Development of low-cost autonomous meteorological measurements system for urban environments

Jan-Paul Konijn

Creative Technology - Faculty of Electrical Engineering, Mathematics and Computer Science, University of Twente

Supervised by: Richard Bults & Hans Scholten

July 2020

Abstract

Urban heat build-up and environmental stresses are becoming more critical topics for the future of cities. Around the city of Enschede, a wireless sensor network (WSN) will be deployed to understand and monitor the development of such stresses. The wireless sensor network is a cooperation with the University of Twente and the municipality of Enschede and requires a high-quality and reliable meteorological measurement system (MMS). The primary objective for this research is to find optimum sensor reliability, system costs and system data quality to measure temperature, relative humidity, solar irradiance, and wind speed, according to the Royal Dutch Meteorological Institute (KNMI) measurement frequency specifications. During the research, optimisation for both qualities, reliability and costs are extensively researched to come with a final prototype that is optimised for measurements in urban environments using off-the-shelf components. The total cost of the system developed can not exceed 400 Euros, and therefore, trade-offs have been made. A custom-mounting system has been developed to mount the various components of the MMS around an average-sized street pole. The system transfers its measurements data using LoRaWan for long-range, low-power data communication enabled by the TheThingsNetwork (TTN). TheThingsNetwork enables for small amounts of data being sent without a fee, to optimise the data transfer; a custom payload structure has been implemented according to the TTN's fair-use-policy. The design iteration of each component of the MMS, power system, meteorological sensor-set, wireless data communication and micro-controller have been discussed to present a final prototype. The final prototype is tested in an outdoor environment to test for the MMS urban application. In the end, an overview of the requirements met by the system, and evaluation is provided and elaborated to define additional improvements. Future works points are provided to help future developers to come with an improved system based on the research findings.

Acknowledgements

This research and development have been conducted over the course of half a year. During the research and development of an MMS, several individuals were critical. Without their feedback, observations, and motivation, this could not have happened. I want to thank both supervisors, Richard Bults, and Hans Scholten for their time and effort, expertise, and critical but constructive feedback. Secondly, I would like to Wim Timmermans for his expertise in the field of weather measurements, as well as Rik Meijer for his knowledge regarding the requirements set by the municipality of Enschede. Last, I would like to thank Peter van der Burgt, this research is has been partly performed in cooperation with Peter van der Burgt, and the cooperation was both fun and successful. He provided helpful insights and was willing to help and share his valuable time.

Contents

1 Introduction

1.1 Role and significance of meteorological measurements systems

Climate change and extreme weather have become topics of interest for many cities, councils, and politicians. Heat stress (HS) is defined as the exposure to severe heat in cities [1]. HS is expected to get worse for many cities in the future [2], HS, in combination with the expected urbanisation of many countries will likely have a significant impact on how future cities will be designed. It has been proven that heat exposure for humans, especially in urban areas, can become a health concern, and as more people move to the cities, cities will become densely populated, and more individuals will be susceptible to these developing conditions [1]. Therefore, city councils, designers, architects, and engineers have to come with new ideas and implementations to make cities heat and extreme weather proof.

To better understand extreme weather and the effects of weather on our surroundings, meteorological measurements systems (MMS) can be used. Autonomous meteorological measurements system has been increasingly used for monitoring weather parameters. These measurements are important for scientific research to make predictions on climate change, and the effects of weather change. Global climate change and extreme weather have become important themes for many countries as weather can have an influence on many areas, such as, e.g. farming where crop-yields in developing countries [3] are dependent on weather, or the area of power generation using renewable sources, like photovoltaic (PV) energy and wind energy [4]. Meteorological measuring systems have also been proven their value in harsh environments such as the Alpine Glaciers [5], and Antarctica [6] to measure the effects of meteorological parameters on these environments.

Initiatives closer to home also play an essential role to combat the consequences of climate change and extreme weather. Around the city centre of Enschede, a wireless sensor network (WSN) is utilised to understand the influences of weather and climate change. The initiative "Wat Heet Eanske Gruene Stad" or WHEGS[7] develops a WSN that is distributed through the city centre of Enschede for measuring meteorological parameters. The project has lead to multiple generations of sensor nodes that have the ability to measure environmental parameters autonomously. Although existing research-grade MMS products have decreased in price, current systems, e.g. the Davis Vantage Pro 2 [8], can still be considered high-cost. For this reason, there is interest for a low-cost solution that can obtain scientific-grade high-quality measurements.

This research will build on previous studies by Creative Technology students from the University of Twente. The projects suggest that there is a correlation between the quality of measurements and the costs [9][10][11]. However, no real effort has been made in analysing and finding optimal sensors for weather measurement applications with respect to required parameters (low-cost, high reliability, high-quality). Moreover, from the previously performed researches, challenges have been identified; finding a solution that is both affordable and precise. According to the previous studies, the use of low-cost components and unreliable supplier channels resulted in sub-optimal solutions. The data received from the sensor node as a whole proved to be insufficient in terms of quality. Secondly, the consistent quality of hardware seemed to be the main bottleneck; hardware ordered from suppliers could deviate from there product description. The primary objective for this research is to find optimum sensor reliability, system costs and system data quality.

This project will be executed as a collaboration between the Municipality of Enschede, University of Twente Creative Technology, and the University of Twente ITC. Outline for development will be a rapid prototype procedure in which a design iteration will be performed and examined.

1.2 Challenges and constraints for designing a meteorological measurements system

The sensor nodes will be distributed over the city centre commissioned by the municipality of Enschede. Although more financial resources make it possible to acquire quality sensors, the stakeholders' primary concern is keeping the budget under the 400 euros threshold. Despite the budget limitations, utilising low-cost sensors in a distributed system should satisfy the constraint of performing high-quality measurements spread over the city of Enschede.

The low-cost sensor system enables for a distributed approach; with limited financial resources having the ability to perform high-quality measurements with many sensors spread over the city of Enschede. Although MMS products like the Davis Vintage Pro 2 are available on the market and provide high-quality measurements, systems can be hard to integrate with other solutions or are closed-source. Therefore, an open-source solution that can compete with the current products on the market is necessary.

This requires research for finding quality requirements for this system and research for optimising quality while maintaining low-cost properties.

1.3 Research question statement

- **How to develop a low-cost autonomous MMS for the city of Enschede?** The answer to that question can be achieved by answering two sub-questions stated below. The Davis Vantage Pro MMS will be employed as a reference system, according to the main requirements set by the Davis Vintage Pro additional specification for the system will be classified. Therefore, the following sub-questions:
  - **What are the MMS quality requirements?**
    - reliability: The system needs to be able to operate autonomously without any supervision or repairs. Housing, hardware, and software should satisfy these requirements.
    - data quality: The data measured will be transmitted and stored, after all the actions interpreting, sending, receiving, the information should be truthful to real environmental values.

    With the use of this sub-question, requirements will be set.
  - **How to optimise the MMS cost-quality of measured data?** The budget for a complete build of the system needs to be $\leq$ 400 Euros. Therefore, trade-offs must be made to ensure a high-quality measurement instrument. For answering the above sub-question, a thorough analysis will be required on sensor choices, hardware, and housing materials.

2 State-of-art

The deployment of meteorological measurement systems is nothing new. As is evident by Davis pro, these systems are already in the market. A lot has been done in the field of meteorological measurements and obtaining environmental data for scientific research. Despite the broad availability of systems and solutions, it is essential to perform analysis on what is out there, and concepts in the field of weather measurements and sensor nodes. Furthermore, as this project will focus on requirements for the development of an autonomous MMS, technology requirements from the literature will be discussed and reviewed. In this chapter, the state-of-art will consist of 5 parts.

– An overview of technologies applied in weather measurement systems
– A review on how urban measurements are performed
– Analysis of low-energy communication protocols
– An overview of existing MMS
– Discussion

2.1 Overview of technologies applied in weather measurement systems

For this research, it is of importance to identify technologies that are applied in MMS. An Autonomous MMS acts as instrumentation that operates without any supervision [12]. In the introduction the Davis Vintage pro [8] was mentioned as the reference system. The following parameters are being measurement by this MMS:

– Temperature
– Relative Humidity
– Wind speed
– Wind direction
– Barometric pressure
– Solar irradiance
– Rain

For identifying the technologies of an MMS, a high-level approach will be used to identify the main components. An MMS consists out of three main components; data-logger unit or micro-controller, power unit, and meteorological sensor [5]. Data-logger or micro-controller can be considered the heart of an MMS as it is responsible for ensuring continuous and reliable measurements and pre-processing of the obtained data. Abbate et al. [5] describes a situation where on site access by humans is not possible. For these circumstances a communication system is required. With the situation described by Abbate et al. [5] in combination with the three leading components mentioned by Susmitha and Bala [12], four core components have been identified.

- power system
- data-logger or micro-controller
- meteorological sensors
- wireless communication

Abbate et al. [5], explores various communication implementations and technologies, such as GPRS, WiFi or satellite for reliable data transfer. Wireless communication systems depend on the availability of energy sources, financial resources, and available wireless connection types.

For temperature measurements, Li [13] applies the DS18B20 [14] (figure: 2) in their MMS. The sensor system interfaces only with one pin to the micro-controller or data-logger [13]. Moreover, the sensor system allows for configuring the measurement accuracy. The analog-to-digital converter (ADC) can be set to 9,10,11 or 12 bits depending on the required resolution of the measurement. Moreover, the sensor offers a accuracy of $\pm 0.5°C$ within the range of $-10°C$ to $+85°C$ [14]. The temperature sensor applied by Li [13] provides an electrical output proportional to the temperature; no calibration or trimming is required. In short, for the design of a weather station, pre-calibrated sensors, hardware with build-in ADCs, sensor system with a low amount of output pins are parameters that can be taken into consideration when selecting applicable hardware.

Besides, temperature measurements, the Davis Vintage Pro MMS [8] measures more meteorological parameters like relative humidity, wind speed, wind direction, solar radiation. Benghanem [15] suggests applying the Campbell Scientific - A100R anemometer [16] for wind speed measurements and the Campbell Scientific - W200P wind vane [17] for respective wind direction measurements. Although the wind speed sensor generates a sinusoidal voltage, the sensor system contains circuitry for conversion to digital signals proportional to the wind speed. In contrast, a similar configuration is used by Li [13]; however, no specific sensors or sensor systems types regarding wind speed and wind direction are mentioned in the paper.

In Addition, to the mentioned temperature, wind, and relative humidity, solar radiation is an important parameter that can be obtained with the Davis Vintage pro MMS. According to the WMO [8] meteorological radiation measurements can be performed by the use of the radiation instruments types depicted in figure 1 [18]. Abbate et al. [5] apply the Kipp & Zonen CGR3 pyrgeometer

[19] to measure the incoming and outgoing long-wavelength radiation. This is in contrast with the applied solar irradiance sensor system by Devaraju et al. [20], in the paper, a Davis-6450 [21] is used for solar irradiance measurements. Moreover, Deveraju et al. [20] suggest that Davis pyranometer is capable of measuring $0 - 1800WM^{-2}$ solar irradiance. What exact sensor type and the measurement range is required for the development for the MMS will need to be specified in the specification phase.

Instrument classification	*Parameter to be measured*	*Main use*	*Viewing angle (sr) (see Figure 7.1)*
Absolute pyrheliometer	Direct solar radiation	Primary standard	5×10^{-3} (approx. 2.5° half angle)
Pyrheliometer	Direct solar radiation	(a) Secondary standard for calibrations (b) Network	5×10^{-3} to 2.5×10^{-2}
Spectral pyrheliometer	Direct solar radiation in broad spectral bands (e.g. with OG 530, RG 630, etc. filters)	Network	5×10^{-3} to 2.5×10^{-2}
Sunphotometer	Direct solar radiation in narrow spectral bands (e.g. at 500 ±2.5 nm, 368 ± 2.5 nm)	(a) Standard (b) Network	1×10^{-3} to 1×10^{-2} (approx. 2.3° full angle)
Pyranometer	(a) Global (solar) radiation (b) Diffuse sky (solar) radiation (c) Reflected solar radiation	(a) Working standard (b) Network	2π
Spectral pyranometer	Global (solar) radiation in broadband spectral ranges (e.g. with OG 530, RG 630, etc. filters)	Network	2π
Net pyranometer	Net global (solar) radiation	(a) Working standard (b) Network	4π
Pyrgeometer	(a) Upward long-wave radiation (downward-looking) (b) Downward long-wave radiation (upward-looking)	Network	2π
Pyrradiometer	Total radiation	Working standard	2π
Net pyrradiometer	Net total radiation	Network	4π

Figure 1: Meteorological radiation instruments table [18]

Furthermore, communication protocols between the micro-controller and the sensor systems, such as the I2C protocol, need to be addressed. Devaraju et al. [20] apply an SHT11 [22] in their system. The SHT11 [22] relative humidity and temperature sensor incorporates a capacitive sensor element to measure relative humidity. Its communication between micro-controller and the sensor operates via the I2C protocol. For Barometric pressure measurements, Kusriyanto et al. [23] apply a BMP-180 sensor system to retrieve the absolute pressure around the sensor system. The BMP-180 [24] developed by Bosch can be interfaced using the I2C protocol. Furthermore, in order to design an autonomous weather station, parameters of data retrieval such as sampling frequency, digital-based hardware, as well as, analog sensor technologies can be considered. All the mentioned reports;[12][5][13][20] apply a form of controller to process the measurements, with some examples storing data locally and others remotely. For such a situation, server software is mainly responsible for decoding, processing and storing the data in a database. A data flow suggested by [13] can be seen in figure: 3.

Figure 2: DS18B20 - Temperature sensor system

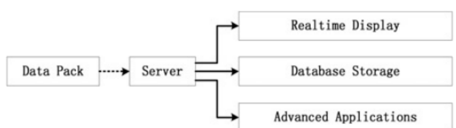


Figure 3: Server software

To conclude, depending on the set of requirements, constraints, and availability of technologies, various wireless communication techniques, micro-controllers, and measurement sensors should be considered. Different sensor types, both analog and digital have been mentioned. However, it is essential that more state-of-art technologies should be researched. As the sensor and micro-controller technology is evolving rapidly, some technologies that are mentioned in the research reports are behind the curve of innovations.

For this envisioned research, four components were identified to later be used to design the system around. However, as mentioned a more state-of-art approach for exact technologies types, like sensors and wireless communication will be necessary.

2.2 A review on how urban measurements are performed

In the previous sub-question, different components have been discussed for an MMS, as the primary goal of the research is to develop an urban MMS. Urban measurements conventions and concepts need to be addressed. Urban sensing strategies can be performed with the use of both static data retrieval and mobile agents [25]. Examples for mobile agents or non-static data retrieval are; balloons, unmanned aerial vehicles (UAVs) such as drones, public transport vehicles, private cars, and persons. Traffic congestion measurement systems such as magnetic road sensors, embedded accelerometers for vibration measurements, and water quality sensor nodes that measure pH, electrical conductivity can be recognised as static sensor networks. For the envisioned research, the focus will be on static sensor networks.

However, Carminati et al. [25] addresses different sensing strategies that can extend or improve spatial resolution. With the use of gamification and participatory sensing, mobile agents can be used for measurements with the utilisation of smartphone. This approach of sensing can extend the static network that will be developed in this research but is for the envisioned research out of scope.

Focusing only on the design of measurement systems seems trivial. However, one can use the above-mentioned approach to improve measurements in urban areas. Nevertheless, data analysis becomes more complicated, and sensors are constrained to the device. Furthermore, the willingness of participants is required if participatory sensing or gamification is to be employed.

Beyond that, the order in which the spatial density of sensor technologies to be used mostly depend on cost considerations, power supply availability, and size of sensor nodes. Muller et al. [26] identify six scales of spatial measurements, with each scale having its own application. Table 1 provides an overview of each spatial scale and its use.

Spatial resolution overview (Tabel 1 [26])		
Spatial scale area extent	Description	Examples
Global-scale $>10^8 m$	Global network of networks, internationally facilitated	Synoptic forecasting, measurement for climate change
Macro-scale $10^5 - 10^7 m$	Networks of national monitoring systems. Used for regional measurements	National measurements, national weather forecast
Meso-scale $10^4 - 10^6 m$	Regional meso-scale measurements. Urban, peri-urban, and rural areas	Temperature changes over urban and rural areas.
City-scale $10^4 - 10^5 m$	Monitoring at the scale of the whole city	Urban heat island studies, urban climate studies
Local-scale $10^2 - 10^4 m$	Monitoring at neighbourhood level, Measuring effects on small topographic.	Urban heat island, air pollution
Micro-scale $\leq 10^2 m$	Mirco-meteorological phenomena, measuring at a level of buildings, trees, roads.	Human comfort, exposure impact, building measurements

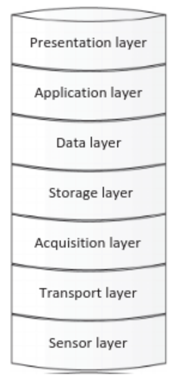


Figure 4: Seven-layer architecture

The scales of resolution can be extended with the seven-layer architecture proposed by Su et al. [27] for urban measurements. This architecture provides a more thorough urban architecture than the proposed architecture by Cenedese et al. [28]. The seven-layered architecture depicted in figure: 4 can be easily extended. The suggested architecture implementation has three advantages. Firstly, due to setting up a wide network, it becomes possible to analyse environmental problems in time and spatial domain. Secondly, different factors can be monitored, allowing for overlay analysis where multiple parameters can be combined. Finally, the paper suggests that the so-called environmental internet of things allows for integration with other measurement techniques for analysis. This is further discussed in the article, where mobile sensor/agents should not replaced, but complement the static sensor network for data measurements. However, this would result in a significant challenge, as heterogeneous data fusion require multidisciplinary efforts [25].

2.3 Communication technologies for low-energy communication

Previously, different components have been identified. The importance of low-power communication in wireless sensor networks has become clear [5]. Although no requirements have been identified regarding the MMS, based on the previous findings; Abbate et al. [5] describing the choice for wireless communication based on power consumption, knowledge on available low-energy data communication technologies can be required for the development of the MMS. Sensor nodes that operate on renewable energy sources have power constrains which makes efficient data transmission critical. In this part, relevant efficient communication protocols will be reviewed based on literature.

Generally, a data communication technologies for the internet of things can be divided into two categories: low-power wide access networks (LPWAN) for long-range and short-range networks [29]. Sarawi et al. [29]; distinguishes two main technologies for (long range) LPWAN:

- Sigfox [30] is low power technology with transfer speeds 10 to 1000 bits per seconds. Moreover, it implements Ultra Narrow Band technology for data transfers up to 50 km while maintaining low-energy properties [29]. A small battery can drive this technology.
- Cellular technology is suitable for applications that require high throughput. This technology takes advantage of the existing GSM/3G/4G and could in the future use 5G. However, cellular connectivity requires more power and thus is not advised for power efficient applications.

The LoRaWan [31] is not mentioned by Sarawi et al. [29]. However, de Carvalho Silva et al. [32] does identify LoraWan protocol as a long-range alternative. Moreover, the range of urban areas and rural areas deviate. For Lora, the urban range is, e.g. 2-5km and for the rural areas; e.g. 45km. For short-range networks, the following technologies are defined by Sarawi et al. [29]:

- 6LoWPAN a commonly applied technology. This technology has low-power properties and supports different kinds of network topologies.
- Zigbee is a low-power wireless technology build on the IEEE802.15.4 physical layer. This protocol also supports various kinds of network topologies.
- Bluetooth low-energy (BLE), designed for short-range, low bandwidth and low-power consumption.
- Z-wave, low-power, MAC-based protocol, low-speed up to 100kbps, and 30-meter point to point. Moreover, this technology supports mesh network topology.

De Carvalho Silva et al. [32], and Sarawi et al. [29] disagree with each other on the future of a low-power communication technology. According to Sarawi et al. [29], 6LoWPAN is the most suitable protocol for the future, because of its big address space and multiple different metrics like network topologies. In opposition, de Carvalho Silva [32] states that LoraWan protocol (LPWAN type) showed advantages over other 6LoWPAN technologies, concerning power-consumption and range.

Moreover, the difference of the architectures can be explained by figure 5 and figure 6 [33]. Comparison of the 6LoWPAN , Sigfox (LPWAN) and Lora (LP-WAN) is depicted in figure 7 [33]. 6LoWPAN devices can directly communicate with each other, whereas LPWAN types of technologies, such as, LoRaWan[34] can only communicate with gateways. Moreover, Al-Kashoash and Kemp [33] state that for 6LowWPAN, the distance is 10 m to 100 m. This influences the distribution of nodes (high density) and gateways over a particular area. Comparison of the 6LoWPAN, Sigfox and Lora is depicted in figure: 7. Although, de Carvalho et al. [33] states a range 5-15 km for the Lora protocol, Al-Kashoash and Kemp [32] state a range 2-45 km. As contradiction in stated specs exist, better analysis of the specifications might be required for choosing a type of data communication.

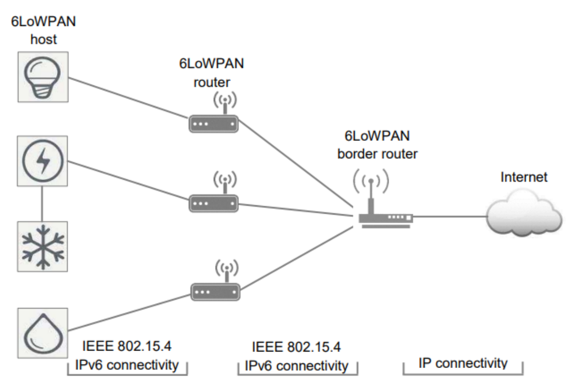


Figure 5: 6-LoWPAN network architecture

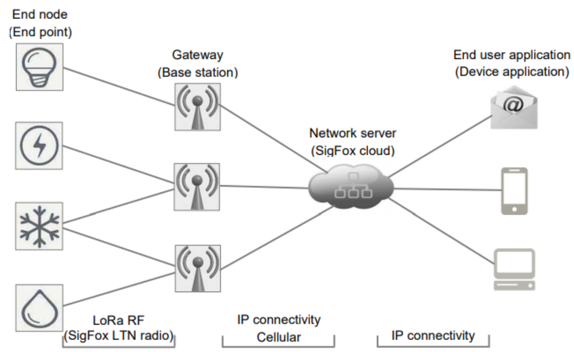


Figure 6: LWPAN network architecture

For transmission protocols in the domain of IoT, there are five main challenges [32].

- Bandwidth; Bandwidth combined with the data rate is used to determine the amount of data that can be transferred. For LoRaWan, the data rate is dependent on the choice between the duration of message and range.

- Battery life; Battery life is a general constraint in IoT solutions. LoRaWAN implements radio frequency control and rate control for maximization of battery life.

- Latency; Latency is the trade-off between uplink communication, downlink communication and battery-life. This can be resolved with the quality of services in the LoRaWAN device.

- Throughput; LoRaWan throughput is dependent on the range. i.e. 2-45km throughput of 290 bps to 50kbps.

- Range; data communication technologies have the objective for high information availability at great distances. To meet such requirements, radio power is mainly increased which influences the battery life.

In short, different low-power technology have been discussed that can be applied for wireless communication applications. However, for the development of the system for this research, bandwidth, battery life, latency, throughput, and range need to be addressed before full implementation. Based on the requirements mentioned a right low-power protocol could be picked and applicable hardware selected. Depending on the availability of gateways, one might choose an LWPAN technology, while mesh networks with the use of 6-LoWPAN can be chosen when there are fewer gateways in the surrounding area.

Parameter	6LoWPAN	LoRaWAN	SigFox
Frequency band	2400 – 2483.5 MHz (worldwide) 902 – 929 MHz (North America) 868 – 868.6 MHz (Europe)	902 – 928 MHz (North America) 863 – 870 MHz and 434 MHz (Europe) 779 – 787 MHz (China)	902 MHz band (America) 868 MHz band (Europe)
Number of channels	16 channels for 2.4 GHz band 10 channels for 915 MHz band 1 channel for 868.3 MHz band	80 channels for 915 MHz band 10 channels for 868 MHz band and 780 MHz band	360 channels + 40 channels are reserved (not used)
Channel bandwidth	5 MHz for 2.4 GHz band 2 MHz for 915 MHz band 600 kHz for 868.3 MHz band	125 kHz and 500 kHz for 915 band 125 kHz and 250 KHz for 868 MHz band and 780 MHz band	100 Hz – 1.2 kHz
Maximum data rate	250 kbps for 2.4 GHz band 40 kbps for 915 MHz band 20 kbps for 868.3 MHz band	980 bps – 21.9 kbps for 915 band 250 bps – 50 kbps for 868 MHz band and 780 MHz band	100 bps – 600 bps
Protocol data unit	6 bytes header + 127 bytes SDU	variable number of bytes header + (19 to 250) bytes	12 bytes header + (0 to 12) bytes
Channel coding	Direct Sequence Spread Spectrum (DSSS)	Chirp Spread Spectrum (CSS)	Ultra narrow band coding
Channel modulation	O-QPSK for 2.4 GHz band BPSK for 915 MHz band BPSK for 868.3 MHz band	LoRa for 915 MHz band LoRa and GFSK for 868 MHz band and 780 MHz band	BPSK and GFSK
Receiver sensitivity	-85 dBm for 2.4 GHz band -92 dBm for 915 MHz band -92 dBm for 868.3 MHz band	-137 dBm	-137 dBm
Transmission range	10 m to 100 m	5 km to 15 km	10 km to 50 km
Battery lifetime	1 – 2 years	$<$ 10 years	$<$ 10 years

Figure 7: Table low-power technologies

2.4 Overview of existing systems

2.4.1 Low-cost Autonomous Temperature Measurements System

This project has been conducted by a former Creative Technology student of the University of Twente. The development of a low-cost autonomous MMS will be built upon the gained knowledge of Pijnappel [9]. His research focuses on the development of a low-cost autonomous measurement system and uses the Davis Vintage Pro [8] as a reference system. His research resulted in the MMS depicted in figure 8 and figure 9. The technical overview can be seen in the schematic depicted in figure 10. The system is built around the ESP-32 micro-controller in combination with a comprehensive sensor system set. The sensor set is applied to measure environmental data while ensuring modularity by making sensors systems interchangeable. This is optimal for testing different hardware components. The sensor system set follows the set requirements of the Davis Vintage Pro [8] reference system and performs measurements on:

- Solar irradiance
- Temperature
- Relative humidity
- Wind direction
- Wind speed

Using LoraWan [31] communication enabled by TheThingsNetwork [35] ensures long-distance low-energy data transfer to a database hosted on a Raspberry Pi.

The housing of the electronics is made with the use of a 3D printer using Polylactic Acid (PLA) filament as printing material.

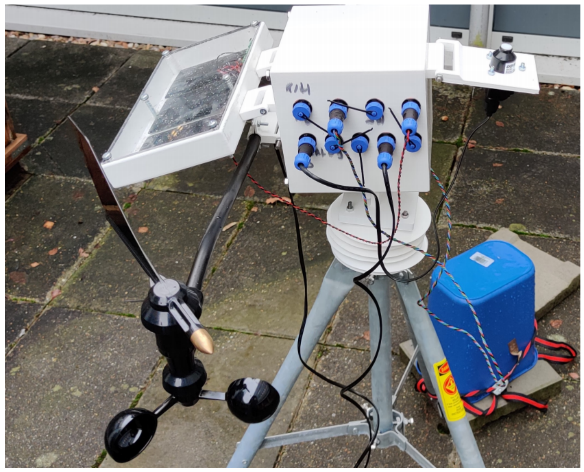


Figure 8: MMS design (Pijnappel)

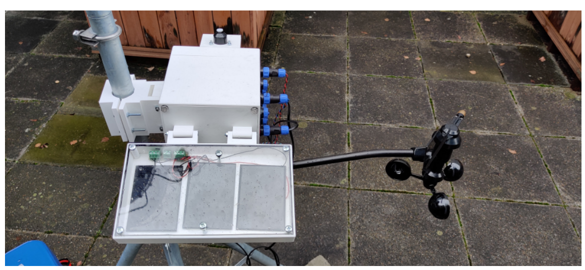


Figure 9: MMS design (Pijnappel)

From the design, it can be concluded that the sensor node fulfilled the quality requirements regarding temperature and relative humidity measurements. The rest of the system; wind speed sensor, wind direction sensor, and solar irradiance sensor have been manufactured by the same supplier as the reference system. This implies that the requirements had been fulfilled regarding measurement quality. The report suggests optimising housing to ensure waterproofing as physical damage did not seem to be the primary concern. The sensor node exceeded the budget of 400 Euros. However, the expensive sensors of Davis Instruments [36] and the off the shelf components added up to 300 Euros. Recommendation for future work versions can be summarised into four main concerns:

– Micro-controller deviated in quality from the specification; ESP-32 micro-controller that was ordered from China proved to be unreliable.

– Over-the-air firmware update; ability to update the micro-controller without using an cable.

– Charge protection; the charge of lithium cells is disabled at ≤ 0 degree Celsius.

– Optimisation for large production; as the entire housing was 3D printed, making multiple sensor nodes becomes hard because 3D-printing is time consuming.

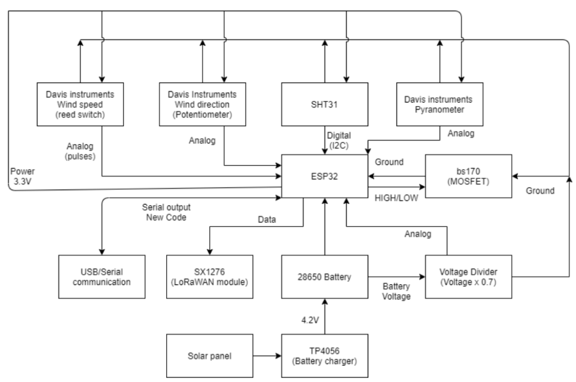


Figure 10: Technical schematic

2.4.2 Climate measurement in public spaces

This research has been conducted by Laura Kester [10]. She focuses on the effects of urban heat stress on the city centre of Enschede. The goal was to develop a monitoring tool to apply in an urban setting, measuring the development of urban heat islands on the city of Enschede. This autonomous sensor design is one of the earlier generations where Pijnappel [9] built upon.

For the design process, a combination of different design phases was used in combination with the spiral design model of Boehm [37]. This resulted in the system depicted in figure 11, containing humidity sensor, temperature sensor and anemometer, an overview of model numbers is given below:

- temperature sensor sub-system: DS18B20 [14]
- humidity sensor sub-system: Sensiron-SHT15 [22]
- anemometer sub-system: Froggit-WH1080 [38]

These sensor were interfaced using a SODAQ One board, this board is LoRa enabled and has built-in GPS.

Figure 11: Sensor node designed by L.Kester (left sensor)

Although, the requirements of the municipality of Enschede were met, according to the Wim Timmermans (UT-ITC), the measurements seemed to be of insufficient for scientific research. The report suggest improving the housing quality, that was made by using PLA 3D-printing. Although, she mentions that the material is able to withstand environmental parameter like, wind, long exposure to UV-rays and freezing water can damage the material overtime. She suggests with her research to look into other printing materials like ABS or PETG for a stronger enclosure.

Moreover, the researcher suggests the addition of a solar radiation sensor, as solar radiation can provide valuable data to measure the development of urban heat islands in and around a city. For the research that will be conducted during this report, the suggestion of adaptable update rate can be considered an interesting one. The rate or frequency of data transmission is in this project static. However, with the use of adaptable data transmission can offer power consumption reduction, making the system more reliable.

