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Universal solar powered water quality monitoring IoT device and notification system

Diploma Thesis

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MASTER‘S THESIS ASSIGNMENT

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Guidelines:

1) Study the topics about water quality monitoring and devices able to do this monitoring.
2) Find the sensors and processes which provide the adequate repeatable accuracy results.
3) Design an autonomous and long lasting solar powered device for a water quality monitoring system showing pH, temperature, conductivity, water level indicators etc.
4) Build a working prototype. Provide a remote monitoring dashboard.
5) Compare your device and its parameters with commercially available solutions.

Bibliography / sources:

1) Smart Sensors for Real-Time Water Quality Monitoring (Smart Sensors, Measurement and Instrumentation Book 4), Subhas C Mukhopadhyay, ASIN: B00HWV2VI4.
2) Water Flow Monitoring System Based on IOT: smart water monitoring (Internet of things) Based On IOT - IOT System - Water Saved, Abdullah Albreiki, ASIN: B07VGVRB37.

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Declaration of originality

I hereby declare that the work presented is entirely a result of my own original and individual work. All the information, figures, and diagrams from external sources are quoted and referenced appropriately.

In Prague on 20th of May, 2020 …..…………………………………

Catherine Kanama

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Abstract

Water constituents are often event-driven so concentrations and properties vary strongly in time. Due to this, there is a high demand for devices which can get accurate and real time measurements as these changes occur. Current methods of monitoring water quality mostly involve a team of people who collect samples which are later analyzed in a laboratory. This process is time consuming, expensive and has a slow reaction time which may lead to missing out on important changes in the water parameters.

This paper describes a prototype solution which is affordable and capable of producing quick and accurate results in real time. This prototype measures the water quality using various sensors which record the pH level, temperature, total dissolved solids, conductivity and changes in the level of water. These sensors are connected to the ESP32 DevKit V4 microcontroller which processes and transmits the data in real time using Wi-Fi to the thinger.io online monitoring dashboard. This dashboard also stores all the data so it can be for analyzing the trends in changes of water quality. In addition to that, this prototype utilizes solar energy harvesting allowing it to be self-sufficiently powered throughout the year.

Keywords: solar energy harvesting, water quality monitoring, Internet of Things, IoT dashboard, real time monitoring system.

Table of contents

Table of figures

Table of tables

List of abbreviations

IoT	…………………………	Internet of Things
WHO	…………………………	World Health Organization
EPA	…………………………	Environmental Protection Act
TDS	…………………………	Total Dissolved Solids
EC	…………………………	Electrical Conductivity
LDO	…………………………	Low Drop Voltage Regulator
LED	…………………………	Light Emitting Diode
ADC	…………………………	Analog to Digital Converter
RTC	…………………………	Real Time Clock
IDE	…………………………	Integrated Development Environment
Li-Ion	…………………………	Lithium Ion Battery
MPPT	…………………………	Maximum Power Point Tracking
SMD	…………………………	Surface Mount Device

1 Motivation

Despite water being one of the most important resources needed to sustain a good quality of life, it is also one of the most polluted resources. This great concern extends to the quality of surface and groundwater as it affects both aquatic and human life. The degradation in the water quality can be highly attributed to the vast increase in global industrial output and rural to urban drift which leads to the over-utilization of the available resources. Other factors such as high use of fertilizers in farms and other chemicals in sectors such as mining and construction have also contributed immensely to the overall degradation of water quality globally. Due to all the factors mentioned above, it is now more important than ever to have better, faster, reliable and affordable ways of monitoring water quality. Regular water quality monitoring will help to evaluate the extent of the pollution and will provide information necessary to develop control methods that will mitigate these effects.

However, the lack of affordable water monitoring equipment is a major hindrance in many poor countries such as Tanzania. Hence the use of sensor based IoT devices will help solve this problem. Using simple sensors, one can easily measure water parameters such as temperature, pH, total dissolved solids and electrical conductivity without the need of using specialized laboratory equipment. Adapting IoT communication protocols such as Wi-Fi will enable these devices to transmit the sensor data to a monitoring dashboard which can be used for remote and real time monitoring of the water quality.

After the successful implementation of this proof of concept, I am planning on using this device to monitor irrigation water supply for my family's avocado farm in Mbeya, Tanzania. Avocado trees are very sensitive to the water quality and they require very specific properties in order to produce many avocados. To get the highest yield, the irrigation water needs to be have very low conductivity of about 0.6 deciSiemens/m and total dissolve solids content of 384 ppm [1]. The trees also need pH levels between 5 – 7 as higher pH levels prevent the trees from absorbing important nutrients like zinc and iron which help in promoting plant growth [2]. Consequently, in order to maintain the health of the trees, the water sources need to be tested regularly to assure that the water quality is within these strict requirements.

Unfortunately, due to the remoteness of the area, the closest water testing laboratory is located 70 kilometers away and you need to wait for several days and even weeks to get back an analysis report. This device will immensely help to speed up the process by providing quick and reliable analysis whenever needed. The farm is located in a tropical region which has 2836 hours of sunlight per year with an average of more than 7:45 of sunlight per day, therefore the incorporation of the solar energy harvesting will allow this device to be independent and have sufficient power throughout the year [3]. With the use of the remote monitoring dashboard and stored data, it will be easier to identify and analyze long and short term changes in the water quality.

2 State of the art

There are currently several varieties of water monitoring systems available in the market but they all have one thing in common, very high prices and limited choices of measuring quantities that are available in a single module. Due to this, one is forced to either buy many of these modules that measure individual quantities or decide on which ones you are willing to skip on. Below are a few examples of some options that are available on the market.

2.1 5200A multiparameter monitoring and control instrument

The 5200A monitoring device manufactured by YSI is a waterproof handheld solution for monitoring water used in aquaculture applications. It measures dissolved oxygen, temperature, conductivity, total dissolved solids, pH and salinity. As seen in figure 1, the measurements can be displayed on an LCD screen located on the front of the device or an app. It uses ethernet or Wi-Fi to transmit the data and is marketed as a plug-and-play solution which doesn't need professional consultants. However, because this module is handheld, if the user needs to get measurements they have to physically go to the location as it cannot be left unattended. It also uses a 12 V DC power source which limits it's placement options to only areas with an available power outlet. Lastly, this device requires purchasing of many special software such as AquaManager for integrating process control, alarming, and data management. It also needs Feed Smart software for managing feed and sensor readings and Aqua Mana software for getting email and SMS notifications. [4] Many other semi-industrial water monitoring devices like Bluelab Combo meter and Libelium Smart water have a very similar design to this model [5] [6]. They all have a central control unit and input ports for connecting test probes such as pH, conductivity, dissolved oxygen and many more.

Figure 1: 5200A multiparameter monitoring and control instrument [4]

2.2 pHin smart monitor

The pHin is a floating devices used to continually monitor chlorine or bromine, pH and temperature of water in swimming pools, swim spas or hot tubs. It is compatible for use with chlorine, bromine and salt water systems. The devices comes with the pHin smart monitor, a wireless bridge and a mobile application as seen in figure 2. The device uses Wi-Fi hence the need for a wireless bridge. The mobile app is used for sending alerts as well as providing recommendations and instructions on chemical dosing. They also provide a monitoring service which stores all the

Figure 2: pHin smart monitor[2]

recorded data and can enlist the help of pool technician if the customer needs assistance on maintaining a desired water quality.

The initial cost of the device is $349, however the user needs to pay an additional $99 per year to keep using the mobile app services which is costly for average pool owners. The device is battery powered and the battery inside the unit is not replaceable as they claim it can last for a few years. In the event it runs out the only options are to send it them or get a new device [7]. This device represents many smart IoT devices such as Sutro which mainly focus on domestic or small scale uses. They have small compact designs which need to placed directly in the water and the collected data is displayed on their mobile applications for a renewable subscription fee.

2.3 Xiaomi Mi TDS pen water quality tester

The Xiaomi TDS pen manufactured by Xiaomi Mijia is a small device used to measure quality of drinking water based on total dissolved solids concentrations. At a price of only $9, the device is marketed as a quick and affordable method of determining if the available drinking water needs further purification. As seen in figure 3, they also provide a scale showing the relationship between the amount of measured TDS and the level of water purity.

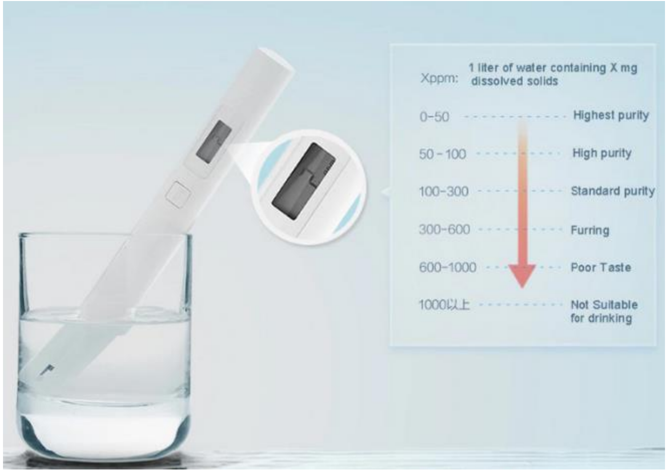


Figure 3: Xiaomi Mi TDS pen and TDS scale for rating water purity [8]

The device is powered using two button cell batteries placed in one of the device. The other end of the device has the TDS measuring probe and an external temperature sensor used for temperature compensation in order to have more accurate readings. The device also has automatic calibration which makes it easier to use.

The manufacturer claims that the device measures the amount of heavy metals, organic materials and water salinity which are used to indicate the level of water purity. However, the results displayed are for the total amount of dissolved solids and does not differentiate the amount of individual ions dissolved in the water. [8] Even though TDS is a good indication of the amount of organic and inorganic materials that are dissolved in the water, it cannot be used as the sole determinant of whether the water it safe to drink or not.

Based on comparison with the available solutions, this device needs to be a portable and affordable solution with the ability to produce reliable and reproducible results. The design also needs to be simple enough so it can easily be modified to adapt to different applications such as aquaculture, aquaponics, hydroponics or simply just domestic water monitoring. Hence prompting the need to incorporate multiple sensors which will reduce the need for purchasing different products for measuring each water parameter. With the use of energy harvesting, the device will be self-sufficient and stable enough to be left unattended for long periods of time, all while receiving sensors readings and device status from an online remote dashboard.

3 Theory

3.1 Energy harvesting

Many IoT devices are powered using batteries and depending on the type of application these batteries can last for hours, months or even years. However, it is very challenging to design a battery powered remote data acquisition device as the lifetime of the battery also limits the long term functionality of the device. Furthermore, the use of primary or non-rechargeable batteries also has the potential of being more expensive since it requires more time and resources to perform maintenance and battery replacements when they run out. Due to these challenges, energy harvesting is becoming a more preferred method for powering wireless devices [9] [10].

Energy harvesting is the process of deriving energy from external sources and converting it into usable electrical energy. It only requires the presence of an ambient energy source and a method of converting this energy into power. The main energy harvesting sources suitable for IoT devices are ambient sources such as thermal, biochemical and radiant sources which are already present in the environment and do not require any artificial power source [11]. The choice of energy source is usually determined by the amount of power needed for application as different sources have different power densities as seen in figure 4 below.

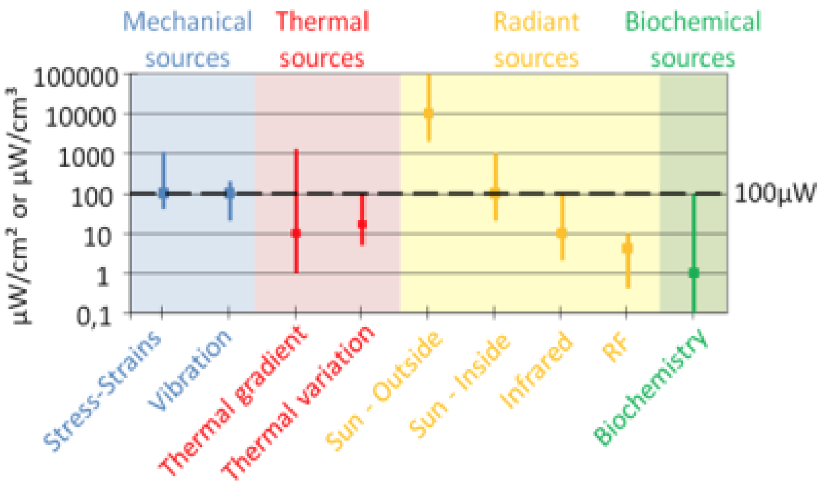


Figure 4: Energy sources and their power densities like [11]

This project uses four different sensors therefore it needs a steady power source that can guarantee high power densities at all times. Also since this device is mostly going to be used in outdoor conditions, the most favorable energy sources are radiant sources. Based in the power density among the radiant sources, solar energy is a preferred choice.

3.2 Energy storage accumulators

Available energy-storage choices for this project were rechargeable batteries or supercapacitors, both of which have their own strengths and weaknesses. Important comparison features between Li-ion batteries and supercapacitors are listed in table 1 below. Supercapacitors have a longer life span of about 100000 charging cycles, they also have the ability to charge faster than batteries. However, they suffer from high self-discharging rates of about 10 % - 20 % per day which will affect the long term usability of this system.

Rechargeable batteries store energy in chemical form and therefore they are capable of storing more energy per weight compared to supercapacitors. Even with more limited life cycles and longer charging times, rechargeable batteries have a lower discharge rate and can maintain a near constant voltage supply all of which are favorable for powering remote data sensing devices. As a result the chosen energy storage method will be Lithium-Ion (Li-Ion) batteries [12] [13] [14].

Table 1: Comparison between li-ion batteries and supercapacitors

Features	Li-ion battery	Supercapacitor
Maximum Voltage (V/cell)	1.2 - 4.2	2.5 - 2.7
Usage Cycles	500 - 10,000	100,000 - 1,000,000
Specific Energy (Wh/kg)	100 - 200	4 - 9
Specific Power (W/kg)	1,000 - 3,000	Up to 10,000
Charge/Discharge Efficiency	0.70 - 0.85	0.85 - 0.98
Charge Time	10 - 60 mins	1 - 10 secs
Self-Discharge rate per day	1 % - 2 %	10% - 20%
Voltage on Discharge	stable	decreasing
Charge Temperature(°C)	0 to + 45	-40 to +65
Discharge Temperature(°C)	- 20 to + 60	-40 to +65
Cost per Wh	~ $2	~ $20

This device is expected to be used in outdoor conditions therefore there needs to be a consideration of how the outdoor temperatures will affect the lifetime and performance of the li-ion batteries. Knowing the effects of temperature will also help to create a safer operating environment for the batteries. The optimal temperature for operating Li-Ion batteries is between 0 to 30 °C [15]. When the temperature is very low, the conductivity of the lithium ions is significantly reduced and as a result it becomes much harder to charge a fully discharged battery [16]. The reduced ion activity also causes an increase in internal resistance leading to the warming effect which results in loss of efficiency due to voltage drop when a load current is applied.

The discharge voltage loss and temporary decrease in battery capacity of a 18659 li-Ion cell at different temperatures can be seen in figure 5 below. The battery used in this experiment had a capacity of 2800 mAh and the current draw applied was 3 A. From the illustration, at lower temperatures the discharge voltage was notably decreased when compared to operating the same battery in room temperature conditions. At lower temperatures the decrease in capacity is only temporary and can be reversed when the temperatures is back to optimal conditions [17].

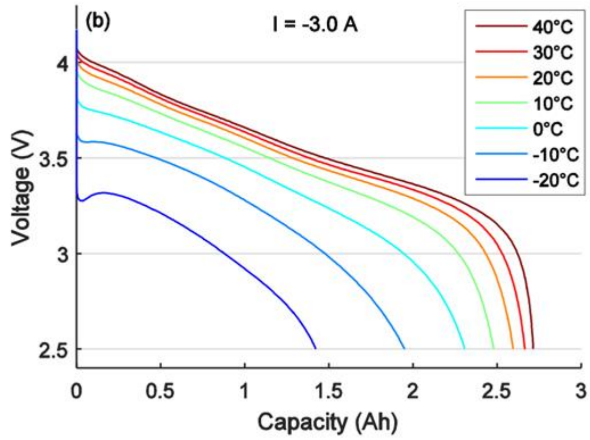


Figure 5: Discharge voltage of a 18650 li-ion cell at 3 A and varying operating temperatures [18]

When operated in higher temperatures, the performance of the Li-Ion batteries is highly reduced and the battery degradation causes irreversible decrease in the battery capacity. This can be seen in the results obtained by Feng Leng, Cher Ming Tan and Micheal Pecht on the effects of high operating temperatures. And as seen in figure 6 below, as the temperature increased, the batteries degradation factor also increases causing permanent decrease in battery capacity.

