweet spot" since LoRa can have issues when it comes to sending data at low intervals.

Overall, this work managed to achieve its objective of creating a low-cost, flexible and sustainable IoT system. The system allows for an easy installation process that can be applied to different environments in order to identify energetic footprints and waste, based on different variables/factors. It's also useful in finding patterns that can, over time, help in identifying appliances and also creating a baseline to how an appliance should be working and thus being one more factor in helping to identify the normal and abnormal functioning of these appliances. It is also important to note that privacy and security were kept in mind while working, however, they were not the focus nor they were on the scope of this work. Security is performed by the communication itself, LoRa provides the necessary tools for a secure connection such as end-to-end AES-128 encryption between the end-Device and the LoRa Server, and HTTPS between the LoRa Server and the Application Server. Privacy was kept with a strong password on the database side.

5.1 Contributions

This work was a contributor to the Gulbenkian Project "*University Community Engagement in Technologies for Sustainability: a Social Architecture*" whose one of the objectives is to improve the university's efficiency with the use of IoT sensors such as the ones presented in this work, this also means that system will be used in the near future in order to measure several electrical boards in the university. Likewise, part of this work was used in forming students in a university's summer school hands-on courses about LoRa technology and the IoT environment. Three papers were also finished based on this research:

- (Accepted, Conference 21st August 2019) Submitted to CCIoT in Tokyo, Japan 20-22 September 2019 - 4th International Conference on Cloud Computing and Internet of Things - Diogo Santos, Bruno Mataloto, João Carlos Ferreira, "Data Center Environment Monitoring System".
- (Accepted) Submitted to SESC 2019 - EAI International Conference on Sustainable Energy for Smart Cities - Diogo Santos, João Carlos Ferreira, "Smart Auditorium: Development and Analysis of a Power and Environment Monitoring Platform".
- (DOI: 10.3390/su11195355) Special issue of Sustainability journal of MDPI (ISSN: 2071-1050), Special Issue "Sustainability in the Built Environment and

Climate Change" – Diogo Santos, João Carlos Ferreira, "IoT Power Monitoring System for Smart Environments".

5.2 Future Work

The work itself will be carried on by researchers at the university and will be used to improve the sustainable characteristics of the building by applying the system to several consumers as part of the Gulbenkian project. This project will aim to, not only measure consumption and identify waste through analysis but also develop mobile applications capable of:

- Warning users when consumers are consuming when not needed (e.g. lights turned on when no one in the room).
- Warning users when consumers are not working as intended (e.g. faulty lights).
- Pattern identification.
- Gamification of electricity consumption (university and tourism house).
- Turning consumers on and off with the mobile application.

Besides this, data is also being gathered and prepared to allow for predictive analytics, one of the future objectives is that data will have enough volume to allow predictions such as:

- Expected consumption of electricity.
- Expected intensity of electricity consumption based on factors.

And, we should also not forget about automatization of consumers, that can be done both based on machine learning algorithms or simply by obtaining better real-time data, always keeping in mind one form of bypassing in case there's the need to. In order to obtain better real-time data it is also important to add other sensors to the mix. Sensors such as occupancy sensors create valuable and precise information about the actual occupancy of a room. Examples of automatization would be:

- Turning on Air Conditioning when temperatures reach certain values.
- Turning on different sets of lights based on the occupancy of the room (e.g. if there are 3 students and one professor in the room, this room would, most likely, only require the lights up front turned on and the ones out back turned off).
- Computers only needed to be on when people are in the room.

5.3 Closing Remarks

Finally, we want to highlight that this work was in no way something aimed to reduce consumption and create improvements by itself, it's a work focused on monitoring and presenting the data in order to influence the users into doing those changes themselves, changes that may come in many forms such as:

- Decision making when buying certain equipment.
- Decision making when using the equipment and when they are able to turn it off (especially the automatic ones).
- Replacement of older appliances that could improve energy efficiency.
- Substitution of certain lifestyles.
    - **Example**: Using an electrical fan instead of the HVAC during not-so-hot summer days.

For all these points there is, of course, the need to be aware, to know what is being consumed and what are the biggest offenders and that's the reason this research was conducted.