2.4.3 Deploying a Communicating Autonomic Weather Station on a Alpine Glacier

Abbate et al. [5] describe the deployment of an automatic weather station on an alpine glacier. The measurement system is located at the La Mare glacier in Italy. The system is based around the CR1000 controller (Campbell Scientific), a technical overview is depicted in figure 13. The sensor node runs on a 12V 24Ah rechargeable battery, charged by a 20-watt solar panel, data-logger and battery are housed in a weather-proof fibreglass enclosure, positioned at the base of the measurement system. A full picture of the system can be seen in figure 12. During the research, an applicable wireless communication system is analysed for the weather measurement system, as the system is based in the Alps and as the location is hard to reach during winter. The researchers analysed different wireless communication technologies. The wireless communication technologies for consideration are; WiFi, GSM/GPRS or satellite communication. Although satellite communication is expensive, it offers a ubiquitous solution compared to WiFi, GSM, and GPRS that require additional hardware to transfer data. The surroundings area offers no additional hardware, nor any signals for GSM or GPRS were present, the researchers picked wireless satellite communication for data transfers.

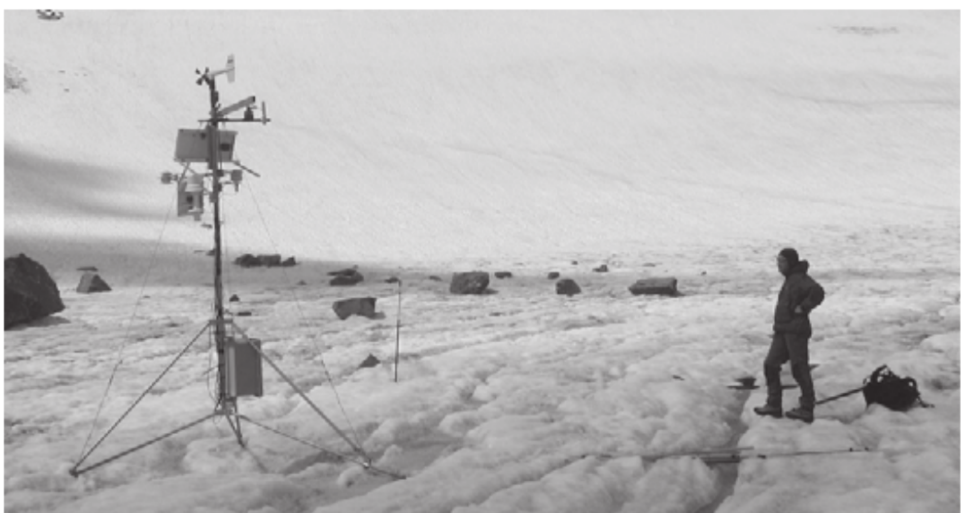


Figure 12: Weather station applied at glacier

As a result, the researchers applied a MiChroSat modem for connecting to the Irridium[1] satellite network. The implementation of wireless communication in the measurement systems would impact energy consumption. Based on the worst-case of energy regeneration and consumption, researchers found that power-aware programming would be sufficient for the system to stay oper-

[1] https://www.iridium.com/

Device type	#	Model	Description	Current drain (mA)
Anemometer	1	Young 05103-5	Wind speed and direction	Always < 0.01
Nivometer	1	Campbell Sci. SR50-A	Snow height, sonic sensor	Sleep 2.25; Active 250
Albedometer	1	Delta Ohm LP Pyra 05	Solar radiation, net between incident and reflected light	Always < 0.01
Thermo-Igrometer	1	Campbell Sci. CS215	Air temp. and relative humidity, passive ventilation shield	Idle 0.07; Active 1.7
Pirgeometer	2	Kipp & Zonen CGR3	Incoming and outgoing long-wavelength radiation	Always < 0.01
Thermo-Igrometer	1	Vaisala HMP45C	Air temp. and relative humidity, active vent shield	Sleep 0; Active 4
Thermistors	2	Campbell Sci. T-107	Temperature from both passive and active shields	Active < 0.01
Datalogger	1	Campbell Sci. CR1000	Datalogger unit	Sleep 0.6; Active 10
Modem	1	MiChroSat 2403	Iridium satellite modem	Sleep 15; Idle 150; Transmission 900

Figure 13: Technical overview weather station

ational. With the use of duty cycles sampling, only a few times per day, system sustainability is reached.

2.4.4 Wireless Portable Micro-controller based Weather Monitoring Station

Devaraju et al. [20] addresses the development of a weather monitoring station around the PIC16F887 micro-controller [39], a picture of the full system can be found in figure 14. The used sensor set in the weather monitoring consists of:

- temperature sensor - SHT11 [22], (PT100)
- humidity sensor - SHT11 [22]
- wind speed - Davis instrument-6410 [40]
- wind direction - Davis instrument-6410 [40]
- solar irradiance - Davis instruments-6450 [41]
- pressure sensor - Bosch BMP180 [24]
- rain gauge sensor - Davis instruments-7852 [42]

An overview of the technical implementation is depicted in figure 15. The paper discusses different protocols such as the I2C protocol to retrieve the data from the sensors on the micro-controller. Moreover, as some sensors do not provide a digital interface that is required by the micro-controller, like the PT100 the use of an ADC is discussed to interface with the micro-controller. For the software architecture a MySQL database is used for storing the incoming data using a sampling frequency of every 30 seconds. The data was compared with the standard weather reports. Resulting in a system that is highly portable and a system that is a good platform for sharing meteorological data.

Figure 14: Weather station

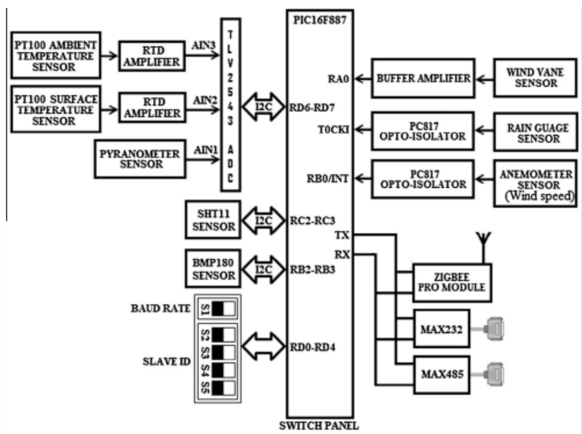


Figure 15: Weather station architecture

2.5 TEMPEST: A revolutionary personal weather system - Kickstarter

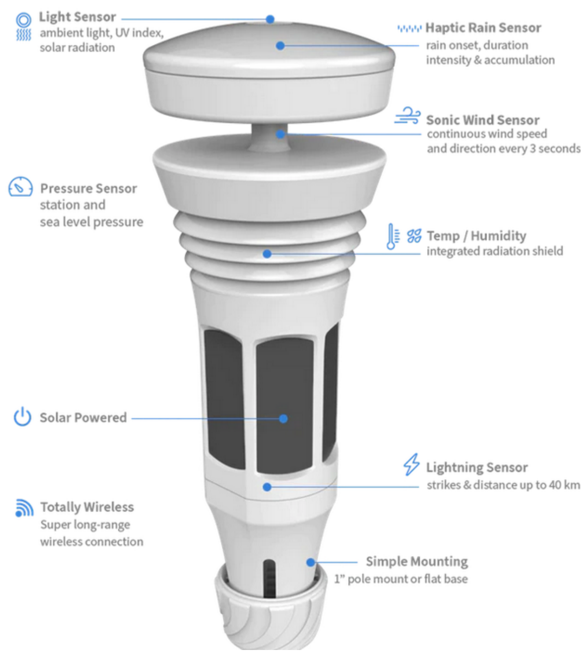


Figure 16: Tempest weather station

Tempest is a new product designed and manufactured by Weatherflow[2]. Currently, the product is in its kick-starter phase and has reached their funding goal of $50,000 by $824,993 (May 4 - 2020)[43]. The system provides an all in one weather station containing sensors for measurements of the following parameters:

- Temperature
- Humidity
- Pressure
- Sunlight
- Rain
- Wind

[2] https://weatherflow.com/tempest-weather-system/

Measurement	Range	Accuracy	Interval
Air Temperature	-35°F to 140°F	± 0.7°F	1 min
Relative Humidity	0 to 100%	± 2%	1 min
Atmospheric Pressure	up to 1100 mbar	± 1 mbar ; station and sea-level	1 min
Lightning activity	0 to 40 km (25 miles)	varies by distance	Instantly
Wireless	300m (1000ft++)	sub-Ghz telemetry	
Wind Speed	0 to 100 mph	± 0.5 mph	continuous sampling
Wind Direction	0-359°	± 5°	continuous sampling
Ambient Light	1 to 128 kLUX	± 100 mLUX	1 min
UV Index	0 to 11+ index		1 min
Solar Irradiance	0 to 1900 W/m2	± 5%	1 min
Rain Onset		first rain drops	Instantly
Rain Intensity	Light to Torrential	± 0.2mm / hr	Instantly
Rain Duration	daily total	1 minute	1 minute
Rain Accumulation	daily total	± 10%	1 min
Mount	Adjustable pole mount		
Power	Solar Powered		

Figure 17: Specifications - Tempest

The system comes with an AI-powered mobile application for providing relevant weather data and weather predictions. A figure of the system can be found in figure 16. The platform offers integration with home assistants software, such as Homey[3]. The technical specification is depicted in figure: 17. The company Weatherflow has over twenty years of experience in the field of weather measurements, apps, and forecasting of weather. The product design intends for a long-lasting design, containing Lithium-Titanate batteries that guarantee a long-life and stability. The system can be extended with additional add-on items, such as battery back-ups. According to the Kickstarter page, the retail price comes at a price of roughly $400, which is in line with this research "low-cost" constraint.

Whether the system fulfils the promises has to be proven by a test, or comparison to another system. However, the project seems like an interesting development as it shows the power of an autonomous measurement system that is highly integratable. Moreover, the amount of money that is raised for the product indicates that there is a broad interest in weather stations like this.

[3]https://homey.app/nl-nl/

2.6 Solar Powered Cellular Weather Station

Figure 18: Weather station

This project has been featured on Hackster.io [44]. In the maker community, a lot has been done regarding weather monitoring systems from sensors connected to an Arduino to advanced weather station builds. This project can be considered a project from the maker community. However, to get expertise, it is also beneficial to look into maker projects, as many projects regarding weather stations and monitoring have been done in that space. The system depicted in figure 18 and figure 19 is built around the Particle Boron LTE development board, this board has build-in cellular connection for remote data transfers. This weather station features a robust build and solar power generation for remote locations without any power. Although, the system is a "makers" build most of the parts are plug&play, which does not require any additional soldering. The circuit box seen in figure: 19 can be ordered on Sentient Things [45] which offers IoT products for a considerably low cost.

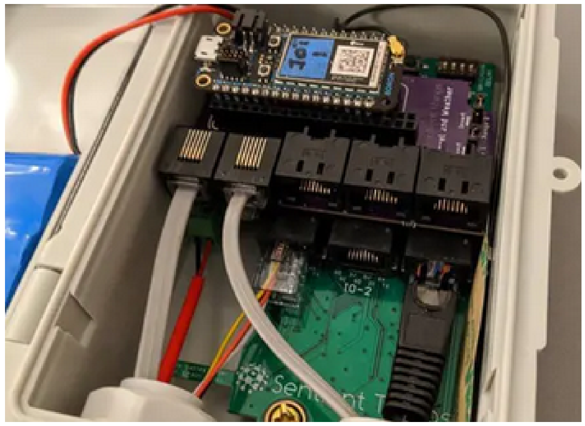


Figure 19: Circuit with enclosure - hackster.io project

The system offers measurements for wind, temperature, humidity, and light. Data is sent wirelessly using a cellular connection. The data is parsed to the ThingSpeak IoT platform [46]. The system also includes a micro-SD card data logging to overcome communication outages. The PCB is housed in a plastic enclosure that is waterproof, with the use of connectors sensors can be easily changed, which offers usability. The sensor set for this project can be ordered from Sparkfun [47] the sensor set is considerably low-cost, and weather contains sensors for precipitation and wind. Although no specific price is mentioned, the total build is estimated at $650; this number is based on the parts list given in the article. No performance regarding precision, accuracy, and resolution is provided in the article. However, based on the listing of parts datasheets could be obtained, but for some sensor systems, the performance is not clear.

- Temperature & humidity - AOSONG AM2315 [48]
- Light - TSL2591 [49]
- Wind vane - unkown type [50]
- Rain gauge - unkown type [50]
- Anemometer - unkown type [50]

2.7 Discussion

Over the years different implementations, technologies, and design considerations have come forward. Although from previous researches it can be seen that many requirements have been met, the necessity for optimisation is still present. The core technologies for an MMS are being identified, consisting out of:

- power-system
- data-logger (micro-controller)
- meteorological sensors
- wireless communication system

All the papers had some differences in the architectures and design choices. However, all the reports seem to miss various requirements according to the Davis Vintage Pro 2 reference system. Sensor accuracies are not sufficient; some systems did not include wireless communication or communication was only short-range enabled; a lot of improvements can be made.

During the literature review, it also became evident that looking broader than just the design of a measurement tool can be beneficial. Designing for different urban measurement conventions can improve spatial resolution. A presented architecture is a seven-layer architecture for an urban measurement system; the seven-layered design can be a good guideline for this project. It should be considered when connecting the different layers of the system, such as the integration of the database with the communication layer.

Different low-power technologies for communication have been discussed. Combining the results with the earlier findings of Pijnappel [9] and Kester [10] on the proposed LoraWan integration using The Things Networks [35] is a promising idea for wireless data communication.

- Bandwidth
- Battery life
- Latency
- Throughput
- Range

However, before picking a communication technology parameters like, need to be considered. Before a system can be developed broad requirement specifications is thus required because it influences many parts of the MMS.

Both Kester and Pijnappel seem to agree on the fact that 3D-printed enclosure does not seem to offer a good solution for deployment as the quality and print efficiency is low. The proposed idea by Abbate et al. [5] of having a weather-proof fibreglass enclosure seems a better solution as their system is applied in a harsh environment.

From the state-of-art also potential parts have been identified, including additional hardware, such as SD cards modules for data-logging, sensors, and enclosures. The idea of local data-logging can improve systems reliability when wireless communication is lost. Moreover, potential enclosures, mounting and sensor options came forward. In the state-of-art, also different wireless data communication were suggested, such as cellular, or sub-Ghz telemetry. What the most fitting sensors, enclosure and communication protocols are, needs to be researched in the coming chapters, requiring an in-depth comparison and specification analysis.

3 Method

For the design and development of a system or product, different approaches are available. The University of Twente bachelor program Creative Technology, design, and, more specifically, design methods are extensively discussed to come to working prototypes, novel, and innovative ideas. The proposed method by Mader and Eggink [51] provides a four-phased design process tailored to the Creative Technology program. In this chapter, the structure of the graduation research will be elaborated according to that proposed design process. Each phase will be discussed in-line with this research; development, and design of an MMS. Figure 20 provides a visual representation of the Creative technology design process that will be applied during the research.

For ensuring valid research, stakeholder identification and analysis is critical. The method applied to perform stakeholder analysis and stakeholder identification will be elaborated. Moreover, the allocation of stakeholders in a so-called power interest matrix will be explained to prioritise each stakeholder. Furthermore, the functional vs. non-functional requirements will be described to separate the elements later on in the project. Finally, the evaluation procedure for this project will be introduced. Due to the Covid-19 virus, a creative approach for the evaluation procedure was required. Therefore, a small part will be dedicated to how the MMS will be evaluated.

3.1 Ideation phase

The ideation phase is the initial phase, where actively ideas and requirements will be explored; relevant information will be processed to develop early ideas and mock-ups. Sources of information are the state-of-art from the section 2, but also stakeholders and experts. Besides, stakeholder identification, situation description is applied to make initial designs. Although the main requirements have been identified by knowledge from previous projects, in short, low-cost (threshold of 400 euros), the necessity of a reliable housing, and autonomous operation, more elements and difficulties might be identified during the ideation phase, resulting in the ability to resolve obstacles early in the analysis. With the use of state-of-art, related works, and stakeholder interviews, initial concepts will be created, preliminary requirements and technologies can be adapted to make a new system design. The primary requirements will come forward by consulting the stakeholders. However, with the use of state-of-art, already existing concepts will be used for discussion with the stakeholder. In this way, a comparison of this project towards the state-of-art projects and technologies can contribute to getting more defined requirements. Moreover, a reflection of initial ideas with clients and stakeholders will be applied to advance early thoughts towards the main specification phase. The method applied for stakeholder analysis is discussed in section; 3.1.1.

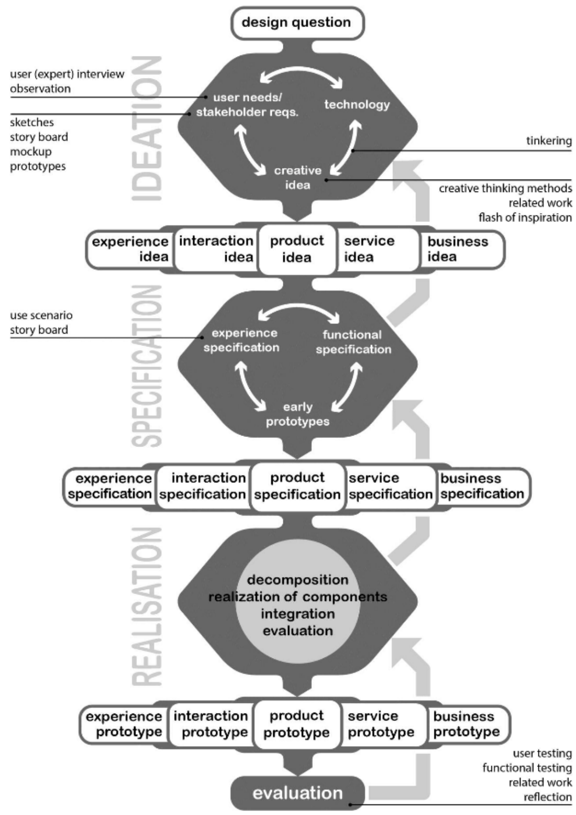


Figure 20: Creative Technology design process

At the end of the ideation phase, several sketches present the main idea for an MMS. According to the ideas, specifications can be worked out to set the hard requirements for the system.

3.1.1 Stakeholder identification & analysis

The suggested definition by Sharp et al.[52] provides a good guideline for stakeholder analysis in the ideation phase. It is important to clarify what a stakeholder means. Sharp et al defines stakeholders as:

'Anyone whose jobs will be altered, who supplies or gains information from it, or whose power or influence within the organisation will increase or decrease.' [52]

Based on this definition the so-called baseline stakeholder will be identified. Baseline stakeholders are analysed into four groups; Users, Developers, Legislators, and Decision makers[52]. For every baseline stakeholder, their role to other stakeholder will be specified. Sharp et al [52]. suggest 'supplier', 'client' analysis in addition to the analysis of the four groups. The supplier provides relevant data and information, while the client requires these resources. Other roles that do not full-fill 'client' or 'supplier' will be indexed as 'satellite's'. Satellite's have various ways to interact with baseline stakeholders like; reading guidelines or searching for information. Based on the identification, a relational web will be made.

With the use of the proposed power-interest matrix for stakeholders, a hierarchy of stakeholders can be created[52]. This method describes four main positions for stakeholders. First group, high-interest and high-power stakeholders, should be managed carefully. Secondly, the less interested but high power stakeholders should be satisfied. The third stakeholder position within the matrix is the keep informed position, this position will be allocated to stakeholders that have low power, but highly interested people. The last position within the matrix contains the least significant stakeholders for the research. The position is allocated to low interest and low power stakeholders. See figure 21 for the full matrix. For this research 'manage closely' indexed stakeholder will be the primary focus.

Figure 21: Stakeholder matrix [52]

3.1.2 Interview

With the baseline stakeholders in mind from section 3.1.1, interviews will be conducted with the stakeholder or representatives of the organisation. Although there are various interview techniques that can be chosen, the semi-structured approach will be applied to interview the main stakeholders. A semi-structured interview will provide a reliable and structured procedure while maintaining the option for discussion and additional open-ended questions that can arise during the interview [53]. The goal of the interview is to get insight into the requirements set by the stakeholders regarding the project. Although this might not directly be asked, a pattern or requirements might be recognised by the use of several different questions. Due to the Covid-19 virus, the interview will be conducted by the use of BigBlueButton[4], Microsoft Teams[5] or Skype[6] or another tool depending on stakeholders preference, as physical meetings should be avoided. The recording of the semi-structured interview will be done using an online documentation tool and a recording function built-in both tools (the recording will only be done with the interviewee if consent is given). Questions that will be used during the interview can be found in Appendix A. The interviews are conducted in collaboration with Peter van der Burgt (development of Low-cost Autonomous Pyranometer) since common stakeholders and requirements regarding both types of research are shared.

3.2 Specification phase

During the specification phase, a more in-depth requirements analysis will be performed. Since there is an overlap between the ideation phase and the specification phase, additional requirements based on specifications of sub-systems will be introduced. A list of requirements that will be categorised in two groups functional vs. non-functional requirements will be stated in the end. The difference between the indexed non-functional and functional requirements is discussed later in paragraph 3.2.1.

Additionally, A functional overview of the architecture and sub-systems will be developed and reviewed. This is done by creating an overview of blocks representing functions and behavior. Based on these blocks, the information exchange with in the project will be depicted, which will be used to perform decomposition on to handle the system complexity.

3.2.1 Functional architecture analysis

To determine the envisioned MMS functionality, functional architecture diagrams will be made. The method proposed by Brinkkemper and Pachidi[54] makes use of "component decomposition." According to the distinct phases

[4]https://bigbluebutton.org/
[5]https://www.microsoft.com/nl-nl/microsoft-365/microsoft-teams/group-chat-software
[6]https://www.skype.com/en/

later presented, the functional architecture of the MMS will be designed. For the functional architecture analysis, three consecutive layers will be analysed with the top layer being most abstract and deeper layers progressively more technical.

Determining the scope: "All external products in the usage environment need to be identified, with which the product will interact. [54]" With this identification, the scope in which the MMS will be applied is described. By the use of a context diagram, the various products used in the measurement scope will be depicted. Moreover, the primary functions of the system in which the MMS will operate in relation to the system as a "black box" will be given. E.g. the various environmental parameters that will be input for the system. This approach can be considered a high-level system analysis, regarding input & output.

Figure 22: Modules & flows examples

Define request-feedback flows: The interaction with the system concerning the scope will be presented. These interactions will be visualised using arrows to show the flows between the system and the context. Example of such an interaction diagram is given in figure 22.

Model the operational module flow: In this part, the different modules contained in the system are modelled and split up into separate sub-systems. The flow between these components that constitute to the full functionality are identified according to their role in the system, resulting in an overview of how the different subsystems interact with each other.

Add control and monitoring modules: The system's modules identified earlier can be controller by several modules. In this part, both planning modules and controller modules are added to the diagram, e.g. timers for deep sleep.

Specify external to/from internal interactions: In the last phase, the interactions of the internal modules are given in relation to the external modules.

3.2.2 Requirement Elicitation

To make a distinction between the requirements, the separation of the non-functional and functional requirements will be used. According to Eriksson, a functional requirement describes what a system should do while non-functional requirements represent how the system works [55]. E.g. non-functional requirement; plastic material enclosure with hinge, functional requirement; hinge mechanism should cope with 5kg force.

3.2.3 MoSCoW method for requirement analysis

When the requirements are set, an index can be made in order to categorise the requirements. The MoSCoW methods describes a listing according to the **M**ust, **S**hould, **C**ould, and **W**ould [56]. Based on this hierarchy clear goals for the realisation phase can be developed.

- Must: requirements that must be fulfilled to consider the developments of an MMS successful.
- Should: requirements that should be met if possible. Requirements can be considered part of the must, but are not essential.
- Could: requirements that could be met if does not affect anything in the project. These requirements will not have impact on the contentment of clients.
- Would: requirements that can be implemented later if time allows. These requirements will not have any impact on the project, only allowed if the time and resources allow it.

Requirements and which categorisation they get are primarily based on the stakeholders interviews. However, technical specification constraints and environmental factors will also be taken into account.

3.3 Realisation phase

Based on the specified functional and non-functional requirements, the realisation can be started. According to the picked components and architecture, implementation of the sub-systems will be performed, e.g. circuit implementation and testing, micro-controller firmware development, and server software development. Moreover, the fusion of the sub-systems as the goal to make the final product is also done during the realisation phase. Functional testing of the system will be part of the realisation phase. All the steps and choices will be documented to ensure repeatability.

Furthermore, applicable hardware and sensors will be identified for the realisation phase, where full-implementation of the system is performed by using the specifications phase findings. A sensor survey based on results in the state-of-art and the internet will be used to index applicable low-cost sensor sub-systems. Datasheet analysis for the parameters cost, range, resolution, accuracy, documentation, manufacturer, and amount of sensing parameters will be used as the main criteria for selection. Reliability will be scrutinised by looking at the manufacturer's credibility since reliability has to be tested.

3.3.1 Tools

Various tools will be used to develop the project. The primary tools for development are shortly described.

3.3.2 Fusion 360

Fusion 360 by AutoDesk [57] is a program for designing 3D objects. This program will be mainly applied to prototype and design parts for the MMS. Fusion 360 has a build in 3D to Stl converter for making 3D-designs 3D-printables.

3.3.3 Visual Studio Code

Visual studio code is a free light-weight IDE which can be easily extended with open-source plugins [58]. This IDE will be primarily used with Platform.io to develop firmware for the embedded controllers.

3.3.4 Platform.io

Platform.io is a development environment for embedded devices [59]. The ecosystem supports several frameworks and is cross-platform. Platforms like Arduino [60], Mbed [61], and Espressif Systems [62] are supported in the SDK. The embedded software can be developed in both C and C++.

3.4 Evaluation phase

The prototype will be tested as much as possible in the context which the system is designed for. With the use of the Davis vintage pro 2 reference system comparison of measurements data is done to determine the reliability and accuracy of the MMS. The setup or context in which the MMS is applied will be thoroughly discussed to ensure a situation that mimics the real-world scenario. However, due to the Covid-19 virus, a different approach might be required since testing labs based at the University were not open during the conduct of this research. Instead, the reference system and MMS are placed in a garden for testing. With the use of an API [63] weather data source comparison between the three results can be performed for validation. However, this source only provides data for wind speed and temperature.

Besides, data comparison between the reference system and MMS, metadata analysis on TheThingsNetwork for wireless data transmission will be performed to see if the fair-use-policy discussed in section 5.3 have been implemented accordingly and if data can be transferred reliably given the distances of gateways in the surrounding area.

In the end, the data will be presented and discussed to come with an overview of the met requirements set in the specification phase.

4 Ideation

During the ideation phase, ideas and requirements will be actively explored. Based on stakeholder analysis and stakeholder interviews, requirements for the first prototype will be compiled. With the first requirements in mind, brainstorms will be performed to come with a plan for a preliminary prototype. The goal is to develop a concept that can be used to develop further.

4.1 Stakeholder identification

As part of the requirements elicitation, identification of individuals or groups involved or affected by the research is essential. Breakdown of the concerned individuals or groups is essential to develop ethical considerations and to gain knowledge about requirements, situations, and the ability to address early issues or problems. Based on the identification, interviews will be conducted with the stakeholders and the requirements of the MMS specified. Based on the method explained in section 3.1.1 an overview of stakeholders is given in table 1. How these stakeholders relate to each other can be found in figure 25.

Stakeholders overview		
Stakeholder	Category	Representative (source)
University of Twente - ITC	User, Decision maker	3
University of Twente - Creative Technology	Decision maker, User	1,2
Municipality of Enschede	Legislator, User, Decision maker	5
Developer	Developer	4

Table 1: Stakeholder overview with category

Legend: Hans Scholten = 1, Richard Bults = 2, Wim Timmermans = 3, Jan-Paul Konijn = 4, Rik Meijer = 5

4.1.1 Municipality of Enschede - Rik Meijer

Enschede is a city-based in the eastern part of the Netherlands. The situation describes one which the city has to cope with environmental changes, more extreme weather, and city heat build-up. Therefore, the municipality is working on several initiatives to cope with these developments; several projects have already been performed, like a smart rainwater buffer in cooperation with the University [64].The primary concern for the municipality is to get insight into how meteorological developments might affect the city and how this can be solved.

Therefore, this research emerged. This research is a part of a cooperation between the University of Twente and the municipality. The municipality funds part of the project and consequently the municipality is a significant stakeholder in this research. Furthermore, as this project is the start of a distributed approach, with spread of several MMS's over the City Centre of Enschede, granting permission and acceptance is required by the municipality. Furthermore, the municipality of Enschede might have useful information on the potential positioning of the sensor nodes for optimal measurements. That is why, the municipality can be viewed as a leading factor for the deployment of the developed system.

For this project, Rik Meijer is the primary contact person within the municipality. The municipality is next to legislator, also decision-maker and end-user. The main concern for the municipality is to get an insight into the environmental development around the city of Enschede. Furthermore, providing the inhabitants information on heat build-up in the city. Rik stated it could create awareness if the public is informed with data-backed claims; they are likely to take their own initiative to combat these developments. A web application can be a great tool to visualise the data and inform the inhabitants. Rik envisions situations where people are updated on which locations to avoid due to high-temperature build-up, ensuring less heat-related health issues.

Since the sensor network will be both in public areas and private locations, data storage, and privacy can be a concern. Whether this can be resolved legally is out of scope for this project. However, acknowledging privacy concerns for future developments is vital.

Projects like these are for the city of Enschede novel initiatives. Enschede aims to go more towards a smart-city. A pilot with the allocation of several sensor nodes developed by Kester[10] and Onderwater[11] already have proven that wireless meteorological measurements are possible. The initial proof of concept regarding the distribution of sensor nodes did not result in vandalism yet. Nevertheless, Rik finds it crucial to make a robust and vandalism proof sensor node. Although no previous experiences with damage of sensor node have occurred so far, scenarios should definitely be taken into account.

Additionally, Rik confirmed the set requirement by Wim Timmermans; the system mounting should not damage the street lantern. Moreover, in the internal meeting for previous research projects performed by Kester and Onderwater, the point of weight came forward. Although a system can be considered light, the mounting position can increase the system's effective weight due to leverage, which can lead to long-term problems.

4.1.2 Ricard Bults & Hans Scholten - UT-Create

The University of Twente is part of a collaboration with the municipality on various projects regarding the development of technological tools to combat and understand environmental change. Both Richard and Hans are the primary supervisors for this research. They are also essential stakeholders due both having expertise in the field of monitoring and sensor node development. Moreover, they supervised the previous researches on the development of an MMS, Pijnappel, Kester, and Onderwater [9] [10] [11]. Their main objective is to build upon the prior researches in order to achieve a low-cost functional MMS.

In cooperation with Peter van der Burgt, a semi-structured interview was conducted. For this project and the previous one, common elements and stakeholder are shared, resulting in performing a collaborative interview. Richard previously worked on the development of a smart-rain buffer which resulted in several iterations of an MMS to look at the weather as a broad concern. Due to the results from the previous researches, the potential for an own build MMS came clear, as the first system provided sufficient data quality for a fraction the costs of builds on the market. The project developed into the initiative WHEGS [7], in which 80 sensor nodes will be allocated over the city centre to measure city heat-build up.

Since the municipality of Enschede requires results in a shorter period, the SenseBox[7] MMS will be introduced to the city street scene to make up a first sensor network. Based on the results of this project, the sensor network will be extended with the designed MMS of this study since the measurements quality of the Sensebox are lower than the Davis Vintage pro 2 reference system. The consideration regarding the most important aspects can be given by:

- Costs
- Accuracy
- reliability

During the interview, the discussion was established concerning the integration of location data by the use of GPS. Originally, GPS would not be required as

[7] https://sensebox.de/en/products

the main system in a static wireless sensor network. However, it became apparent that GPS is crucial for timestamps and verification of measurements; GPS integration is now a must-have requirement for the MMS.

According to the interview, the frequency of measurements and data transmission will need to be based around the KNMI manual for weather measurement; this is also discussed in section 5.2.1. Richard & Hans proposed LoRaWan for wireless data communication as the central wireless data communication technology. This technology will be a must-have requirement for the MMS, as Hans suggested that the coverage of the network around Enschede is reliable. However, it should be taken into account that both the up-&down-link policies of the LoRaWan provider TheThingsNetwork[35] (TTN) are limited.