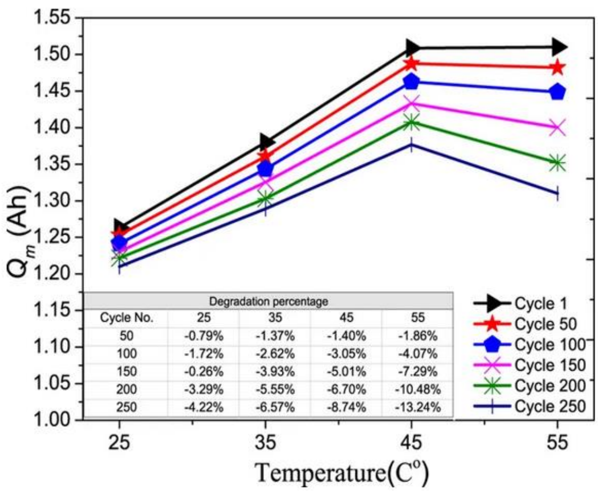


Figure 6: Effect of increasing temperature on the degradation rate of li-Ion batteries [19]

Therefore in order to avoid and mitigate the issues discussed above, several measures need to be implemented. First, the enclosing container for the devices needs to be well ventilated when using the device in high temperatures. In extremely hot places, the enclosure can also be equipped with some cooling mechanisms like a small fan or a water cooling system. Similarly, when used in lower temperatures the enclosure needs to be well insulated to prevent further heat loss.

3.3 Water quality parameters

The following sections discuss the importance of monitoring water temperature, pH, total dissolved solids and electrical conductivity as changes in one parameter also affects the other parameters. These sections will also describe the acceptable limits of these parameters as set by the World Health Organization (WHO), Environmental Protections Agency and European Union Directives.

3.3.1 Temperature

Changes in temperature have a great influence on the chemical, physical and biological properties of water. Accurate temperature measurement is very important in this project since changes in the water temperature also affects other water properties such pH, conductivity and concentration of total dissolved solids. [20] When the water temperature increases, the number of ions in the water also increases due to the dissociation of ions already present in the water. Thus causing a variation in the pH level as well as the conductivity and the concentration of total dissolved solids also changes [21]. These variations can also be observed on the results obtained in a study of how changes in water temperature affects the quality of spring water. The results can be seen in figure 7 below, when a sample of water is warmed up, the pH level, conductivity and amount of TDS increases and when the sample is cooled down the pH level, conductivity and amount of TDS also decreases [22].

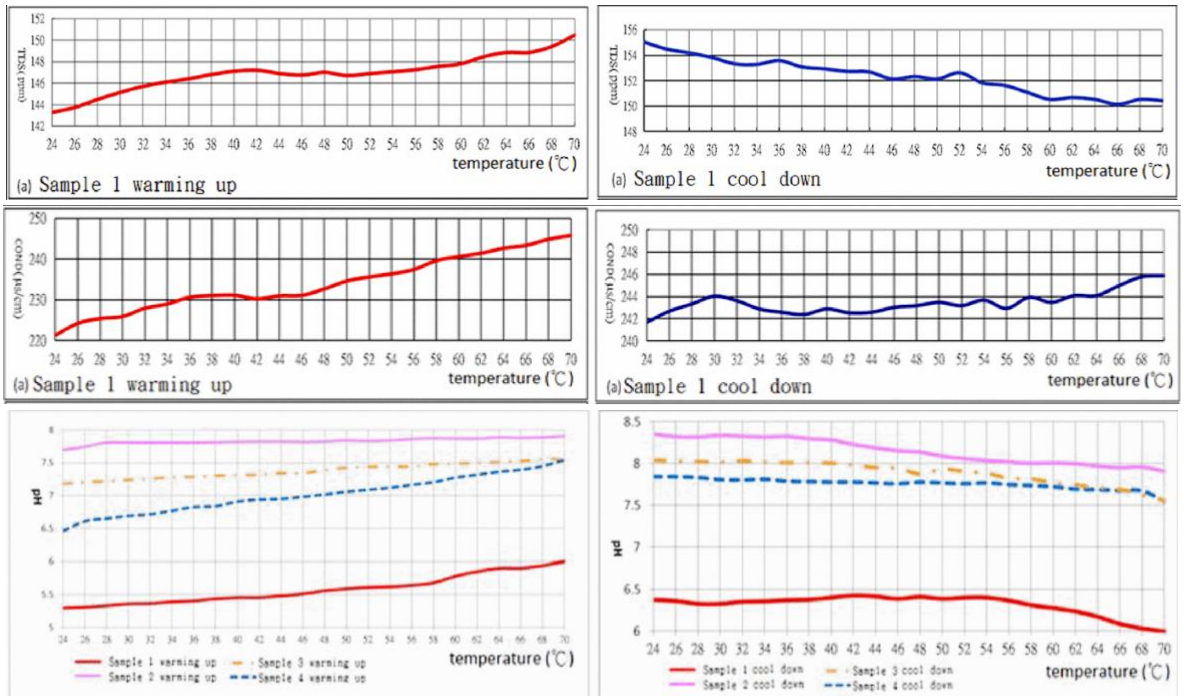


Figure 7: Changes in conductivity, total dissolved solids and pH with increase and decrease in temperature [22]

Changes in the liquid temperature also affects the electrodes of the pH sensors, hence it is important to also record the water temperature and include an temperature compensation factor in the pH measurement, Results from a study by S. Bhandra, G. E. Bridges, D. J. Thomson and M. S. Freund, shows that when the temperature compensation factor is added, the accuracy of the pH reading is increased and the errors due to temperature dependence of the electrodes becomes significantly suppressed.

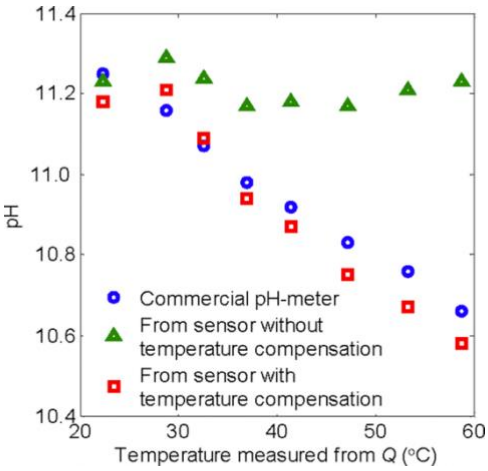


Figure 8: Effect of temperature compensation on the accuracy of measured pH value [23]

This can be seen in figure 8 , where the pH measurements of a solution with pH = 11.25 at room temperature were taken using a commercial pH meter and an electrode based pH sensor. From the results obtained, they observed that when the temperature compensation factor was added, the measured pH value from the pH sensor has increased accuracy value of within 0.1 pH compared to the measured values without the temperature compensation. [23]

3.3.2 pH level

pH is a measure of hydrogen-ion concentration in water-based solutions, it determines whether a solution is basic alkaline or acidic based on a logarithmic scale. The scale ranges from 0 to 14, with 7 being neutral. pH values of less than 7 indicate acidic solution with more free hydrogen ions while pH of greater than 7 indicate alkaline solution with more free hydroxyl ions [24]. Different water sources have varying pH values based on many natural and artificial factors. Naturally, water flowing near limestone rock is less acidic as the stone naturally neutralizes the acid while water flowing in an area with decomposing plants is more acidic as the plants release carbon dioxide which dissolves in the water. Artificial factors affecting pH levels are mostly due to human activities such as the release of untreated industrial affluent or the seeping of fertilizer runoffs into the water [25].

Water used for different applications such as agricultural purposes, aquaculture and drinking water all have different pH level requirements. For example, according to the European Water Quality Standards, the acceptable pH levels for tap water is between 6.5 to 9.5. This is because water with pH less than 6.5 is considered too acidic and corrosive and may contain metal ions such as lead, iron, zinc, copper and manganese which can be toxic. On the other hand, water with pH higher than 9.5 is considered too alkaline and may lead to the formation of scale deposits in water pipes [26]. Further European Union directive on pH limits for surface water, aquaculture water, drinking water and other uses can be seen in figure 9 below.

pH : Recommended or Mandatory Limit Values

EU Directive or National [Ministerial] Regulations		*Units of Analysis*	*G Value*	*I/PV Value*	*Note(s)*
Surface Water Regulations [1989]	A1 waters	pH units	n/a	5.5-8.5	
	A2 waters	pH units	n/a	5.5-9.0	
	A3 waters	pH units	n/a	5.5-9.0	
Bathing Water Regulations [1989-1998]		pH units	n/a	$\geq$ 6 and $\leq$ 9	[1]
Freshwater Fish Directive [78/659/EEC]	(S)	pH units	n/a	$\geq$ 6.0 and $\leq$ 9.0	[2,3]
	(C)	pH units	n/a	$\geq$ 6.0 and $\leq$ 9.0	[2,3]
Salmonid Waters Regulations [1988]		pH units	n/a	$\geq$ 6 and $\leq$ 9	[2,4]
Shellfish Directive [79/923/EEC]		pH units	n/a	7.0-9.0	
Drinking Water Directive [98/83/EC]		pH units	n/a	$\geq$ 6.5 and $\leq$ 9.5	[5]

Figure 9: EPA recommended pH limit values [27]

Knowing the pH levels in water is important because it indicates the chemical properties of the water and helps in selecting proper water sources suitable for each specific use.

3.3.3 Total dissolved solids and electrical conductivity

Total Dissolved Solids (TDS) is a measure of the total amount of soluble organic and inorganic solids that are dissolved in one liter of water. The amount TDS in water is quantified in parts per million (ppm) or milligrams per liter (mg/L) such that the higher the TDS, the more soluble solids are dissolved in the water and therefore the water is considered unclean. These dissolved solids include all particles which are small enough to pass through a 2 micron filter such as salts, organic matter, minerals and heavy metals which originate from natural sources, sewage, industrial wastewater, urban and agricultural runoff [28].

High concentration of TDS indicates the presence of harmful contaminants like bromide, arsenic, sulfate and manganese in the water. These contaminants are toxic and make the water unfit for the environment and any human activities. High concentrations of TDS also causes changes in water tastes causing it to be to bitter, salty, acidic or brackish therefore making it undesirable for drinking. According to a panel test done by the World Health Organization, table 2 below shows a rating of how different concentrations of TDS affect the taste of drinking water [29].

Table 2: WHO panel results on the changes in drinking water taste based on the amount of total dissolved solids [29]

TDS level (ppm)	Taste rating
< 300	Excellent
300 - 600	Good
600 - 900	Fair
900 - 1200	Poor
> 1200	Unacceptable

Different countries have their own TDS limits in water sources but the World Health Organization and other institutions such as the Environmental Protection Act suggests 500 ppm as the maximum acceptable TDS in tap water [29] [30]. Typically, natural mineral water and tap water have TDS value of 100 – 250 ppm, further illustration of the TDS concentration in water from different sources can be seen in figure 10 below. The amount of TDS in water can be reduced using filtering technologies such as distillation, ion exchange, reverse osmosis and the use of active carbon filters [31].

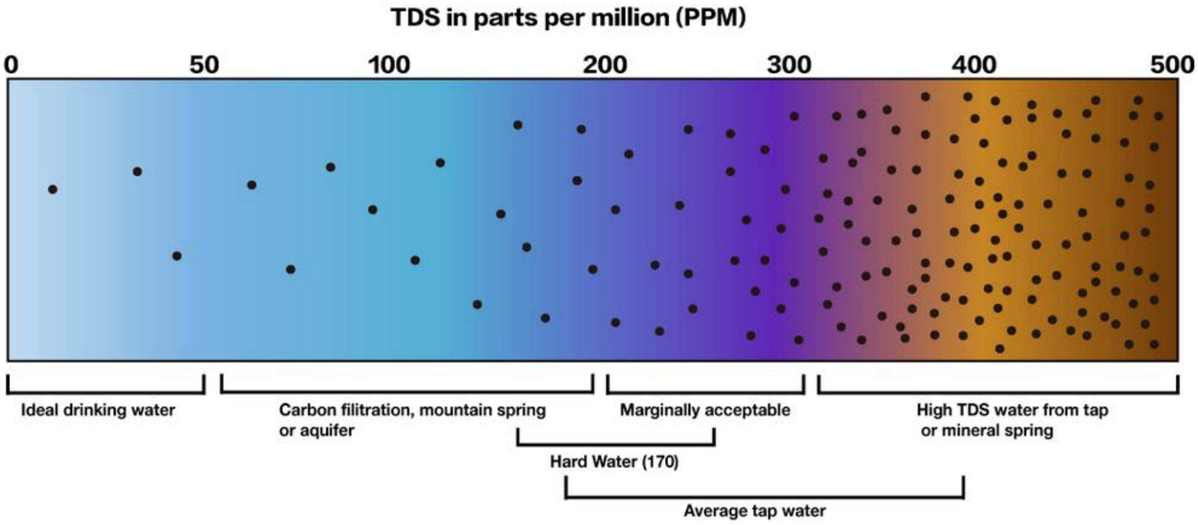


Figure 10: TDS concentration in various water sources [32]

Electrical Conductivity (EC) measures the water's ability to pass electrical flow and provides the concentration of charged ions in the water. These ions come from dissolved materials such as salts and inorganic materials like calcium, magnesium, potassium, sodium, nitrates, carbonates, chlorides, alkalis and sulfide compounds. High the amount of ions indicate high conductivity measurement and lower amount of ions indicates lower conductivity. Conductivity is measured in micro Siemens per centimeter (µS/cm) or milli Siemens per centimeter (mS/cm) and one Siemens is equal to one mho [33]. Typical electrical conductivity of water can be seen in table 3 below.

Table 3: Typical electrical conductivity of water from different sources [34]

Water	EC (mS/cm)
Ultra-pure water	0.00005
Distilled water	0.0005 – 0.003
Drinking water	0.05 - 0.5
Tap water	0.05 – 0.8
Fresh water streams	0.1 – 2
Sea water	50

Electrical conductivity and TDS are related such that the TDS can be estimated from the electrical conductivity assuming the dissolved solids are predominantly ionic species of low enough concentration to have a linear EC-TDS relation. This relation can be expressed using the equation 3.3.3.1 below [35].

$$\text{TDS (mg/L)} = k_e * \text{EC } (\mu\text{S/cm}) \qquad [3.3.3.1]$$

Where by k_e is a constant of proportionality which reflects the type of water. This relation depends on the type and nature of the dissolved ions, for example the value of k_e = 0.47 to 0.50 for water containing sodium chloride (NaCl) and k_e = 0.50 to 0.57 for water containing potassium chloride (KCl). This is because a NaCl solution and KCl solution with a same conductivity of 10000 μS/cm will not have the sample concentration of NaCl or KCl and they will have different total dissolved solids concentration. Measured conductivity is usually 100 times the total amount of dissolved ions therefore when the amount of TDS is estimated using a conductivity meter, the TDS in ppm constant of proportionality usually ranges from 0.5 to 1.0 times the electrical conductivity [36].

3.4 Remote online monitoring dashboard and notification system

The Internet of Things can be described as a network of "things" or devices which are connected to the internet. These things are embedded with sensors and are used to collect and share data about the environment around them [37]. A complete IoT device consists of hardware such as sensors to collect the data, connectivity so the data can be transmitted to the cloud, and finally a user interface such as a dashboard so the user can interact with the collected data. IoT dashboard is a data visualization tool used for displaying and organization of the data collected and transmitted by the device. The dashboard can also be used to control the device and giving the user remote access to the device and collected data in real time [38].

The remote online monitoring dashboard is one of the most important requirements for this project. The data collected water quality monitoring sensors needs to be displayed in an online dashboard so that the user has unlimited access to the data recorded by the device at all times.

Currently, there are many available options of IoT dashboards and platforms. Dashboards are mostly used for data visualizations while platforms have an integrated dashboard as well as the added advantages of data storage and device management. This project will focus on using a platform with a real time IoT dashboard and data storage feature. In order to keep the project affordable, the selected platform needs to have an option for a free or student account. The platform should have no limitations on the amount of data transmission as well as unlimited data storage time. The platform also needs to provide security and authentication for the devices and users.

It is also important that the platform can handle different communication protocols as well as the ability to integrate with other web services such email notifications. Therefore, based on these requirements, thinger.io platform was selected. A typical dashboard can be seen in figure 11 below and a full description of its features is described in the implementation section 5.3.

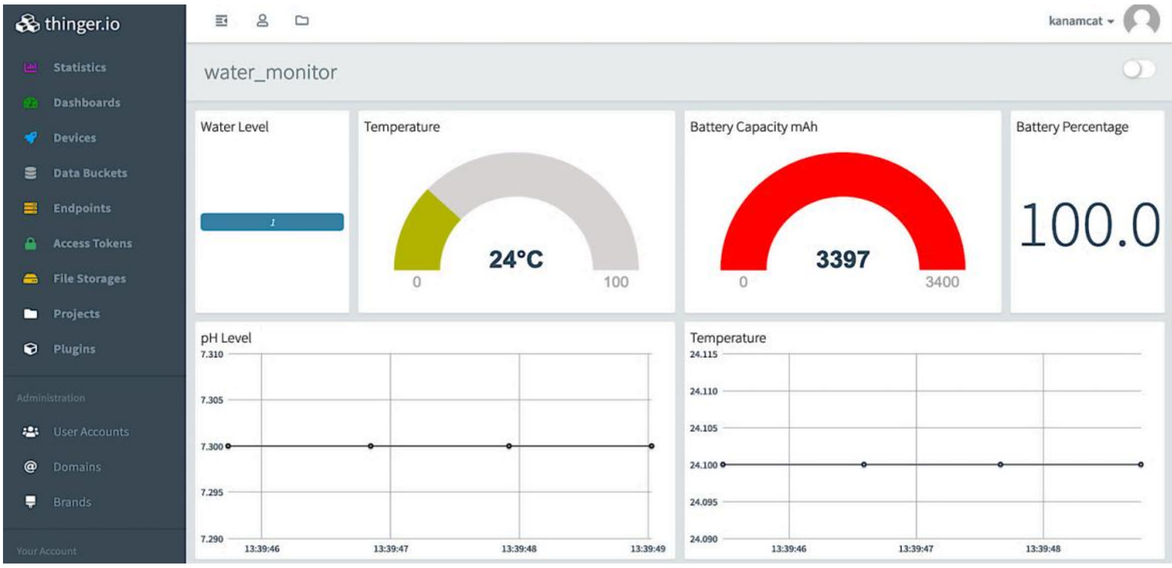


Figure 11: thinger.io dashboard showing multiple types of data visualization options

4 System design

The implementation of the prototype is divided into three major blocks consisting of the solar energy harvesting module, water quality monitoring module with sensors and wireless interface and lastly the remote monitoring dashboard which displays sensor readings and status of the solar harvesting module in real time. A block diagram illustration can be seen in figure 12 below.