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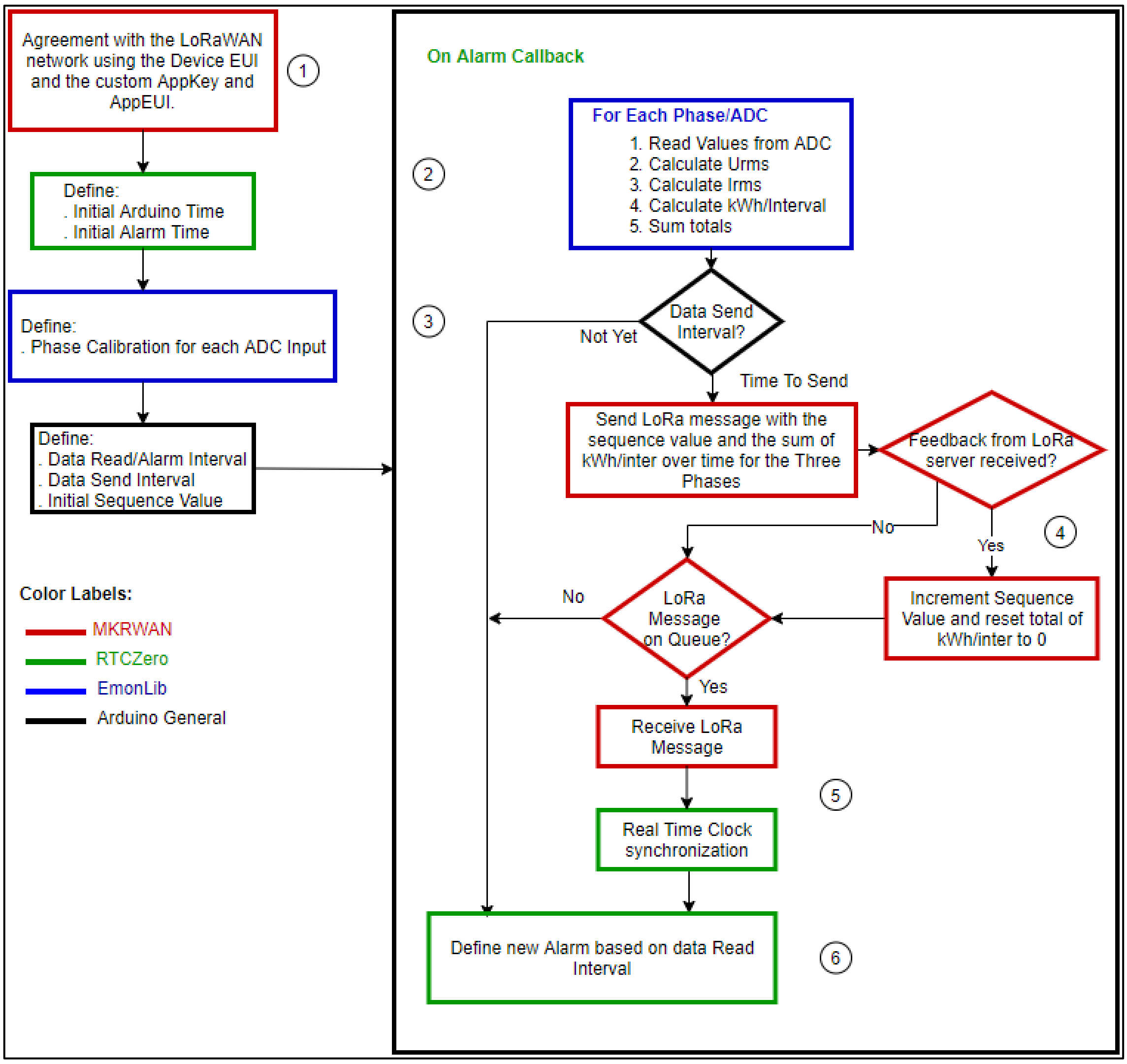
Annex

Annex 1: Arduino Written Workflow



- **Step 1 - Setup**:
    - The Arduino needs to agree with the LoRa server on the device's keys in order to communicate with the server.
    - The initial time and date for the Arduino's RTC are also defined by the user.
    - Calibration, data read, and data send interval are also set on the setup phase, this alarm, at every data read period, calls the main method of this workflow, and inside this method, the Send Interval defines whether or not the data is sent to the server.

- **Step 2 – Generate data**:
  - The alarm calls the method on a set interval, defined on the data read interval. The first part of this method is the use of the EmonLib to calculate the values measured by the current transformer connected to the Arduino which presents us with potency in Watt-Hour that is turned into kilowatt-Hour/interval and then summed.
  - The library runs a continuous loop with as many iterations as the user-defined for each electrical phase/input, each iteration takes a few milliseconds, so in order to have continuous reads, the developer can create an iteration within an iteration and then do an average of alliteration inside the interval between data sends.
- **Step 3 – Verify Send Interval:**
  - This step verifies if a threshold of alarms has been reached, i.e., 5 alarms activated every minute means 5 minutes has been reached.
    - If the defined threshold has been reached, the data is ready to be sent to the LoRa Server.
    - If the defined threshold has not been reached, nothing is sent, and the alarm is defined for the next data Read time (**Step 6**).
- **Step 4 – Data Sent, Feedback response:**
  - Once the data is sent to the LoRa server, immediate feedback from that server is sent.
    - If that feedback is received, the Arduino increments the sequence value and reset the sum of kWh/interval to zero.
    - If the feedback is not received, the Arduino keeps his current sequence value, and the sum of kWh/interval is not reset, keeping the total values from that timestamp from disappearing. This values are sent over the next Data Send threshold.
- **Step 5 – Data Sent, Application Server Message, and Time Correction:**
  - Once the data is sent to the LoRa server, the Arduino awaits a message from the LoRa's server queue that may contain a packet from the Application server.
    - If a message is received, it means that the Arduino has gone out of sync with the real-time, most likely by one or two seconds, and

therefore requires correction, this message contains the corrective value that the Arduino uses to correct itself.

    - If a message is not received then, the Arduino moves on and defines the next data read alarm (**Step 6**).

- **Step 6 – Set data read Alarm:**
  - According to the data read interval, the next alarm is set based on the last alarm, i.e., last alarm was set at 10:11:00 then the new alarm is set for 10:12:00 in case the data read interval is set to 1 minute.

Annex 2: Derived Data JSON File


```
[
    {"id": "light_room1",
     "fields" : [
        {
          "id_field": "total_light_other_room1",
          "op_field":"+",
          "value_field":-1
        },
        {
          "id_field": "other_room1",
          "op_field":"-",
          "value_field":-1
        }
     ]
    },
  {"id": "total_light_other_avac_room2",
     "fields" : [
        {
          "id_field": "light_room2",
          "op_field":"+",
          "value_field":-1
        },
        {
          "id_field": "other_room2",
          "op_field":"+",
          "value_field":-1
        },
        {
          "id_field": "avac_room2",
          "op_field":"+",
          "value_field":-1
        }
     ]
    }
]
```


Figure 57 Annex 2: Example of Derived Data JSON File