Additionally, the TTN does not provide a robust way for package acknowledgement, which cannot satisfy the project's reliability requirement regarding data transmission. So whether the sensor network will operate reliably needs to be taken into account when placing the sensor nodes, as TTN operation is not possible to control. Nevertheless, they both mentioned; ensuring that the sensor node should be well powered in different situations like; winter, at which less light is present. This can influence the amount of battery recharging. A so-called method, "graceful degradation," ensures sustained operation of the MMS when the battery capacity does not allow for multiple parameters being measured due to low battery capacity. Based on a predefined hierarchy of parameters, the sensor node is able to decrease power consumption by disabling sensor systems. Battery level checking ensures appropriate disabling of sensor types based on the hierarchy when necessary.

4.1.3 Wim Timmermans - UT-ITC

Wim Timmermans is a researcher at the ITC UT (the ITC faculty is a research centre for geo-information science and earth observations). As part of current research conducted by Wim, roughly 80 sensor nodes will be installed in both private and public spaces (see figure 23 or Appendix B) around the city of Enschede. The environmental impact and heat build-up will be investigated to see how this might relate the city infrastructure. Wim is a researcher and expert in the field of meteorological measurements and urban heat build-up, therefore, and important stakeholder for this research. He knows what is required for scientific measurements tools.

Figure 23: Locations of sensor nodes; yellow MMS, magenta soil moisture sensors, green ground water level sensors (source: Wim Timmermans, Appendix B)

During the interview, in cooperation with Peter van der Burgt, it became evident that the sensor nodes will be applied in different kinds of spaces. Wim suggested a secure mounting system suitable for poles. This, in combination with the proposed "making the system as invisible as possible" in a compact and robust form factor, would ensure easy placement and add reliability to theft. However, he acknowledged that using low-cost hardware can result in equipment failing quicker. He noted for his research the system is required to operate 24/7 since for long-term environmental research, data is essential. Making the system accessible, easy to maintain and fix would solve this issue by incorporating modularity. If in any case a sensor system would fail, ability to easily change sensor systems will add to the reliability of the sensor network.

Furthermore, from experience, he noted that a reliable power supply is essential for continuous operation. With the lack of solar energy generation, the data presence can be affected. According to the KNMI book, measurements like temperature and humidity must be taken at a height of 1.5 meters. However, Wim stated that in urban areas, it becomes a lot harder to perform measurements conform to the KNMI measurements book, as the situations in urban areas are not ideal. So whether the KNMI book should be followed or not will depend on the context of measurements.

During the last part of the interview, his view on the accuracy of the location was requested. His response contradicts the initial idea proposed by Hans and Richard about GPS integration as a must-have. According to Wim, the integration of GPS does not add value to the sensor node and should be reconsidered.

Points for consideration:

- Small and compact form factor
- Modularity for ease of changing sensor sub-systems
- GPS is not important
- Pole mounting system
- Different mounting options

During the second interview with Wim, more technical specifications were addressed. Wim mentioned that the pole mounting system should ensure no damage to the street lanterns poles. The poles are coated, and having a mounting system that damages the poles can result in the occurrence of corrosion. He mentioned that the municipality would like to see protection for the mounting to poles. The LoRaWan protocol offered by TheThingsNetwork has restriction regarding the amount of data that can be transmitted. Wim suggested sending the smallest measurement frequency as this would be beneficial to his research. For his research, he wants to check all the data points for validation. However, whether this will fit within the constraint of TheThingsNetwork needs to be researched. As a minimal requirement, every 30 minutes at least ten 1-minutes averages need to be available. For the sampling frequency of each parameter, he mentioned following the KNMI book for measurements as much as possible.

Additionally, during the interview, Wim mentioned a new idea for the WHEGS project. Since accurate measurements are essential, every two weeks students will check and clean the system to ensure reliable measurements. Most systems will be located at the height of 3 meters. The street lanterns that will be mainly used to have a total height of 6 meters. The elevation of 3 meters above the surface ensures that the systems are hard to reach while still being close to the 1.5 meters set by KNMI book.

4.2 Stakeholder Power Interest Matrix

Figure 24 presents the power interest matrix, based on the interview and an evaluation of each stakeholder position within the project. It can be observed that both Richard and Hans are both highly interested and influential stakeholders as they are engaged in the development of an MMS. As explained earlier, they have guided several iterations of the project and are the leading experts in this field and project. Based on the earlier projects, they have developed a substantial experience for the elements and problems that might arise. The conditions set by Richard and Hands have a signification weight within this project.

Wim Timmermans, his interest is more on the side of scientific research; this project is a small part of a broader research. Therefore, he is classified as lower interest and lower power stakeholder within this project. Although the information is valuable and describes the user needs well. He does not have a broad technical background that is required for this research.

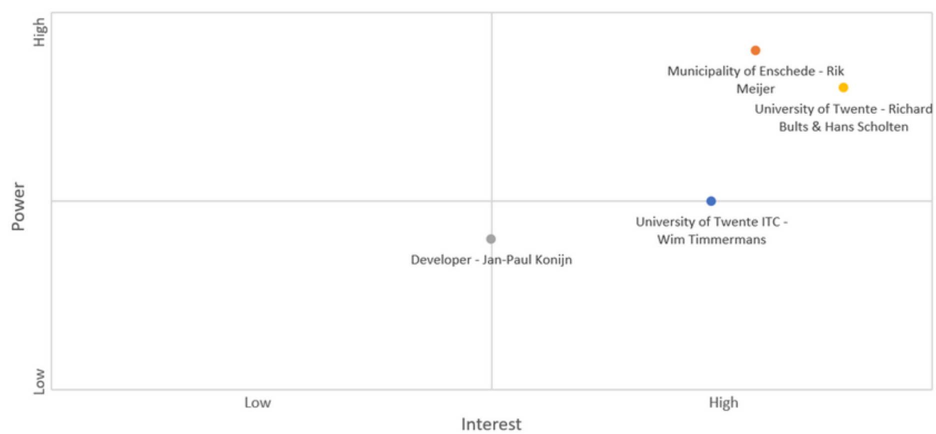


Figure 24: Stakeholder power Interest Matrix

Rik Meijer and to be more specific the municipality is indexed as high power, high interest. The municipality is the leading authority for allowance of sensor node allocation within the city, moreover, and they provide funding for the project. However, as can be obtained from the figure 24, the municipality is indexed at a lower position regarding interest compared to Hans and Richard.

Based on the finding and the explained power interest matrix described in section 3.1.1. Both Richard Bults Hans Scholten and Rick Meijer should be managed closely, Wim Timmermans should stay informed/managed while keeping satisfied.

4.3 Stakeholder web

Figure 25 depicts the relations between the different stakeholders. The small black lines show the information flow of each stakeholder towards the developer. This indicates the supply and consuming of information and requirements. The big line shows the interaction between two components of the diagram. The dotted line indicates the different relationships within this research. The diagram is based on the earlier identification and the interviews with the stakeholders. How the stakeholder relate is crucial to identify the needs.

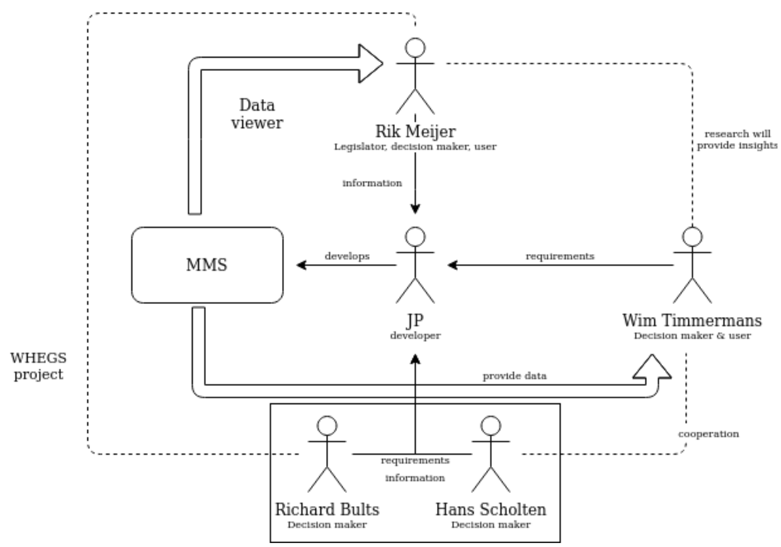


Figure 25: Stakeholder web - relation between stakeholders

4.4 Environmental factors

Initially, the MMS will be distributed in and around the city centre of Enschede. As part of the MMS development understanding of the environmental factors is required to identify the conditions in which the MMS will operate. The environment can influence how the MMS will perform; moreover, analysis of meteorological parameters measured in and around the city can provide insights into the ranges of measurements that will be required. A data source [65] provided by the Royal Netherlands Meteorological Institute (KNMI) will be used to see the meteorological parameters of 2019 measured at the weather station located at Twente Airport (weather station 209 Twente) [65]. The data is selected for the year 2019 starting from 1 January 2019 until 1 January 2020, based on a 365-day data set containing the highest and lowest values regarding a specific days, extremes can be identified to get an idea on the environmental parameter range. The maximum wind speeds measured in 2019 is 12m/s (09-02-2019) with wind-guts being measured up-to 23m/s (12-03-2019). Temperatures can deviate from winter $-10.1°C$ (21-01-2019) to summers where $40, 2°C$ (25-07-2019) was reached. These extreme temperatures tend to become more common due to the climate change. This also proves the necessity for proper heat management in cities, as hotter days are appearing more often. At the 27th of July the highest solar irradiance what recorded at $3055j/cm^3$.

Furthermore, relative humidity in 2019 deviated from 37% to a 99% saturation. Although as observed the Netherlands has a soft winters and relatively chilly summers, temperatures can reach up to over 40 degrees during summer, while having the possibility to get freezing days during the winter. As for precipitation days can occur where 43.8mm is measured. The MMS should be able to cope with these extremes, while having the ability to obtain accurate measurements during these days.

4.5 Measurement requirements

To obtain valid measurements, the stakeholders; Richard Bults, Wim Timmermans, and Hans Scholten indicated using the KNMI book for measurements [66]. During the previous researches, the KNMI rules for scientific measurements were not taken into account for the MMS design[9][10]. In particular, measurement timing was not considered. In the last project, a set deep sleep timing was used to wake the micro-controller, take a measurement and transfer the data to the database [9]. However, as one might expect, this does not conform to the required measurement rules as KNMI frequencies were not followed. In this section main the specifications for valid meteorological data measurements set by the KNMI will be introduced.

4.5.1 Temperature

In meteorological measurements, there are three main variables regarding temperature[66]:

1. primary measured:
   (a) air temperature
2. measured during an interval
   (a) minimum air temperature
   (b) maximum air temperature
3. other traceable temperatures
   (a) dew point temperature & ripening temperature
   (b) saturation temperature
   (c) virtual temperature

The temperatures types that are of importance for the KNMI:

Dry-bulb temperature: Dry-bulb temperature is denoted as T_{air} or t_{air} is the temperature measured 150 cm above the surface. KNMI denotes this measurement as the “temperature”.

Maximum temperature: KNMI denotes the maximum temperature as the highest temperature within a specific period. Notation: T_{max}. E.g. interval of 6 hours, depending on how it is defined, can be various sizes of intervals.

Minimum temperature: KNMI denotes the minimum temperature as the lowest measured temperature within a specific period. Notation: T_{min}. E.g. interval of 6 hours, depending on how it is defined, can be various sizes of intervals.

Dew-point temperature: The dew point temperature or the T_{dew} is the temperature where humidity starts to condensate. The dew-point temperature is dependent on the density of humidity in the air $T_{dew} \leq T_{air}$

Requirements: The KNMI states specific requirements for obtaining temperature measurements.

- range: $-30°C, +60°C$, Note this is corresponding with the set requirements by WMO.[66][8]

As there can be previously found measurements need to be performed $150cm$ above the surface or $10cm$ above the surface. The surface must be flat, and grass must be cut short (max 3cm). The surface should ensure there is no influence on the measurements. For both $150cm$ and $10cm$ measurement an accuracy of $\pm 0.5°C$ is required [8]. The maximum margin of $\pm 0.2°C$ uncertainty is allowed.

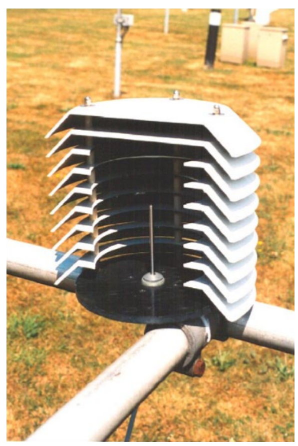


Figure 26: Temperature sensor setup

Figure 26 depicts a temperature sensor setup with a radiation shield. This shield provides protection against direct exposure to the environmental elements that can affect the validity of the measurements. Obstacles that might be near the sensors and can have an influence on the measurements should be avoided. KNMI states the following requirements: $100m$ no trees or shrubs. $400m$ no obstacles like buildings that can influence measurements. Moreover, vegetation around the sensors should be within a radius of $25m$ can not exceed a height of 50cm, within a radius of $50m$ plants can not exceed a height of $1.5m$.

Measurement frequency: The 1-minute average for temperature is in line with the WMO[8]. The report states for the 1-minute average five samples are taken each at the 12th second in a minute. Based on these five samples, the average is calculated. For autonomous measurements systems; the KNMI states that 10-minute averages are gathered. This means for every tenth minute, the most recent 1-minute average is stored.

4.5.2 Relative humidity

'The relative humidity or the RH is based on the partial pressure e of water vapour to equilibrium vapour pressure according to the current temperature noted as $e_s(T)$.'[8] Or the definition can be given by the percentage of water-vapour in the air given by a certain temperature.

$$RH = e/e_s(T) * 100 \tag{1}$$

Requirements: The KNMI states specific requirements for obtaining humidity measurements:

- relative humidity range: 5%-100%
- resolution 1%
- dew-point temperature resolution: $0.1°C$
- uncertainty dew-point temperature can not exceed: $0.5°C$
- uncertainty relative humidity 3%

Setup: According to the WMO[8] the sensor height placement should be between $1.25m - 2.00m$ above the surface. The sensor should not be placed at a location that can be influenced by other object, resulting in inaccurate measurements. KNMI states no objects in a radius of $100m$ of the sensor location. Moreover, humidity sensor distance should be at least $5m$ from water surfaces. The sensor sub-system should be located in a radiation shield to protect against

Measurement frequency: Comparing to temperature measurements frequency, humidity measurements are comparable. The measurement frequency is also conform the WMO [8] requirements. The 1-minute average is based on five samples of each taken on the 12th seconds. E.g; 14:09:12,14:09:24, 14:09:36, 14:09:48 and 14:10:00 Based on the five sample the average value is calculated. For the MMS; the KNMI uses the same rule the 10-minute average. Each 10th minute the average 10-minute average is calculated based on ten 1-minutes averages.

4.5.3 Wind

The wind is the horizontal movement of air. The main reason for the movement is the difference between air pressure at different locations. The difference between the two areas in air pressure is denoted as the air pressure gradient. Essential weather parameters according to the KNMI[66] guideline book for weather measurements are the following three parameters:

- wind speed (m/s)
- wind gust (m/s)
- wind direction (degrees of arc)

Wind speed: The horizontal speed of air measured in m/s

Average wind speed The horizontal speed of air measured of a period of time. Depending on the specifief interval.

Maximum wind-gust: The maximum wind peed that is being measured over a period of time example is the three highest averages values in 10 minutes.

Wind direction: The convention is to note the wind direction as to where the wind comes from. The direction is determined by the angle between the positive y-axis as can be seen in figure 27. Figure 27 is south-west wind which is equals to angle of 225°.

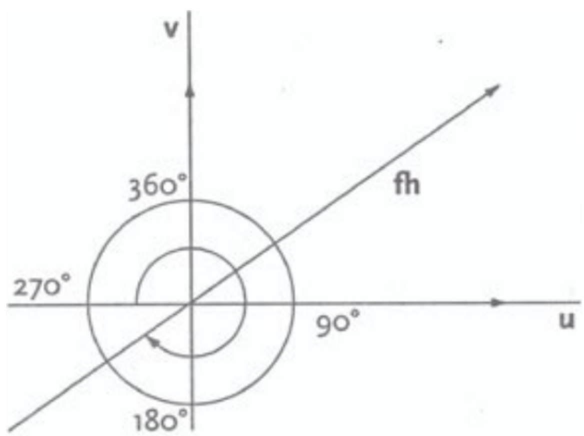


Figure 27: Wind direction

Requirements: According to the WMO [8], the ability of measurement should be an average wind speed with a range of $0 - 70m/s$ and wind gust $5 - 75m/s$. The wind direction should be $>0° \& \leq 360°$. However, the KNMI measures up-to the $50m/s$ as speeds $>50m/s$ are unlikely and can be denied.

Wind speed accuracies are given below:

- Average wind speed $\pm 0,5 m/s for \leq 5 m/s, \pm 10\% for > 5 m/s$
- Wind gust $\pm 10\%$
- Wind direction $\pm 10°$

Setup: KNMI uses a cup-anemometer. The wind blows in the hollow sides of the measurement instrument, which makes it turn almost linear to the wind speed. According to the turns per second, the wind speed can be determined. Figure 28 shows a cup anemometer.

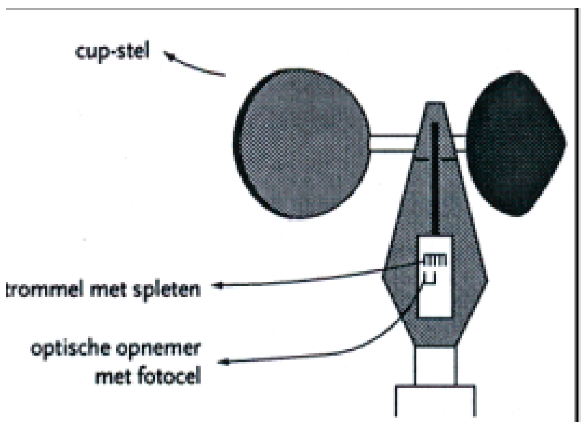


Figure 28: Anemometer

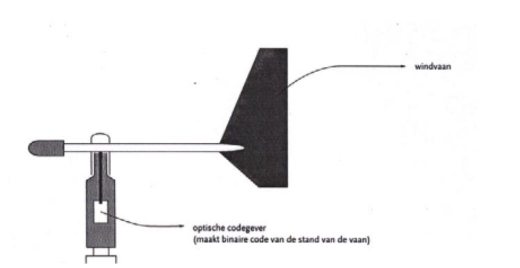


Figure 29: Wind direction meter

For direction measurements, a wind-direction vane is used, depicted in figure 29. Tip of the wind moves towards the direction of the wind. With an encoder, the position of the wind can be determined.

Specifications cup-anemometer:

- range $0.5 - 50m/s$
- resolution $0.1m/s$
- accuracy $\pm 0.5m/s$

Specifications wind direction meter:

- range $360°$
- resolution $1°$
- accuracy $\pm 3°$

Both the wind speed instrument and the wind direction instrument should be positioned at least 6m above the surface. However, KNMI preferably suggest a height of 10 m above a flat surface. The distance to other obstacles should be at least 20 times the obstacle height. The position should give a good representation of actual wind speeds. Thus, the position should allow the measurements to be valid. Protection factors of other obstacles should be taken into account while conduction measurements on wind parameters.

Measurements frequency: The measurement frequency for wind is somewhat different compared to the temperature and humidity. The KNMI proposes the 3-second average wind speed. For this measurement, every 1/4 second, a measurement is taken based on the past 3 seconds. So for the 3th-second average a total of 12 samples are used.

Furthermore, the KNMI advises using a 12th-second average; for this average, the 3-second averages are sampled within 12 seconds (total 48 samples). This averages four samples of 3-second samples. Based on this 12th-second average, the 1-minute average wind speed can be calculated (240 samples). This consists of five samples of the 12th-second averages. These values are calculated as the average wind speed. However, different parameters can be measured regarding wind speeds; parameters like average wind speeds or wind gusts can be considered. For the 10-minute average, there are various values; average wind speed, maximum wind speed, minimum wind speed, and the standard deviation. Which value will be applicable for the MMS will be based on the suggestions by Wim Timmermans. Wim suggested using the average wind speed, and not looking at wind gusts measurements for this research. The KNMI states for the 10-minute average wind speed; this value is based on ten samples of the 1-minute averages. Thus, in total, 2400 3-second averages.

For the wind direction, every 12 seconds a measurement is taken. For the 1-minute average, it is the same for temperature and humidity; it is based on five samples. According to these five samples, a vector is calculated. The 10-minute average vector average is based on ten 1-minute averages.

4.5.4 Solar Irradiance

Solar Irradiance includes several relevant spectral areas. The KNMI measures the short-wave radiation and long-wave radiation. Long-wave radiation mainly contains IR solar radiation (wave-length $4 - 100m$).

Short-wave radiation contains light that is visible by humans and a part that includes both UV-A and UV-B solar radiation. Short-wave radiation is light that mainly hits the earth's surface directly or indirectly. The short-wave radiation is distinguished into diffuse radiation, global radiation, Netto short-wave radiation, and outgoing short-wave radiation. For this research, the global radiation or global solar irradiance is the most important. This is the total incoming short-wave radiation that hits the earth's surface. The short-wave radiation quantity is expressed as w/m^2.

Requirements: According to the KNMI, there is no specific requirement set by the WMO regarding solar Irradiance and the required accuracy, precision, and range. For further requirements, the set requirement by Wim Timmermans will be used.

Setup: The KNMI uses the Kip&Zonen pyranometer CM11 [67]. The global radiation sensor is mounted at a height of 1.5 meters above a flat surface. In the near surrounding, it is suggested not to have any object within a 200-meter radius, that can influence the measurement. The sensor must be level, and the sensor should be clean.

Measurements frequency: Measurements are sampled every 12 seconds. The 1-minute average energy-flux is determined based on the last five 12-second registrations. Based on the five samples, the average is determined. The 10-minute average is in accordance with temperature, humidity; it is based on ten 1-minute samples, thus 50 samples in total. E.g., 1-minute average value is based on 14:05:12, 14:05:24, 14:05:36, 14:05:48 14:15:00.

4.6 Preliminary Requirements

According to the sources from the state-of-art, stakeholder analysis, and previous projects a preliminary requirements list is made in accordance with the MoSCoW method. This method is discussed earlier in 3.2.3

Must have requirements:	
Preliminary Must Have Requirement	Source
GPS integration of time and location data	1&2
LoraWan for wireless data communication	1&2
Working according to TTN fair-use-policy[35]	1&2
Measure wind speed, temperature, relative humidity, and solar irradiance	1&2,3
Efficient power management	1&2,3
Follow the KNMI measurements frequencies	1&2,3
Operate autonomously	1,2,3
Offer modulartiy for easy sensor replacement	3
Pole mounting system	3
Avoid damage to street lanterns	3,4
Withstand the environmental factors	4
Operate for a year without any supervision	3
Save obtained data in database	4
Withstand the environmental factors	1,2,3,4
Preliminary Should Have Requirement	Source
Graceful degradation	1&2
Preliminary Could Have Requirement	Source
Sending error reports	1
Local data-logging option	1

Table 2: Preliminary requirement overview

Legend: Hans Scholten = 1, Richard Bults = 2, Wim Timmermans = 3, Rick Meijer = 4

4.7 State-of-art findings for Ideation

In the state-of-art several systems, conventions, ideas, and future works are present. Based on these researches, interesting findings can be adapted to this research. Some ideas can give insights into the specification phase and ideation.

4.7.1 Power system

In several projects the use of solar energy harvesting system are present [9][10][5][43]. The papers suggest variable sizes and mounting options for solar panels. Two interesting findings of different designs is the Tempest [43] depicted in figure: 16 and the system by Abbate et al. [5]. Tempest provides an all-in-one solution containing all the sensors a neat housing. It also contains a power system; solar panel, and batteries in one form factor. However, Abbate et al. [5] make use of an external solar panel. This option might be better if different mounting locations become required.

For the design, a separate solar panel can be considered, or it can be incorporated into the sensor node itself. An all-in-one solution seems to be a logical choice as one of the requirements set by Wim Timmermans should not be overlooked. As the system will be placed at various locations, it should be mountable to conditions of such locations. Attaching a solar panel statically to the central frame can hinder with how one might want to place the MMS. An external solution is more logical as it offers modularity and freedom.

Furthermore, the proposed idea of Pijnappel [9] of using an electronically switched MOSFET to enable or disable for power consumption purposes can be extended with providing each sensor with a MOSFET instead of using one for all. This provides more control over each individual sensor and enables for the implementation of graceful degradation.

4.7.2 Meteorological sensor set

Data quality is one of the important components for this research. This creates necessity of finding the right sensors for the requirements. To do that a thorough analysis for both the specifications and sensors are needed. In the next section 6.1, parameters are identified and with the use of a sensor survey applicable sensor are found.

4.7.3 Wireless communication

Based on stakeholder analysis, one a must-have requirement came forward regarding wireless data communication. LoRaWan was suggested by Hans Scholten as a way to transfer data without a fee, have long-range capabilities, and energy efficiency. Moreover, the LoraWan network enabled by TheThingsNetwork is used before by Pijnappel[9], and Kester [10] for a long-distance, low energy communication. Early testing is required if enough reliability of data transfers can be achieved.

4.7.4 Micro-controller/data-logger

Pijnappel used a TTGO Lora Esp32 [68] as the central micro-controller for the MMS. Due to the Covid-19 virus, ordering parts from China can result in late shipments, which could impact the development timeline for this project. Although the board is from a Chinese manufacturer, the board was ordered from a Dutch-supplier.

4.7.5 Enclosure

During the previous researches, water intrusion seems to be the primary concern regarding the reliability of the systems [9][10]. In all cases, a full 3D-printed enclosure was applied. Although this offers a creative platform for the design of housing using 3D-printing enclosures is not scalable when manufactured in larger quantities. Furthermore, it can be learned that water protection is essential for extended periods of operation, operation of one year without any supervision. To ensure extended operation without any problems, an IP rated enclosure can be applied [69].

4.7.6 Requirements for previous Create researches

Max Pijappel [9] developed the latest iteration of the MMS. According to his report, the specifications displayed in table 3 had to be fulfilled. These requirements were introduced by the expert Wim Timmermans and according to Wim, the provisions concerning the MMS stayed the same. This table is also confirmed by the set requirement in the research by Kester [10].

Parameters	
Parameter	Required Accuracy
Temperature	$0.3 - 0.5°C$
Humidity	3%
Windspeed	$0.1 - 0.2m/s$
Temperature	$0.3 - 0.5°C$

Table 3: Previous requirements overview [9][10]

4.8 Brainstorm

Based on this early set requirements in table 2, and the knowledge obtained from interviews and state-of-art, a mind-map depicted in figure 30 is made to explore the sensor subsystems, software, and hardware. It gives a broad overview of all the aspects of the project. Based on the mind-map depicted in figure 30 a brainstorm was done making some sketches. The sketches can be found in the figures; 31 and figure 33, and in a bigger format in the Appendix C.

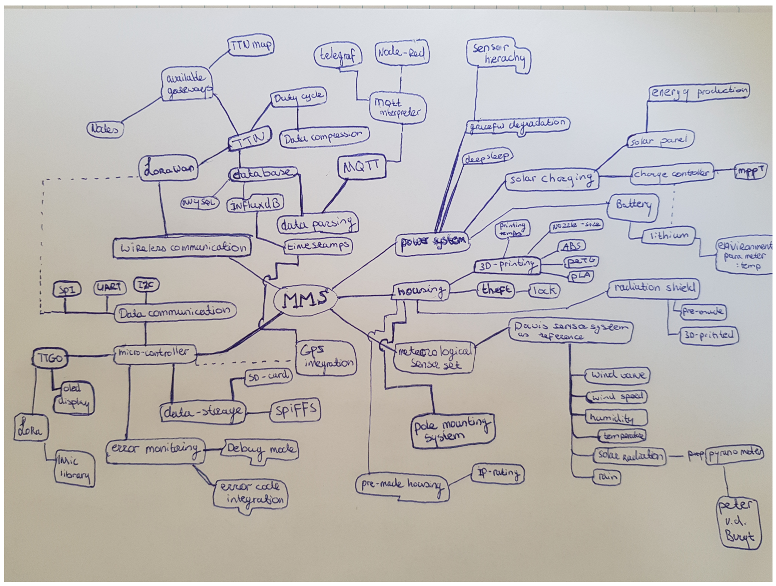


Figure 30: Mind-map brainstorm (see Appendix C)

The idea has a central hub containing the main micro-controller, batteries, conversion circuitry for solar charging, and solar charge controllers. Moreover, the hub has multiple waterproof connectors for connecting various sensors subsystems. This idea is proposed by Pijnappel [9] and can also be seen in the figure 8.

Instead of using a 3D-printed enclosure, a commercially available enclosure is applied that is specified for outdoor use, this will ensure better reliability and is more efficient for production. The main pole will mount the meteorological sensor-systems, the enclosure with the circuitry, micro-controller, and the power-system. After the interview with Wim Timmermans, an iteration of the idea depicted in figure 31 had to be performed. According to Wim Timmermans, the MMS should be capable of being installed on average-sized poles, such as streets lantern poles. In the previous (figure 31, idea the system was self-mounted, meaning the system was one, and could not be applied to various sized poles).

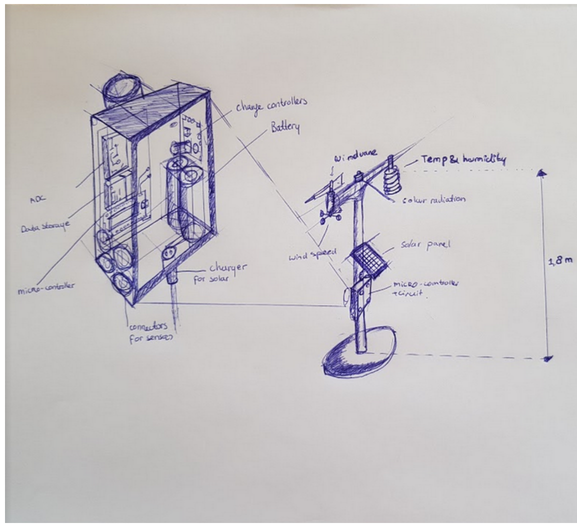


Figure 31: First brainstorm sketch (see Appendix C)

Figure 32 shows a few designs for pole-mounted MMS's. From the previous researches, mainly 3D-printed pole mounting systems were used [9][10]. However, as to make it more robust to cope with environmental factors materials like aluminium, or steel can be considered for a more reliable solution, figure 33 depicts a good alternative. How the sensor housing exactly will look is, for now, unclear, as no specific sensor sub-system types have been chosen yet.

4.9 Conclusion Ideation

In the ideation phase, the stakeholders have been identified, interviews conducted, and preliminary requirements overview formed. Based on the stakeholders, and the preliminary requirements, initial ideas were made on how the software and the hardware would relate. Furthermore, a small part has been dedicated to; how measurement in an ideal situation should be performed. As in an urban situation, measurement setups can not be conformed to KNMI requirements. Nevertheless, for scientific research, the measurement frequency of each parameter should conform the KNMI specifications to have the ability to compare the measured data with data of KNMI measurement locations. If the measurement frequencies are related, but, the setups for each sensor node is not, the influence of urban architecture on environmental parameters can be compared.