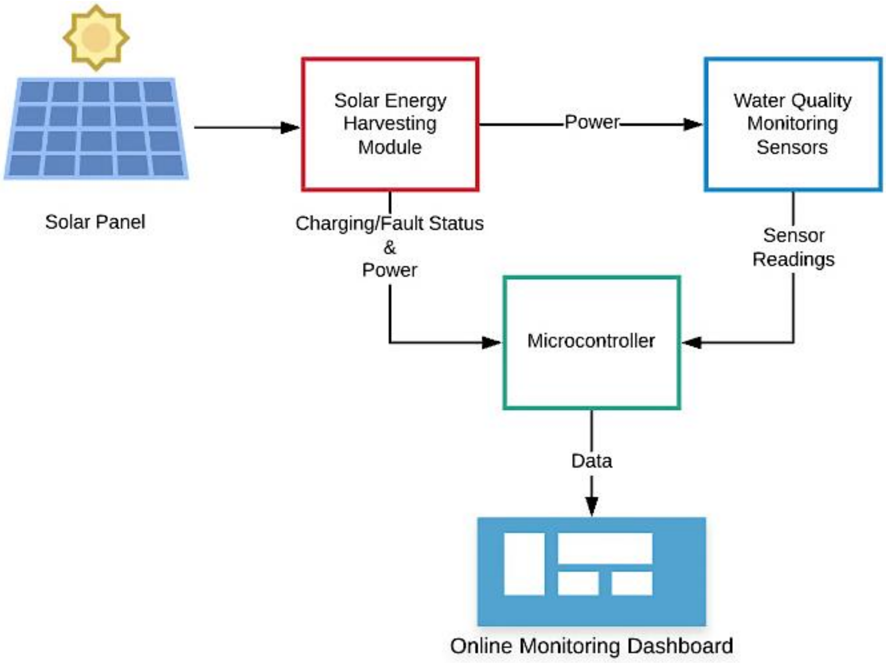


Figure 12: Functional block diagram of the device showing the main modules

4.1 Solar energy harvesting module

This module is the main power source for the device. It consists of a solar powered battery charging circuit, a battery fuel gauge and output regulation circuits. The charging circuit works as a power path such that the solar panels power the system and charge the battery at the same time. When the solar input goes to 0 V, the battery begins to power the system. The fuel gauge is used to monitor the battery capacity and usage while the output regulation circuit is used to step down the output voltages to 3.3 V and 5 V so it can be compatible with the sensors and the microcontroller.

This power source is implemented as a separate unit so it can also be used as an independent power source for any other low power IoT projects. In addition to that, separating this circuit will increase flexibility of the use cases for water monitoring module as it creates the potential for use with other power sources.

4.2 Water quality monitoring sensors

This module consists of various sensors which measure different water constituents like pH, temperature, total dissolved solids, conductivity and change in the water levels. The choice of measurement quantities is based on properties that are required for monitoring water used for agriculture, hydroponics, remediation, tap water and drinking water. The sensors will be powered by the solar power supply module and the data collected will be processed by the microcontroller and eventually displayed in an online dashboard.

4.3 Remote online monitoring dashboard and notification system

The data collected by the sensors will be transmitted to the online monitoring dashboard via Wi-Fi so the data can be viewed in real time. The monitoring dashboard will also store all the collected data so that it can be used for long term analysis of the changes in water properties. The use of the dashboard will also allow for remote monitoring of the device status by displaying the battery capacity, charging or fault status as well as the location of the device. Lastly, the dashboard sends the user notifications or alerts when the changes in water parameters exceeds the specified limits.

5 Implementation

5.1 Solar energy harvesting module

This section will describe in detail the implementation of the charging circuit, batteries, fuel gauge and output regulation circuits. The general block diagram for the power supply can be seen in figure 13 below. Detailed discussions for each block are explained in the sections that follow below.

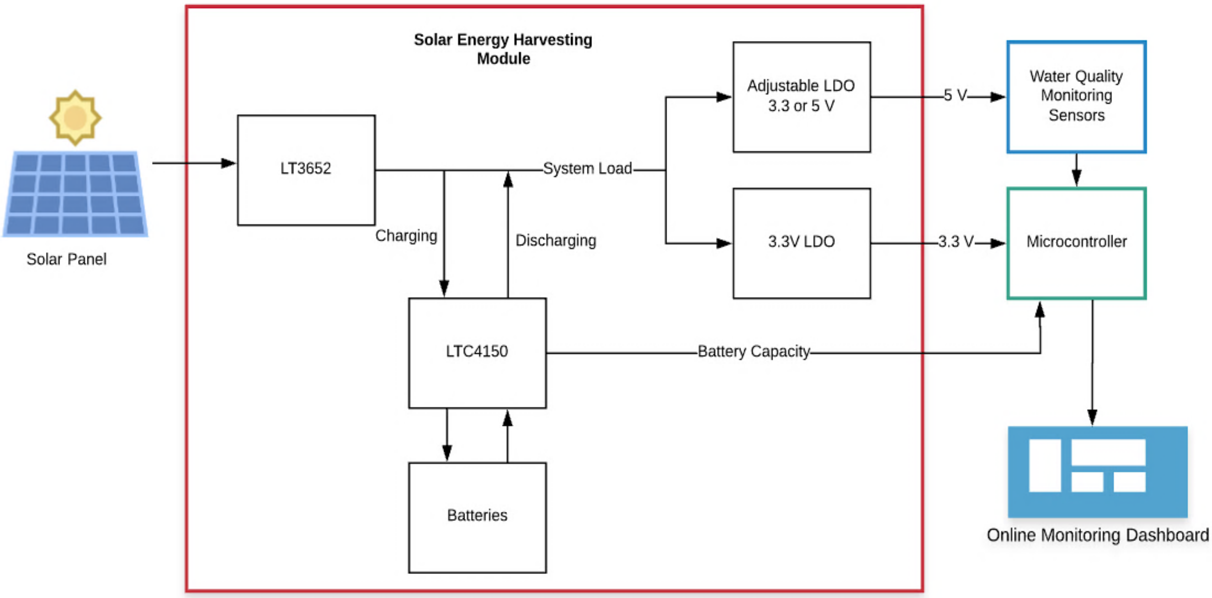


Figure 13: Block diagram of solar energy harvesting module

5.1.1 Solar panels

Solar photovoltaic panels provide the main energy source to the device, they convert ambient sunlight into DC voltage based on the photovoltaic effect. To accommodate for applications in different lighting conditions, the solar panels can be connected to the input in different orientations such that a single panel can be used or two panels can be connected in parallel or series by adjusting the position of the jumper as illustrated in figure 14 below. When used in areas with high amounts of lighting such as under direct sunlight, a single panel or two panels in series would suffice. But when used in poorly lit conditions such as shaded areas, parallel connection of the panels would yield more power due to increased current flow [39].

This device will use two panels in series in order to increase the surface area and attain enough power for the device. Each panel has a rating of 5 V 200 mA and size of 120 x 70 mm. These panels are chosen for areas with many sunlight hours like countries close to the equator. In order to use this device in places with less sun hours, the panels used need to have a larger surface area and power rating.

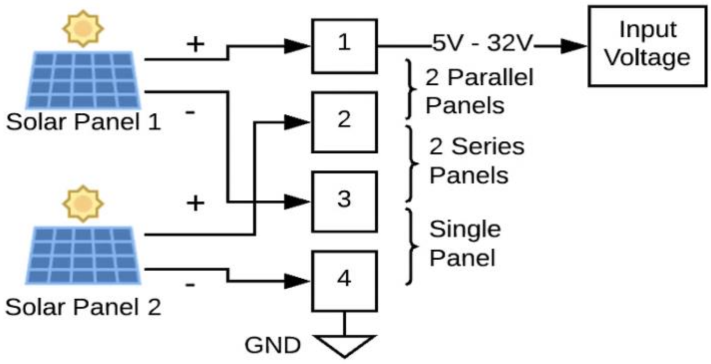


Figure 14: Different jumper positions to achieve single, parallel or series orientation of solar panels

5.1.2 LT3652 solar battery charger

This device uses the LT3652 chip manufactured by Linear Technologies to implement a solar power manager with 7.2 V Li-Ion batteries. The LT3652 chip is a step-down battery charger which operates with a wide input range of 4.95 V to 32 V. It uses a constant current/constant voltage charging characteristic with programmable charge voltage of up to 14.4 V and charge current of up to 2 A. It also has two options for terminating battery charging based on battery current capacity detection or an on-board timer in order to prevent overcharging of the battery.

This chip was selected because it has the ability to control charging of the batteries while providing an output power supply to the rest of the device. This is a very important feature because the device can be powered even when the batteries are completely depleted. This function is implemented by the input voltage regulation loop which controls the solar panel output voltage to produce peak output power while still charging the batteries. Likewise, when the solar panel voltage drops to zero, the batteries provide power to the application. A simple illustration of the power path can be seen in figure 16 below [40].

The LT3652 chip also features Maximum Power Point Tracking (MPPT). MPPT is a technique used to operate solar cells at their peak power of the IV curve in order to obtain maximum charging efficiency, where by maximum power point is the voltage at which the solar cells produce maximum power [41]. As seen in figure 15, this voltage varies with ambient temperature, solar radiation and the solar cell temperature, therefore it needs to be adjusted accordingly [42].

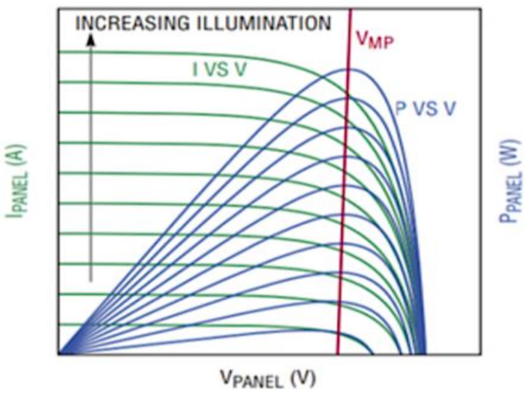


Figure 15: Change of MPPT voltage with light intensities [42]

The LT3652 chip maximizes the output power of a solar panel by regulating the input panel voltage on the VIN_REG pin. When this input voltage is set correctly (recommended voltage is greater than 2.7 V), the efficiency of energy harvesting can reach up to 98%. In this circuit, the voltage regulation loop is adjusted using a 500 $k\Omega$ potentiometer connected to the VIN_REG pin and this set voltage can be measured on the Set breakout pin located on the J4 connector as seen in the circuit in figure 16 below.

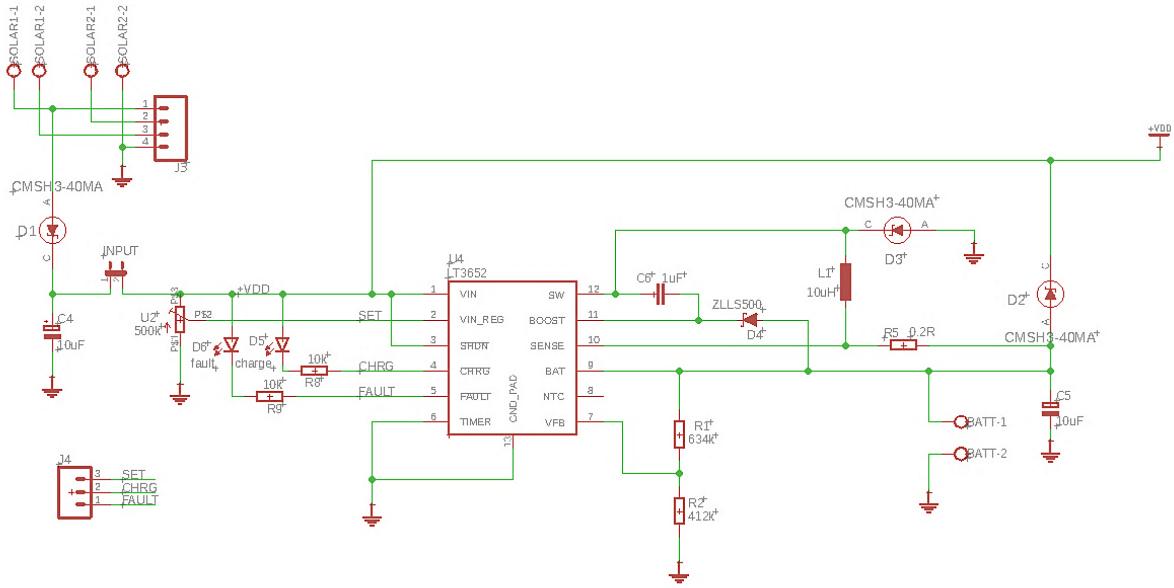


Figure 16: Schematic for LT3652 solar power path

The schematic used in this project is based on the typical circuit described in the LT3652 datasheet with a few added modifications to make charging voltage and current more suitable for this project. A new charging cycle begins when the battery voltage falls below 2.5 % of the programmed float or charging voltage. The battery charging voltage is resistor programmable by changing the values of a resistor divider connected to floating voltage pin 7. This pin has a 3.3 V float voltage feedback reference so the charging voltage can programmed up to 14.4 V. The values of these programming resistors (R1 and R2 in figure 16) are calculated using the provided formula below.

$$R_1 = \frac{V_{BAT(FLT)} * 250000}{3.3} \qquad [5.1.2.1]$$

$$R_2 = \frac{R_1 * 250000}{R_1 - 250000} \qquad [5.1.2.2]$$

When using 7.2 V Li-Ion batteries, the recommended charging voltage is 8.4 V, therefore the required resistor values are:

$$R_1 = \frac{8.4 * 250000}{3.3} = 636363 \sim 634 \text{ k}\Omega \qquad [5.1.2.3]$$

$$R_2 = \frac{634000 * 250000}{634000 - 250000} = 412769 \sim 412 \text{ k}\Omega \qquad [5.1.2.4]$$

The charge current can also be controlled by calculating the appropriate value for the sense resistor. Charging is terminated when the output current from the charger falls below 1/10th of the maximum current programmed by the sense resistor. The recommended charge current is 1/10th of the total capacity and the total capacity of batteries used is 3400 mAh. Therefore the charge current needs to be

349mA. However, in order to have faster charging times the current can be safely raised to 500mA. Using the provided formula, the value for the current sense resistor R5 in the schematic can be estimated as follows using the provided formular:

$$R_{SENSE} = \frac{0.1}{I_{CHG(MAX)}} \quad [5.1.2.5]$$

for a current draw of 500 mA,

$$R_{SENSE} = \frac{0.1}{0.5} = 0.2\ \Omega \quad [5.1.2.6]$$

The LT3652 has a charge pin (pin 4) that is used to indicate when the battery is charging. In the schematic, this pin is connected to an LED which will light up when the batteries are charging for quick on site debugging. For remote monitoring of the device, this pin has a binary output and can be used by the microcontroller to monitor the charging state and cycles. The chip also has a fault pin (pin 5) which has a high binary output when a temperature or battery fault occurs. As seen in the schematic above, this pin is connected to an LED and is also routed to the connector J4 so it can be used by the microcontroller to detect faults in the charging circuit [43].

5.1.3 Lithium ion batteries

In order to pick an appropriate battery capacity, we need to make an estimate of the power consumption needed for the whole system. In this device, most of the power is consumed by the ESP32 microcontroller when transmitting sensor data over Wi-Fi. Therefore, to improve the power efficiency the sensors will collect data at time intervals and during down time the microcontroller goes into deep sleep and power to the sensors can be shut off.

Table 4: Power specifications for each component [44] [45] [46] [47] [48]

	Operating voltage (V)	**Current draw (mA)**
ESP32 active mode(connected to Wi-Fi)	3.3 / 5.0	160 - 240
ESP32 active mode	3.3 / 5.0	38 - 70
ESP32 deep sleep	3.3 / 5.0	< 3.5
pH sensor	5.0	5 - 10
TDS sensor	3.3 - 5.0	3 - 6
Temperature sensor	3.0 - 5.0	4
Float water level switch	3.3 - 5.0	< 3

The maximum current draw is estimated by considering the ESP32 microcontroller is always connected to Wi-Fi and all the sensors are taking measurements at all times. Therefore, based on this maximum current draw and an expected minimum continuous battery run time of 12 hours, the battery capacity can be estimated using the equation below:

Battery capacity (mAh) = Time (hrs.) * Max. current draw (mA) [5.1.3.1]

Battery capacity (mAh) = 12 * 263 = 3156 mAh [5.1.3.2]

Based on the estimated capacity above, two Li-ion batteries with a total rating of 7.2 V 3400 mAh were chosen. The actual runtime is expected to be much longer than the calculated time since the system will be in idle mode for long periods of time. This device will be used to monitor still or non-flowing water therefore the sensor readings will be measured and transmitted at an interval of 1 hour, significantly reducing the total power consumption.

5.1.4 LTC4150 coulomb counter

The initial design on the device had a custom made circuit for the fuel gauge using the LTC4150 chip by Linear Technologies. However due to the Coronavirus lockdown, I was not able to get the chip on time and instead resorted to using the SparkFun Coulomb Counter Board which is also based on the LTC4150 chip.

The LTC4150 chip is used to accurately determine the remaining battery capacity based on the battery voltage. The chip measures the amount of charge flowing in and out of the batteries through a current sense resistor. Then a voltage to frequency converter translates the current sense voltage into pulses which correspond to the amount of charge flowing in and out of the battery. These pulses are generated from the interrupt pin which is usually high but pulses low every time 0.614 coulombs or 0.1707 mAh pass through the resistor. This interval is calculated using the provided formulas in the datasheet. The chip also indicates the changes in polarity which helps to determine whether the battery is currently charging or discharging.

In order to get an accurate estimate of the battery capacity, you need to start with a full battery of known capacity and for every pulse, depending on the polarity, 0.1707 mA is added when charging and subtracted when discharging [49].

The schematic of the SparkFun coulomb counter board is very similar to that described in the LTC4150 datasheet. The board has an operating voltage 2.7 V – 8.5 V and maximum operating current of 1 A. The LTC4150 chip has a current draw of 115 – 140 μA but it can be lowered to 10 – 22 μA by setting the shutdown pin to low. However when this pin is low the board stops measuring the current consumption [50].

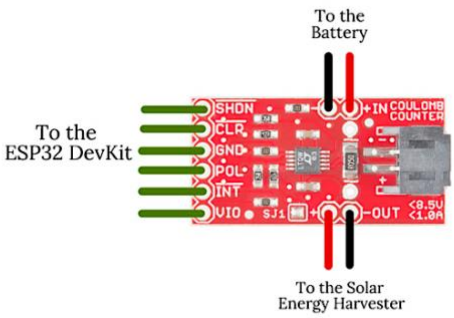


Figure 17: SparkFun coulomb counter connections to the device

In order to get a more accurate representation of the battery charging and discharging cycles, this board is placed between the battery and the solar power charger as seen in the block diagram in figure 13. It is also connected to the ESP32 microcontroller via the interrupt, clear, polarity, shutdown and voltage input power pins as seen in figure 17.

The ESP32 microcontroller will use interrupts instead of polling to sample the interrupt signal pulses from the coulomb counter board. This will allow the ESP32 microcontroller to asynchronously listen so we don't miss any pulses from the LTC4150 chip. The total battery capacity is stored in the RTC memory of the ESP32 microcontroller because this memory preserves it's state after deep sleep so the previous battery capacity is always stored. With every interrupt received, if the polarity is low, it means the battery is discharging so 0.1707 mA is subtracted from the stored capacity and if the polarity is high the battery is charging so the same amount is added to the total stored capacity. For better accuracy, the device starts with a fully charged batteries with maximum capacity, this implementation in code can be seen in the snippet in figure 18 below.

```
#define INT 18
#define POL 5

#define BATTERY_CAPACITY_MAH 3400 // full capacity mAh
#define AH_QUANTA 0.17067759 // mAh for each INT

// battery capacity tracking
RTC_DATA_ATTR volatile double battery_mAh = BATTERY_CAPACITY_MAH;

void handleFuelGaugeInterrupt() {
  boolean polarity = digitalRead(POL);
  if (polarity) {
    battery_mAh += AH_QUANTA; // charged capacity
    if (battery_mAh > BATTERY_CAPACITY_MAH) {
      battery_mAh = BATTERY_CAPACITY_MAH;
    }
  } else {
    battery_mAh -= AH_QUANTA; // used capacity
    if (battery_mAh < 0) {
      battery_mAh = 0;
    }
  }

void setup() {
  pinMode(INT,INPUT_PULLUP);
  pinMode(POL,INPUT);
  // interupt function call
  attachInterrupt(digitalPinToInterrupt(INT), handleFuelGaugeInterrupt, FALLING);
}
```

Figure 18: Code implementation for calculation of battery capacity

5.1.5 Output regulation circuits

Most IoT devices operate at 3.3 V or 5 V hence this device will require voltage regulators to step down the output voltage. The output voltage regulation is realized using low drop voltage regulators (LDO). LDO were chosen because they are easy to use and require only a few other peripheral components. They are also affordable and readily available in many choices of compact packages. Most importantly, they have low noise, can operate with low dropout voltage of about 400 mV and have low power losses [51].

Both the ESP32 microcontroller and sensors used in the water monitoring sensors module operate at 3.3 V or 5 V. However, the sensors don't need to be powered all the time since the measurements are taken at time intervals. Therefore in order to improve the power efficiency, two independent LDO were added to the device.

The first LDO is implemented using the LF33CDT-TR chip by STMicroelectronics which provides 3.3 V to the ESP32 DevKitC V4 board. This LDO is enabled at all times so that microcontroller is always available to respond to interrupts and turn on the sensors. The LF33CDT-TR chip was chosen due to previous experience as well as affordability, reliability and ease of availability. It also has a maximum input voltage of 16 V which is suitable for this project since the selected solar panel can produce up to

11 V. The output voltage also has an accuracy of 2 % which is important because when powering the ESP32 DevKitC V4 board with 3.3 V, there's no further regulation so any voltages higher than 3.3 V will destroy the chip.

The schematic used can be seen in figure 19 below. This schematic is based on the one provided in the datasheet but has a few modifications such as the addition of jumper JP1 which is used as a test point for accurate current consumption measurements. A smoothing capacitor C1 was also added in order to have a more stable power supply [52].

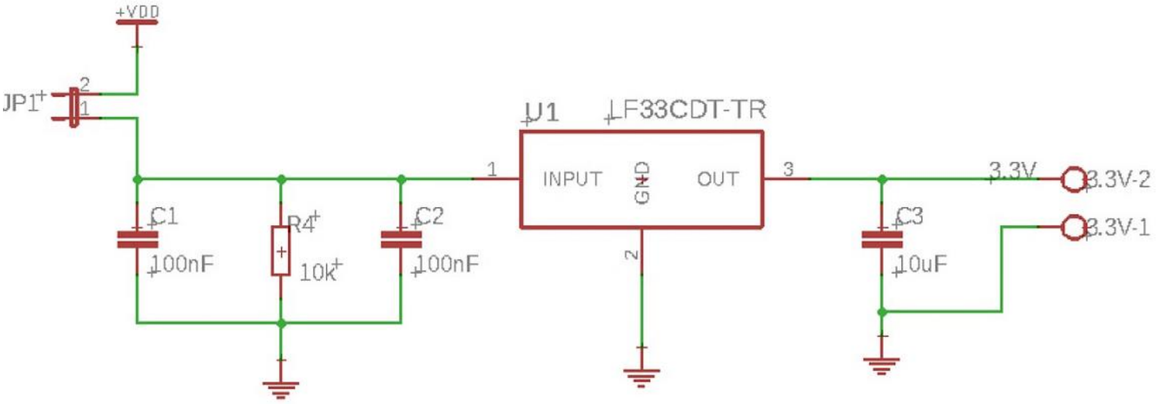


Figure 19: Schematic for the L33CDT-TR LDO

The available sensors suitable for water quality monitoring mostly operate on either 3.3 V or 5 V or both. For this reason, an adjustable LDO was chosen so that I can have the option of choosing suitable sensors without worrying about the operating voltage. The L6932D1.2TR chip from STMicroelectronics is used in the device. It is an ultra-low drop output linear regulator with a 1 % voltage regulation accuracy. It has an input range of 2 V – 14 V and an adjustable output range of 1.2 V to 5 V. Using the provided formula seen in equation 5.1.5.1, the output voltage is adjusted by changing the values of resistors R1 and R2 voltage divider connected to the ADJ pin 3 as seen in the typical operating circuit in figure 20 below [53].

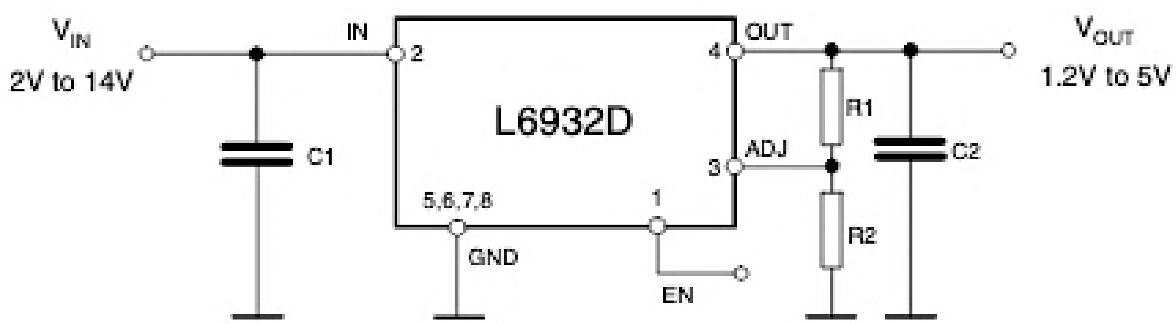


Figure 20: Typical operating circuit of the L6932D1.2TR [53]

To obtained the desired 3.3 V and 5 V outputs, first R1 was selected as a fixed resistor with value 10 kΩ for ease of design and R2 is calculated as follows:

$$V_{out} = \frac{1.2}{R_2} * (R_1 + R_2) \qquad [5.1.5.1]$$

R_1 is already selected, therefore solving the equation for the value of R_2:

$$R_2 = \frac{1.2 * R_1}{V_{out} - 1.2} \qquad [5.1.5.2]$$

For V_{out} = 3.3 V, R_2 is solved as:

$$R_2 = \frac{1.2 * 10000}{3.3 - 1.2} = 5714.29\ \Omega \qquad [5.1.5.3]$$

The closest resistor to the calculated value is a 5.62 kΩ resistor, providing an output of 3.33 V ~ 3.3V.

For V_{out} = 5 V, R_2 is solved as:

$$R_2 = \frac{1.2 * 10000}{5 - 1.2} = 3157.89\ \Omega \qquad [5.1.5.4]$$

The closest resistor to the calculated value is a 3.16 kΩ resistor, providing an output voltage of 4.95 V ~ 5 V.

As seen in the schematic in figure 21, 3.3 V or 5 V output voltage is can be chosen by adjusting the position of a jumper on header J7 which selects the appropriate resistor for each output.

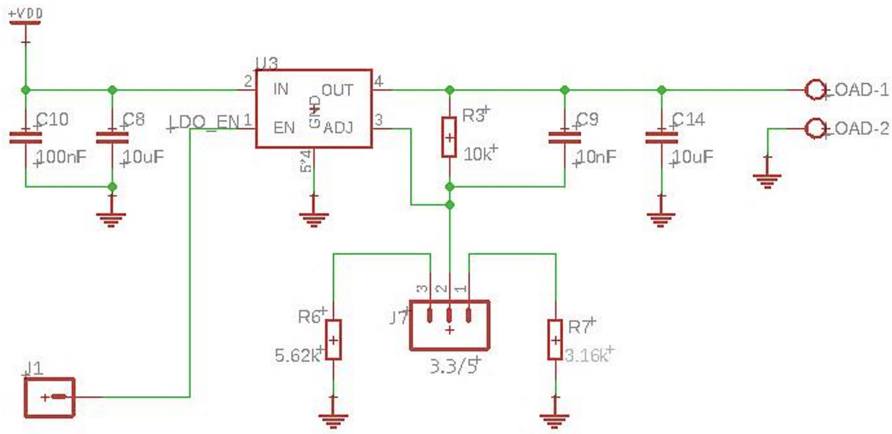


Figure 21: L6932D1.2TR schematic with 3.3 V or 5 V output

The L6932D1.2TR chip also has an enable pin which will be connected to an output pin on the ESP32 DevKitC board. This pin will be used to shut off the output voltage to the sensors in between measurement taking measurements in order to minimize energy consumption of the device.

5.2 Water quality monitoring sensors

Professional industrial grade sensors have higher accuracy and can be left in the water for very long periods times but they are also very expensive. This device is a proof of concept, therefore sensors used are simple and more suitable for compatible with the ESP32 microcontroller. Figure 22 below illustrates the block diagram of this module.

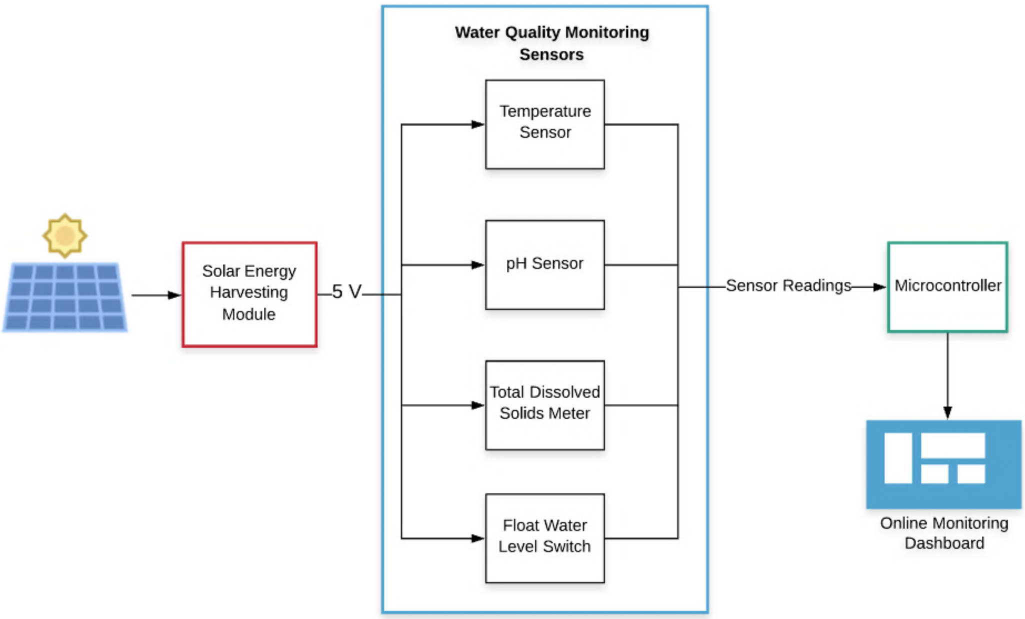


Figure 22: Block diagram of the water quality monitoring sensors

5.2.1 ESP32 DevKitC V4 microcontroller

The main part of this device is the ESP32 DevKitC V4 board which is based on the ESP32 microcontroller manufactured by Espressif. This microcontroller already has Wi-Fi, Bluetooth and Bluetooth Low Power (BLE) modules integrated into the microcontroller making this board perfect for our project because there is no need for an extra communication module. It also has many I/O pins which can be multiplexed and used for different peripherals such as SPI, I2C, UART, ADC, DAC and PWM which are required to integrate other components used in this device.

All the data from the sensors and monitor signals from the solar power module will be processed by this board. Figure 23 shows how they will be connected to the board. The device will also utilize the Wi-Fi module to send data to the online remote dashboard. The board also has a UART to USB interface chip which can be used to program the board using the Arduino IDE platform. All the coding for this device is done using the Arduino IDE platform complete the code can be seen in appendix E below.

This project mostly utilizes the ADC and RTC GPIO pins. The built in analog to digital converter will be used to read data from the pH and TDS sensors which produce analog signals. There are two ADCs and a total of 18 channels with each pin having a resolution of up to 12 bits and hence 4096 voltage levels. The GPIO pins will be used to connect the float sensor, temperature sensors, LDO enable, charge and float control signals from the power supply and LTC4150 fuel gauge.

The ESP32 microcontroller has pins which are 3.3V tolerant, but the board has an in-built 3.3V regulator which enables you to power the board with either the micro USB port, 5V or 3.3V header pins. For this device the board will be powered by the dedicated 3.3 V output from the solar power supply module. The ESP32 microcontroller also supports low power and deep sleep modes which will be useful for power consumption management [54].

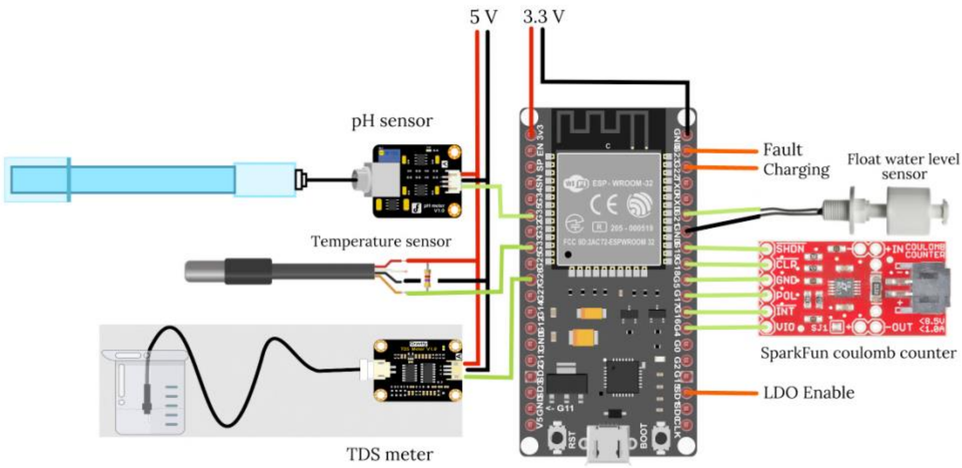


Figure 23: ESP32 DevKitC V4 board with connections to the sensors, coulomb counter and control signals from the solar energy harvesting module

5.2.2 DS18B20 temperature sensor

This device uses a waterproof DS18B20 digital temperature sensor. It provides 9 – 12 bit temperature measurements with programmable resolution over 1-wire bus communication interface. It has a range of -55 to +125°C and accuracy of +/- 0.5°C for temperatures between -10 to 85°C. This sensor is suitable for the device because it does not require any external components and it can either be powered by 3.3 V – 5 V or it can derive power from the data line [55]. This sensor was chosen because of its high accuracy and ability to detect even small changes in temperature. It also available in a waterproof version covered PVC which is perfect for use in wet areas. Multiple sensors can be connected in the same 1-wire bus if more sensors need to be added to the project.