The current thought of the ideation phase emphasises the system that is placed around an average pole. With the use of universal base plates, the different components can be mounted. This base amount will be adjustable to various

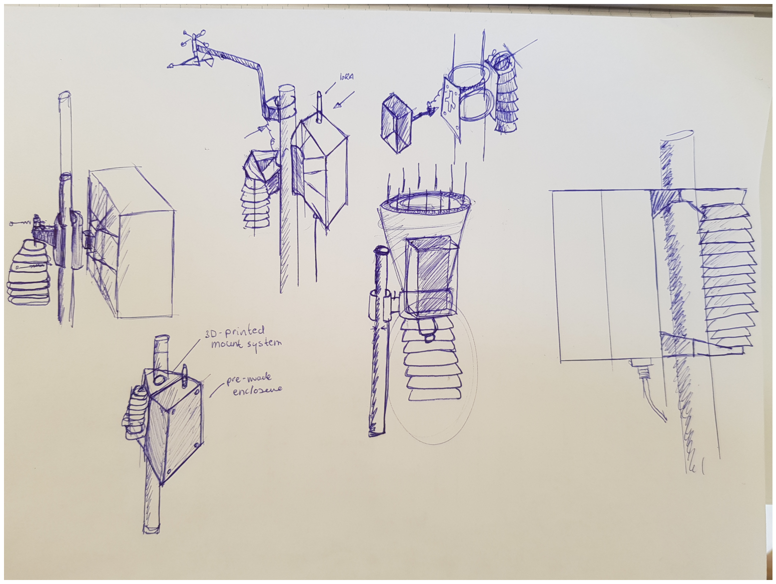


Figure 32: Brainstorm sketches iteration 2 (see Appendix C)

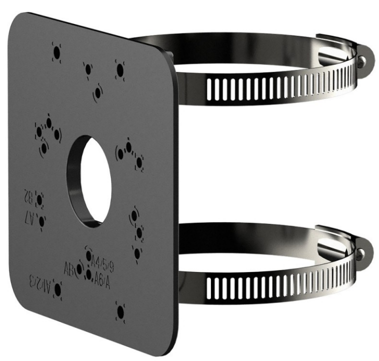


Figure 33: Pole mount system

sizes to ensure different mounting options, providing placing freedom at various locations. The first idea is to have two primary base plates, one mounting the housing and the other mounting the sensor as depicted in figure 32. In this way, person who is placing the system can come with different configurations that are best suited for the placement of the system.

float

5 Specification

In this chapter, the functionally, sensor specifications, firmware architecture specifications, and system design will be explained. Based on the stakeholder requirements and data collected from the previous chapters, functional and non-functional requirements will be introduced. With the findings from this chapter, the realisation of the project will be completed.

5.1 Enclosure Specification

The enclosure must be able to cope with the environmental factors of Enschede specified in section 4.4.

Wim Timmermans previously stated that the system should operate without any supervision for at least a year. Therefore, a robust enclosure is essential for system reliability. For the main housing, an IP-rated enclosure is selected, this offers a good basis for the PCB, battery and the internal electronics. The enclosure is a grey ABS box manufactured by Kradex[70], with the dimensions; 176x126x57mm, and IP index of IP65. Technical drawings can be be found in Appendix G. This offers a waterproof solution and ensures the scalability of the project when manufacturing a large quantity sensor nodes. Although scalability is out of this scope for the research, enclosures can be efficiently designed with minimal 3D printed parts, as a pre-made enclosure is applied.

Appendix G provides all the technical drawings and dimension specifications for the mounting system and enclosure mounts. The system will be placed around an averaged size pole. Wim Timmermans mentioned placing the system on a 6-meter pole at a 3 meter height. Therefore, a lamp post was sampled in Enschede. The pole number 10 located at the Volksparksingel Enschede has a diameter of 16.5 cm. The design provided in appendix G, uses clamps to ensure a strong mount, the clamps are available in a variety of sizes.

5.1.1 IP-rating for enclosure

Preferred enclosures are the ones with an IP-rating, which describe the degree of protection in a particular environment, such as rain and dust. The environmental factors for Enschede are described in section 4.4. Based on the factors and the IP-rating, an IP-rating of IP-33 would suffice for the entire system. This describes the following requirements: Protected against, a solid object greater than 2.5 mm such as a screwdriver, and protected against sprays of water up to 60 degrees vertical, limited ingress permitted for three minutes [69].

5.1.2 Sensor shielding specification

To perform reliable measurements and stay operational in various weather conditions, sensor shielding is required. KNMI [66] measurements guide mentions the application of radiation shielding for temperature and relative humidity sensor sub-systems. Radiation shields allow for airflow while keeping the sensor protected from direct exposure to precipitation and solar radiation. As both the temperature and humidity sensor needs to be exposed to airflow, both sensors will be applied in a sensor shield. An additional fan located within the radiation shield can help avoid biases when the local climate inside the screen/shielding is different compared to the outside temperature. Deviations can occur with wind speed $< 1ms^{-1}$. The radiation shielding must ensure that the temperature is uniform to the outside air [71]. The material has to be either a non-oxidised metal, that is highly reflective and has low heat absorption properties. Alternatively, a plastic-based material that has high thermal insulating properties can be used. Thermally insulating material is required if systems rely on natural ventilation [71]. Most of the screens have a louvred screen to allow for ventilation. A double-louvred screen is preferable, as depicted in figure 34.

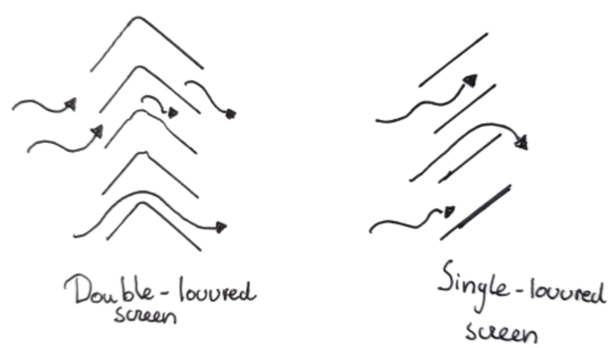


Figure 34: Double-louvred vs Single-louvred

5.2 Measurement Specification

Measurements primarily need to be taken in accordance with the KNMI book for measurements. To measure the influence of urban infrastructure and have the ability to compare with the data of KNMI measurements data. Measurement frequencies require to be the same. In this section, the measurement frequencies will be specified and elaborated.

From section 4.5, it is known that for the parameters, humidity, temperature, and solar irradiance, the sampling frequencies are the same. However, the method of measurement frequency for wind speed is different. When measuring temperature, relative humidity, or solar irradiance, each 12th-second a measurement is taken. Based on five samples, a 1-minute average is calculated. Figure 35 provides an example of how this works. As can be seen, on the 12th-second, a measurement is taken; on the 24th-second, a measurement is taken until the 60th-second is reached. Then a total of five samples have been taken. All the samples are added-up and divided by the total number of samples which result in the average. The timestamp for the particular 1-minute average will be the last sample, the 60th-second sample.

For raw data availability, each 12th-second measurement is required to be available on the server-side. Although stakeholders prefer raw-data availability, However, as shown in section5.3, with the current choice of the TheThingsNetwork (TTN), this is not possible within the fair-use-policy. Therefore, the 1-minute average will be transferred. A second option is to send over the 36th-second average. This is the maximum data resolution allowed by the transmission specification in section 5.3. Three 12th-second average are added-up and divided by three to come with the 36th-second average. However, Wim Timmermans advised integrating based on the 1-minute average instead of the 36th-second average.

From figure 36, the measurement requirements for the wind speed are depicted. Wind speed measurement require continues measurements. A 12th-second sample is based on four 3rd-second samples. The 3rd-second sample is based on measurements each taken on 1/4 second for the past 3 seconds. This is also shown in figure 36. Meaning a 3rd-second average is based on 12 samples. Since the startup time for deep-sleep is greater than the 1/4 second, continues measurements are required for wind speed measurements. Meaning, no deep-sleep can be used to retain power consumption. The one 1-minute average is then based on the five 12th-second measurements like temperature, humidity, and solar irradiance.

5.2.1 Measurement frequency design

The current design will utilise deep-sleep based measurement sampling to ensure a low-power consumption. Figure 37 depicts current design which implements the deep-sleep mode measurements. Since no continues measurements can be

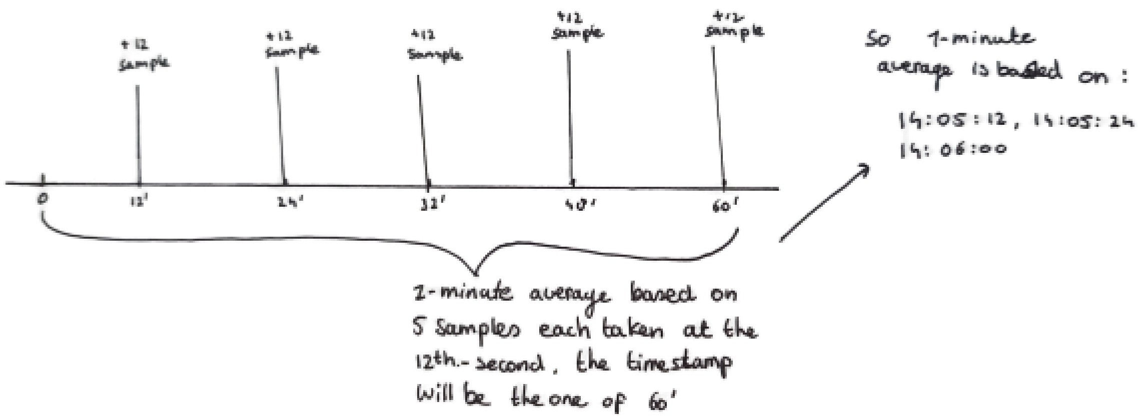


Figure 35: Timing of measurements for 1-minute average

performed, measurements regarding wind speed follow a different method. This is a trade-off between measurement quality and reliability of the system. Either, the system takes measurements to conform with KNMI measurement frequencies but uses a higher power consumption, or the system implements deep-sleep mode resulting in lower power consumption, but not taking wind speed measurement to conform with KNMI.

Currently, a decision has been made for the second option which implements deep-sleep based architecture. The timeline for deep-sleep based measurement can be seen in figure 37. After approximately 9 seconds of deep-sleep, the system turns on and the wind speed measurement takes places based on a 3-second interval. Then the measurement for temperature, solar irradiance and relative humidity are conducted. If all the measurements are taken and stored, a new deep-sleep of approximately 9 seconds is calculated before going to sleep. In this way, the timing is exact for the 12th-second measurement. In addition, times-

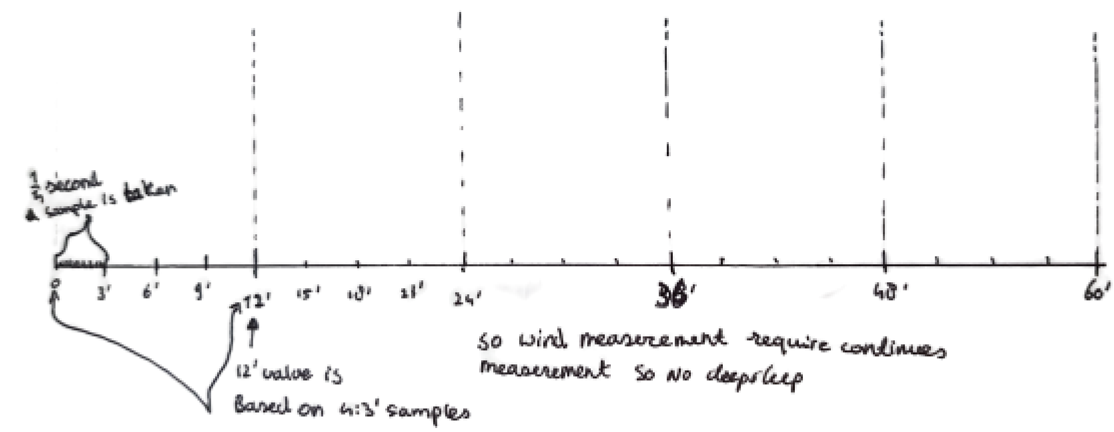


Figure 36: Wind speed measurements according to KNMI requirements

tamps with each measurement are not required since the timing is calculated for each cycle. The timestamp is only required for the last measurement and based on the exact interval timing, measurement timestamps for each 1-minute average can be calculated using the one timestamp as the intervals are known.

5.3 Measurement Transmission Specification

In this section (performed in collaboration with van der Burgt), the wireless communication protocol will be discussed. As ideated in the ideation, the LoRa communication method will be used. The pyranometer will be a sub-system of the AWS designed by Jan-Paul Konijn, and as such the data communication of the pyranometer will be integrated with the AWS data communication. Therefore this section describes the entire data communication of the AWS. LoRaWAN offers a low power solution for sending small amounts of data over long distances. There are different networks with different specifications all over the

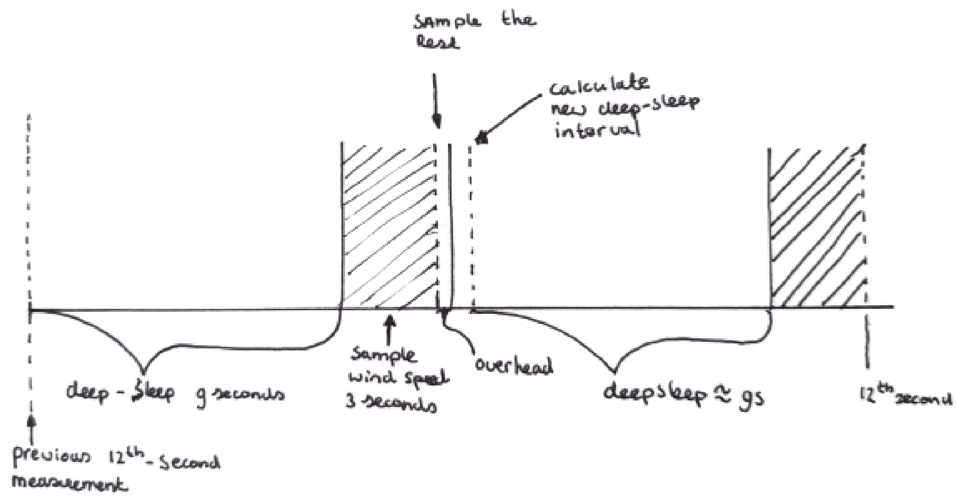


Figure 37: Timing for all measurements

world. The specifications given in Europe are:

- The airtime of a given LoRaWAN node is limited to a duty cycle of 1% (EU regulations).
- The LoRaWan communication works on a frequency of 863 to 870MHz, the common name for this is EU868.

For the infrastructure of the LoRaWAN, a community-driven platform will be used: TTN. TTN is a service that offers gateways to which a LoRaWAN nodes can be connected and as such data can be sent from the nodes to the gateway. From this gateway and such, the data is sent over the internet to the online service. TTN, as a provider, handles a set of rules and regulations to ensure fair usage among its users. The most important being the following:

- Every LoRaWAN node can send messages for a total of 30 seconds airtime per day per device.
- The frequency band used by the TTN is the EU868.1-869.525MHz (for Europe).

As can be seen in the restrictions posed by the LoRaWAN communication technology and the TTN regulations, it is important to calculate the amount of data that can be sent. This will be done in the next section.

5.3.1 The Things Network Timing Calculations

To help calculate the overall time that a LoRaWAN node is sending messages, the TTN offers a service called the TTN LoRaWAN airtime calculator. Here, one can see that when working with LoRaWAN, there are four different parameters that influence the transmission time:

- Payload in the amount of bytes: For the EU868 network, there is a maximum payload size of 51 bytes
- Spreading Factor: see figure 38. The value ranges for the spreading factor range from SF7 to SF12. A higher Spreading Factor provides the gateway more opportunity to sample the signal power, increasing the sensitivity, thus the likelihood of the data being received. However, a higher spreading factor takes a longer time to send and has a higher power consumption. Thus using a low spreading factor would be best for the battery life of our system, as well as the amount of data that can be sent.
- Region: The region indicates the main frequency being used. For the MMS, this will be EU868. The frequency deviates from 868 to 870 MHz
- Bandwidth: The possible bandwidth for EU868 is 125 and 250 kHz. A higher bandwidth results in the possibility to send more data. However, the micro-controller library that is in use, LMIC, does not allow to change the bandwidth, therefore, the 125kHz bandwidth is a given.

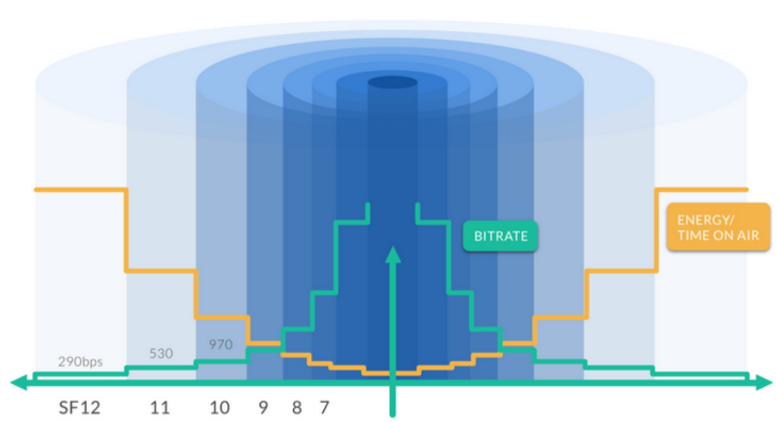


Figure 38: Spreadings factor: range and bandwidth [72]

$$Toff_{subband} = (TimeOnAir/DutyCyclesubband) - TimeOnAir \quad (2)$$

The first calculation to be made is the overall restrictions given by the LoRaWAN's 1% duty cycle. For calculating the off-time of a particular sub-band, the equation 2 is provided. The equation provides the amount of time that a device is not allowed to send messages for a sub-band after sending on that particular sub-band. The air-time of the node per message will be calculated with the help of the TTN LoRaWAN air-time calculator [73]. Filling in the air-time calculator with the appropriate parameters (51 bytes, SF7, EU868, and 125 kHz), gives that the entire message takes 118ms to send.

Using this 118ms together with the 1% duty cycle and filling in formula 2, the off-time should be 11.7s. This would mean that about every 12 seconds a message could be sent on that sub-band. Besides the restrictions given by the LoRaWAN communication technology, the TTN also has the restriction of a maximum air-time of 30 seconds per node per day.

The fair-use-policy rules by the TTN are more restrictive compared to the 1% regulations, and this is due to the fact that TTN is an open network. Given that 254 messages can be sent, each consisting of 51 bytes, it is concluded that 12954 bytes can be sent per day, resulting in 103632 bits per day as every byte contains 8 bits. This means, that a message can be sent every 6 minutes. However, together with the stakeholders, it was decided that every 10 minutes a message would be sent, containing the ten 1-minute averages of every variable. The exact timing calculations can be found in Appendix D.

5.3.2 Payload structure

As the maximum payload that is possible for the communication technology is 51 bytes, the type of data that should be sent must be limited to the essential data. The data will need to include location data, time of measurement, and the measurements data itself. For the location data, the GPS latitude and longitude coordinates are the most important, and height can be omitted. As mentioned by Wim Timmermans in his interview, the height does not influence the solar irradiance measurement much. There are two ways to go about sending the data, using an existing standard method, or writing a custom payload structure.

Cayenne payload structure: The first option for sending messages is the standard Cayenne Low Power Payload (Cayenne LPP) [74]. This means that one can use existing libraries to send data over LoRaWAN. The advantage of using Cayenne LPP is a convention for payload structure, resulting in the fact that others are easily able to read the messages. In addition, the TTN console provides an existing decoder for Cayenne, making it easy to use on the server-side as no custom decoder is required. Next to that, identifier bytes are used to identify the different variables that can be sent with Cayenne LPP. These variables can be seen in Table 4.

This is also where Cayenne LPP has several disadvantages. Every variable that is sent, has two extra bytes, one being an identifier, one being a channel. Lastly, not every byte is fully used, leaving some bits empty or unused. An example of this is, that the Temperature uses 2 full bytes, meaning that it has a range of 0 to 65535. With a 0.1 C resolution this means that a range of about 0 C to 6553.6 C can be implemented. This is only done because of the fact that using one byte gives a range of 0 - 255, thus 0 C to 25.5 C is not enough. As can be seen, this results in a lot of extra range which is not needed.

Type	IPSO	LPP	Hex	Data Size	Data Resolution per bit
Digital Input	3200	0	0	1	1
Digital Output	3201	1	1	1	1
Analog Input	3202	2	2	2	0.01 Signed
Analog Output	3203	3	3	2	0.01 Signed
Illuminance Sensor	3301	101	65	2	1 Lux Unsigned MSB
Presence Sensor	3302	102	66	1	1
Temperature Sensor	3303	103	67	2	0.1 °C Signed MSB
Humidity Sensor	3304	104	68	1	0.5 % Unsigned
Accelerometer	3313	113	71	6	0.001 G Signed MSB per axis
Barometer	3315	115	73	2	0.1 hPa Unsigned MSB
Gyrometer	3334	134	86	6	0.01 °/s Signed MSB per axis
GPS Location	3336	136	88	9	Latitude : 0.0001 ° Signed MSB Longitude : 0.0001 ° Signed MSB Altitude : 0.01 meter Signed MSB

Table 4: Cayenne payload sizes [72]

Unique payload structure: The second option for sending messages over LoRaWAN is designing a custom payload structure. The benefit of this is that bytes can be fully utilised by the MMS, meaning a higher measurements frequencies can be reached. The full potential of the bytes can be used when they are divided into loose bits, and the bits are assigned to variables. A disadvantage is that such a payload structure is not widely known, and thus requires to described very clearly. To maximise the measurement frequency, the designing of a unique payload structure will be chosen. First and foremost, the different types of data that should be sent are identified. For the MMS this will be; wind speed, temperature, relative humidity, and solar irradiance.

In table 5, these variables are further explored to find out how many bits should be used, to cover the range and resolution of the measurements when sending the data of these variables. With the data structure as described in table 6, three or five measurements are combined into a 36-second average (three samples) or 1-minute average (five samples). When there are ten such measurements averages for each parameter (relative humidity, temperature, solar irradiance, and wind speed), they will be sent over LoRaWAN to TTN. This is done with the following data structure, presented in table 6. This payload consists of 51 bytes, thus in 408 bits to be allocated for each measurement.

The compression is achieved by the implementation of delta measurements or the difference between the initial measurement and the next measurement. As each parameter is given by the delta value, an example is provided in figure 39. This ensures a decrease in the amount of data when sending several measurements since the delta is in terms of bit size smaller than the initial variable or the non-compressed variable.

Table 6 provides for each parameter the initial bit size and the decreased bit size. For the wind speed measurement parameter, no delta will be calculated as the wind speed can increase and drop too fast in an interval. Solar irradiance measurement is also too volatile as cloudy weather can create significant differences between the measurement intervals. This means for both wind speed, and solar irradiance, full-size in terms of bits is allocated. For temperature and relative humidity, the difference for each 12th-second will be more stable. In order to achieve data compression without any losses, the assumption is made that for humidity the difference between 12th-second measurements is the difference between $\pm 7\%$, and for temperature; $\pm 3.1°C$. This can also be found in table 6. The higher the amount of measurements included in one payload, the higher the relative compression. Which concludes that the biggest size payload is favourable in this case.

Variable	Range and Resolution	Start Measurement	Start Measurement Mapping	Delta Measurement	Delta Measurement Mapping
Wind speed	Range: 0 – 50m/s Resolution: 0.1m/s	9 bits (0 – 511)	0: 0m/s 500: 50.0m/s	9 bits (0 – 511)	0: 0m/s 500: 50.0m/s
Temperature	Range: -30 – 60 °C Resolution: 0.1 °C	10 bits (0 – 1023)	0: -30.0°C 900: 60.0°C	6 bits (0 – 63)	0 – 62: -3.1°C –+3.1°C 63: error
Humidity	Range: 0 – 100% Resolution: 1%	7 bits (0 – 127)	0: 0% 100: 100%	4 bits (0 – 15)	0 – 14: -7% – +7% 15: error
Solar Irradiance	Range: 0 – 1800 W/m² Resolution: 1 W/m²	11 bits (0 – 2047)	0: 0 W/m² 1800: 1800 W/m²	11 bits (0 – 2047)	0: 0 W/m² 1800: 1800 W/m²

Table 5: Exploring of the to be sent variables. Here the different mappings that will be used, can also be seen.

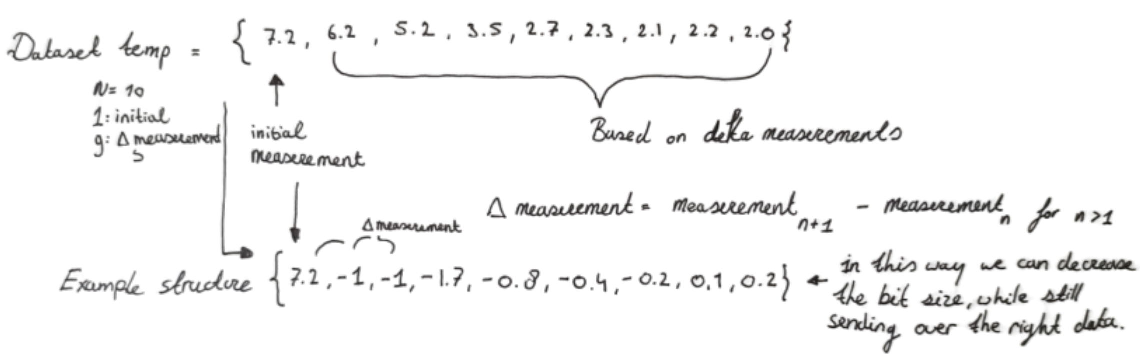


Figure 39: Example of delta-measurement calculation

Variable	Sub-Variable	Amount of bits
Time Stamp (Unix Time)		32 bits
GPS	Longitude (0.00001°) (around 1 m {})	24 bits
	Latitude (0.00001°) (around 1 m {})	24 bits
System logging	0-255 system codes	8 bits
Start Measurement	Windspeed	9 bits
	Temperature	10 bits
	Humidity	7 bits
	Solar Irradiance	11 bits
Delta Measurement (x 9)	Windspeed	9 bits
	Temperature	6 bits
	Humidity	4 bits
	Solar Irradiance	11 bits
Total		395 bits out of a possible 408

Table 6: Payload structure of one message. There are some bits left, these are put at the end of the message.

5.4 Functional System architecture

In section 3.2.1 functional architecture decomposition method has been explained. With the use of this proposed method of analysis figure 41 depicts the scope and the environment in which the system will operate in. As can be viewed from figure 41, the arrow represents the different flows between components of the total project. The MMS is a "black box" that takes in measurements and solar energy to send the measurements, location data, and timestamps to a TTN gateway.

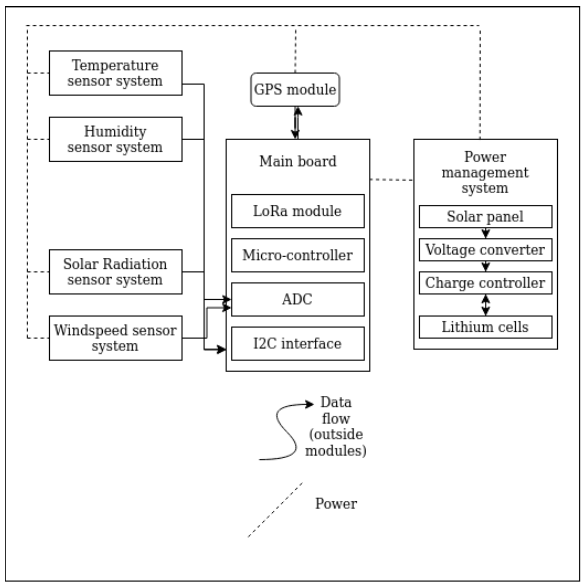


Figure 40: Decomposition of system - hardware scope

The architecture depicted in figure 40 shows the decomposition of two levels deep. There are three main components; meteorological sensor sub-systems, micro-controller combined with wireless communication and the power-system. The lines in the figure represent the interactions between the different components.

Figure 42 shows the architecture for the main micro-controller firmware. Measurements data will be stored in the non-volatile memory. A temporary counter keeps track of the amount of 12th-second measurements. Based on the specified threshold, either the 36th-second average can be calculated or a 1-minute average depending on the preference. As for the current calculation explained in section 5.3, the protocol size can only hold ten values for each parameter, which translates to a send counter of size ten. When either ten 1-minute averages or ten 36th-second averages are calculated, and the send counter reaches the threshold, the GPS is enabled, and a timestamp received from the mod-

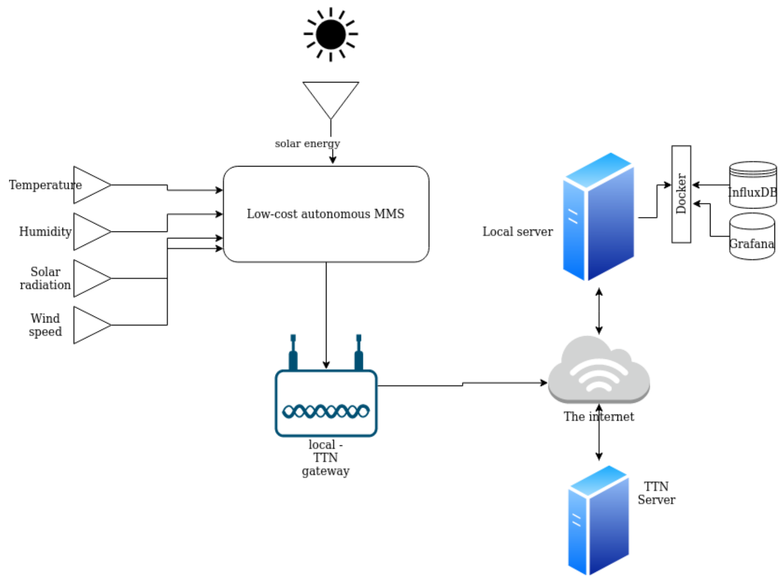


Figure 41: System scope

ule. In the firmware, there can be chosen between sending every 6 minutes based on the 36th-second average (maximum resolution) or sending every 10 minutes the 1-minute average. Since the timestamp is not in epoch format, the conversion will be performed. Data will be parsed from the flash-memory and converted to a byte array for transmission. After conversion and parsing, all data will be purged from memory, and data will be sent. After the transmission is completed, the right sleep time will be calculated according to the 12th-second measurement.

Note that for the firmware architecture deep-sleep based measurement frequencies are applied this choose is explained in section 5.3. In figure 42 the action "calculate deep-sleep time" can be found. This is as explained earlier in section 5.3 based around the 12-second measurements intervals. Since the micro-controller has to load all the sensor data, save the data in the non-volatile storage, each cycle of the deep-sleep time have to be calculated again as it can deviate each time. When using continuous measurement architecture, this would not apply (future work). Figure 43 shows how the timing of a cycle is done.

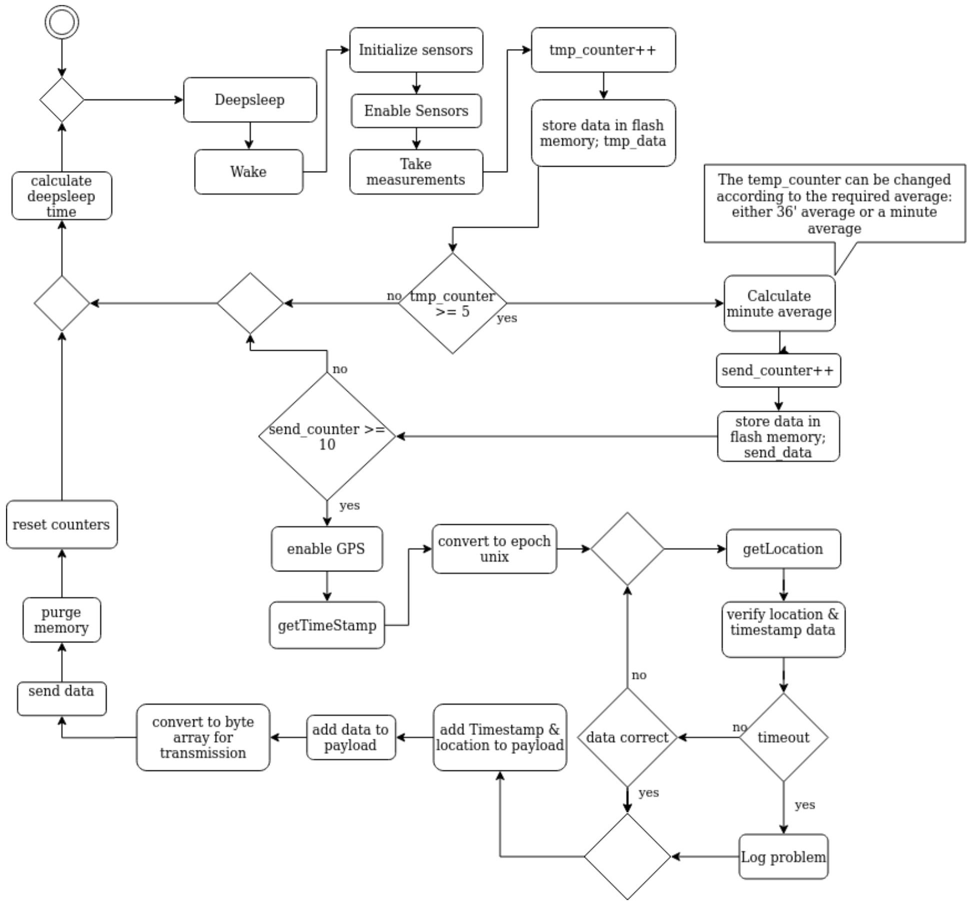


Figure 42: Firmware architecture for micro-controller

5.5 Power System specification

Several components require power; taking measurements, enabling GPS for both location and timestamps, and wireless transmission of data. To perform the mentioned action, reliable, theoretical analysis for power consumption is necessary. Whether this analysis is representative for reliable system operation needs to be confirmed in the evaluation. The primary micro-controller TTGO Esp32 Oled [68] LoRa V1.O development board is applied in this MMS. Due to the Covid-19 virus, no access to the labs at the University is possible. Therefore, no measurements regarding the power-consumption can be taken, and a theoretical estimation based on the specification will be provided instead.

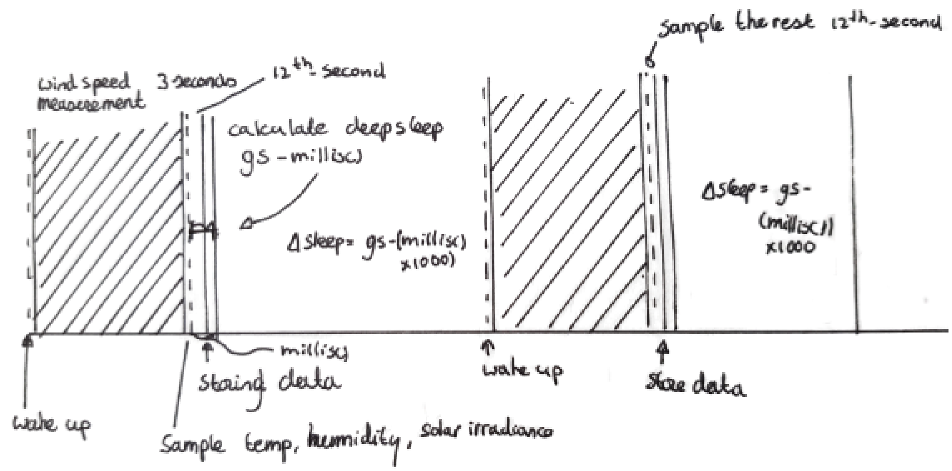


Figure 43: Time Line for deep-sleep based sampling

5.5.1 Power consumption specification

Table 7 provides the specification for the power consumption for each component in the system. An additional margin of 20% will be used to ensure reliable operation. When using a custom-developed pyranometer, the total power consumption will be; 716.1mW. When using the Davis-6540 sensory sub-system, the power consumption will be 488.4mW. Adding for both cases a safety margin of 20% the power consumption will be; (with van der Burgt's system): 859.32mW, and (with Davis 6450): 587.08 mW.

5.5.2 Power supply specification

To ensure reliable operation, the supply must always ensure $> 859.32mW$. In addition, Graceful degradation can be used. Graceful degradation is an efficient way to reduce power consumption by disabling sensors according to a pre-configured hierarchy. Moreover, sub-systems can be disabled to ensure they do not consume power when not used. The current strategy only enables the sub-system when data is required from each sub-system. So if location data or timestamp data is required, the GPS module is enabled only for the particular time when data is required. The implementation does allow for graceful

Theoretical power specification		
Sensor type	current draw at 3.3v given in mA	power consumption in mW
Micro-controller (TTGO Esp32)	50mA	165mW
Time & location(NEO 6m GPS)	45mA	148.5mW
Temperature & relative humidity (SHT31)	1mA	3.3mW
Temperature & relative humidity (BME280)	1mA	3.3mW
Wind speed (Davis 6410)	unknown (50mA assumed)	165mW
Alternative 1		
Solar irradiance (Davis 6450)	1mA	3.3mW
Alternative 2		
Solar irradiance (Pyranometer Peter van der Burgt)	70mA	231mW

Table 7: Power consumption specification

degradation but is a concern for future works.

5.6 Final requirement specification

Table 8 and 9 provide an overview of the non-functional requirements and functional requirements. Both are based around the earlier explained method in section 3.2.2, stakeholder interview, and ideation and specification. The tables provide the requirement and the source, the main goal is to match or improve on the requirements of the reference system.

Non-Functional requirements:	
Must Have Requirements	Source
Not exceed the 400 euro threshold	1,2
Measure: temperature, wind speed, relative humidity, solar irradiance,	1,2,3
Efficient power management	1,2
Operate autonomously	4
Offer modulartiy for easy sensor replacement	3
Pole mounting system (average sized street lanterns)	3
Withstand the environmental factors	1,2,3,4
Operate for a year without any supervision	3
Easy to fix if any problems occur	3
Protection for pole mounting	3,4
GPS location integration	1,2
Should Have Requirements	Source
Graceful degradation	2
Save obtained data in database	1,2,4
Configurable update-rate	1,2,3
IP-rated enclosure	2,4
Raw data availability	1,2
Could Have Requirements	Source
Allow for various mount options	3,4
Sending error reports	1
Cayenne LPP for payload management	1,2
BLE-local for raw data transfer	1
Over-the-air firmware updates	1
Configurable update-rate	1,2,3

Table 8: Non-functional requirements table

Legend: Hans Scholten = 1, Richard Bults = 2, Wim Timmermans = 3, Rick Meijer = 4

Functional requirements:	
Must Have Requirement	Source
Temperature requirements	
Accuracy $0.5°C$ Range $-30°C + 60°C$ Resolutie $0.1°C$	3,5 3,5 3,5
Relative Humidity requirements	
Accuracy 3% Range 5%-100% Resolution 1%	3,5 3,5 3,5
Wind requirements	
Average Wind speed accuracy $0.1m/s - 0.2m/s$ Average Wind speed range $0 - 50m/s$ Average wind speed Resolution $0,5m/s$	3,5 3,5 3,5
Solar Radiation Requirement	
Accuracy of $10W/m^2$ Range $0 - 1800W/m^2$ Resolution $1W/m^2$	3 3 3
System requirements	
Withstand 43.8mm of rain a day for one full year Withstand humidity %37 - %99 Withstand temperature range of $-10.1°C$ to $40.2°C$ Withstand wind-gusts of $23.3m/s$ ($83.88km/h$) Send at least 10 1-minute average values every half-hour Working according to TTN 30-second policy Ensure enough power-generation for cloudy day with 8 hours of light Mount size of 16.5mm (diameter)	1,2,3,4 1,2,3,4 1,2,3,4 1,2,3,4 3 1,2 1,2,3,4 3,4
Should Have Requirement	
Won't Have Requirement	
Barometric pressure requirements	
Accuracy 0.3 hPa Range 940-1060hPa Resolution 0.1hPa	5 5 5
Wind direction requirements	
Wind direction accuracy of $\pm 5°$ Wind direction resolution $10°$ Wind direction range $0° - 360°$	5 5 5

Table 9: Functional requirements table

Legend: Hans Scholten = 1, Richard Bults = 2, Wim Timmermans = 3, Rick Meijer = 4, KNMI = 5

6 Realisation

In this chapter, full-implementation of the specified design made in the previous chapters will be documented. Several iterations of the prototype are performed to come to a final prototype that will be used for evaluation. The approach is to prototype and iterate the components, instead of performing iteration on entire builds.

6.1 Sensor selection

The measurement data generated by the MMS should be of sufficient quality to validate for Wim Timmerman's model and meet the requirements from section 5. A sensor survey of relevant hardware components is made based on the state-of-art and available off-the-shelf components available on the internet. In this section, different sensor types that suffice the quality requirements will be observed. The list of sensor survey can be found in the appendix E. The requirements full-filled should follow the table 9. For each sensor type, price, accuracy, resolution, documentation, measurement parameters, and reliability will be examined. For reliability, manufacturers will be scrutinised based on credibility, e.g. Bosch would be indexed higher comparatively than an unknown online seller. Whether the sensor would meet all the requirements stated in table 9 needs to be tested in the evaluation phase.

Temperature & Relative Humidity: If we look at the table provided in appendix E, the SHT-31 manufactured by Sensirion fulfils both the temperature requirements and the humidity requirements. The sensor properties have an accuracy of $0.2°C$ for temperature and 2% for relative humidity. The resolution for the sensor is $0.015°C$ which is in line with the requirements set in table 9. Moreover, Sensirion [75] provides extensive documentation and can be considered a credible sensor company. Technical specifications can be found in the reference overview [76].

Wind speed For wind speed, the Froggit - WH1080 [38] can be found in the sensor survey appendix E. Although it has considerably low-cost, no additional documentation is available, nor is the manufacturer available. Kester [10] used this anemometer in her sensor node, and from the report, the interfacing can be learned. However, the unknown accuracies, documentation, and manufacturer do not make the sensor a reliable choice for this MMS build.

Moreover, two additional sensors, one from a Chinese manufacturer and one from Kiwielectronics[8], were found (can be seen in appendix E). However, there is no clear datasheet or manufacturer information, which makes selecting these sensors questionable. In the previous research performed by Pijnappel, he selected the Davis-6410 sensor for the MMS. This sensor is the identical sensor

[8] https://www.kiwi-electronics.nl/

applied in the reference system and, therefore, would meet the minimal criteria. However, as can be observed from the KNMI requirements listing, table 9, the accuracy of the Davis-6410 is too low regarding wind speed (required accuracy: $0.1m/s$). The accuracy for wind speed of the Davis 6410 is $1.m/s$ or $\pm 5\%$ depending on which is higher. With the range being from $0.5 - 89m/s$. The Davis-instruments 6410 has a built-in wind direction meter with an accuracy of $\pm 3°$, and a resolution of $22.5°$ (on compass rose) [77]. Although wind direction is out of scope for this research having the option for future work can contribute. The documentation availability, price, and reliability were major factors to balance for the low accuracies. Therefore, the Davis 6410 wind speed sensor subsystem has been selected.

Solar irradiance The pyranometer, in particular, is not an off-the-shelf component due to its pricing and specific hardware; the pricing of most systems is out of range for this research. Although pricing is not the main selection criteria if pricing is > 300 euros, the system can not be chosen, the specification states the must-have to have an accuracy of $10W/m^2$. Unfortunately, no sensor systems could be found within the specified accuracy. Therefore, the Davis-6450 [21] sensor sub-system is selected. The research of van der Burgt; low-cost autonomous pyranometer can be applied in the MMS as measurement specifications are sufficient. However, until his sub-system is ready for integration, the Davis-6450 solar irradiance sensor will be utilised. The price is relatively low-cost compared to other manufacturers like Kipp&Zonen[19].

Furthermore, an additional I2C interface for the pyranometer developed by Peter van der Burgt will be made. Although the leading and current choice is the Davis instruments, the possibility of integrating the pyranometer of Peter van der Burgt should not be dismissed, and the current MMS should allow for fusion for both researches to improve the accuracy for the solar irradiance system in the MMS.

6.2 Sensor radiation shielding

An open-source 3D-printable radiation shield available on Grabcad [78] will be applied in the system. Figure 44 depicts the solar radiation shield. It offers a sensors mount that can be screwed into the shield. This offers easy replacement when a sensor is broken. Moreover, an additional internal mesh protects against additional water intrusion and intruding objects. Additionally, the internal mesh depicted in figure 45 creates an extra internal air-layer to protect the sensor from the radiation of the shield itself, this ensures more truthful measurements and add to the quality of the measurements. However, whether the radiation shield provides sufficient protection against the environmental factors needs to be researched. The model will be printed using a Creality Ender 3 [79], nozzle width 0.4 mm, using PLA as printing material.

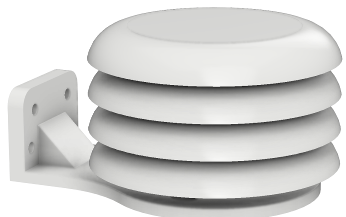


Figure 44: Solar radiation shield for sensor

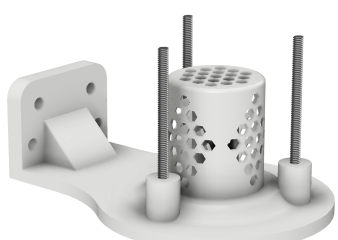


Figure 45: Solar radiation shield internal with mesh protection

6.3 Power management

To power the system in a reliable way the system should be able to generate energy and store this energy. Kester [10], Pijnappel[9], and Onderwater [11] proposed the usage of small sized solar panels. Solar is a reliable way for generating electricity at remote locations. In this part, the power system realisation is elaborated.

6.3.1 Power delivery

To allow higher resolution sensor sampling, taking measurement at higher frequencies, a 10-Watt solar panel [80] will be used in combination with a 2P or two-cell configured lithium battery pack. The applied batteries; Samsung INR18650-29E [81] with a capacity of 2,850 mAh. In a dual configuration (2P) providing a total theoretical capacity of 5700 mAh. The discharge current; 2,750 mAh of continuous discharge and 8250 mAh for non-continuous discharge. The maximum voltage when fully charged is 4.2V and discharge voltage is 2.5V. Since lithium-ion cells needs to be charged and protected in a safe way, a parallel configuration of two TP4056 modules [82] will be applied.

For charging the 2P lithium configuration, a 10-watt solar panel of the size 290 x 240 x 18mm is used [80]. The maximum output voltage is 22v when fully exposed to the sun. The ideal current delivery is 560mA. However, due to the nature of solar panel maximum power point tracking might be required. The maximum power-point voltage for the current solar panel is at a voltage of 17.56V. Since $V_{solarpaneloutput} > V_{battery}$ holds voltage conversion is required. The TP4056 takes in 5v, therefore, conversion to 5v is required. For voltage conversion a LM2596 [83] module is used. This steps down the 22V voltage generated by the solar panel to a workable voltage for the TP4056.

6.3.2 Power consumption

Table 7 provides an overview of the current draws for each component. To see how long the system can reliably operate on the dual-battery configuration. Whether this analysis is representative for reliable system operation needs to be confirmed in the evaluation. The primary micro-controller TTGO Esp32 Oled [68] LoRa V1.O development board is applied in this MMS. Due to the Covid-19 virus, no access to the labs at the University is possible. Therefore, no measurements regarding the power-consumption can be taken and a theoretical estimation will be provided instead. The TTGO Esp32 features deep sleep capabilities with an estimated power consumption of roughly 10mA while in that state. While awake, the power consumption is estimated to be 38-50mA. Based on the table 7, an estimation on the lifetime when fully charged can be made. Adding up all the current draw provides us with a total current draw of 148mA*1.2 = 177.6mA (with safety margin of 20%) in the worst-case. This would give us $5700mAh/177.6mA = 32h$ hours run time without a required recharge. Whether this will be reliable when operation in darker days needs to be tested. An other alternative is interfacing with van der Burgt's pyranometer, this requires additional power consumption of 70mA at 3.3V. Replacing the Davis-6450 with the developed pyranometer of Peter would provide us with a total current draw of 217mA*1.2 = 260.4mA (with safety margin of 20%) at 3.3v, and a total theoretical operation of $5700mAh/148mA$ = 21.9 hours with out any solar recharging. Note that these estimates are for continues operation. So operation without solar charging using deep-sleep based operation can be $> 24h$.

6.4 First prototype

6.4.1 Enclosure

To ensure waterproofing, two Cable Glands (25mm) for two cables are installed in the Kradex enclosure. Additionally, a 2-pin waterproof connector is added for a cable to the solar panel. Currently, it is unknown whether the LoRa antenna that comes with the TTGO ESP32 board sends out a strong enough signal to leave the antenna inside the enclosure. Therefore, an additional hole is drilled at the bottom of the enclosure to mount the antenna as can be seen in figure 46.

6.4.2 Pole Mounting system

As roughly 80 sensor nodes will be distributed over Enschede and attached to average-sized street lantern poles, the mounting system of the mount needs to be of high-quality to cope with both the weight and environmental stresses. A base plate design needs to have the ability to be mounted onto different kinds and sizes of poles and surfaces. The system needs to be both adjustable and modular. The base plates will mount the several sensors and enclosure. In this way, the different sensors can be easily placed on the base plate allowing for a variety of sensors while still maintaining strength.

Although the main criteria is to mount an MMS on a 6-meter tall pole at the height of 3 meters, having the ability for the system to be mounted to walls can be useful for the various locations discussed with Wim Timmermans. Figure 47 depicts the initial mount design; the base plate can be installed with clamps but also with straps, screws, and tie rips depending on the preferred deployment: long-term or short-term.

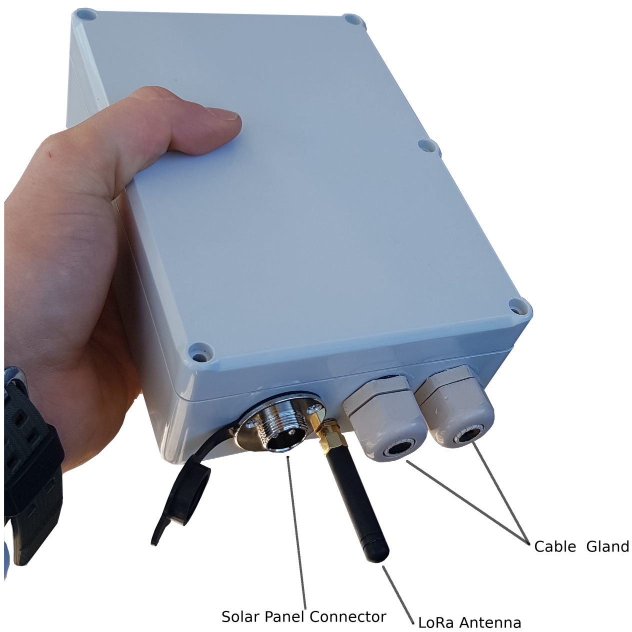


Figure 46: Enclosure with installed connectors, and cable glands

Although the first base plate depicted in figure 47 and figure 48 seems to work accordingly with different sized poles, the base plate needs to be improved. The current design is too bulky, and contains few design mistakes.

Additionally, to mount the radiation-shield and the solar radiation sensor

Figure 47: Initial mounting prototype design

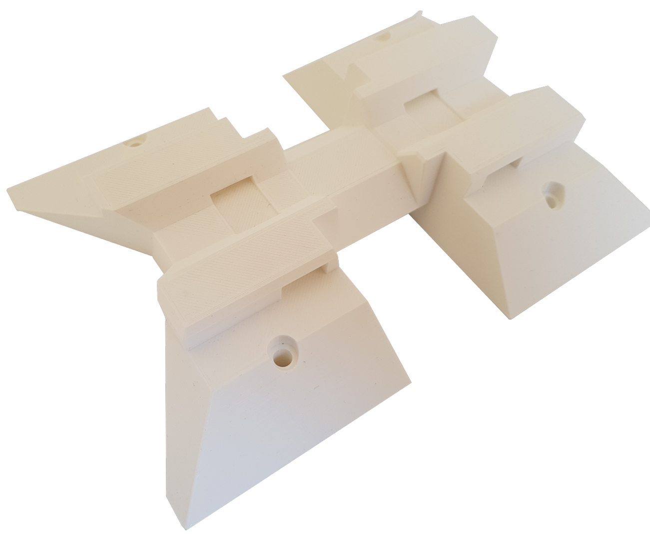


Figure 48: Initial mounting prototype - enclosure base plate

holder, a base plate depicted in figure 49 is made. The sensor mount base plate will be located other side of the poles. In this way, the entire system can be placed around the pole using clamps. The main contact point will primarily be on both base plates. Moreover, both base plates can be separated when necessary, providing more placing freedom on the pole to optimise measurement quality.

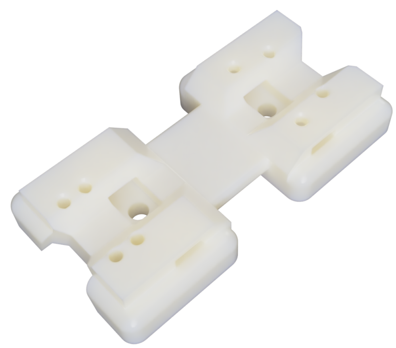


Figure 49: Initial mounting prototype - sensor base plate

6.4.3 Sensor mounting

In section 6.2, the radiation shield design was introduced. The shield was printed using a Creatily Ender 3 with a 0.4mm extruder width. Both the BME-280 sensor and the SHT31 were mounted to the internal sensor holder. As can be obtained from the figure 50 a JST-XH connector is introduced to add modularity and easy replacement. To ensure sensor sub-system stays in place, a small drop of hot glue is used. On the other side of the same sensor probe, the BME-280 is mounted. Figure 51 depicts the place mount of the sensor on the probe. The criteria are the same for the SHT31. A four-pin JST-XH connector is used to add modularity and to connect the sensor with the main wire, a UDP cat-5 cable of 1 meter. The cable has eight wires, four dedicated to each sensor on each side.

The Davis-6450 will be mounted on a custom 3D printed holder, which can be seen in figure 52. This main holder will be attached to one of the mount base plates using M3 nuts and bolts. The sensor comes with three springs ensuring the sensor can be leveled.

6.4.4 Circuit design

The current design includes a TTGO Esp32 Oled LoRa V1.0[68] as the primary interface for the sensors. A full circuit design around this micro-controller can be found in figure 53 and the Appendix F. The tool used for the schematic design is EasyEda[9], which offers a user-friendly interface for schematic designs.

[9] https://easyeda.com/nl

Figure 50: Sensor probe with SHT31

Moreover, a broad user library of electronic components is available, ensuring almost all the components are on the platform. For future works, the schematic design can be converted to a custom PCB, which is a necessity when building a large number of sensor nodes.

Figure 51: Sensor probe with BME-280

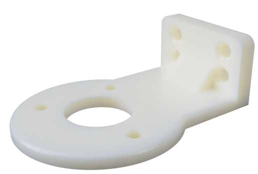


Figure 52: Solar radiation mount for Davis-6450

Interfacing of Davis-6450: The Davis-6450 solar irradiance sensor subsystem comes with an RJ-11 male connector. The analog sensor returns a voltage proportional to the solar irradiance. Therefore, a female RJ-11 connector break-out module by Spark-fun is used to interface with the sensor. This ensures that the sensor can be easily replaced. As can be seen from figure 53 a BS170 MOSFET is used to enable/disable the sensor system. The analog pin is connected to pin 36 on the TTGO, and the control pin is connected to pin 12 to enable or disable the particular sensor.

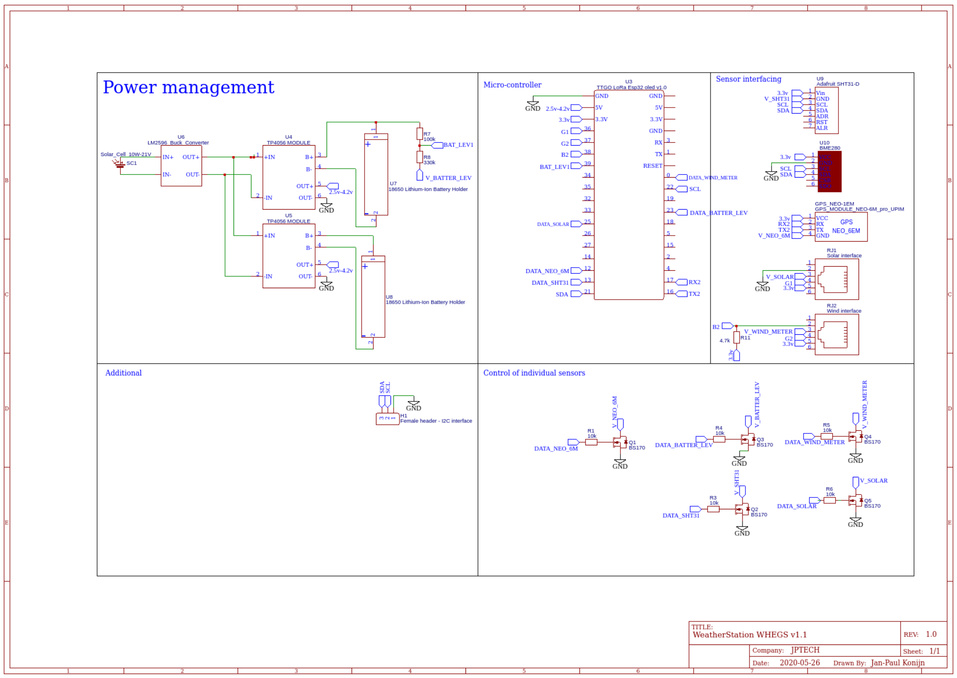


Figure 53: Initial circuit design (See Appendix F)

Interfacing of Davis-6410: The Davis-6410 wind sensor sub-system comes like the solar irradiance sensor system with an RJ-11 4-wire male connector. Two wires are dedicated to output signals for both the wind-direction sensor and the wind-speed sensor. The wind speed pin requires an additional pull-up resistor of 4700Ω to ensure no floating-point input signal [84]. In order to connect the main RJ-11 connector, a Spark-fun break out module within combination with RJ-11 6 pin connector is used. Although this can be considered a more temporary solution, this can be integrated into the PCB in future works. To retain power consumption and to integrate for graceful degradation, a BS170 MOSFET is connected to the ground terminal, as can be seen in figure 53. The wind speed sensor contains a reed switch that provides a high or low value depending on the cup anemometer's turns. The current configuration detects the moments at which the signal is low. Each time from high signal to low signal is counted as a rotation. The Formula for the speed of the anemometer is given by; $V = P(2.25/T)$ in mph [84]. To convert the value to m/s this value can be multiplied with 0.447 to get speed in m/s. This can be performed on the micro-controller, to detect the rising or falling edge internal interrupts are used to count the rotations in a certain interval.

Although the wind-direction is out of scope for this research, the current design allows us to read the wind direction value. The wind-direction signal is an analog variable output since it implements a potentiometer, which provides an analog value proportional to the position of the wind vane.

For wind-direction, the process is quite straight forward; the analog output is connected to one of the analog pins on the micro-controller. The 12-bit analog to digital converter on the micro-controller with gives a range of 0-4095, according to the position of the wind vane.

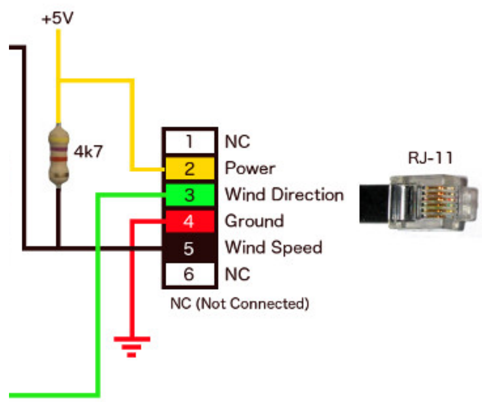


Figure 54: Davis-6410 wire configuration [84]

Interfacing of SHT31: In the specification phase, the SHT31 module was picked temperature and relative humidity sensor subsystem for the MMS. The sensor sub-system applied in the system is an Adafruit module that is calibrated and performs onboard relative humidity calculation accessible over an I2C bus [85]. The TTGO ESP32 Oled LoRa v1.0 I2C pin allocation is the pin 22 SCL and pins 21 SDA. These pins are directly connected to the I2C pinout of the SHT31. To implement the graceful degradation option and power efficiency, the sensors individually connected to a BS170 MOSFET. With the use of the GPIO data pins on Esp32, each sensor can be activated and disabled individually to achieve power retention.

Interfacing of NEO-6m GPS: The NEO-6m GPS can receive data from satellites and provides accurate location data and UTC time data. The module features a UART serial communication bus. There are three hardware serial busses on the ESP32 starting from UART0; in this case, UART2 will be used to interface with the GPS module. Pin allocation of the RX and TX pin is GPIO 16 for the RX pin and GPIO 17 for the TX pin. In order to retain power consumption and alow for graceful degradation, an additional BS170 MOSFET is used. The pin allocated for the GPS control pin is set to GPIO 12.

Interfacing of BME-280: The by Bosch developed BME-280 features an I2C bus with the address $0x76$. Interfacing is on the same bus as the SHT-31, connecting the pin 22 to SCL and pint 21 to SDA. Although both sensor are on the same bus, they can be accessed using different addresses given by the I2C protocol. According to the datasheet, the BME-280 features a $0.1\mu A$ in sleep mode [86]. Due to the low-power state that the sensor subsystem features, no additional BS170 MOSFET is required. Whether this is correct will need to be evaluated. The mount to sensor probe has been introduced earlier but can be found in figure 51. The sensor requires a 3.3 supply voltage, which is delivered by the TTGO ESP32 3.3v rail, as can be seen from the main schematic in figure 53.

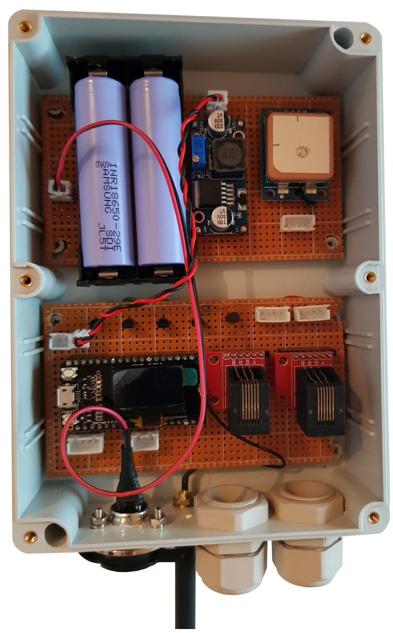


Figure 55: Inside Enclosure

6.5 Second prototype

6.5.1 Circuit design

Several updates have been performed regarding the circuit design, update on the power system, extra pull-up resistors for a reliable I2C. The findings and changes are elaborated below.

Power system: After a discussion with both Richard Bults and Hans Scholten, some adjustments were advised regarding the power system and charging of both lithium cells. In the previous configuration depicted in figure 53, Two TP4056 are configured in a parallel connection, although at first sight, this seems to be fine as the main supply voltage are equal. Situations can occur in which one TP4056 module takes over the other due to the parallel connection. Moreover, if, in any case, there is a voltage difference between the two cells, problems with the modules can occur. Therefore, an iteration of the circuit design has been done. Instead of using two TP4056 modules, one module will be used to charge both cells in parallel, as can be obtained from figure 58.

Additionally, the previous schematic measures the battery voltage directly on positive battery output, in the updated version of the schematic voltage will be measured on the output of the TP4056. This ensures that the battery is protected against over-discharge caused by directly connecting to the microcontroller's input pin.