5.2.3 pH sensor

This device uses the E201 laboratory grade probe and PH-4502C signal processing module from DIY More to measure the pH levels of water. The probe cannot be immersed in water for long periods of time, however it can be replaced by an industrial grade probe and still use the same signal processing module. Using the E201 probe, the amount of hydrogen ions is measured by the potential difference between a reference electrode made of silver or silver chloride and a second glass electrode which is sensitive to hydrogen ions. This probe can measure pH levels in the range of 0 to 14 with a response time of less than two minutes. The PH-4502C module is used to condition the signal into analog voltage of 0 to 5V that can be interpreted by a microcontroller.

The E201 probe has an accuracy of +/- 0.2% when the water temperature range is within 7 – 46 °C. As mentioned above, the pH levels are dependent on the temperature of the water, however the PH-4502C signal processing module already has a NTC thermistor for temperature compensation on board, the thermistor can be seen in figure 24 below. In order to maintain the accuracy of the results, the PH-4502C module needs to be calibrated every month [56].

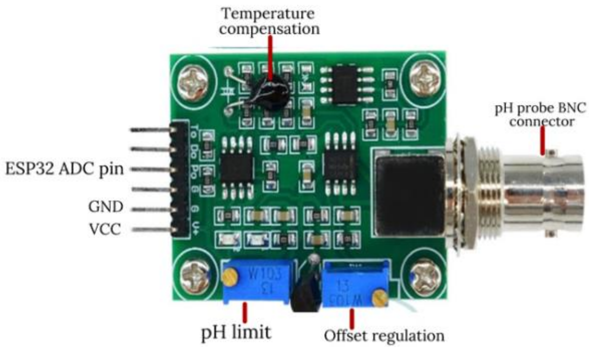


Figure 24: DIY More PH-4502C signal processing module

This is done by adjusting the pH limit and offset regulation potentiometers to obtain a linear approximation equation which will be used to convert voltage levels to pH value. In order to calibrate the pH sensor, first the BNC connector of the PH-4502C module is short circuited to remove any interference, then the pH offset regulation potentiometer is adjusted till the output voltage on pin Po is 2.5V, this offset provides a center value of the readings equivalent to pH value of 7.0.

The next step is calculating the voltage conversion to the pH value using a linear approximation. This is done by recording the output voltage of pin Po when the probe is placed in calibration solutions with pH 4.01 and 6.86 and the measured voltages were 4.76 V and 3.74 V respectively.

Using the linear approximation equation ($y = mx + b$) where by the x is the measured output voltage from the Po pin and y is the known pH value of the calibration solution, you can solve for the slope m and intercept b. Using the measured voltages measured above, the obtained voltage conversion equation for the pH values is:

pH value = -2.79x + 17.31 [5.2.3.1]

5.2.4 Total dissolved solids and electrical conductivity sensor

This device uses the Gravity TDS meter manufactured by DFRobot, it measures the amount of total dissolved solids based on the electrical conductivity of water. Only a few manufacturers make TDS sensors that can be used with a microcontroller. Most TDS measurements are made using TDS pens which cannot transmit data so it would not be suitable for this project. Another alternative is using professional instruments, they have higher accuracy than the TDS pens but they are also very expensive. Ultimately, this sensor was chosen because it is affordable, it can be easily interfaced with a microcontroller and from repeated tests, it was observed that it produces accurate and reliable results.

As seen in figure 25, the sensor consists of a measuring probe and a small circuit board which generates the excitation signal. The measurement probe of the sensor is made of two partially exposed electrodes covered in waterproof coating which enables it to be immersed in water for long periods of time. The sensor uses an analog excitation source which prevents the probe from rusting and polarization thus increasing the probe's lifetime. The two electrodes in the probe are placed one cm apart and when an AC voltage from the signal transmitter board is applied across the electrodes, the current flowing through the wire is proportional to the amount of dissolved charged ions in the water. Therefore, the sensor gives a voltage output which corresponds to the electrical conductivity of the water. The amount TDS is then estimated from conductivity using the relation 3.3.3.1 described above such that 1 EC is approximately equal to 900 ppm.

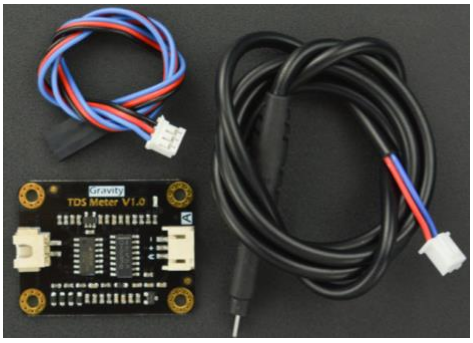


Figure 25: Gravity TDS meter [57]

This sensor works with an input voltage range of 3.3 – 5.5 V and has an analog output of 0 – 2.3 V making it compatible with 3.3 V or 5 V boards like the Arduino Uno and ESP32 microcontroller. It also has a measurement range of 0 to 1000 ppm with an accuracy of +/- 10 %. However, to further improve the accuracy, readings from the DS18B20 temperature sensor will be used for temperature compensation as the changes in temperature also affects the conductivity and amount of total dissolved solids in the water.

Calibration of the sensor is done using an Arduino IDE library provided by the manufacturer which has a calibration mode. It is advised to calibrate the sensor every 6 months when it is being continuously used. During calibration the sensor is placed in a standard EC buffer solution with conductivity of 1413 μS/cm which is equivalent to 707 ppm and the voltage measured by the sensor is used to update the constant of proportionality k_e as described in section 3.3.3 [57].

5.2.5 Float water level sensor

For applications such as aquaculture, agriculture and hydroponics it is important to detect if there is a significant change in the water level as it may indicate a possible water leakage or blockage in the water supply. Therefore, a float water level switch was added to this prototype.

The float sensor has a reed switch and a magnet float that adjusts with the changes in the liquid surface level. The reed switch is connected to two wires which conduct only when the reed contacts are closed and the switch can operated as normally open (NO) or normally closed (NC) circuit. The float sensor has a digital output of either 1 or 0 indicating whether the contact is open or closed.

When operating in a normally open circuit, the reed switch contact is open and as the liquid level rises, the magnet float rises and it attracts the contacts of the reed switch together completing the circuit. In other words, the sensor is placed at a desired height and when there is no water, the magnet stays at the bottom, the contacts remain open and the output from the sensor is 0. When the water level rises, the magnet float rises closing the reed contacts and the output of the sensor is 1 indicating water is at the desired level. A simple illustration of this process can be seen in figure 26 below [58].

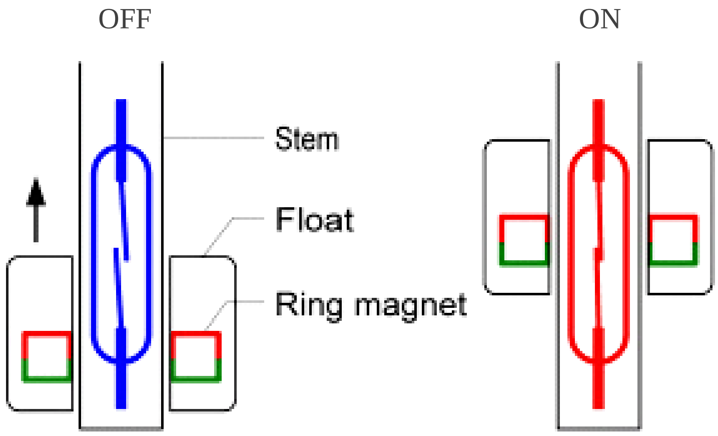


Figure 26: Operation of a reed based float liquid level switch [58]

The float level switch used in this device has a temperature rating of -20 to + 80 °C and can be used to switch a load of up to 100 V DC and 0.5 A, so it can easily be used to control a water pump or a water sprinkler [59]. The output from this sensor is displayed on the dashboard with an indicator showing when the water level is high or low.

5.3 Thinger.io online monitoring dashboard and notification system

Thinger.io is a free cloud based IoT platform used to send data to the cloud from any Internet-enabled device. They provide a freemium account which has allowed access to all their features without any fees. The platform is hardware agnostic therefore it can be used with any device such as Arduino, ESP32, ARM mBed, SigFox and any Linux system like Raspberry Pi. When using the Arduino IDE, they provide a complete library which allows simple and easy integration with just a few lines of code. Using the collected data, it also allows the user to create visualizations dashboards with display charts, actions and trigger alerts based on real-time data. The time interval of displaying the data is user selectable regardless of how much data is being transmitted by the device. The user can also create data buckets which are used for storage of data. This data is valuable since it can be used for analyzing trends and changes in properties over time. In addition to that, the user can send notifications such as emails, SMS or even push data to external web services such as HTTP requests using defined endpoints.

Thinger.io also has very favorable features such as bidirectional efficient communication and the ability to send data to a device with extremely low latency which is very suitable for remote controlled devices. They also provide the option of displaying location of connected devices based on IP address without the need for a dedicated GPS module on the device.

Using this platform, the data collected from the sensors will be transmitted from the ESP32 microcontroller via Wi-Fi and displayed in real-time at an interval which is selectable by the user. This data includes; water level, temperature, pH level, electrical conductivity, amount of total dissolved solids, remaining battery capacity and location of the device. To send data to the thinger.io platform, each of the data values mentioned above is defined as an output resource which takes a PSON type variable. This can be simply implemented using functions defined in their library as seen in the code snippet in figure 27 below [60].

```
#include <WiFi.h>
#include <ThingerESP32.h>

// Thinger Configurations
#define USERNAME "kanamcat"
#define DEVICE_ID "Water_Monitor"
#define DEVICE_CREDENTIAL "a!zUbDzvew02"

// thinger.io setup
ThingerESP32 thing(USERNAME, DEVICE_ID, DEVICE_CREDENTIAL);
boolean notificationsSent = false; // send notifications once

// send notification based on set limits
void handleThingNotifications() {
  if (notificationsSent) {
    return;
  }

  if (ph < 6.5 || ph > 8.5) {
    pson pHData = ph;
    thing.call_endpoint("pHLimit", pHData);
  }
  // send low water level notification
  if(waterLevel < 1) {
    pson waterData = waterLevel;
    thing.call_endpoint("waterLevel", waterData);
  }
  // send high conductivity notification
  if(ec > 0.6) {
    pson condData = ec;
    thing.call_endpoint("conductivity", condData);
  }
  // send low battery notification
  float batteryPercentage = calculateBatteryPercentage(battery_mAh);
  if (batteryPercentage < 40) {
    pson battData = batteryPercentage;
    thing.call_endpoint("batteryCapacity",battData);
  }

  notificationsSent = true;
}

void setup(){
  thing.add_wifi(SSID, SSID_PASSWORD);
}

voild loop (){

  thing["ph"] >> outputValue(roundFloat(ph, 1)); // Send pH
  thing["temperature"] >> outputValue(roundFloat(temp, 1)); // Send temperature
  thing["waterLevel"] >> outputValue(waterLevel); // Send water level
  thing["conductivity"] >> outputValue(roundFloat(ec, 2)); // Send conductivity
  thing["tds"] >> outputValue(tds); // Send tds
  thing["battery_mAh"] >> outputValue(roundf(battery_mAh)); // Send battery capacity
  thing["battery_percent_soc"] >> [](pson& out) {
    out = roundf(calculateBatteryPercentage(battery_mAh)); // Send battery percentage
  };

  thing.handle();

  handleThingNotifications();
}
```

Figure 27: Code used to send data to the thinger.io platform

6 Printed circuit boards

As described in the implementation section, this device has many individual circuits that need to be integrated together. For the sake of simplicity and ease in debugging, the whole implementation was divided into two separate printed circuit boards. The first board contains the solar power supply circuit and the output regulation circuits while the second board has the breakout for the ESP32 DevKitC V4 board, breakout for the SparkFun LTC4150 fuel gauge and sensor inputs.

In terms of general design, both boards apart from the jumpers and terminal blocks, most of the components used in this project are surface mounted devices (SMD). A surface-mount device is an electronic device whose components are placed or mounted onto the surface of the printed circuit board. This method of manufacturing electronic circuit boards is based on the surface-mount technology. SMD components were preferred because they can easily be placed on both side of the board and the price of PCB manufacturing is much cheaper compared to using through hole components which require several drill sizes.

All the passive components are in the 1206 package size for uniformity and ease for hand soldering. Terminal blocks instead of pinheads were chosen as the main connectors. The reason being, when using terminal blocks only a small part of the conductive wire is exposed and this part is securely clamped inside the insulated case. Thus preventing any accidental loose wires which can cause short circuits that might destroy the device. Terminal blocks are also easier to use and they eliminate the need for having a special connector for each input or output terminal.

6.1 Solar power supply board

The solar power supply was designed so it can be used as a universal power supply for any IoT project therefore it was implemented on a separate board. The board consists of the solar power path circuit and output regulation circuits. This solar power supply is implemented as a power path and can be fully functional without the battery. Hence the decision to only have a battery connector so if you decide to use a battery, you can also connect a fuel gauge between the battery and this board as need as needed.

Images of the boards can be seen in figures 28 and 29, the size of the board is 53.32 x 45.39 mm. Starting with the bottom left corner, there are terminal blocks for connecting the solar panels. By moving the position of the jumper on pinhead J3, you can select to use one panel or two panels parallel or series. The INPUT jumper is used to disconnect the solar panels input from the rest of the circuit. It is also used as a test point for measuring input current. The output regulations are on the top of the board, the 3.3 V terminal is connected to the output from the LF33CDT-TR LDO and the LOAD terminal block is connected to the L6932D1.2TR LDO. 5 V or 3.3 V can be selected by moving the position of the jumper on pinhead J7.

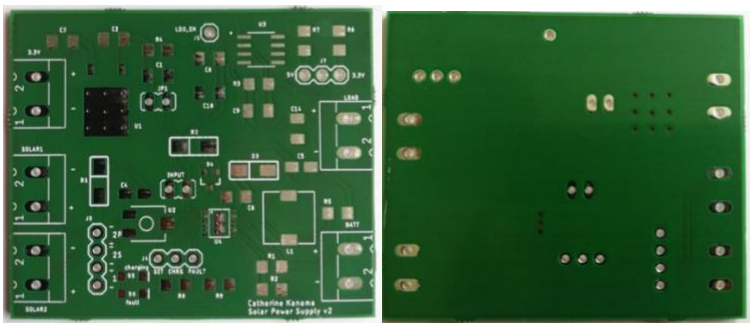


Figure 28: Top and bottom images of the solar power supply board (unsoldered)

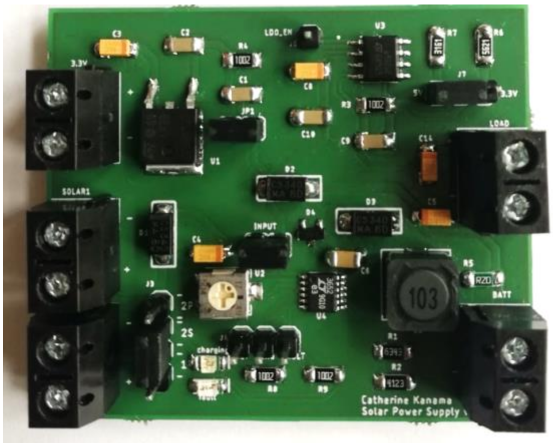


Figure 29: Soldered solar power supply board

6.2 Sensor board

In the initial prototype stage, all the sensors, the fuel gauge and control signals from the solar power supply board were connected to a breadboard and the signal wires were routed to the ESP32 microcontroller. Unfortunately, this caused a large amount of wires which were hard to control and crossed over each other creating a tangled mess. It also led to many incidences of short circuits that became a common problem every time the board was moved around to another location. Therefore to fix the loose wire problem and reduce the amount of wires, the decision was made to make a separate sensor board where you can plug in the ESP32 microcontroller and connect the sensors to the terminal blocks which are already wired to the correct pin on the ESP32 microcontroller. Images of the board can be seen in figures 30 and 31 below.

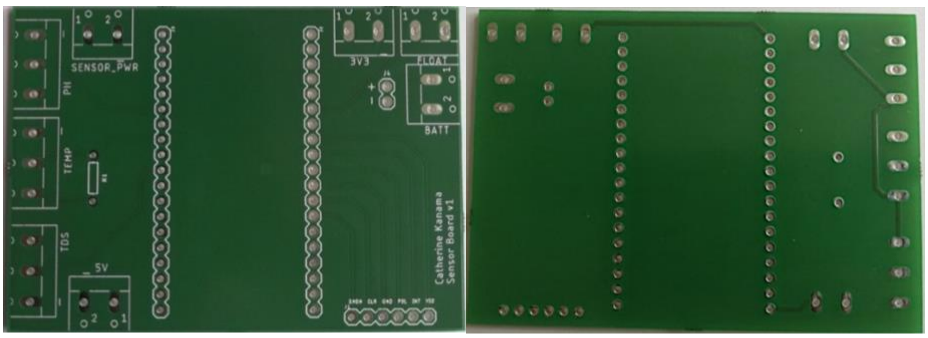


Figure 30: Top and bottom images of the sensor board (unsoldered)

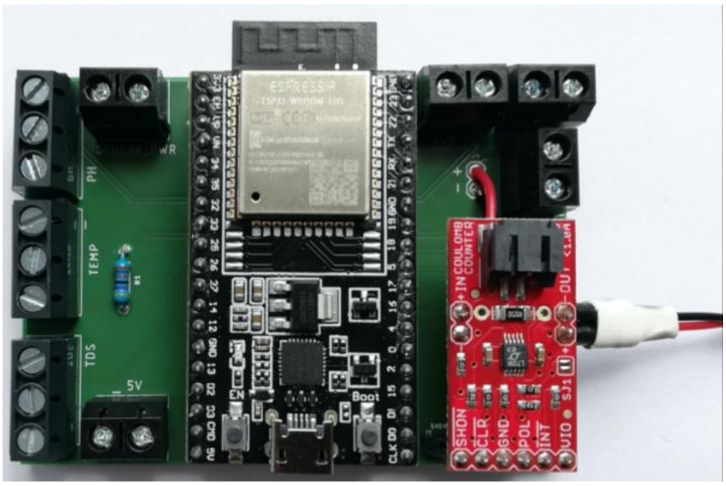


Figure 31: Soldered sensor board

The final size of the sensor board is 76.18 x 54.28 mm. This board has three input power terminal blocks, one input provides power to all the sensors and it is externally connected to the 3.3V/5V linear regulator located in the solar power supply using two wires. The ESP32 microcontroller can be powered with 3.3 V or 5 V therefore there are two input blocks for each voltage choice. Currently in this device, the ESP32 microcontroller is powered by the 3.3 V linear regulator located in the solar power supply board. However, the choice to have a 5 V input was added so the board can easily be integrated to other water monitoring projects that have a 5 V power supply. This 5 V input can also be used when there is only one power source available so the ESP32 microcontroller is powered by 5 V and 3.3 V pin on the board is used as a power supply for the sensors.

On the right hand corner of the board is a breakout for the SparkFun LTC4150 board, all the pins are also routed directly to the ESP32 microcontroller GPIO pins. The battery is connected to the sensor board on the BATT terminal block, and then to the input of the SparkFun LTC4150 board through the J4 header. The output of the SparkFun LTC4150 board is connected directly to the solar power supply BATT connector as described earlier in the fuel gauge implementation.

7 Assembly

The final assembly of the solar power supply board and sensor board with all the sensors attached can be seen in figure 32 below. As described earlier, all the sensors and the SparkFun coulomb counter are attached to the sensor board. SENSOR_PWR and 3.3 V terminal blocks are connected to the solar power supply board LOAD and 3.3 V terminal blocks respectively. The input of the SparkFun coulomb counter is connected to the battery and the output is connected to the BATT terminal block on the solar power supply board.

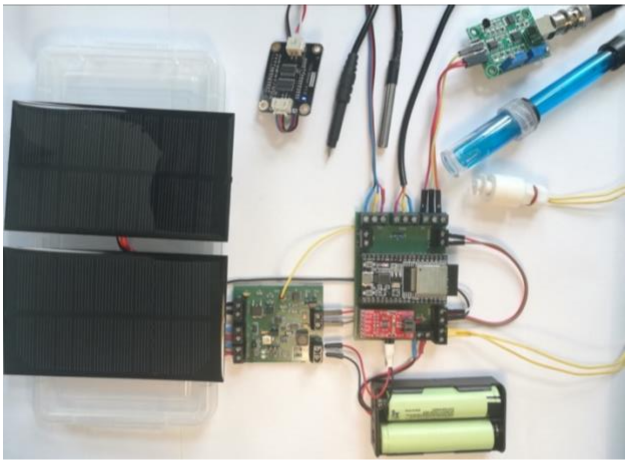


Figure 32: Assembled sensors, solar panels, batteries, sensor board and solar power supply board.

For ease of installation and transportation of the device, the whole circuit is placed in a water proof box and the sensor probes and float water sensors exit through the top left corner of the box. Due to lack of resources, I used a generic waterproof box. The solar panels are attached to the lid of the box and will always be facing upwards for maximum sunlight exposure. A cardboard separator divides the box into a top and bottom level. The batteries and sensor board are placed on the bottom of the box as seen in figure 33, the solar supply board is placed on the top of the board for easy access to the solar panels.

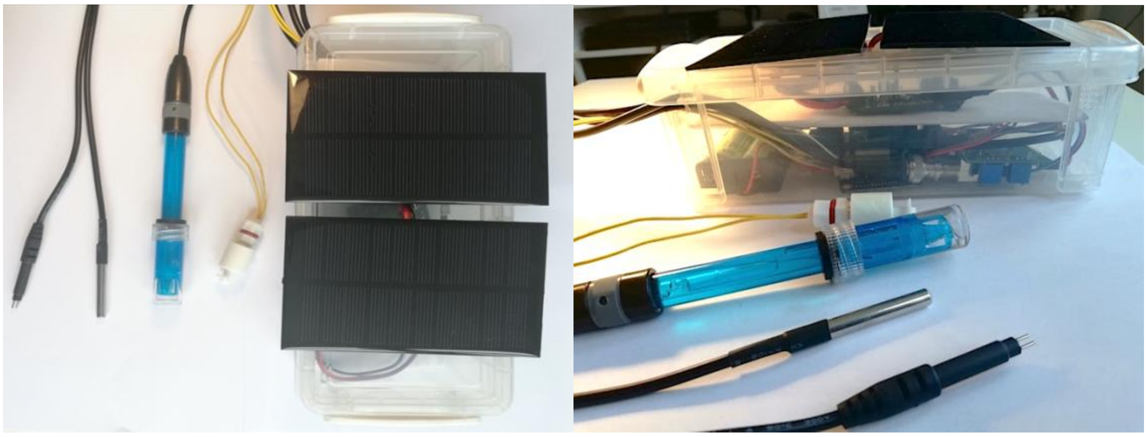


Figure 33: Top and side view of the solar powered water monitoring device

8 Results

Due to unforeseeable lockdown circumstances, testing conditions and options for this project were very limited. In the future, I intend to perform all the described tests for a longer period of time in order to better establish the reliability of the device in more realistic conditions.

8.1 Measuring the solar panels

To measure the power output from the solar panels, the 2 panels were connected in series connection and placed outside on a flat surface facing directly upwards. Without any load attached, the voltage is measured on an open loop circuit and current is measured on a short circuit. The measurements were taken on May 7, 2020 from 9 am to 1 pm and the weather was cloudy in the early morning and more clear sky and sunny towards the afternoon. The measured current and voltages can be seen in table 5 below. The measured current was low during cloud cover and high during clear sky, while the voltage was approximately 11 V throughout the day.

Table 5: Solar panel voltage and current measurement

Time	**Voltage (V)**	**Current (mA)**
9:00	10.7	12
9:30	10.5	11
10:00	10.7	12
10:30	10.9	99
11:00	11.1	108
11:30	11.2	100
12:00	11.1	115
12:30	11.3	133
13:00	11.3	146

8.2 Measuring the solar power supply board

A laboratory power source was used to simulate the voltage and current from the solar panels during a sunny in order to confirm that the implemented power path is working as expected.

First the batteries were discharged to 6.6V then connected directly to the solar power supply board BATT terminal block and the laboratory power source was connected to the SOLAR_1 terminal block. The sensors and ESP32 microcontroller were also connected to the board.

The voltage increase in the batteries was observed for a period of 1 hour at 10 minute intervals. Constant voltage of 11 V and constant current of 130 mA were applied to simulate a sunny day. The applied voltages and current are based on the measured solar panel outputs from sunny weather as described in section 8.1. When charging The obtained results can be seen in tables 6 below.

Table 6: Increase in batteries voltage when charging in sunny conditions

Voltage = 11 V, Current = 130 mA		
Time (minutes)	**Batteries voltage (V)**	**ESP32 & sensors**
0	6.62	On
10	6.75	On
20	6.89	On
30	6.93	On
40	7.04	On
50	7.45	On
60	7.52	On

The measured results show that the board is capable of powering the device and charging the batteries at the same time. During the first stage of charging a li-ion battery, when constant current is applied, the voltage of the batteries is expected to increase linearly. Likewise, the voltage of the batteries is increasing linearly indicating that the batteries are charging as expected.

8.3 Measuring power consumption of all components

To optimize the power consumption, the device measures the water parameters at an interval of 1 hour and then the ESP32 microcontroller enters deep sleep mode and the power to the sensors is turned off using the LDO enable pin. For testing purposes, the device was set to measure and transmit sensor data every 5 minutes and in between the measurements, the ESP32 microcontroller enters a time delay and the power to the sensors it turned off. The current measuring point for the ESP32 microcontroller was between the solar power supply 3.3 V output and the 3.3 V terminal block on the sensor board while the sensors current measuring point was between the solar power supply 5 V and the sensor power supply terminal block on the sensor board. The measured current consumption can be seen in table 7 below.

Table 7: Power consumption on different operating modes

	Current draw (mA)
Consumption by all the sensors	12
ESP32 in active mode (not connected to Wi-Fi)	70
ESP32 transmitting data to thinger.io	127
ESP32 in deep sleep mode	0.5

As seen from the measured current, the most power is consumed when the ESP32 microcontroller is connected to Wi-Fi and transmitting the data to the thinger.io dashboard. Fortunately, with the measurement interval of every 1 hour this only lasts for 21 seconds and will not cause any alarming power consumption. Using the battery capacity equation 5.1.3.1, with this amount of consumption, the device can be entirely powered by the battery for 108 days.

8.4 Water quality test

To test the reliability of the water sensors, the pH level, conductivity and TDS of tap water and filtered water were tested for the course of one week. The setup used can be seen in figure 34 below and the results are discussed in the sections below.

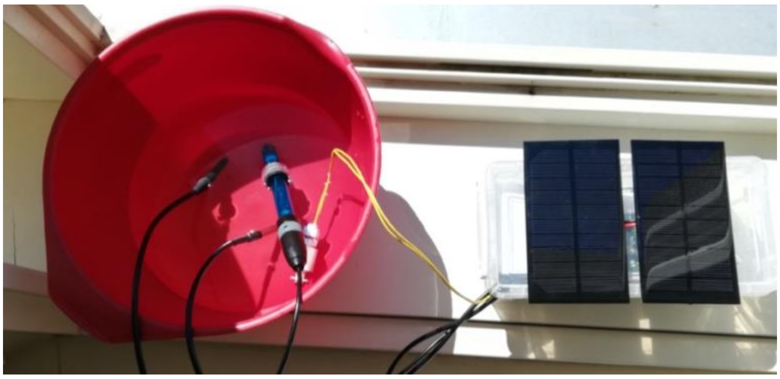


Figure 34: Set up for measuring tap water and filtered water

8.4.1 Prague 2 tap water

According to Prague Water Supply and Sewage (Pražské vodovody a kanalizace), the acceptable pH level of tap water in Prague is 6.5 - 9.5 and the maximum conductivity is 125 mS/m. The measured average pH and conductivity for April 2020 were 7.62 and 40.7 mS/m, therefore the measured quantities by this device are expected to be close to these values [61]. The measurements were taken from April 24, 2020 to April 30, 2020 and the results obtained can be seen in table 8 below.

Table 8: Measured pH level, conductivity and TDS in Prague 2 tap water

	Day						
Quantity	24/4/20	25/4/20	26/4/20	27/4/20	28/4/20	29/4/20	30/4/20
pH level	7.5	7.3	7.5	7.6	7.6	7.7	7.7
EC (mS/cm)	0.52	0.39	0.46	0.55	0.49	0.43	0.44
TDS	189	152	163	200	181	164	167

8.4.2 Filtered water

The samples for filtered water were obtained from a Brita Filter manufactured by Brita company from Germany. The filters use active carbon to remove substances such as chlorine and chlorine compounds which affect the taste and odor of the water. The filters also use a second process of ion-exchange which reduces carbonates, limescales, copper and lead that may be in the water [62]. Based in these claims, the filtered water is expected to have lower TDS levels, conductivity and pH level compared to the tap water. The measurements were taken also from April 24, 2020 to April 30, 2020 and the results obtained can be seen in table 9 below.

Table 9: Measured pH level, conductivity and TDS in filtered water

	Day						
Quantity	24/4/20	25/4/20	26/4/20	27/4/20	28/4/20	29/4/20	30/4/20
pH level	6.9	6.8	6.9	6.9	6.9	6.9	6.8
EC (mS/cm)	0.28	0.24	0.27	0.30	0.28	0.29	0.23
TDS	113	103	108	120	113	115	94

Observing the measured results from tables 9, all the pH levels and conductivity levels are all within the specified limits and close to the measured averages from the April 2020 report. There are slight variations within the day to day readings but this is expected at the test samples are not exactly the same. The measured pH, conductivity and amount of total dissolved solids in the filtered water samples is lower than that of the tap water samples. This was expected as the filtered water goes through the process of ion exchange which is used to effectively reduce TDS levels in water as discussed in section 3.3.3 above.

Based on the measurements from tables 9 and 10 above, it can be concluded that the sensors are working as expected and are capable of producing reproducible results.

8.5 Thinger.io dashboard

Each thinger.io user has a unique username and password. When using a free account the user is limited to adding two devices and four customizable dashboards. The dashboards can be accessed either from the thinger.io webpage or from the thinger.io mobile phone app using an admin generated QR code or token.

For testing purposes, the ESP32 microcontroller sent the sensor data to the thinger.io dashboard in shorts bursts every interval of 30 seconds. The data is sent to the dashboard many times in bursts to assure that all the data is sent and received correctly. This is done in the code by iterating the measurement loop 50 times before the Wi-Fi on the microcontroller is shut down, the complete code can be seen in appendix C. A representative screenshot of the dashboard display can be seen in figure 35 below. This image was taken on May 12, 2020 from 11:30 am to 12:30 pm using a similar measurement setup to the one seen in figure 34. The experiment was conducted using tap water and the measured pH level is 7.5, conductivity is 0.46 mS/cm and amount of total dissolved solids is 163 ppm. The weather was clear and sunny therefore the device was entirely powered by the solar panels and the battery capacity remained full throughout the experiment. As the weather got hotter, the temperature of the water also steadily increased.