I2C bus capacitance: Since the primary wire for the I2C bus is the UDP cat-5 cable with a length of 1-meters, additional capacitance is added to the I2C bus interface. Although the main modules, SHT31 and BME-280, come with built-in pull-ups resistors, the size of both resistors is not sufficient to cope with the capacitance created by the long wires, connectors, and pins. If pull-up resistors are too high, the logical high may not be reached before a logical low. In this way, data is lost [87]. Moreover, if the pull-up is too high by the implementation of small resistors values, the modules might not be able to drive the signal low, and data is lost. The behavior of the I2C bus can be described by a resistors capacitor circuit given by equation 3.

$$V(t) = V_{cc}(1 - e^{-t/RC}) \tag{3}$$

The minimal pull-up resistor value can be calculated using the equation 4. With V_{cc} being the 3.3v voltage supply and the V_{OL} being the Low-level voltage which is 0.4 [87].

$$R_{p(min)} = (V_{cc} - V_{OL})/I_{OL} \tag{4}$$

For the maximum pull-up resistor value the equation 5 can be used [87]. The pull-up resistor is a function of the rise time t_r and the bus capacitance given by C_b.

$$R_{p(max)} = t_r/0.8473 * C_b \tag{5}$$

Based on the I2C metrics depicted in figure 56 the graph depicted in figure 57 can be plotted.

During the development, the universities' labs were closed, and no measurements could be taken regarding the bus capacitance. With unknown capacitance value for the bus, the values could not be calculated. With the provided graph depicted in figure 57 and testing the size of the pull-up, resistors were decreased until stable reading from the SHT-31 sensor sub-system could be obtained. In the initial schematic, the pull-up resistors are not included. However, in the new schematic should be included. There should be noted that the values are

	Parameter	Standard Mode (Max)	Fast Mode (Max)	Fast Mode Plus (Max)	Unit
t_r	Rise time of both SDA and SCL signals	1000	300	120	ns
C_b	Capacitive load for each bus line	400	400	550	pF
V_{OL}	Low-level output voltage (at 3 mA current sink, $V_{CC} > 2$ V)	0.4	0.4	0.4	V
	Low-level output voltage (at 2 mA current sink, $V_{CC} \leq 2$ V)	–	0.2 x V_{CC}	0.2 x V_{CC}	V

Figure 56: I2C metric [87]

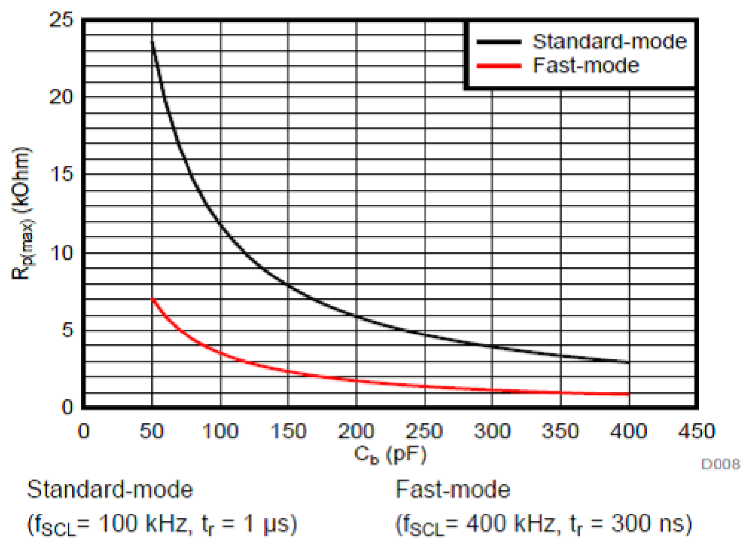


Figure 57: Pull-up resistor graph [87]

a function of the bus capacitance. Therefore, it deviates according to the type of wire, length, and quality. It might be more beneficial to make the bus capacitance as low as possible by having better wiring or smaller sized cables in future designs.

A pull up resistor value of 1625Ω seems to be stable. This was reached by starting with a value of 6500Ω and adding 6500Ω resistors in parallel to the starting resistors. In this way, four resistors of 6500Ω on both the SDA and SCL seems to work accordingly. Based on the figure 57 there can be seen that bus capacitance is $\geq 300pF$. Currently, the BME-280 is not connected since this adds more capacitance and makes the bus unstable. A solution to this does not have a separate bus for the BME-280 and SHT-31 to the sensor probe, as currently is used, but use one dedicated I2C bus to the end of the probe to ensure lower capacitance.

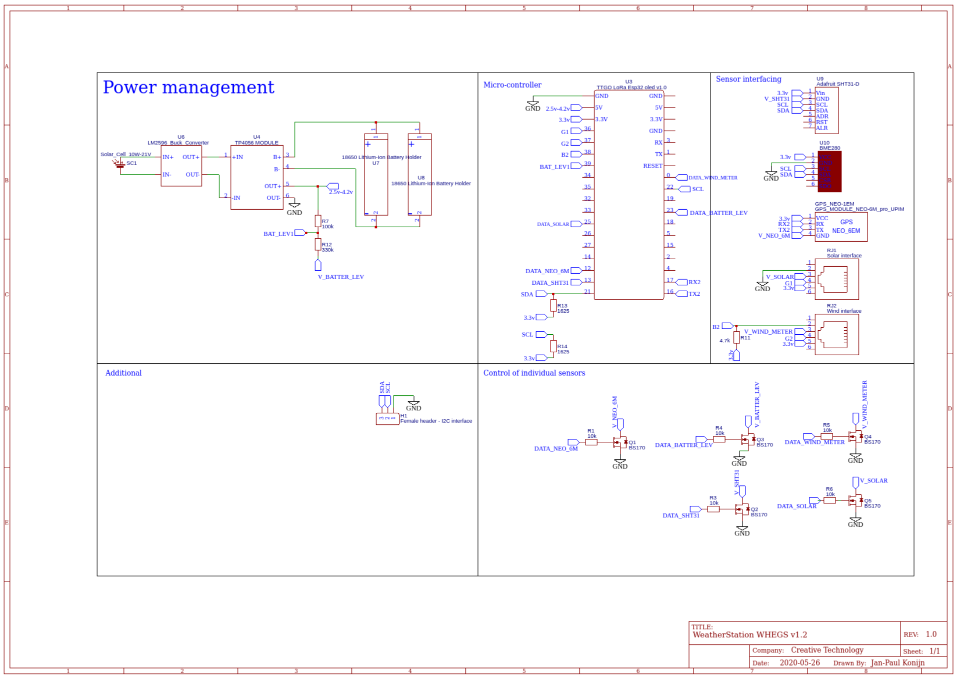


Figure 58: Updated schematic (See Appendix F)

6.5.2 Mounting system

Several updates regarding the mounting system have been implemented and are elaborated below.

Standard mount size: The initial base plate for the sensor had various sizes for the screw holes. In the second, prototype a standard size for all sensor holders is introduced. Size can be seen in figure 59.

Pole mount system: From the initial base plate design depicted in figure 47, an iteration is performed. Although the initial design was primarily to test if the proposed clamp idea would suffice the pole mounting system of various sizes poles, which worked accordingly. However, several points are changed with regard to the initial design. The body of the first base plate wasted 3D-printing resources while not adding to the base plate's structure and strength. Furthermore, the Kradex enclosure has nobs located at the bottom of the enclosure that caused space between the base plate and the enclosure. This has been taken into account in the new design shown in figure 60 and figure 61. Additionally, a mounting option for the Davis-6410 has been added. This can be seen in figure 61 were the top part has openings on both sides; allows the Davis-6410 to be installed on both sides depending on the placement preference. Two additional holes are present in the design allowing for nut and bolts securing the

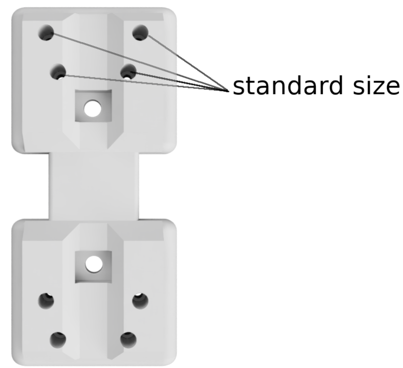


Figure 59: Mount size (See Appendix G)

Davis-6410. The middle part is the same as the initial design, as it proved to be beneficial for strap or tie-rips mounting. Moreover, it reduces the amount of printing material.

To ensure optimal solar charging, the placement of the solar panel is essential. The solar panel mount is based around the same base plate for the radiation shielding and the solar radiation sensor. With the use of a wood bracket angled at 30° as this would be the best position of a solar panel [88]. Figure 62 depicts the mount to the solar holder, with the use of nuts and bolts, the solar panel is mounted to the base plate using M3 sized nuts and bolts.

Mount pyranometer Peter van der Burgt:

Peter applies a Els Spelsberg enclose of 162 x 82 x 85 mm [89]. To have the option to securely mount Peter's developed pyranometer an additional mount, depicted in figure 63 for his enclosure is made. The mount features standard mount sizing to have the ability to be mounted to the base mounts.

6.5.3 Software design

Firmware design for MMS: The firmware developed for the MMS is developed using the Platform.io [59] extension in Visual Studio Code [58]. The firmware architecture can be found in figure 42. In this part, additional choices will be elaborated in accordance to the firmware design.

Deep-sleep is used to facilitate a lower power consumption when no transmis-

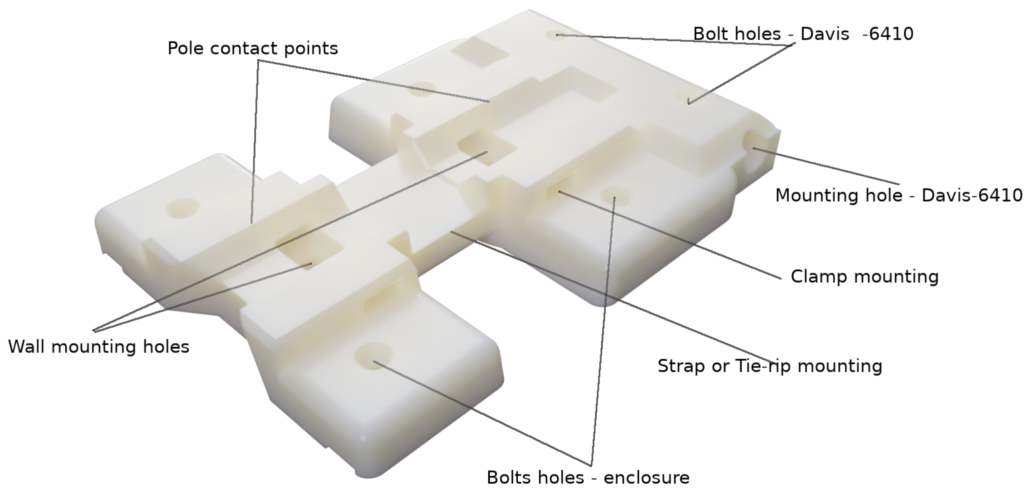


Figure 60: Initial circuit design (See Appendix G)

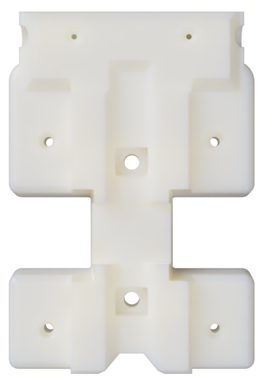


Figure 61: Initial circuit design (See Appendix G)

sion or measurements are taking place. Larger data structures can not be stored in the micro-controller's main volatile memory when going to deep-sleep mode. The Esp32 has two overlapping forms of non-volatile memory required for storing data in non-volatile memory. The types for non-volatile memory featured by the Esp32 are; EEPROM and Flash-memory. EEPROM memory has 512 ad-

Figure 62: Pole mount (See Appendix G)

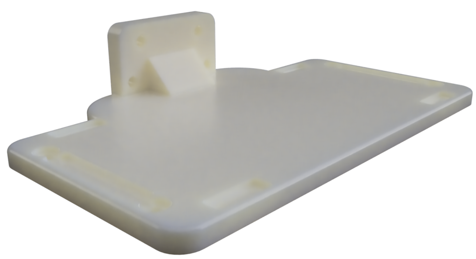


Figure 63: Mount for Pyranometer (See Appendix G)

dresses, with each allowing for 1 byte of data, while flash-memory enables 4MB of memory depending on the Esp32 board type. Both types of memory have a limited amount of reading and write cycles. The Esp32 does not feature true EEPROM but emulates EEPROM by allocating it on the flash-memory [90]. Even if there is a major difference between the flash-memory and EEPROM in terms of write cycles, it does not apply for the Esp32 as both are flash-memory in essence. Whether the read/write cycles of the flash-memory chip are sufficient for reliable long-term operation needs to be tested in future works.

The current data structure uses 3 main files allocated at the Flash-memory, using the serial peripheral interface (SPI). The format uses the widely applied JSON data format. Each allocation and its use is given below.

- /Senddata.json: data storage of averaged values
- /Tmpdata.json: data storage of 12th-second values
- /Data.json: data storage of TTN and device configuration

For both the senddata.json, and the tmpdata.json the data structure is given in figure 64.


```
{
  "measurement_data": {
    "temp": [
      21.74,
      21.68,
      21.7,
      21.71,
      21.71
    ],
    "humid": [
      68,
      68,
      68,
      68,
      68
    ],
    "solar": [
      0,
      0,
      0,
      0,
      0
    ],
    "wind": [
      0,
      0,
      0,
      0,
      0
    ],
    "counter": 5
  }
}
```


Figure 64: Storage architecture non-volatile memory

Server design: The TTN API provides an MQTT interface which is interpreted by Node-Red [91] to parse the data into a time-series based database; InfluxDB. The topic which the MQTT interpreter listens to is +/devices/+/up, which provides us with the decoded payload send by the MMS. The decoder has been made in cooperation, and primarily is written by Peter van der Burgt. The decoder detects when there is no timestamp included because of the failure of the hardware or a slow-response by the GPS. If no timestamp is detected, the timestamp of the payload arrival at the gateway is used. In this way, no data is lost. The Node-Red flow used for parsing is depicted in figure 65. Additionally, current flow provides a manual input for parsing values from the Davis Vintage pro 2, which have to be read and parsed manually into the database.

InfluxDB, Node-Red, and Grafana run on a Docker-compose stack and can be easily scaled and enabled using a few commands terminal commands. The Linux Debian server is located at the University of Twente campus and is remotely accessible using SSH. The current retention policy of InfluxDB is set to the default of 7 days, after which data will be deleted to ensure enough storage on the device.

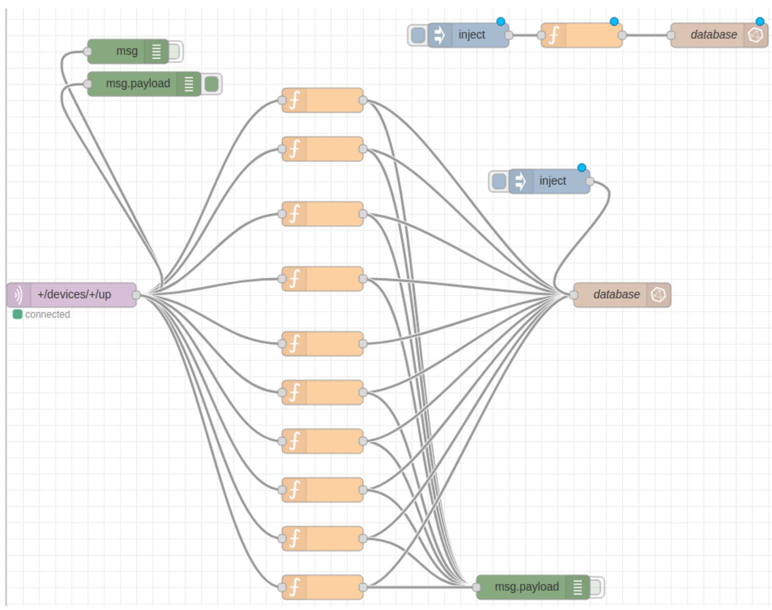


Figure 65: Node red flow for data parsing

6.6 Final prototype

The final prototype before the evaluation is depicted in figure 66. All the different components, solar panel and sensors subsystem, are based on a PVC pipe to simulate the street lantern pole. The advantage of this prototype is that the three mounts configuration is configurable according to position requirements. Various combinations can be made to ensure each component is placed to maximise reliability and data quality. Base plates can be combined with separated.

Moreover, all the base plates allow mounting to walls as well. With the use of various camp sizes, the systems can be attached to different diameters of poles. The final prototype does not feature additional rubbers on the inside to avoid corrosion on painted poles. However, this feature can be easily added if required. The total pricing and parts listing is provided in table 66.

Parts list overview		
part	amount	price (euros)
TTGO Esp32 Oled LoRa V1	1	17.5
10-Watt Solar panel	15	15
Lithium cells - Samsung 18650	2	5.5
Kradex enclosure 176x126x57mm - IP65	1	7.00
GX connector	1	2.75
RJ-11 connector	2	5.6
2s battery Holder 18650	1	2.5
Adafruit SHT31	1	13.95
Prototyping PCB	1	0.8
BS-170 MOSFET	5	2.5
Clamps 10mm	4	24
Female headers	1	4
3D-printing material	1	10
Davis 6410	1	184.95
Davis 6540	1	195.00
GPS neo-6m module	1	8
Bosch BME-280	1	4.5
M3-nuts and bolts	1	5
incl VAT excl VAT		508.55 420.29
Over budget		20.29
Integration with Peter van der Burgt		
incl VAT excl VAT		313.55 259.1

Table 10: parts overview and pricing

Figure 66: Final protoype MMS

7 Evaluation

In the evaluation results of the final prototype are logged and evaluated. The evaluation will consist out of three parts; Comparison with Davis Vintage pro 2 reference system, Evaluation of eight days operation and evaluation of TheThingsNetwork for wireless data communication.

7.0.1 Testing setup

The Covid-19 virus required a creative testing procedure. For the evaluation, two primary testing setups have been used and are elaborated below.

Initial testing setup: to test the MMS for its reliability, measurements data, and operation. The system is placed in a garden at a height of 1.90m above the grass, as can be seen in figure 67. Although the system is located considerably further from other objects, it still should be taken into account. In the current setup, trees and a small building are present that might influence the measurements. To be specific, two trees are present at a distance of 6m and 10m. A building is located at 9m from the MMS location. The setup is not following the measurement requirements set by the KNMI book for measurements. The sensor shield points to the east to ensure it is not located above the hedge and, therefore, not influenced, this is also depicted in figure 67.

However, as for the Covid-19 situation, it is the best option. Since no controlled environment testing could be performed, the system will be exposed for eight days in an outside environment, ensuring exposure to different weather conditions, such as various humidity levels, rain, sun, cloudy weather, and high ($> 30°C$) and low temperatures. The measurements are taken starting from 19th June 2020 00:00, to 26th June 2020 23:59. In this way, a prolonged operation like operation in the urban environment, which the system is designed for, is simulated. The solar panel is pointed towards the south to ensure optimal energy generation for reliable operation. Besides, focusing on the meteorological data generated by the MMS, metadata will be analysed to evaluate the performance and reliability of the TTN.

Test setup with Davis Vintage pro 2: for data comparison, the Davis Vintage Pro 2 is located at a 53cm distance from the MMS. The housing is located at a height of 130cm and the cup-anemometer at the height of 220cm, this can be seen in figure 68.

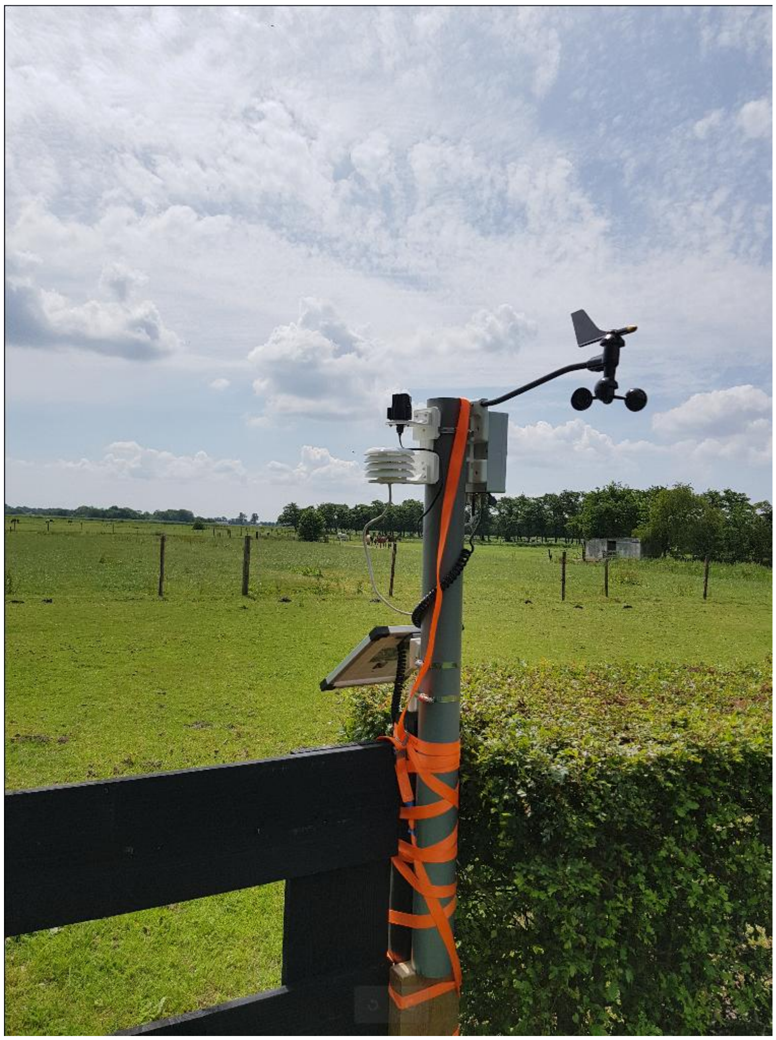


Figure 67: Initial setup

Figure 68: Second setup with Davis Vintage pro 2

7.1 Data comparison with Davis Vintage pro 2

Data of both the MMS and Davis vintage pro 2 was recorded for two days; June 19 and June 20. Starting at 9.00 to 16.00 every ten minutes, a measurement was taken from the Davis vintage pro. Data can be obtained from the Davis Vue console, which comes with the reference system. Unfortunately, it does not provide direct interface to access the data using a computer. The additional manual monitoring of measurement made the test more prone to mistakes and faulty data-points. While the data was manually inserted to database, variables could deviate already making measurement not precise. Especially for volatile variables like wind speed measurements and solar irradiance measurements, this seemed to be a concern. On June 19, the Davis reference system was located at a distance of 44 meters of the MMS. This resulted in a considerable difference in the results. Therefore, an additional test on June 20, 2020, was done using the setup described in section 7.0.1 to ensure better test quality.

7.1.1 Results June 19

Results for each parameter of June 19, 2020, is provided below. Note the setup difference with June 20. The data is provided in graphs, the green graphs indicates MMS measurements data, and the yellow graphs indicate the Davis Vintage pro 2 measurements data provided by the Vue console that comes with the reference system.

Temperature: for temperature measurements, the resolution for the MMS is better compared to the reference data. The Davis vintage pro reference system provides only integer values, which can also be seen in figure 69. There are occurrences where data is lost; this is depicted by the open spots in the green graph. During the measurements of 19 June 2020, the most extended missed interval of packets started at 10:04:38 at which the last packet was received until 10:51:17 at which a new packet arrived. This means the maximum interval of lost data took 46 minutes and 39 seconds. Generally, the temperature values returned by the MMS deviate more since the MMS temperature and relative humidity sensor sub-system are more exposed to the open.

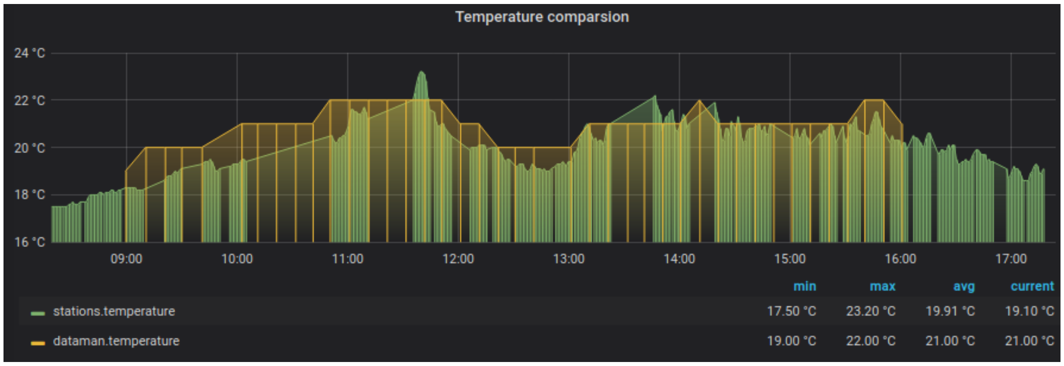


Figure 69: Temperature results

Solar irradiance: from figure 70 directly, a considerable difference can be noticed marked by the blue line at the start of the graph. The green graph indicates the MMS measurement data and the yellow graph the Davis reference system measurements data. As earlier explained, the location difference of both systems resulted in the MMS solar sensor sub-system being affected by shadows or the objects around the MMS location. Moreover, the mentioned data loss of roughly 47 minutes resulted in missing data with regards to the shadow moment. At the lower ranges, the MMS provides us with generally a negative offset compared to the reference system. While at the higher ranges, the MMS provides a positive offset compared to measurements of the reference system.

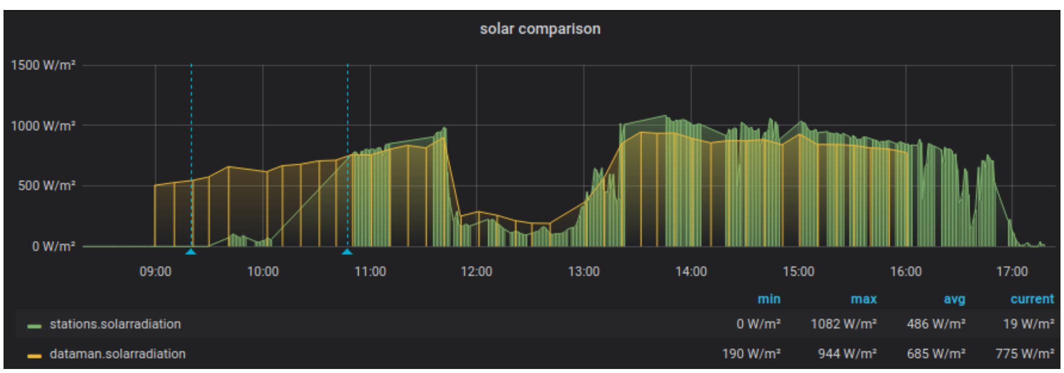


Figure 70: Solar irradiance (green:MMS, yellow:reference)

Relative Humidity: when comparing the graphs for humidity data, the importance of positioning can be viewed. On 19 June, the reference systems were located at pavement while the MMS was directly above the grass. Although, both follow the same line still deviations present. This is most likely caused by the evaporation above the grass. The most significant difference being up-to 4%.

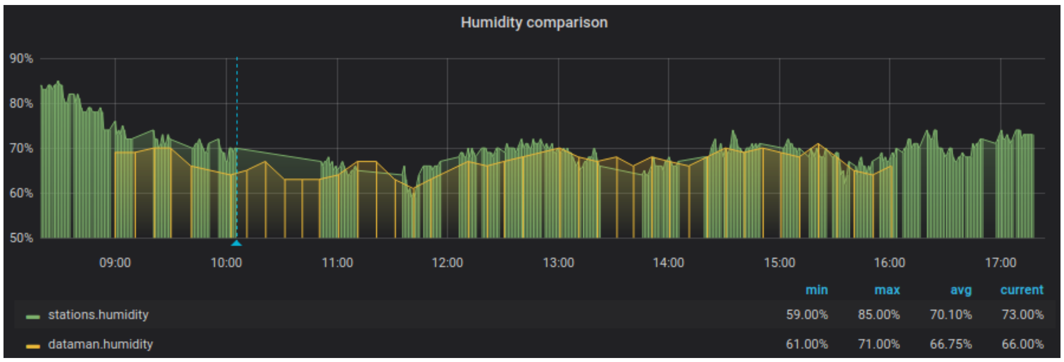


Figure 71: Relative Humidity results (green:MMS, yellow:reference)

Wind speed: for the wind data depicted in figure 72 a clear distinction is noticeable. For the test, the reference system was heavily influenced by the building surrounding the reference system. Therefore, data can not be used to perform an evaluation on. A new test is required to test the wind speed variable.

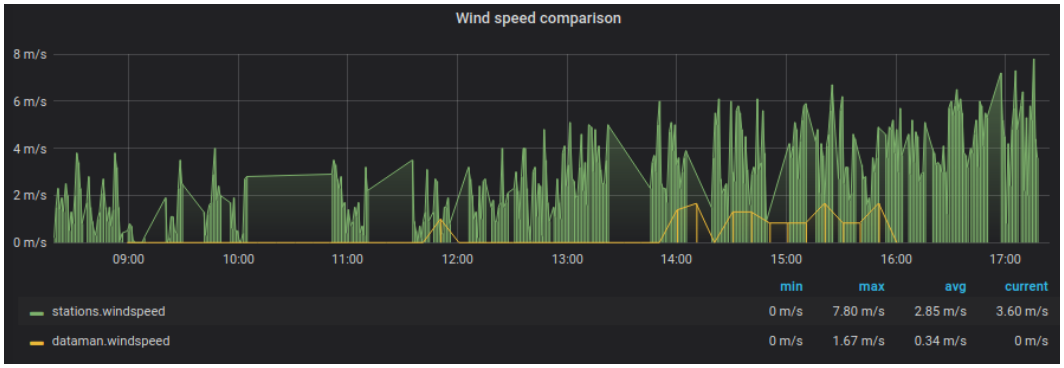


Figure 72: Wind speed results (green:MMS, yellow:reference)

7.1.2 Results June 20

Results for each parameter of June 20 2020 is provided below. After the result of June 19, the test setup was improved. As described at section 7.0.1. The data is provided in graphs, the green graphs indicates MMS measurements data, and the yellow graphs indicates the Davis Vintage pro 2 measurements data provided by the Vue console that comes with the reference system.

Temperature: comparing the MMS data to the Davis Vintage pro 2 data, there can be stated that the resolution is better. During the measurement staring at 9:00 up-to 16:00, a maximum temperature of $21.40°C$ was obtained by the MMS. The reference system provided a maximum value of $21.00°C$, during the same measurement interval. This shows a better resolution comparatively. The Davis reference system returns values with a resolution of $1°C$. In contrast, the MMS has a resolution of $0.1°C$. The most significant difference between the reference system and the MMS is reported at 14:54:52 with a difference of $1.1°C$. Why there is such a difference is unknown. Several causes are proposed; update-rate or measurement frequency of reference system is different, the MMS solar radiation shield is smaller, therefore, can pick up temperature differences faster or the larger sized radiation shield of the reference system is less venerable to inside heat build-up. Despite, these small deviations, the MMS can be considered to be accurate. The data is not sufficient to provide a number of accuracies. This will be later elaborated.

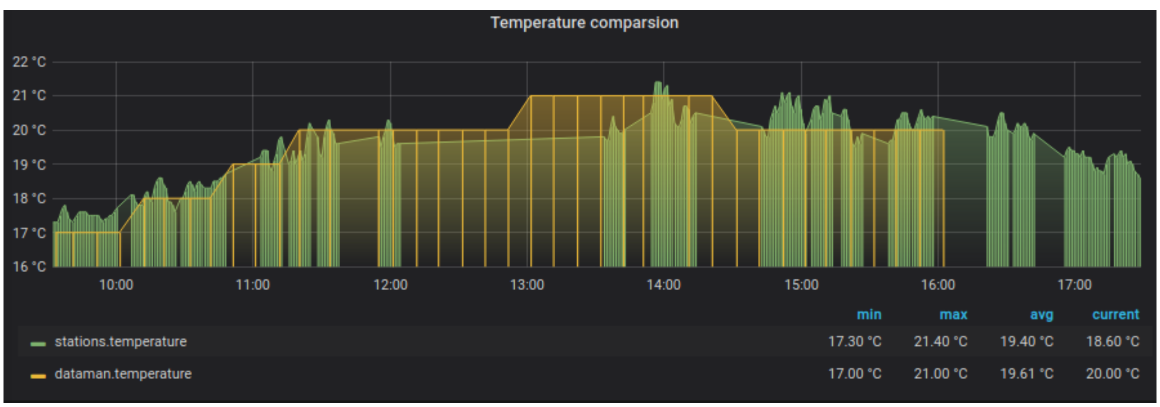


Figure 73: Temperature results (green: MMS, yellow:reference)

Solar irradiance: based on figure 74 still the occurrence of shadow can be noticed. Although both system are located at a distance of 53 cm, the trees still influence the solar measurements. At 11:00:00, both systems were fully exposed to maximum solar radiation. Figure 74 depicts the longest packets loss during the measurement interval; the loss interval starts at 12:03:58 up-to 13:33:36, meaning no data was received for 1 hour, 30 minutes, and 36 seconds. After 11:00:00 until the end of the measurement at 16:00, a clear positive offset between data from the reference system and the MMS data is present. The largest difference is at 12:00:58 where a total difference of $79W/m^2$ recorded. The ESP-32 ADC has a non-linear curve, which could have caused the compared offset to the reference system.