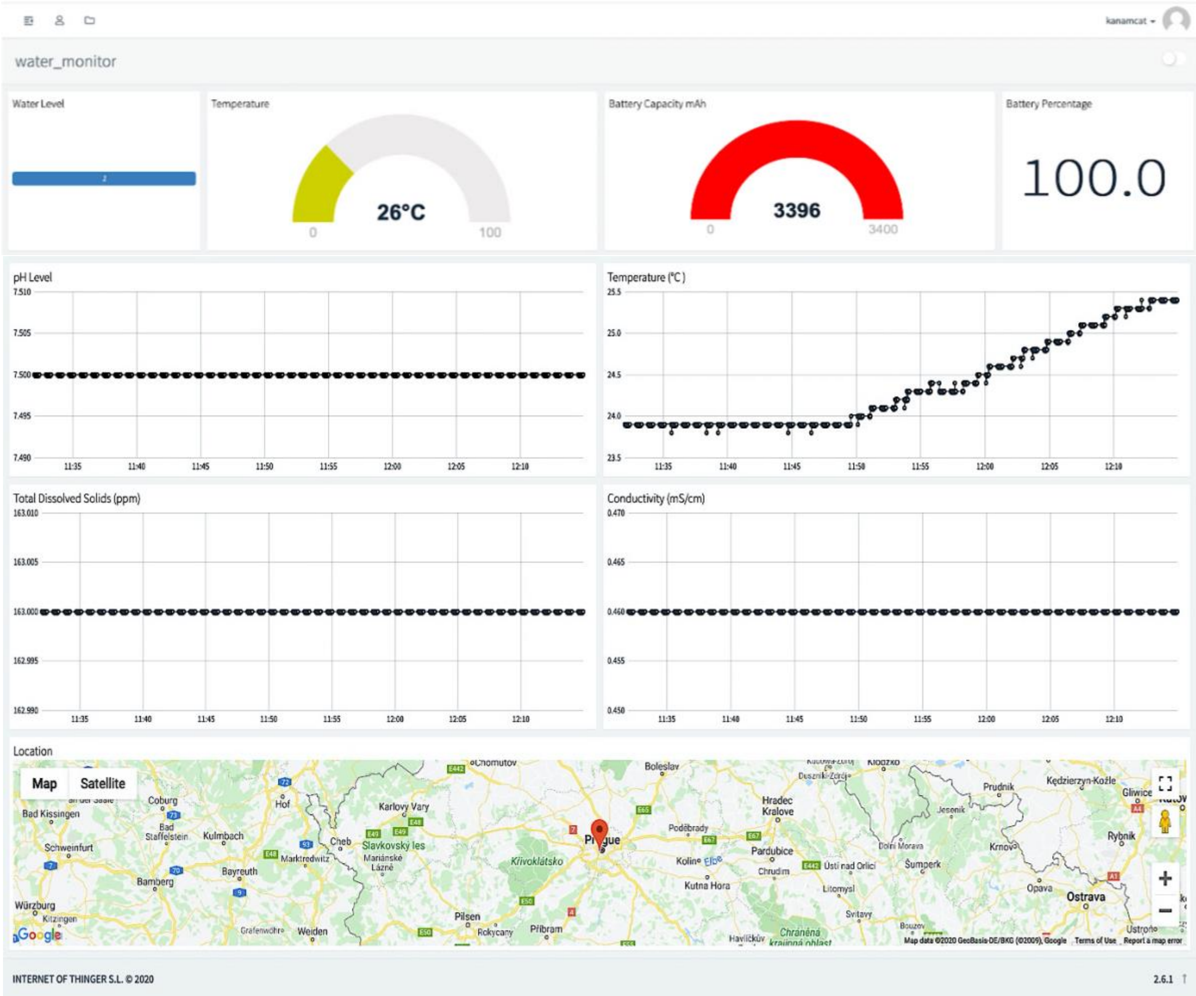
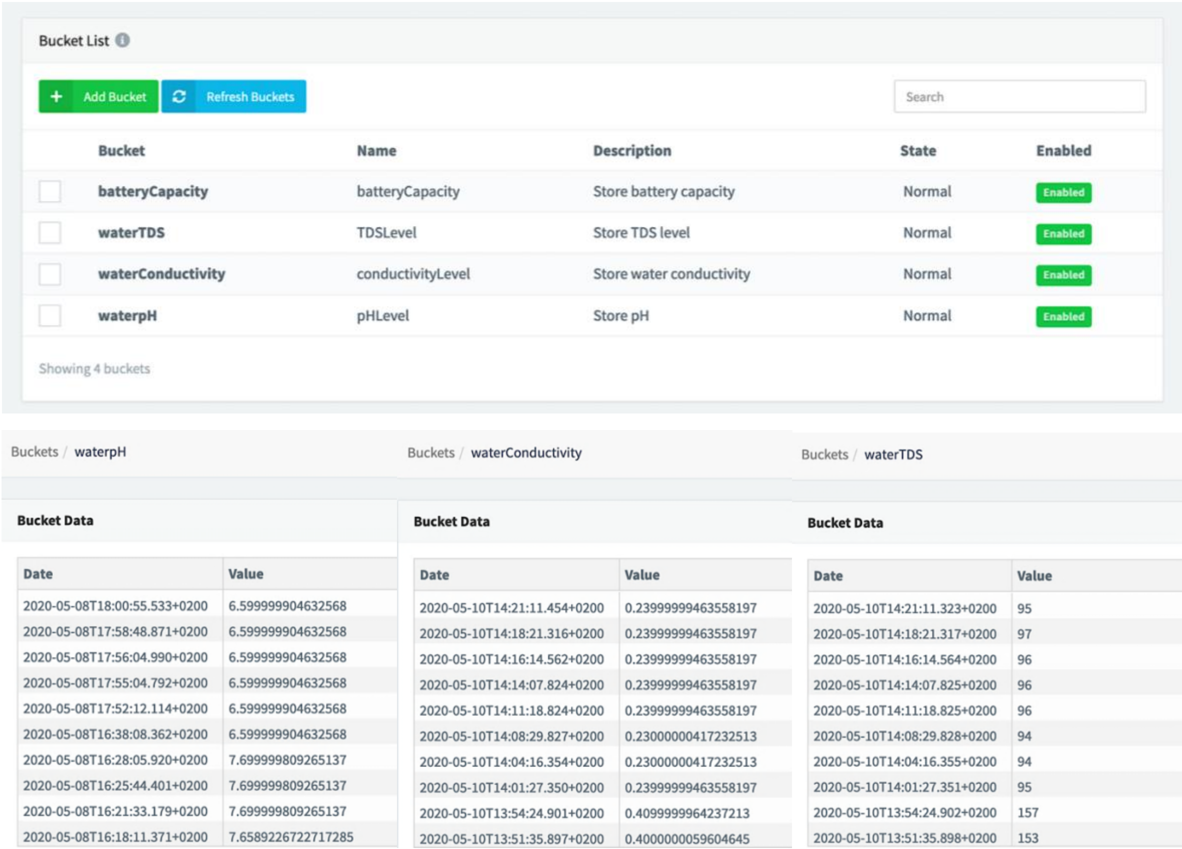


Figure 35: Screenshot of the thinger.io dashboard showing water level, battery capacity and percentage, pH level, temperature, total dissolved solids, electrical conductivity and location of the device

Previous attempts sent the data to the dashboard only once and as a result the data sent was sometimes incomplete or corrupted, hence the decision to send the data in bursts. Sending multiple data points at a time also helps to identify small data anomalies that might have occurred during the measurement or transmission process. For example the temperature measurements displayed in figure 35 above, the temperature is constantly rising and all the data points sent at a time have a similar reading but once in a while there is a small error which is represented by the spike. If the data was sent one point at a time, this error might have been harder to identify and stored as a representative data point during this time interval.

The received data is stored in the data buckets, each parameter has its own data bucket. Figure 36 below shows a snippet of the data stored when the probes were moved from the tap water sample to the carbon filtered water when performing the sensor tests.



Bucket	Name	Description	State	Enabled
batteryCapacity	batteryCapacity	Store battery capacity	Normal	Enabled
waterTDS	TDSLevel	Store TDS level	Normal	Enabled
waterConductivity	conductivityLevel	Store water conductivity	Normal	Enabled
waterpH	pHLevel	Store pH	Normal	Enabled

Date	Value
2020-05-08T18:00:55.533+0200	6.599999904632568
2020-05-08T17:58:48.871+0200	6.599999904632568
2020-05-08T17:56:04.990+0200	6.599999904632568
2020-05-08T17:55:04.792+0200	6.599999904632568
2020-05-08T17:52:12.114+0200	6.599999904632568
2020-05-08T16:38:08.362+0200	6.599999904632568
2020-05-08T16:28:05.920+0200	7.699999809265137
2020-05-08T16:25:44.401+0200	7.699999809265137
2020-05-08T16:21:33.179+0200	7.699999809265137
2020-05-08T16:18:11.371+0200	7.6589226722717285

Date	Value
2020-05-10T14:21:11.454+0200	0.23999999463558197
2020-05-10T14:18:21.316+0200	0.23999999463558197
2020-05-10T14:16:14.562+0200	0.23999999463558197
2020-05-10T14:14:07.824+0200	0.23999999463558197
2020-05-10T14:11:18.824+0200	0.23999999463558197
2020-05-10T14:08:29.827+0200	0.23000000417232513
2020-05-10T14:04:16.354+0200	0.23000000417232513
2020-05-10T14:01:27.350+0200	0.23999999463558197
2020-05-10T13:54:24.901+0200	0.4099999964237213
2020-05-10T13:51:35.897+0200	0.4000000059604645

Date	Value
2020-05-10T14:21:11.323+0200	95
2020-05-10T14:18:21.317+0200	97
2020-05-10T14:16:14.564+0200	96
2020-05-10T14:14:07.825+0200	96
2020-05-10T14:11:18.825+0200	96
2020-05-10T14:08:29.828+0200	94
2020-05-10T14:04:16.355+0200	94
2020-05-10T14:01:27.351+0200	95
2020-05-10T13:54:24.902+0200	157
2020-05-10T13:51:35.898+0200	153

Figure 36: Snippets of pH, TDS and conductivity stored in the data buckets

The endpoints on the thinger.io dashboard are used to send notifications to the user. Currently the device is configured to send an email notification to the user when the water level is low, the battery capacity is less than 40%, the electrical conductivity is above 0.8 and the pH level is less than 6.5 or higher than 9.5. The limit for the pH is similar to the tap water pH limit set by Prague Water Supply and Sewage and the electrical conductivity limit is set to 0.8 mS/cm is similar to the maximum conductivity for typical tap water. Figure 37 below shows some examples of the email notifications received when the pH level, electrical conductivity and water level exceeds the set limit.

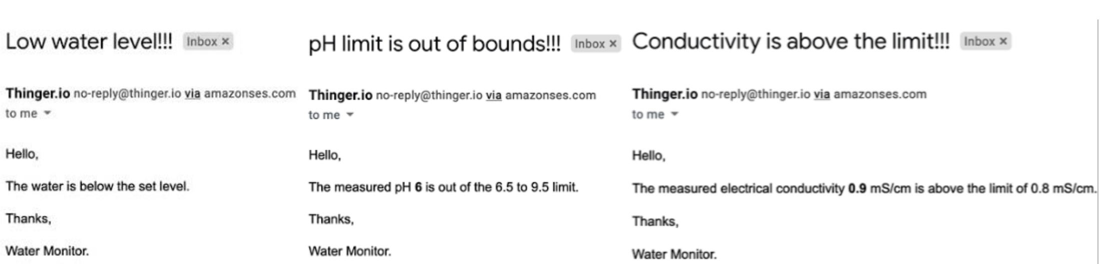


Figure 37: Email notifications from the water monitoring device

9 Problems encountered during implementation

The coronavirus (COVID19) pandemic has really affected the way the project was implemented. Due to lockdown and shipping restrictions, it was extremely difficult to get any parts on time. This is particularly evident in the selection of sensors and the lack of a custom made fuel gauge circuit using the LTC4150 chip. As soon as I realized the parts will not arrive on time, I had to quickly change the solar power supply board and remove all the circuitry related to the LTC4150 chip. I also had to get an alternative pH probe and the options available were only laboratory grade probes which take more than 2 minutes to settle when first placed in the testing sample.

The shipping restrictions also largely affected access to PCB printing services, the two PCB's used in this project were delivered with a 3 week delay, so I had no time to make a better iteration before submitting the project. Luckily the second version of solar supply board worked as expected, however the sensor board was only the first version and I later found out that the ADC2 pin connected to the TDS meter does not work when the Wi-Fi is connected so I had to find a hack around in the code without changing the pins. This led to a cascade of more complicated coding problems as the previous implementation of the code no longer worked.

Since all the soldering had to be done in house, the size of all the component had to be limited to 1206 or larger to make the soldering process more achievable. Hence the size of the boards are much larger than expected. I also had to purchase all the soldering equipment and setup a soldering and testing station so I can keep working on the project at home.

Even though the device is not designed to be fully immersed in water, the initial approach was to design a customized IP67 enclosure so it can be fully protected from the weather elements. During the lockdown I had no access to 3D printer so instead I used a generic box and cut out holes for the sensors and the solar panel wires. The used box is functional but I still needs further improvements to ensure that it is well ventilated and the circuit boards inside are well secured.

Despite all these challenges, I found creative ways to solve these problems and at the end of the quarantine period I had a fully working device.

10 Future improvements

All the future improvements were discussed with the supervisor, but were intentionally not be included in this version of the device due to either the level of complexity or lack of immediate availability. However they are discussed below as I think they would increase the functionality of the device in future iterations making it more adaptable to different applications

The device would benefit by the addition of an SD card which will be used for local data storage. It can be used in situations where remote transmission of the sensor data is not needed. In addition to that, it can also be used as data backup storage when the Wi-Fi connection is not reliable and the data is not successfully transmitted to the online dashboard.

One of the main challenges for this project will be designing a weather proof enclosure of the device. While the sensors used have probes are waterproof, the microcontroller, batteries and solar harvesting boards are not and need to be protected. The best implementation would use a single water-tight entry point where all the sensor probes would go through, avoiding multiple cutouts as custom each hole added to the design would also increase the cost. The printed circuit boards would also have to be redesigned to include mounting holes so they can be securely attached to the enclosure. The design prototype would first be 3D printed as its easier to make changes and adjustments. Eventually the final design would be custom made using plastic which is more sturdier.

As for the solar panels, there are current many weather proofed solar panels that are available. Many companies such as Voltaics and SwitchDoc Labs are mainly focused in making waterproof solar panels suitable for IoT applications. These panels are small and lightweight but are capable of producing enough power because they are made from high efficiency monocrystalline solar. The panels are also waterproofed and covered with UV and scratch resistant coating making them tough enough to last for even more than 10 years in outdoor conditions [63] [64].

Lastly, the pH probe would need to be replaced with an industrial grade probe. Using the same signal processing module, only the probe would need to be replaced as industrial probes can be immersed in water for longer periods of times, and they do not take 10 minutes to have a settled reading.

11 Applications

The main advantage of this prototype is its ability to provide reliable multiparameter data in real time all while keeping the cost affordable. The use of automated data collection and incorporation of the online remote dashboard will help reduce the manpower and time that was previously needed for sample collection and laboratory analysis. This system is also versatile enough for use in many commercial and domestic applications, some of which are described below.

This device can be used in monitoring water used for agriculture as many crops are highly affected by the properties present in irrigation water. This is because different plants require specific water constituents in order to grow properly therefore changes in water properties can cause some plants to flourish or cause plant retardation in others. It is important to know the water constituents, this simple water quality monitor can help farmers monitor the irrigation water so they can maximize their crop yield. For example, very acidic water can prevent some crops like cauliflower and cabbage from absorbing soil nutrients while the same level of acidity improves absorption of magnesium and aluminum in crops like blueberries and peppers [65].

This device can also be used in aquaculture to monitor the quality of water used for the cultivation of aquatic animals as changes in water quality affects their physical condition, growth and increases the chances of a disease outbreak occurring. Different species of aquatic animals flourish in different water conditions, however the most important parameters that affect all species are changes in temperature, conductivity and pH all of which can be reliably measured and monitored using this device [66].

The implementation of this devices allows for easy replacement or addition of other sensors making the device universally adaptable to any application. The ESP32 still has more GPIO pins and other peripherals such as I2C and SPI which are available for use with other sensors. For instance, this device can be adapted to for measuring drinking water by adding an oxidation-reduction potential (ORP) sensor and dissolved oxygen (DO) sensor. These sensors measure the amount of dissolved oxygen in the water which helps to determine if there are bacterial organisms in the water. High levels of ORP indicate the water is incapable of supporting bacterial organisms and therefore suitable for drinking. Together with other measured parameters like pH level, conductivity and amount of total dissolved solids, the device will be able to safely determine of the water is suitable for drinking [67].

Based on the test results described above, the sensors can also be reliably incorporated to monitor the quality of remediated water in real time. Water remediation requires the use of accurate and reliable water quality sensors in order to ensure that the water is properly treated before it is released back into nature or used for human consumption.

In addition to the applications mentioned above, this device can also be used in well water, domestic water and many other endless applications that need specific water properties.

12 Conclusions

This project proposes the design for a solar powered water monitoring IoT device. The device consists of water monitoring sensors, an ESP32 microcontroller and a thinger.io dashboard for remote monitoring of water parameters and a notification system. This device aims to provide the much needed method of quick on site testing and real-time remote monitoring of water parameters like pH level, temperature, total dissolved solids, electrical conductivity and changes in water level. The device has been tested and is capable of producing accurate results. Using the thinger.io dashboard, all the measured data is displayed and time logged data so it can be used for further analysis of the trends in changes of water properties.

The device will be installed in a very sunny region and the implemented power path will allow the device to still be self-sufficiently powered by either the solar panels or batteries. The user only needs to place the device in any location that has direct sunlight and the battery charging process is automatically regulated the LT3652 chip. The battery capacity can also be monitoring through the thinger.io dashboard so the user is always informed about the state of the batteries. Despite all the encountered issues, this device is fully functional as a proof of concept and is capable of producing accurate measurements.

All things considered, small scale and personal uses such as monitoring swimming pools, small fish ponds, and even domestic water storage tanks can easily rely on this device and will no longer require laboratory testing. In addition to all the advantages, the difference in cost and convenience compared to the other existing brands will also put this proposed water monitoring device forward in the market.

Lastly, I’m looking forward to installing this device in our farm during the summer of this year, as it will help in the selection of a suitable water source for the next farming season.

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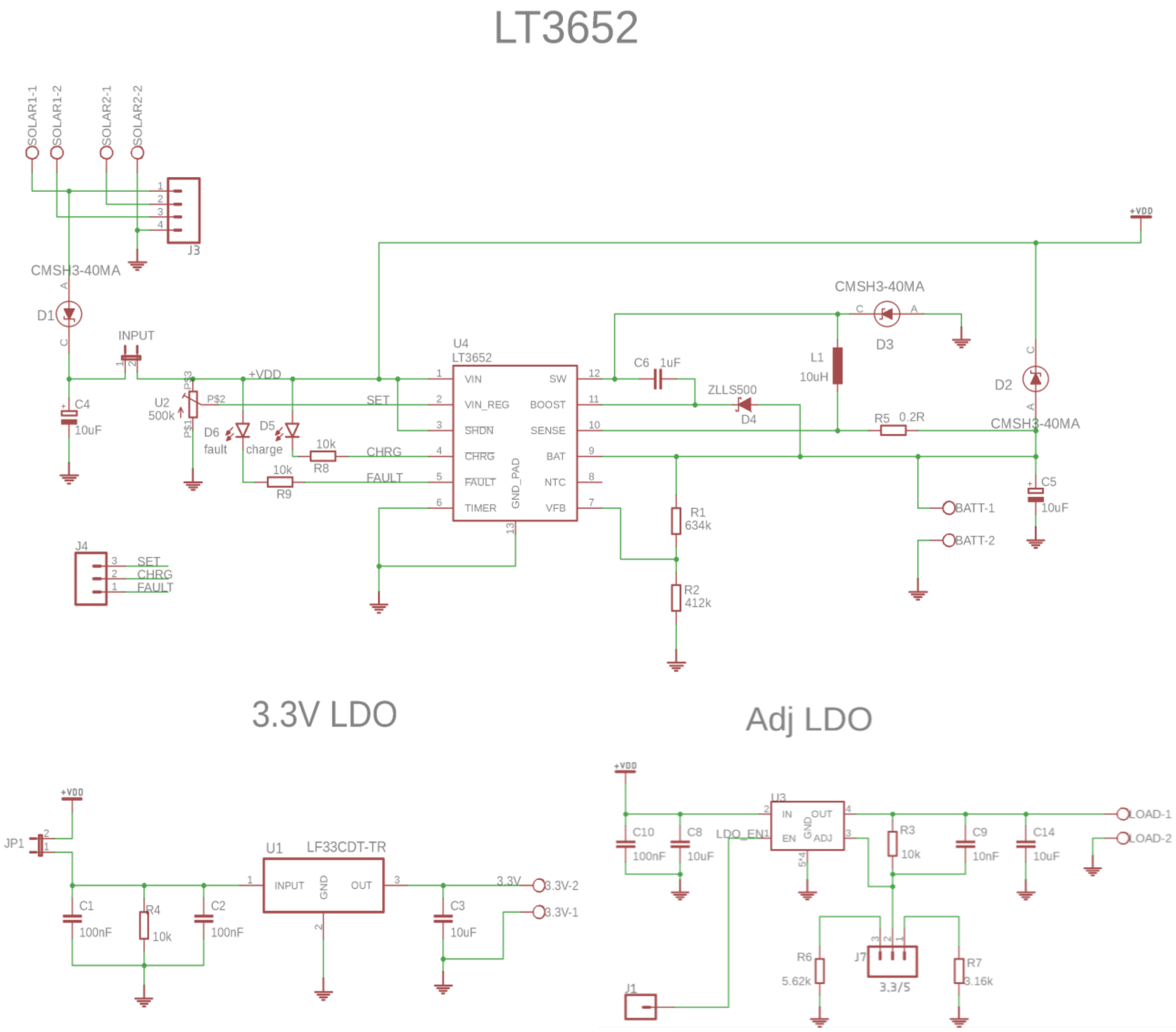
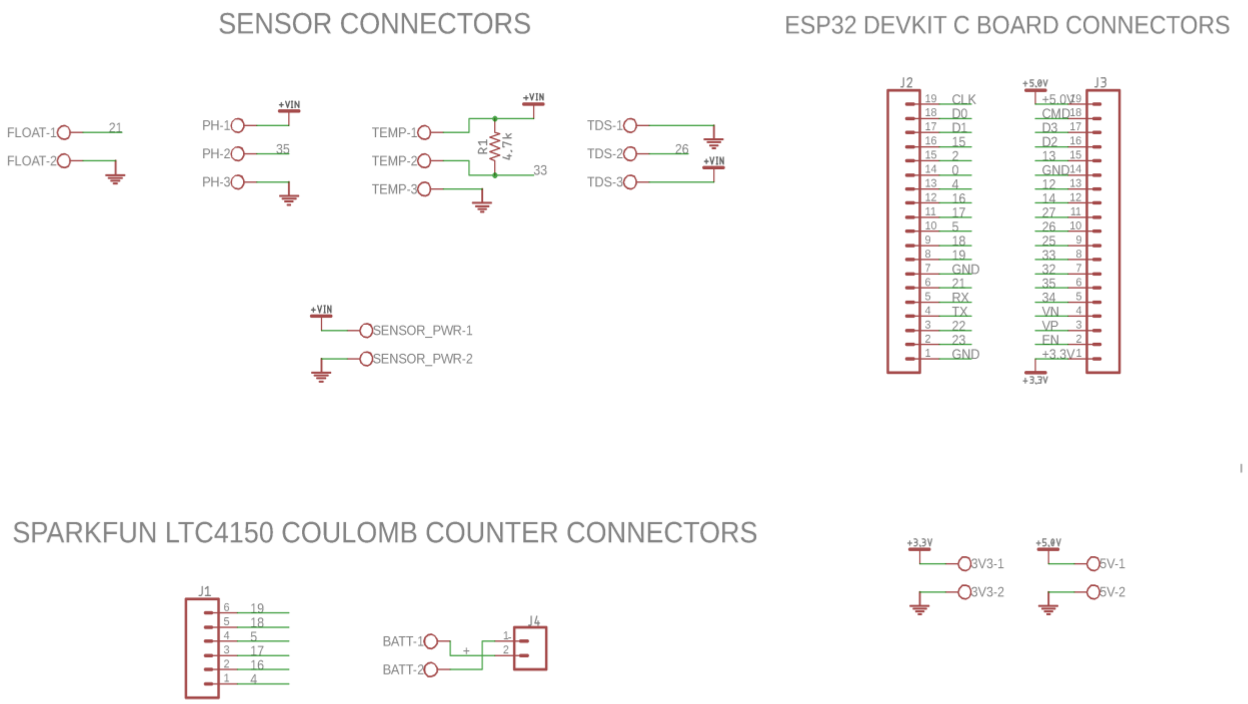
14 Appendices

14.1 Appendix A

14.1.1 Solar power supply board schematic



14.1.2 Sensor board schematic



14.2 Appendix B

14.2.1 Part lists for the solar power supply board

Part	Footprint	Label on board	Amount	Manufacturer
LT3652	MSOP-12	U4	1	Linear Technologies
LF33CDT-TR	T022	U1	1	Linear Technologies
L693D1.2TR	SOIC12	U3	1	Linear Technologies
ZLLS500	SOT23-3	D4	1	Diodes Incorporated
CMSH3-40MA	DO-214	D1,D2,D3	3	Central Semiconductor
GREEN LED	LED-1206	D5	1	Kingbright
RED LED	LED-1206	D6	1	Kingbright
500 kΩ Potentiometer	TS53Y	U2	1	Vishay
10 uH Inductor		L1	1	Pulse Electronics
634 kΩ	R1206	R1	1	Vishay
412 kΩ	R1206	R2	1	Vishay
10 kΩ	R1206	R3,R4,R8,R9	4	Yageo
0.2 Ω	R1206	R5	1	CTS Electronic Components
5.62 kΩ	R1206	R6	1	Panasonic
3.16 kΩ	R1206	R7	1	Panasonic
100 nF	C1206	C1,C2,C10	3	Yageo
10 nF	C1206	C9	1	Yageo
10 uF	A/3216-18R	C3,C4,C5,C8,C14	5	AVX
1 uF	C1206	C6	1	Yageo
Jumper	JP1	INPUT, JP1	2	ckmtw
2 Pin Terminal Block	W237-102	3.3V, BATT, LOAD, SOLAR1, SOLAR2	5	Molex
1 Pin Generic Header	1X01	J1	1	ckmtw
4 Pin Generic Header	1X04	J3	1	ckmtw
3 Pin Generic Header	1X03	J4,J4	2	ckmtw

14.2.2 Part lists for the sensor board

Part	Footprint	On board Label	Amount	Manufacturer
6 Pin Generic Header	1X06	J1	1	ckmtw
19 Pin Generic Header	1X19	J2,J3	2	ckmtw
2 Pin Generic Header	1X02	J4	1	ckmtw
4.7 kΩ	AXIAL-0.3	R1	1	Multicomp Pro
3 Pin Terminal Block	W237-103	PH,TDS,TEMP	3	Molex
2 Pin Terminal Block	W237-102	3V3, 5V, BATT,FLOAT, SENSOR-PWR	5	Molex

14.2.3 List of water monitoring sensors

Sensor	Manufacturer	Retailer Site
DS18B20 temperature sensor	Eses	Arduino-shop.cz
pH sensor (E201 probe + PH-4502C)	DIY MORE	laskarduino.cz
Gravity TDS meter	DFRobot	mouser.cz
Float Liquid Level Sensor	LasKKit	laskarduino.cz

14.3 Appendix C

14.3.1 Code

```
// float.h
float readWaterLevel(int sensor);

// float.cpp
#include "Arduino.h"
#include "float.h"

float readWaterLevel(int sensor){
  if (digitalRead(sensor) == LOW){
    return 0.0;
  }else{
    return 1.0;
  }
}

// temperature.h
#include <DallasTemperature.h>

float readTemperature(DallasTemperature &sensors);

// temperature.cpp
#include "temperature.h"

float readTemperature(DallasTemperature &sensors){
  sensors.requestTemperatures();
  return sensors.getTempCByIndex(0);
}


// ph.h
float readPh(int sensor);

// ph.cpp
#include "Arduino.h"
#include "ph.h"

#define SAMPLING_INTERVAL 20
#define SAMPLES 40

float readPh(int sensor)
{
  float voltageSum = 0;
  float averageVoltage;
  float voltage;

  for (int i = 0; i < SAMPLES; i++) {
    voltageSum += analogRead(sensor);
  }

  averageVoltage = voltageSum / SAMPLES;
  voltage = averageVoltage * 5 / 4096;

  return (-2.79 * voltage + 17.31);
}

// tds.h
float readConductivity(int sensorPin, float temperature);
float readTDS(float compensationVoltage);
```

```
// wifi.h
#define SSID "happy_ending" // wifi SSID
#define SSID_PASSWORD "on@r4Q805S" // wifi password

// thinger.h
// Thinger Configurations
#define USERNAME "kanamcat"
#define DEVICE_ID "Water_Monitor"
#define DEVICE_CREDENTIAL "a!zUbDzvew02"

// fuelGauge.h
#define BATTERY_CAPACITY_MAH 3400 // full capacity mAh
#define AH_QUANTA 0.17067759 // mAh for each INT

float calculateBatteryPercentage(double battery_mAh);

// fuelGauge.cpp
#include "fuelGauge.h"
#include "Arduino.h"

float calculateBatteryPercentage(double battery_mAh) {
  return (battery_mAh / BATTERY_CAPACITY_MAH) * 100;
}


// tds.cpp
#include "Arduino.h"
#include "tds.h"

#define SAMPLES 30
#define VREF 3.3 // analog reference voltage(Volt) of the ADC

float readConductivity(int sensorPin, float temperature) {
  int voltages[SAMPLES];
  for (int i = 0; i < SAMPLES; i++) {
    voltages[i] = analogRead(sensorPin);
  }
  // get median value and convert to voltage
  int medianVoltage = getMedian(voltages, SAMPLES);
  float voltage = (float) medianVoltage * VREF / 4096.0;

  //temp compensation formula: fFinalResult(25^C) = fFinalResult(current)/(1.0+0.02*(fTP-25.0));
  float compensationCoefficient = 1.0 + 0.02 * (temperature - 25.0);
  return (voltage / compensationCoefficient) ;  //temperature compensated conductivity value
}

float readTDS(float compensationVoltage) {
  //convert voltage value to tds value
  return (133.42 * compensationVoltage * compensationVoltage * compensationVoltage -
  255.86 * compensationVoltage * compensationVoltage + 857.39 * compensationVoltage) * 0.5;
}
```

```
// get median value from an array
int getMedian(int bArray[], int iFilterLen)
{
      int bTab[iFilterLen];
      for (byte i = 0; i<iFilterLen; i++)
      bTab[i] = bArray[i];
      int i, j, bTemp;
      for (j = 0; j < iFilterLen - 1; j++)
      {
      for (i = 0; i < iFilterLen - j - 1; i++)
          {
        if (bTab[i] > bTab[i + 1])
            {
        bTemp = bTab[i];
            bTab[i] = bTab[i + 1];
        bTab[i + 1] = bTemp;
         }
      }
      }
      if ((iFilterLen & 1) > 0)
    bTemp = bTab[(iFilterLen - 1) / 2];
      else
    bTemp = (bTab[iFilterLen / 2] + bTab[iFilterLen / 2 - 1]) / 2;
      return bTemp;
}
```

```
// pins.h
// LDO Enable Pin
#define LDO_EN 14

// LTC4150 Fuel Gauge Pins
#define VIO 19 // Used for the HIGH reference voltage
#define INT 18
#define POL 5
#define GND 17 // Used for the LOW reference voltage
#define CLR 16
#define SHDN 4 // Unneeded for polling, set to input

// Water Float Level Sensor Pin
#define FLOAT_SENSOR 21

// TDS Meter Pin
#define TDS_SENSOR 26

// Temperature Sensor Pin
#define TEMP_PIN 33

//pH meter
#define PH_SENSOR 35

void setupPins();
```

```
// pins.cpp
#include "Arduino.h"
#include "pins.h"

void setupPins() {
  // Temperature sensor
  pinMode(TEMP_PIN, INPUT);

  // Water Float Level Sensor
  pinMode(FLOAT_SENSOR, INPUT_PULLUP);

  // TDS Sensor Pin State
  pinMode(TDS_SENSOR, INPUT);

  //pH Sensor Pin State
  pinMode(PH_SENSOR, INPUT);

  // LTC4150 Pin States
  pinMode(GND,OUTPUT);
  digitalWrite(GND,LOW);

  pinMode(VIO,OUTPUT);
  digitalWrite(VIO,HIGH);

  pinMode(INT,INPUT_PULLUP);

  pinMode(POL,INPUT);

  pinMode(CLR,INPUT);

  // disabled by setting to input
  pinMode(SHDN,INPUT);

  // LDO Pin State
  pinMode(LDO_EN,OUTPUT);
  digitalWrite(LDO_EN,HIGH);
}
```

```
// water_monitor.cpp
#include <OneWire.h>
#include <DallasTemperature.h>
#include <math.h>
#include "soc/sens_reg.h"
#include <WiFi.h>
#include <ThingerESP32.h>
#include "pins.h"
#include "wifi.h"
#include "thinger.h"
#include "ph.h"
#include "temperature.h"
#include "float.h"
#include "tds.h"
#include "fuelGauge.h"

uint64_t reg_b;

// Setup a oneWire instance to communicate with any OneWire devices
OneWire oneWire(TEMP_PIN);

// Pass our oneWire reference to Dallas Temperature sensor
DallasTemperature temp_sensor(&oneWire);

ThingerESP32 thing(USERNAME, DEVICE_ID, DEVICE_CREDENTIAL);
boolean notificationsSent = false;
```

```
float ph;
float temp;
int waterLevel;
float ec;
int tds;

// run for this many iterations before going to deep sleep to ensure the data is sent
#define ITERATIONS 50
int iteration = 0;

#define SLEEP_SEC 5

// battery capacity tracking
RTC_DATA_ATTR volatile double battery_mAh = BATTERY_CAPACITY_MAH;

void setup() {
  reg_b = READ_PERI_REG(SENS_SAR_READ_CTRL2_REG);
  Serial.begin(115200);
  setupPins();
  attachInterrupt(digitalPinToInterrupt(INT), handleFuelGaugeInterrupt, FALLING);
  thing.add_wifi(SSID, SSID_PASSWORD);
  setupThing();
  temp_sensor.begin();
}
```

```
void loop() {
  ph = readPh(PH_SENSOR);
  temp = readTemperature(temp_sensor);
  waterLevel = readWaterLevel(FLOAT_SENSOR);

  // hack to get arround analoRead() and WiFi issue https://github.com/espressif/arduino-esp32/issues/102
  WRITE_PERI_REG(SENS_SAR_READ_CTRL2_REG, reg_b);
  SET_PERI_REG_MASK(SENS_SAR_READ_CTRL2_REG, SENS_SAR2_DATA_INV);
  ec = readConductivity(TDS_SENSOR, temp);
  tds = readTDS(ec);

  thing.handle();
  handleThingNotifications();

  if (iteration < ITERATIONS) {
    iteration++;
  } else {
    iteration = 0;
    goToDeepSleep();
  }
}

void handleThingNotifications() {
  if (notificationsSent) {
    return;
  }

  if (ph < 6.5 || ph > 9.5) {
    pson pHData = ph;
    thing.call_endpoint("pHLimit", pHData);
  }
  // send low water level notification
  if(waterLevel < 1) {
    pson waterData = waterLevel;
    thing.call_endpoint("waterLevel", waterData);
  }
  // send high conductivity notification
  if(ec > 0.8) {
    pson condData = ec;
    thing.call_endpoint("conductivity", condData);
  }
  // send low battery notification
  float batteryPercentage = calculateBatteryPercentage(battery_mAh);
  if (batteryPercentage < 40) {
    pson battData = batteryPercentage;
    thing.call_endpoint("batteryCapacity",battData);
  }

float roundFloat(float number, int decimalPoints) {
  int multiplier = pow(10, decimalPoints);
  return roundf(number * multiplier) / multiplier;
}

void goToDeepSleep() {
  esp_sleep_enable_timer_wakeup(SLEEP_SEC * 1000000);
  esp_deep_sleep_start();
}

void handleFuelGaugeInterrupt() {
  boolean polarity = digitalRead(POL);
  if (polarity) {
    battery_mAh += AH_QUANTA; // charged capacity
    if (battery_mAh > BATTERY_CAPACITY_MAH) {
      battery_mAh = BATTERY_CAPACITY_MAH;
    }
  } else {
    battery_mAh -= AH_QUANTA; // used capacity
    if (battery_mAh < 0) {
      battery_mAh = 0;
    }
  }
}
```

14.4 CD contents

- boards
  - sensorBoard.sch……………………………schematic for sensor board
  - sensorBoard.brd……………………………pcb layout for sensor board
  - solarPowerSupply.sch………………………schematic for solar power supply board
  - solarPowerSupply.brd………………………layout for solar power supply board
- src……………………………………………………code for water monitor
- thesis.pdf………………………………………thesis in pdf format