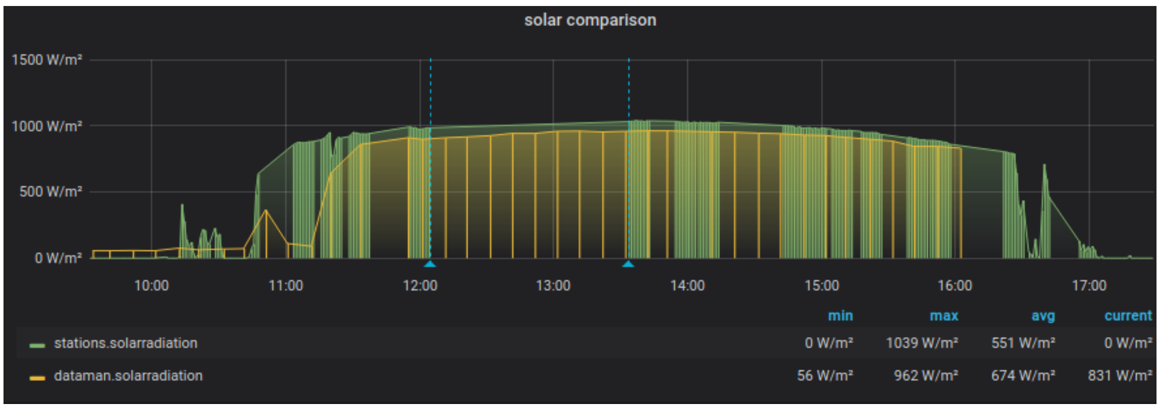


Figure 74: Solar irradiance results (green: MMS, yellow:reference)

Relative Humidity: the sensor sub-system for humidity and temperature is located 50 cm higher compared to the Davis reference system. Figure 75 depicts the data for humidity. The biggest difference for humidity is recorded at 14:52:01, with a total difference of -6% compared to Davis Vintage pro 2. The MMS seems to pick up humidity changes faster compared to the Davis Vintage pro 2. Generally, the Davis vintage pro 2 seems to provide a positive offset compared to the MMS. There should be taken into account the position of the Davis. The reference system is closed to grass. This has probably resulted in additional local relative humidity difference.

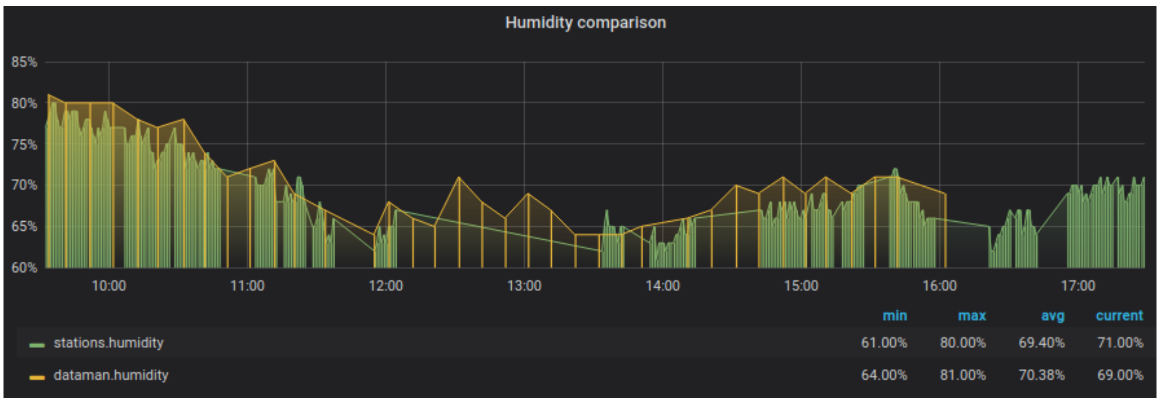


Figure 75: Humidity results (green: MMS, yellow:reference)

7.2 TTN for wireless data transmission an evaluation

Part of this Graduation Project was executed together with Peter van der Burgt. The cause of this lies in the overlap regarding the integration of the autonomous aspect of both graduation projects. To make sure that the work was not done twice, the supervisors advised cooperation on the execution of the autonomous aspect of both Graduation Projects. This includes wireless communication capabilities of the systems, communication protocol, as well as the battery management system and the time and location data.

The MMS is located in the area of Alkmaar, North-Holland the map depicted in figure 76 indicates the gateways surrounding this area. The measurements for the sending of data over the LoRaWAN network were done over the course of four days, starting at the 19th of June 2020 00:00 until 23rd of June 2020 00:00. Figure 76 depicts the current location of the MMS at the purple square.

Figure 76: The location of the MMS and Gateways around Alkmaar.

During this time, a total of 576 packets were successfully transmitted, and out of this, 316 packets were successfully received. This means that approximately 55% of all packets were transferred successfully.

The reasons for this packet loss can be attributed to multiple factors. These factors all have to do with the reliability of the connection of the LoRaWAN network. This can also be seen in the metadata of the packets that were sent later, as the Received Signal Strength Indicator (RSSI) value for these packets varied around the -120dB mark, indicating that the connection was very weak. Possible factors for this are the antenna and the distance between the node and the gateway. The antenna could be improved to increase the range that it could cover. As of now, it is a relatively short omnidirectional antenna. This means, for example, that the antenna could be designed to reach further over the horizontal plane, and less further in the vertical plane, as well as being longer. When this is used, it should be made sure that the antenna is mounted correctly, as this could negatively influence the RSSI when not done correctly.

Another possible solution is to decrease the distance between the gateway and the node. This test was done in the surrounding area of Alkmaar, and as for the testing location, it would be better to also test in Enschede, as Enschede has a denser network of LoRaWAN gateways (depending on the location). If this were not enough, it could be chosen to increase the number of gateways in Enschede.

One of the factors that influence the connection, is the weather. As described by Riegsecker[92], the weather can influence the strength of the LoRa connection. He suggested that humidity is a predictor in LoRa reliability. However, in the experiment done in this report, no suitable evidence was found to support that claim. The weather conditions did not seem to influence the data communication reliability as at 17th of June at 22:08 data packets still arrived with a rain rate of 61.6mm/hr (measured using Davis Vintage Pro 2). Even the days after there seemed to be no clear correlation between humidity and the amount of arrived data packets. The suggested correlation of humidity and signal strength did not seem to correlate with the claims suggested by Riegsecker.

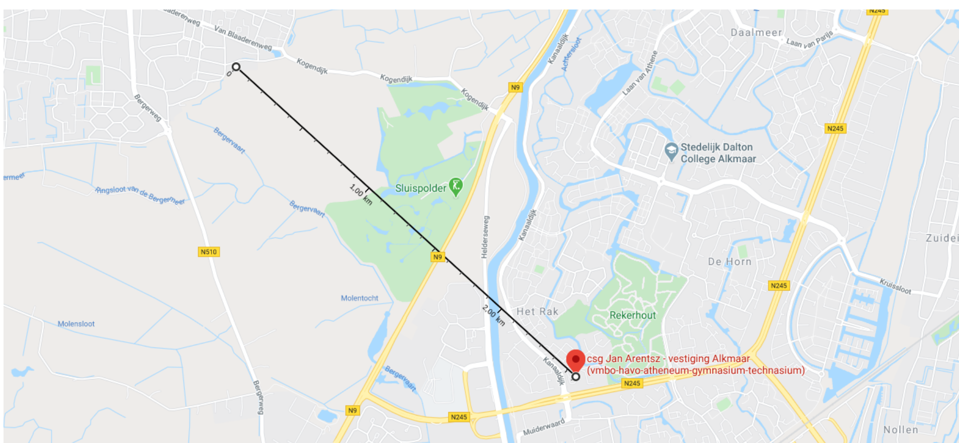


Figure 77: The distances from the MMS to the LoRa gateways.

Another factor that influences the reliability is the distance between the MMS and the TTN gateways. The closest gateway is located at a distance of 2.57 km. This has been measured by using google maps in combination with TTNmapper. Various packets even arrived at the gateway located at a distance of 3.42 km, and 3.2 km as depicted in figure 77, and figure 78.

Figure 78: The distances from the MMS to the LoRa gateways.

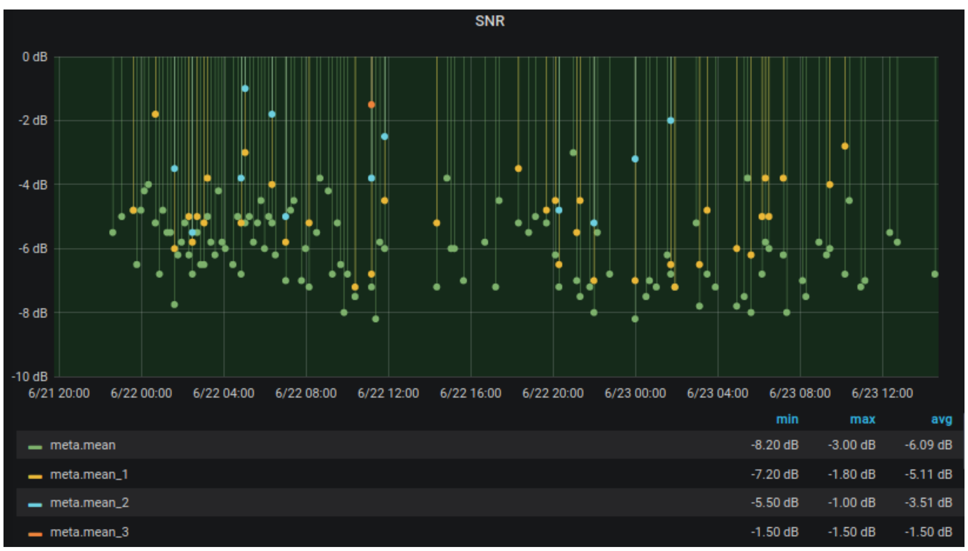


Figure 79: SNR metadata overview

Both the RSSI values and SNR values depicted in figure 79 and figure 80, seem to be the most critical for packets arrival. The longest interval of packet loss was detected on 22 June 2020 the last transmission was recorded at 11:51 up to 14:28 resulting is 2 hours, 37 minutes of lost packets. However, no correlation

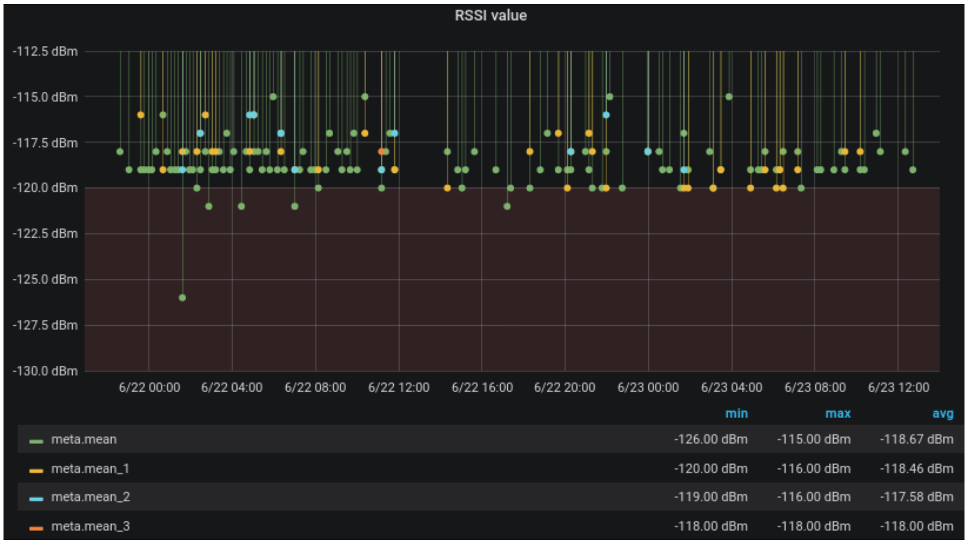


Figure 80: RSSI metadata overview

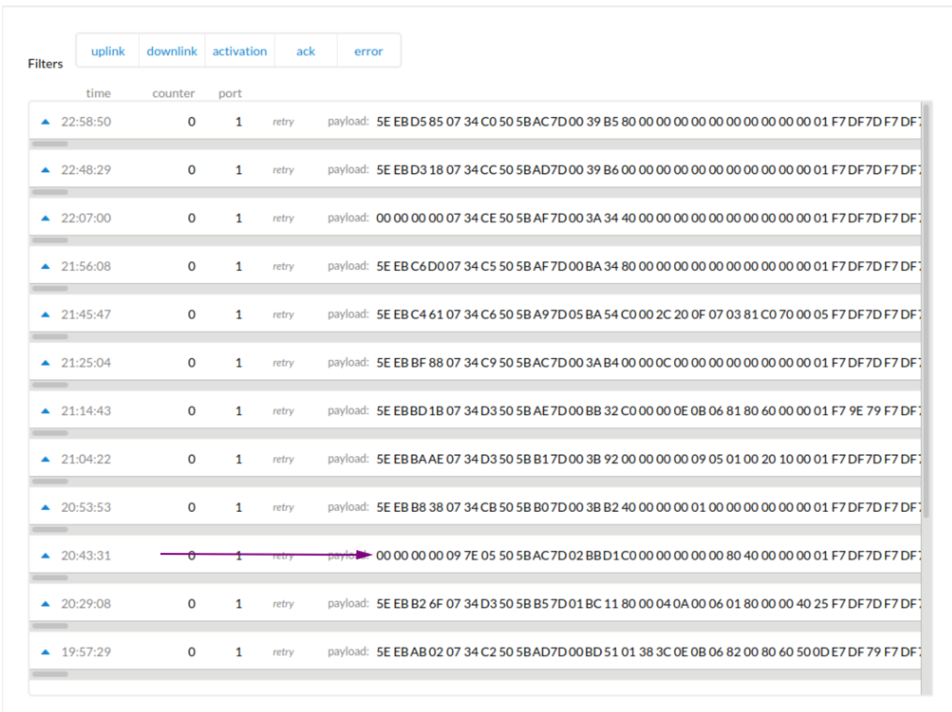
was found between the various variables like; temperature, relative humidity, solar irradiance or wind speed.

7.3 Evaluation of eight days operation

Besides comparison with the Davis reference system, the evaluation operation of eight days will be performed. Measurements are taken starting from 00:00 18 June 2020 up-to 00:00 26 June 2020. During that time, each morning at 10:00, the MMS was opened, and battery reading was taken, using a Fluke Multimeter. During these days, no battery reading of less than 4.0v was measured. Meaning the solar panel is more than capable of reliable operation. Note, that this is measured during summer (June). In addition, the MMS was exposed to; rain, warm weather $> 30°C$, thunder, and high humidity. For humidity, it occurred that reading above 99% will never be measured. Data transmission occurred on average more during the day, with the longest transmission loss being; on 22 June 2020, where last packed was send at 11:58:00, and a new packet was received at; 14:21:00, meaning a total interval of 2 hours, 23 minutes was lost on data.

Occasionally payloads were sent without timestamp or GPS location, as depicted 81. This was fixed by getting the gateways arrival timestamp. However, why these situations occurred currently is unknown, the GPS module serial connection could be faulty prone, or the GPS occasionally requires more setup time. Further research is required to identify the problem. Figure 82 shows the GPS location for recorded during the eight day interval. The location is not more off than 5-meters, during the interval. The GPS location data provides us, therefore, with accuracy of 5-meters.

The mounting system after eight days of outdoor exposure and testing did not indicate any damage or water-intrusion. All the mounts stayed at the same position on the PVC pipe; this suggests that the mounting system can cope with both the stressed and the weight. However, there should be noted that this is important to be tested over an extended period, and more environmental stresses.


Filters uplink downlink activation ack error

time	counter	port		
22:58:50	0	1	retry	payload: 5E EB D5 85 07 34 C0 50 5B AC 7D 00 39 B5 80 00 00 00 00 00 00 00 00 00 00 01 F7 DF 7D F7 DF
22:48:29	0	1	retry	payload: 5E EB D3 18 07 34 CC 50 5B AD 7D 00 39 B6 00 00 00 00 00 00 00 00 00 00 00 01 F7 DF 7D F7 DF
22:07:00	0	1	retry	payload: 00 00 00 00 07 34 CE 50 5B AF 7D 00 3A 34 40 00 00 00 00 00 00 00 00 00 00 01 F7 DF 7D F7 DF
21:56:08	0	1	retry	payload: 5E EB C6 D0 07 34 C5 50 5B AF 7D 00 BA 34 80 00 00 00 00 00 00 00 00 00 00 01 F7 DF 7D F7 DF
21:45:47	0	1	retry	payload: 5E EB C4 61 07 34 C6 50 5B A9 7D 05 BA 54 C0 00 2C 20 0F 07 03 81 C0 70 00 05 F7 DF 7D F7 DF
21:25:04	0	1	retry	payload: 5E EB BF 88 07 34 C9 50 5B AC 7D 00 3A B4 00 00 0C 00 00 00 00 00 00 00 00 01 F7 DF 7D F7 DF
21:14:43	0	1	retry	payload: 5E EB BD 1B 07 34 D3 50 5B AE 7D 00 BB 32 C0 00 00 0E 0B 06 81 80 60 00 00 01 F7 9E 79 F7 DF
21:04:22	0	1	retry	payload: 5E EB BA AE 07 34 D3 50 5B B1 7D 00 3B 92 00 00 00 00 09 05 01 00 20 10 00 01 F7 DF 7D F7 DF
20:53:53	0	1	retry	payload: 5E EB B8 38 07 34 CB 50 5B B0 7D 00 3B B2 40 00 00 00 01 00 00 00 00 00 00 01 F7 DF 7D F7 DF
20:43:31	0	1	retry	payload: 00 00 00 00 09 7E 05 50 5B AC 7D 02 BB D1 C0 00 00 00 00 00 80 40 00 00 00 01 F7 DF 7D F7 DF
20:29:08	0	1	retry	payload: 5E EB B2 6F 07 34 D3 50 5B B5 7D 01 BC 11 80 00 04 0A 00 06 01 80 00 00 40 25 F7 DF 7D F7 DF
19:57:29	0	1	retry	payload: 5E EB AB 02 07 34 C2 50 5B AD 7D 00 BD 51 01 38 3C 0E 0B 06 82 00 80 60 50 0D E7 DF 79 F7 DF

Figure 81: Data payload without timestamp

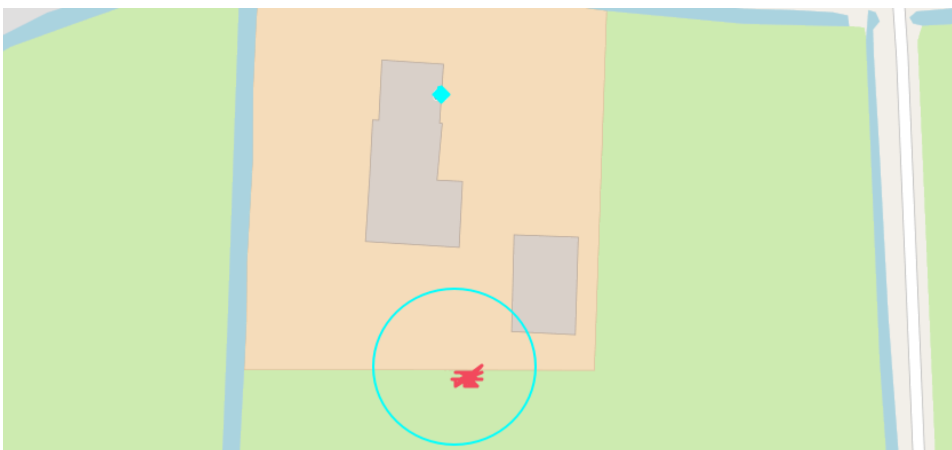


Figure 82: GPS location over eight days (red line)

7.3.1 Evaluation of Requirements

Table 11 and 12 provides an evaluation for each points set in section 5. Unfortunately, due to a poor test setup, and missing data some points can not be confirmed with enough significance. Additional controlled environments testing is required to determine the accuracies for the measurement parameter. However, most of the non-functional requirements are met. For requirements that require long-term testing mostly insufficient data is stated. Some requirements could not be tested due to a time constraint and will be required to be tested in future works later discussed.

Non-Functional requirements:	
Must Have Requirements	Met?
Not exceed the 400 euro threshold	416.98 (excl. VAT), 255.33(excl. VAT) with integration with pyranometer Peter van der Burgt
Measure: temperature, wind speed, relative humidity, solar radiation,	confirmed
Efficient power management	confirmed
Operate autonomously	confirmed
Offer modulartiy for easy sensor replacement	confirmed
Pole mounting system (average sized street lanterns)	confirmed
Withstand the environmental factors	confirmed
Operate for a year without any supervision	Insufficient data
Easy to fix if any problems occur	Insufficient data
Protection for pole mounting	Not included currently, but easy to include
Should Have Requirements	
Graceful degradation	hardware allows for option, but not implemented in software (not required with current solar panel)
Save obtained data in database	confirmed
GPS location integration	confirmed
IP rated enclosure	confirmed (but only circuitry enclosure)
Raw data availability	Not possible with TTN
Could Have Requirements	
Allow for various mount options	confirmed
Sending error reports	Implemented in protocol, but not in firmware
Cayenne LPP for payload management	Not possible
BLE-local for raw data transfer	Not implemented
Over-the-air firmware updates	Not implemented

Table 11: Non-functional requirements table evaluated

Functional requirements:	
Must Have Requirement	Met?
Temperature requirements	
Accuracy $0.5°C$ Range $-30°C + 60°C$ Resolution $0.1°C$	Insufficient data Insufficient, confirmed range ($11.2°C$-$30.7°C$) confirmed
Relative Humidity requirements	
Accuracy 3% Range 5%-100% Resolution 1%	Insufficient data Insufficient data, confirmed range (38% - 99%) confirmed
Wind requirements	
Average Wind speed accuracy $0.1m/s-0.2m/s$ Average Wind speed range $0 - 50m/s$ Average wind speed Resolution $0,5m/s$	Insufficient data Insufficient data, confirmed range (0-10.8m/s) confirmed
Solar Radiation Requirement	
Accuracy of $10W/m^2$ Range $0 - 1800W/m^2$ Resolution $1W/m^2$	Insufficient data Insufficient data, confirmed range (0-$1061w/m^2$ confirmed
System requirements	
Withstand 43.8mm of rain a day for one full year Withstand humidity %37 - %99 Withstand temperature range of $-10.1°C$ to $40.2°C$ Withstand windgusts of $23.3m/s$ ($83.88km/h$) Send at least 10 1-minute average values every half-hour Working according TTN policy[35] Ensure enough power-generation for cloudy day with 8 hours of light Mount size of 16.5mm (diameter)	based on 8 day of data, confirmed confirmed Insufficient data Insufficient data confirmed, but depends on interval, 55% successful transferred payloads confirmed confirmed (never < 4.0v, 10:00 AM) confirmed
Won't Have Requirement	Met?
Barometric pressure requirements	
Accuracy 0.3 hPa Range 940-1060hPa Resolution 0.1hPa	Not tested Not tested Not tested
Wind requirements	
Wind direction accuracy of $\pm 5°$ Wind direction resolution $10°$ Wind direction range $0° - 360°$	Not tested Not tested Not tested

Table 12: Functional requirements table evaluated

8 Conclusion

In this section, the main research question will be answered by answering the two sub-questions determined in section 1.3. Additionally, during the research, challenges and findings came forward that have not been implemented due to time constraints. These discoveries will be elaborated for future developers and designers to come with an MMS that can be applied for scientific research.

8.1 Discussion

The MMS has been operating successfully for ten days without any problems; the system has encountered various types of weather, such as heavy rain 61.6mm/hr, temperature $> 30°C$, and hard winds $14.7m/s$. However, the MMS has not been exposed to conditions like; sub-zero temperatures and hard winds. For future works, the MMS needs to be tested for an extended period of time (at least 6 months) to see whether it can cope with all meteorological stresses of the city of Enschede. As mentioned earlier, due to the Covid-19, no controlled-environment test could be performed, and as a result, a comparison test was performed with the Davis Vintage pro 2. The current setup explained in section 7.0.1 let to a significant packet loss during the two tests. This packet loss resulted in poor quality measurements preventing to come with concluding accuracies for the two testing days. During the evaluation, no explicit accuracies have been stated.

However, in Appendix J the graphs for the theoretical accuracies are provided for each measurement parameter. The manual insertion of data made the test prone to mistakes and is not advised to repeat. Although the setup allowed the systems to be relatively close, the environment's influence, such as trees, and other objects, still seemed to be of significance even at small distances, this reduced the accuracy of the experiment. Since the MMS depends on the TTN for measurement transmission, it can occur that packets are lost during transmission, the setup of the MMS in relation with the gateways in the surrounding area lead to a significant data loss during the testing with the Davis Vintage pro 2 reference system. The distance between the gateway and the MMS seems to be the most important factor for reliable measurements transmission.

As of writing this section, hardware, like the micro-controller, has not operated for more than a month. Especially when using deep-sleep cycles and non-volatile memory, data can be corrupted due to the limited read/write cycles of the memory. The data obtained of the testing is currently insufficient to state enough about this form of reliability; testing for an extended period of time, such as half a year would be required to research if these kind of situations can occur.

This section will further discuss the main research question. The main research question will be answered by first answering the two sub-questions set in section 1.3.

8.1.1 What are the MMS quality requirements?

Initially, this question was categories into two main components; reliability, and data quality. During both the ideation in section 4 and specification phase in section 5, these two components were extensively researched. With the stakeholders, a preliminary overview of requirements was made. The KNMI book for measurements requirements was thoroughly analysed as stakeholders mentioned the necessity to perform measurements that conform with the KNMI measurement frequencies.

The main findings found during the research can be summarised into a few concerns. The MMS system needs to be able to operate at least for a year without any supervision; 24/7 operation with various environmental stresses, such as heavy rain or hard winds. Although stakeholders indicated that the MMS would be supervised by students, the system should still be able to operate for year without any supervision. Meaning the MMS must have the ability to generate enough energy during the darker days, and to cope with the environmental stresses.

Additionally, having the ability to replace components quickly would ensure long-term operation, since parts can be easily replaced. To measure how city infrastructure might affect heat build-up, data needs to conform to the KNMI measurements frequency. In this way, the data of the KNMI (optimal measurement situation) can be compared to the MMS data. To provide Wim with sufficient data for his model, the MMS needs to transfer ten 1-minute averages at least every half an hour. During this research, it has been found that the occurrence of data loss can be longer than 2 hours. With the use of meta-data analysis based on meta-data provided by TheThingsNetwork (TTN), there has been found that with the current LoRaWan module in combination with the antenna, data can be transferred over a range of 2.5-3.5km with a success rate of 55%. The TTN meta-data indicated that range seems to be the main concern for reliable data transfers.

When using the TTN for measurements data transmission, the amount of data essential and must be carefully considered. The stakeholders; Richards Bults and Hans Scholten had a preference for a 12th-second measurement or raw data availability. However, the findings indicated that the fair-use-policy set by the TTN would not allow for such data resolution. A private owned LoRaWan network would allow for more data to be transferred but requires the user to install private gateways in a particular area. Therefore, 1-minute measurement data availability was sufficient for Wim Timmermans. Although this is not raw-data availability, the nation-wide TTN network could be used without installing private gateways. Although losses seemed to occur more during day time, further research is required to verify this claim.

In order to optimise the MMS quality, the environmental factors which play an essential role for its reliability, need to be taken into account, to cope with the influences of the environment and stay operational in different situations. To ensure this an reliable enclosures with preferred IP-rating of IP-33 index is necessary.

8.1.2 How to optimise the MMS cost-quality of measured data?

This question was primarily answered during the specification phase in section 5, and realisation phase in section 6. The combination of the set requirements and the selected hardware within the low-cost aspect resulted in the answer to this question. The system implements off-the-shelf components that have been selected using a sensor survey based on internet findings and state-of-art findings. The combination of low-cost sensors sub-systems, 3D-printed parts, and low-cost hardware provided a reliable system at a price of 420.29 euro, parts given in table 10. During the research, the autonomous aspect of the research has been done with cooperation with van der Burgt. Since van der Burgt's research and this research had an overlap, some work such as the implementation of a custom protocol has been done together. The intent was to integrate van der Burgt's developed pyranometer with the MMS. Due to time constraints, this was not achieved. However, if the systems would be integrated a total price of 260 euro can be achieved, which provides an extra margin to improve the system further in future works.

8.2 Future work

In this section, findings will be provided that allow for future improvement of the project. During the research, elements have been identified that could not be implemented or further researched. However, for future designs, these findings might be of importance to improve the current MMS prototype and elevate it to a final product that can be placed in and around the city of Enschede.

8.2.1 Further develop power system

The MMS has now a considerable large sized solar panel. Since the MMS will be placed in and around the city, having a large solar panel can obstruct the city view. Moreover, as the solar panel is considerably large, it becomes an easier target for vandalism. The tests during the evaluation have proven that with the current power consumption, the solar panel can be decreased in size while still maintaining reliable operation. The size and further specification of this solar panel should be, must be further researched. An additional option is to have the solar panel integrated into the enclosure, which would make the MMS more compact and therefore, more robust.

8.2.2 UV resistant material

The current printing material PLA is not UV resistant, meaning after a while, the material will experience degradation and will get weak. Printing or casting a material that is capable of coping with long-term exposure to UV is a must to ensure reliable operation for a year. Materials like ABS, or PETG can be considered in future works. Moreover, having 3D-components moulded can contribute to the strength of the parts.

8.2.3 Research and implementation of continues measurements

In the specification phase, it has been found that wind speed measurement frequency requires almost continues measurements. Since in the specification a decision was made to optimise for power consumption, it was also decided to perform deep-sleep cycled based measurements. This allowed wind speed measurements to not be in accordance with the KNMI guide for measurements. A custom measurements interval was chosen instead. The solar panel provided during the evaluation enough energy to allow for continues measurements. In further works, the implementation for continues measurements and deep-sleep cycles based measurements need to be implemented together. In that way, the user can decide on the measurement strategy depending on the available energy supply.

8.2.4 Custom PCB

There is a circuit design present that can be easily transferred to a custom PCB. When making the system in larger quantities, custom PCBs are a must. Due to time constraints, the PCBs could not be developed or ordered. In future works, this could be further developed.

8.2.5 Sensor system set

Currently it is not necessary by stakeholder to have wind direction. However, wind direction can play a crucial role in city heat build-up so further research into implementation of wind direction or the influence of wind direction can be beneficial since the current design also implements a wind direction sensor sub-system.

Additionally, the system implements an additional BME-280 for reliability. As both sub-system are exposed to environmental stresses having a additional sensor sub-system can validate measurements. The current firmware and I2C bus do not allow of the BME-280.

8.2.6 Future works for measurements transmission

Note that this part has been performed in cooperation with van der Burgt. With regards to the reliability of the communication, it would be good to look into the possible reasons for packet loss and how these losses could be kept to a minimum. The positioning seems to be one of the main factors for data packet loss, and there are a few options to handle this. First of all, the distance between the MMS and the LoRa gateway can be minimised. An alternative is to increase the density of the LoRa gateways in the area. As this MMS is to be deployed in the city of Enschede, this is an overseeable task to do. Another benefit of increasing the number of gateways is redundancy. This would mean that the data packets sent by the MMS are received by multiple gateways, which in turn increases the overall reliability of the LoRa infrastructure. Besides increasing the number of gateways, LoRa communication subsystems can also be improved. This can be done by testing other LoRa chips to be used in the MMS or by changing the gateways. Since most gateways are already in place, it would be best to try other LoRa chips to be used by the MMS. The focus should be to investigate quality performance in relation to the power consumption used by the subsystem. Beside the LoRa chip, the antenna could also be improved upon. The antenna that is used now is a relatively short, omnidirectional antenna. A longer antenna can be used, as the increased length corresponds to a better transmission. Besides the length of the antenna, it can be beneficial to do research into directional antennas, as the MMS needs to be able to send data almost exclusively horizontal.

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Appendices

A Interviews

Interview Richard Bults and Hans Scholten

1. **What has been the main motivation to switch from a Davis system to a low-cost system (both pyranometer and MMS)?**
    1. *MMS: contact HJ Teekens two or three years ago. What can we do with the rainwater problem, smart rain buffer, further from a creathon? Soon the idea arose to look wider next to the rainfall. Then look at Enschede's climate adaptation. So also an insight into the temperature structure → Heat island.*
    2. *Tom was the first to develop a complete system to be placed at a location in the city. Independence came from a solar panel, communication tool and 3D printing to experiment housing, to measure temperature. Yoann Latzer then made the data presentable. (initially a proof of concept)*
    3. *When that turned out to be going well, the plan continued, from then on with Wim Timmermans, by Laura Kester and Adam Bako. Laura's system went further than that of Tom Onderwater but added humidity and wind speed. She also looked at solar radiation through Wim Timmermans.*
    4. *That system gave its own weather station that was relatively cheap. Good feeling about communication technology, just like the skills of Creaters. From there, a big step up. Then there was a plan for an own MMS. Together with Wim Timmermans, WHEGS was born to start a research project to get 80 WSN in Enschede.*
    5. *In the end, it was decided to buy SenseBox due to financial considerations. The quality left it to new plans since it was actually below level.*
    6. *Finally, it was Max's turn, he just did not get far enough, so JP was added*
    7. *Hans and Richard also saw that the UV and Solar Radiation sensor together is 500 euros. This resulted in Peter's assignment.*
    8. *There is a solid interest in the municipality of Enschede, as they want MMS to provide insight into the temperature in the city. Wim is interested in the data of the systems, and Hans and Richard are interested in making low-cost MMS.*
    9. *It is, of course, also great for CreaTe to use students with the latest technology, and it provides a nice graduation assignment.*
    10. *Ultimately, the system can, of course, also provide economic aspects with insight for the municipality of Enschede. It can ensure that you can search for warmer places in the city.*

2. **What are the most important aspects for you that the (Low-Cost Autonomous Pyranometer) and the (MMS) can / have?**
    1. *How would you prioritise this? / which would drop out first*
    2. *Cost price*
    3. *Quality*

4. *The two things that are mainly looked at can buy an expensive system for 800 euros and for everything, even double that. It is now the challenge to keep it as low-cost as possible.*
5. *Within Hans his department there is also research into communication, and a LoRa plays a major role, which gives you more contact and data that you obtain from typing Lora, such as triangular measurements*
6. *Educational aspect, creativity works better than obstruction. It is more fun to look at solutions creatively instead of putting down a lot of money.*

3. **Is it important that the system can determine its own location, or is it sufficient to keep track of the years of identification system?**
    1. *Not necessary to determine locations, because they are stationary systems. On the other hand, GPS can be very useful; for example, a kind of theft alarm. More importantly, if the system is moved, the measurements may become invalid. Furthermore, the GPS can determine a very accurate time. Almost at the microsecond level, and determine right measuring moments. Furthermore, GPS is useful for when you want to measure mobile. (equip buses or means of transport)*
    2. *Stationary measuring does not require a GPS*
    3. *Richard: Having accurate location information during a measurement is a must-have requirement. For example, the mobile measurement of patients, patients who are mobile, who have data collection and which is sent. Is the quality of the data good enough to let a machine decide. Yes, it is true that the MMS is stationary, and you also want it to hang in a place that belongs to the data. And so this is also part of the quality of the data. [questions to Wim Timmermans and municipality] bring GPS, although it takes a lot of energy and takes a lot of money. Time stamping can be important. So if you are wondering if you can take GPS, you have to think creatively about how you want to do this. This has to do with the Data quality. Do this especially if the option is available.*

1. **What would be the best data frequency? According to the KNMI, there should be a measurement every 12 seconds, but what do you think the minimum usable data frequency would be?**
    1. *This is determined by the KNMI manual, measuring according to the standardised way. KNMI does not measure per 12 seconds, but sometimes measures once per minute and then determines the average. Determine a kind of hierarchy of temperature. For example, the average per hour, which is then divided by minutes and the like. It is clear to Hans that we must measure according to KNMI's standards. Richard agrees.*
    2. *These are often fed from the wall-socket, but this is again seen as a challenge. One way of saving energy is to turn things on when measuring (relay transistors, etc.). Follow here the manual as well as measuring in an energy-saving way.*
    3. *Richard agrees and adds the difference between a sensor and sensor system or the MMS. There is a possible difference between the measuring frequency of a system than a measuring frequency of a sensor system. The MMS transmits*

    measured values to the server once in a while, but that one meeting is based on possibly several measurements from one sensor. What the MMS transmits is different from the sensor.
    4. *GPS is necessary to divide the day into hours, and that into minutes, and in some minutes, you need to take more readings than others.*

1. **Is there a preferred communication method for you?**
    1. *As far as Richard is concerned, we note that we use LoRaWAN. Looking at the scatter radius, MMS aren't always close to private homes. Things like Wi-Fi are also dropped here.*

1. **It still happens that the data sent does not arrive properly. This is of course not what we want, but what is a maximum number of unpacked packets, for example in percentages?**
    1. *Interesting question. If you make a choice for your data communication infrastructure, it can also mean how reliable, how big and how fast your data is. When we say that we are going to use LoRaWAN, TTN only says that uplink is needed. Here the provider chooses not to choose bidirectionally. This would block the entire network. If we are only committed to uploading data, you are not sure that your data has been uploaded correctly. Because you have no feedback. You can solve this by placing a fine-meshed network. If it is finer, then it makes less difference that there are nodes over a large area. (what is acceptable in terms of fine to coarse-meshed network. Ask Wim Timmermans about data loss)*
    2. *A certain amount of redundancy is needed to ensure that if one node is not communicating properly, another must accommodate it.*
    3. *(Possibly less important for us, because this network is determined by Wim Timmermans)*
    4. *Take a good look to ensure that there are still measurements for each type of measurement.*
    5. *Example, 20 systems, 10 for green 10 for buildings. Falling out by half is okay, as long as it's a bit with both groups and not all 10 of a group.*
    6. *A bit out of the scope of the individual system.*
    7. *It depends on the reason for the failure.*
    8. *When looking at reliability is. One of the most important aspects is that the system must remain powered, so enough battery capacity. Can the system be operational 24/7, or would it be 50% enough, but when or not. Take a good look at those dependability parameters and analyse, which we have to address in our system design.*
    9. *We can do less about LoRa that breaks down, but if there is not enough power. If we have less energy like winter, we can send data once a day instead of once an hour.*

10. *Possibly graceful degradation and how is it communicated. So there is also a kind of notification so that the recipient knows how the system functions (For example, use a byte in your package.)*

1. **What do you see as the minimum resolution/accuracy/precision of the sensors?**
    1. *Wim Timmermans does have an opinion about this. Max's report does state this. Here are things stated like the accuracy of sensors.*
    2. *If we know the accuracy that Wim wants to see, we have to take this into account and also say something about the resolution.*
2. **In the previous projects, what are the measurement qualities that you want to see improved?**
    1. *The quality of the system must be considered. For example, there was a very good digital sensor that tom used, but the new ones that were bought suddenly all broke.*
    2. *General reliability and component reliability. You don't want to go there for maintenance all the time.*
    3. *The first systems were a kind of sniffing phase.*
    4. *Now it is important not only that it works, but also how well and how long it works, that the system continues to work.*
3. **I heard that you bought Senseboxes in collaboration with the municipality. Why did you choose this system? What are the advantages? And what are the disadvantages?**
    1. *It was decided to choose SenseBox because the three participants in the project are in the project for their own reason.*
    2. *Ultimately, there was pressure from the subsidy provider that a system had to be created, so that SenseBox was determined to be used.*
    3. *Then it came from Richard and Hans that they make an MMS for less than 400 euros that has just as good data as the Davis vantage pro 2 system. That whole thing costs about 1200-1500 euros.*
    4. *This also resulted in requirements that have been given to measure all sensors.*

1. **How do you see the placement process of an MMS? What should be the steps for a user to get the system up and running?**
    1. *Wim Timmermans is now discussing with the municipality where all systems should be located in order to obtain good quality data. So nothing is sure yet.*
    2. *Placement of systems are not necessarily compliant with standard MMSs, but it is compared to the situation with concrete buildings and brick buildings and the like [ask Wim Timmermans]*
2. **Should the data be publicly accessible? And what about making/calibrating the system?**
    1. *If such a system is correct and works, it is also great that everyone can make and use such a system with a limited system.*
    2. *The data is outside the scope, but should actually be publicly available.*
    3. *However, this would also mean that it should be clear how a data unit is created.*

Interview Wim Timmermans

1. **It still happens that the data sent does not arrive properly. This is of course not what we want, but what is a maximum number of not received packets, for example in percentages?**
    1. *Not immediately a number, except of course one hundred percent that arrives. In the event that things don't arrive, then one should know how much is received, then you know if it's good data.*
    2. *Especially the time of the observation is important. The temperature fluctuates more during the day than at night. At night it is less bad if it breaks down.*
    3. *That depends on the data, and it varies a lot. Those criteria are not necessarily fixed either.*
    4. *It also depends on the weather pattern, sometimes it is very fixed, and sometimes it changes at once.*
    5. *A percentage of how much data was retrieved and the time of that data is the best.*
    6. *It mainly depends on who uses the data. For a model that produces warnings, or to residents of Enschede.*
    7. *Mesh network, how much is needed and how good the data must be. (given a "data loss" of 25 or 10 percent, how would he place the sensor systems in the city Enschede. If there are four systems and 1 doesn't work, what does the quality of the data do?)*
    8. *What are the parameters/sensors that you need 24/7, and which can possibly fail, for example, to save power? (graceful degradation)*
2. **You are talking about a sensor network of 80 units. Can you give us an indication of where these may be placed?**
    1. *Can send a map where it will be placed globally. Exact has not yet been determined.*
    2. *A little bit of everything, a square, a park. Radiation applies less too, but the other variable, you want to measure at the same level because otherwise it cannot be compared.*
    3. *Measure on the street, in a clearing, near a house.*
    4. *Scientifically, you have to measure it at a meter and a half, but that becomes difficult because then they are stolen.*
3. ***Does it have to have a mounting system/slot?***
    1. *In principle, it is thought to attach to poles. Existing poles especially, because that is the universal solution imaginable.*
    2. *Possibly make something that fits on different types of poles, lampposts are somewhat inconvenient because of the light. In principle, a fixed time (13 minutes before sunset and 13 minutes after sunrise) preferably as vandal-proof as possible, and as little attention as possible. As small as possible*

4. **With regard to previous studies, what were things that should receive some extra attention from us?**

    1. *The reliability, how long does it last. Especially the power supply is very important. Actually, he just needs the MMS to be in the air 24/7.*
5. **If you purchase sensor nodes, what are the most important quality requirements that a system must meet?**
    1. *What do you see as the minimum resolution/accuracy/precision of the sensors?*
    2. *See previous studies*
6. **Which parameters are most important for your research? And which least?**

    1. *Temperature and radiation, but wind speed is also important.*

1. **If you install an autonomous measuring instrument, how long should it be able to operate alone without intervention?**
    1. *About 50-60 years*
    2. *At least a year, because you want to be able to measure all seasons and pick up all influences.*
    3. *For Wim's research, there must have been something until the end of time.*
    4. *For climate you can only measure in 30 years, so for climate change, you need 60.*
    5. *It is mainly in the context where you place it.*
    6. *If he does not last long, he should also be able to indicate that he needs to be replaced.*
2. **What should be the accuracy of the location?**
    1. *For Wim, it is not important what GPS value the station indicates, Wim will measure it itself, so that does not matter that much.*
    2. *Wim thinks that monitoring a sensor's location does not add much value*
    3. *Not necessarily a requirement.*
3. **I had heard from Richard that it might be possible to get data from a calibrated Pyranometer from the ITC, is this still correct?**
    1. *Just send an email. On average, he sends values for half an hour. He is not fully in accordance with the KNMI measures. It is not always well-calibrated.*
    2. *Just put it on the mail for the dates of yesterday.*
4. **In a previous interview with an old CreaTe student, you had noticed that a solar radiation resolution of 10 W / m 2 should be sufficient, do you still agree?**
    1. *This is a number that Wim hopes is feasible.*

5. **A pyranometer is generally placed a meter and a half above-cut grass, how do you envisage this in the municipality of Enschede?**
    1. *The diffuse radiation is less of reflection from buildings but still from clouds. The requirements set by KNMI are designed for the perfect weather stations, which must meet the requirements.*
    2. *This is simply not possible within the city, so the requirements should be as close to acceptable levels as possible.*
    3. *This is a lot of consideration and sees how good the measurements are going to be.*

6. ***Also, look a bit at measuring in cities. There are probably manuals for that.***
    1. *WMO has initial guide to obtain meteorological observations at urban sites.*
7. ***Further ideas about the SenseBox***
    1. *There is now an idea for making those sensors. Alfred is mainly working on a 3D model. It is mainly a matter of waiting for a number of factors before it comes to hang again.*

Second Interview Wim Timmermans

1. **Pre-questions**
    1. *Conversation municipality Enschede. Lampposts: fix rubber or something. Otherwise, the paint of the lampposts and the like will be damaged*
    2. *Wim is also going into town with Hendrik Jan Teekens to scout for places for the measuring systems.*
    3. *What about the technical measurement, according to the expert.*
2. **What is the desired measurement frequency required for all variables (also looking at LoRa restrictions)**
    1. *The minimum measurement frequency is mainly about the scientific measurements being taken primarily as the scientists find it interesting.*
    2. *This ensures that the rules are certainly not always followed.*
    3. *The systems in Enschede are used to compare with the systems of the KNMI, so try to get as close as possible.*
    4. *Wim also understands that it causes problems with the transmission of data.*
    5. *The minimum resolution would, in principle go to half-hourly average. Based on how many measurements. These samples can then come from the manual.*
    6. *Basic storage of half an hour would be nice. If you then assume that you then calculate everything on the node, and send that, then that thunders away. Especially the average is interesting. Minimum, maximum and standard deviation are okay, but then Wim prefers the raw data.*
    7. *The data forwarded would be nice if it can be checked.*
    8. *There will be a system that students will check the entire system every 2 weeks.*
    9. *A GPS determination can be more interesting for things like APP measurements on a mobile.*
    10. *Closer to the surface is the most interesting variation.*
    11. *They turn off 13 minutes before sunrise and turn on 13 minutes after sunset. So lampposts can be a problem, this makes it interesting.*
    12. *Optionally, you can use an SD card for data logging of samples. Whether you let it be overwritten or stopped.*
    13. *Where does your timestamp belong to? This is the beginning, middle or end of the measuring interval, the most common is the end.*
    14. *For Wim, it is also a fundamental discussion since it is also part of the type of measurement. Also, because the system is now placed and it is still a manageable amount. Also, because a certain accuracy has to be achieved. You also record how you do the measurement, see whether you measure at a wall or at a park or not.*

3. **What is the desired communication frequency (how bad should it be in real-time.)**
    1. *Solar radiation*
    2. *Temperature*
    3. *Humidity*
    4. *Barometric pressure*
    5. *Wind speed*
    6. *Wind direction*

Interview: Rik Meijer – Municipality of Enschede

1. **What is the end goal that the Municipality of Enschede wants to achieve with these sensor nodes?**
    1. *That is not quite clear yet. There is a need for flat insight, how it divides with the heat in Enschede and you can visualise something of a relationship about certain establishments and what you measure about it. Think of new construction situations but also adjusting things*
    2. *If you have a web application, people can also see where it is warmer and cooler. What does the municipality think is important, it must be colder near a nursing home.*
    3. *Giving people insight. Heat affects people, so maybe people will also adjust things to suit their own lot.*
    4. *It would be great to be able to show people what is going on and what people can do about it themselves.*
2. **What is your experience with vandalism of this type of project?**
    1. *By changing the things that are hanging now, they ensure that you cannot reach them with a long stick from the ground. This is already handy with a four-meter-high lamp post.*
    2. *Of the five hanging, not one is broken yet.*
    3. *Possibly hanging at people's house, this must be discussed. It is necessary to measure in public places, so it is a difficult subject.*
3. **What measuring instruments does the municipality of Enschede currently use and what are the purposes?**
    1. *What did you run into when using these measurement systems?*
    2. *A number of systems have already been installed, which mainly measure temperature, as a first pilot on how to make something like this (Tom / Laura).*
    3. *Those insights have not yet yielded much for the municipality, especially because additional things must also be measured such as humidity and wind speed and direction.*

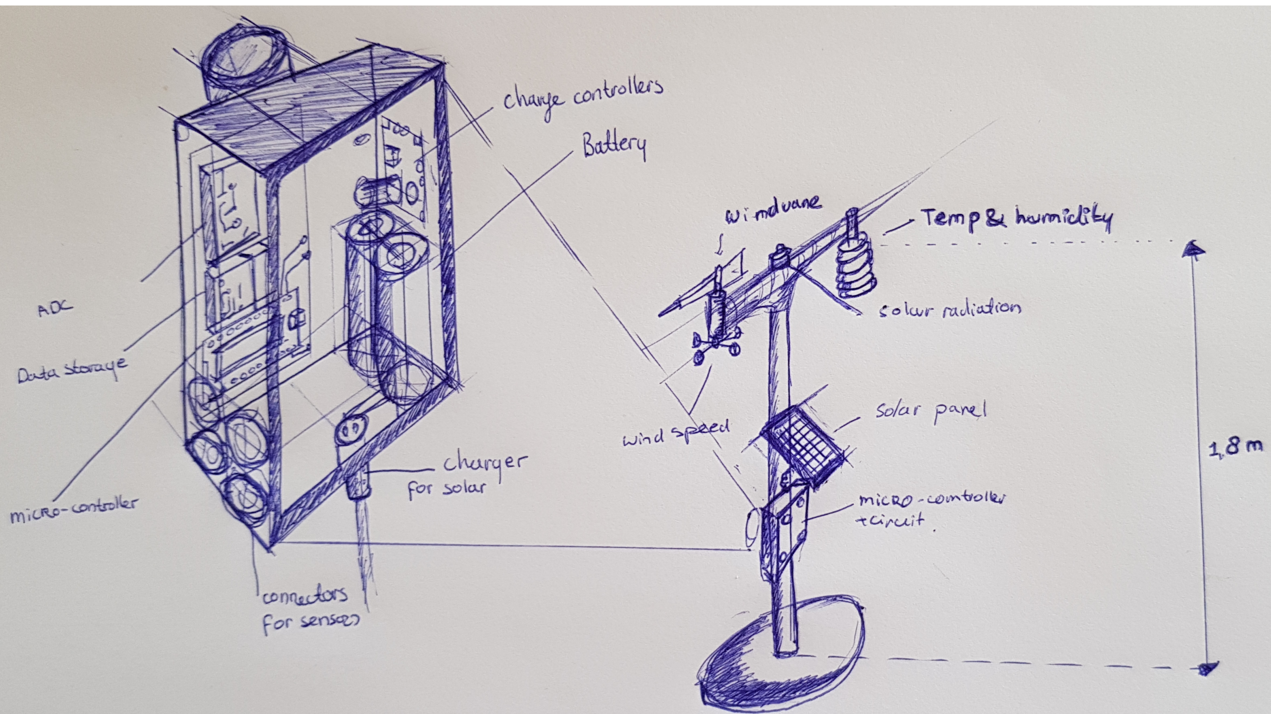
1. **How important is the design of the device? And what are the requirements of the municipality with regard to design?**

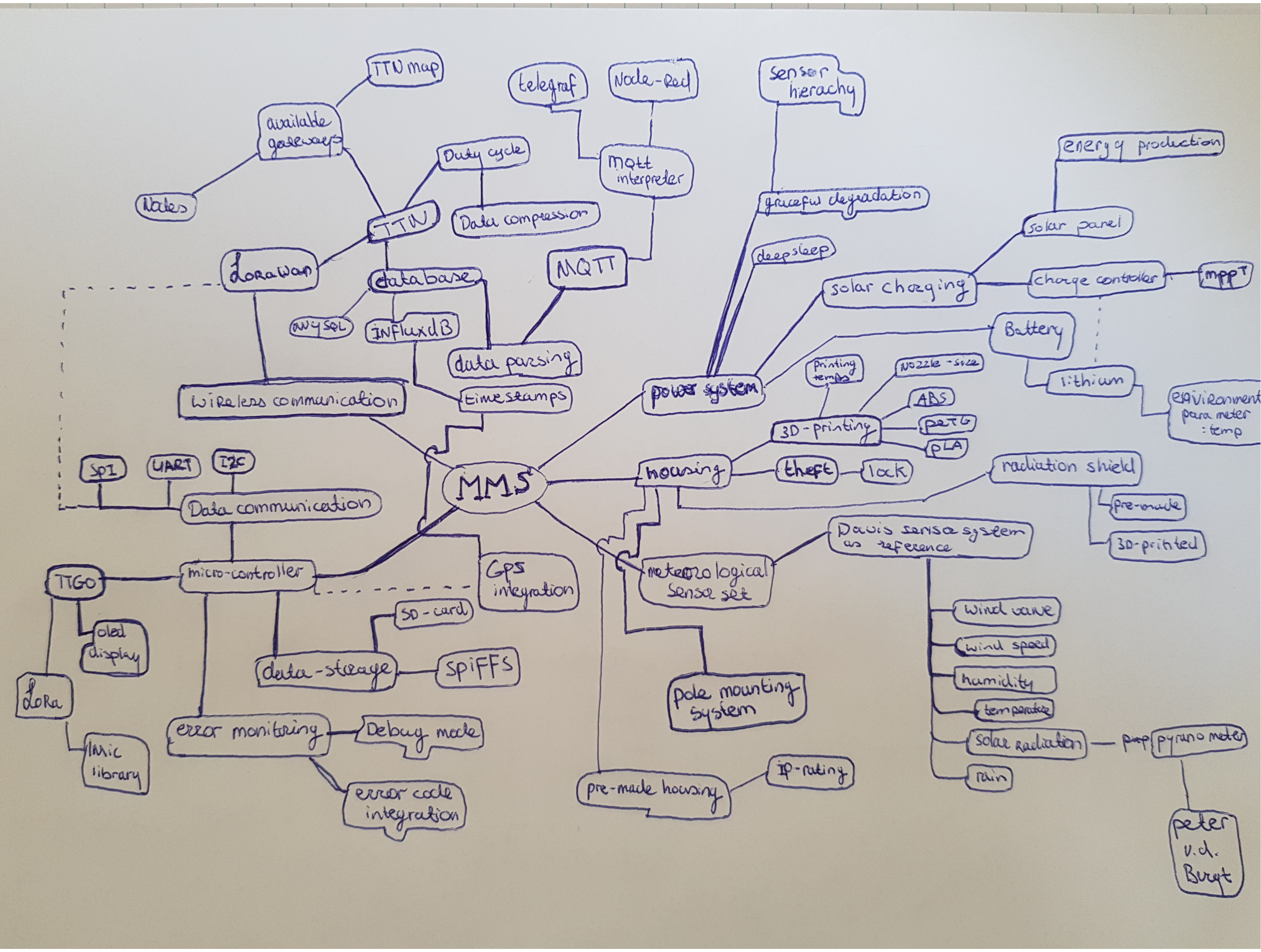
    1. *Not much agreed upon. The models shown were white. No idea if that is the easiest. Colour is useful to match the environment. When placed on a light pole, the orange straps of today are clumsy. They stand out.*
    2. *In a green environment perhaps in a suitable colour.*
    3. *Here, colour is mainly related to the places where they are placed*
2. **Is the data generated used for policymaking and if so, which?**
    1. *Example building regulations., Greening of the city*
3. **Should the data be publicly accessible to not only people from the municipality but also residents of Enschede?**
    1. *Yes, but it depends on where they are placed. If they are placed on private land, it is inconvenient for privacy.*
    2. *Is it information that can be made available just like that, or that it gives a problem with the GDPR.*
    3. *It is important to consider what information can and cannot be made available.*
    4. *Subsidised from municipal money, but getting enough information.*
4. **For the placement of technologies, there are laws that prevent that. How does that legally work?**
    1. *No idea, Rik thinks it is not so bad because there are often no people to trace. This shouldn't really be possible with this technology.*
    2. *If it is all made then, it should be doable.*
    3. *There are now in the centre of Enschede cameras.*
5. **Have you previously applied a sensor network or sensors in the city, if so? Which?**
    1. *The smart water buffer, heat build-up what we do. These are the two things that are currently running with the UT. Also, a pilot project to build an extra city stream in the Elferinksweg.*
    2. *Which communication methods work to get private individuals working.*

1. **How do you foresee Enschede in the future, which technologies will you use?**
    1. *Colleagues are working on a smart city concept*
    2. *All transport movements due to corona are made transparent. So flows of traffic.*
    3. *For example, smartphones are also used to see how many people can be where. No idea what it will be used for and where it can be used.*
    4. *Smartphones that measure whether roads need maintenance. Quality of measurements then becomes a number of measurements.*

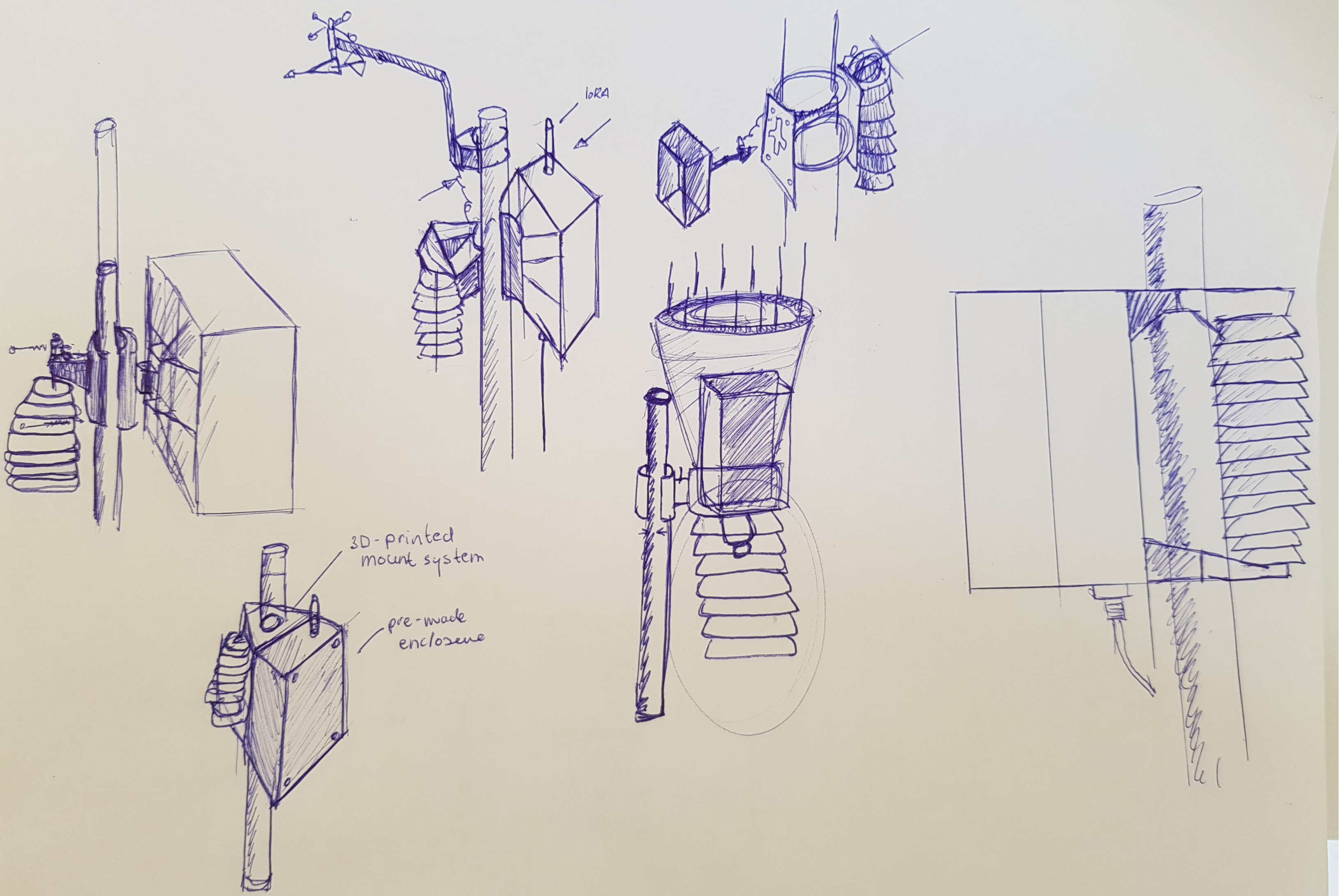
B Location overview

C First brainstorm


charge controllers
Battery
ADC
Data storage
micro-controller
charger
for solar
connectors
for sensors
windvane
Temp & humidity
solar radiation
wind speed
solar panel
micro-controller
+circuit
1,8 m



MMS
TTN map
available gateways
Nodes
TTN
Duty cycle
Data compression
telegraf
Node-Red
MQtt interpreter
MQTT
LoraWan
database
mysql
InfluxdB
data parsing
timestamps
Wireless communication
Sensor hierachy
graceful degradation
deepsleep
power system
energy production
solar panel
solar charging
charge controller
mppT
Battery
lithium
environment parameter : temp
printing temps
nozzle-size
ABS
petG
pLA
3D-printing
housing
theft
lock
radiation shield
pre-made
3D-printed
SPI
UART
I2C
Data communication
micro-controller
TTGO
oled display
LoRa
lmic library
GPS integration
SD-card
data-storage
SPIFFS
error monitoring
Debug mode
error code integration
Davis sensor system as reference
meteorological sense set
wind vane
wind speed
humidity
temperature
solar radiation
pyranometer
rain
pole mounting system
pre-made housing
ip-rating
peter v.d. Burgt


loRA
3D-printed mount system
pre-made enclosure

D Timing calculations

Spreadings factor SF 7
Bandwidth 125 kHz
Region EU 868
Payload size 51 Bytes

Air-time 118 ms

fair-use-Policy = 30 s
30000 ms / 118 ms = 254 messages

51 bytes x 254 = 12 954 Bytes / 24 h ≈
539.75 bytes / hour

254 messages / 24h = 10.58 Messages / hour
~~0.18 messages / hour~~ 0.18 messages / minute

approx 1 message / 6 minutes

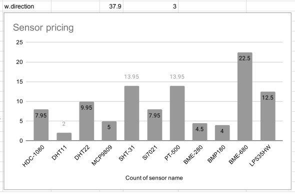
Timestamp + Location + Temperature + humidity + wind speed + Solar Irradiance
— 9 bytes 2 bytes 1 byte 2 bytes 2 bytes

No timestamp in cayenne so message size will be 16 bytes
16 bytes + 2 bytes per parameter = 26 bytes without timestamp

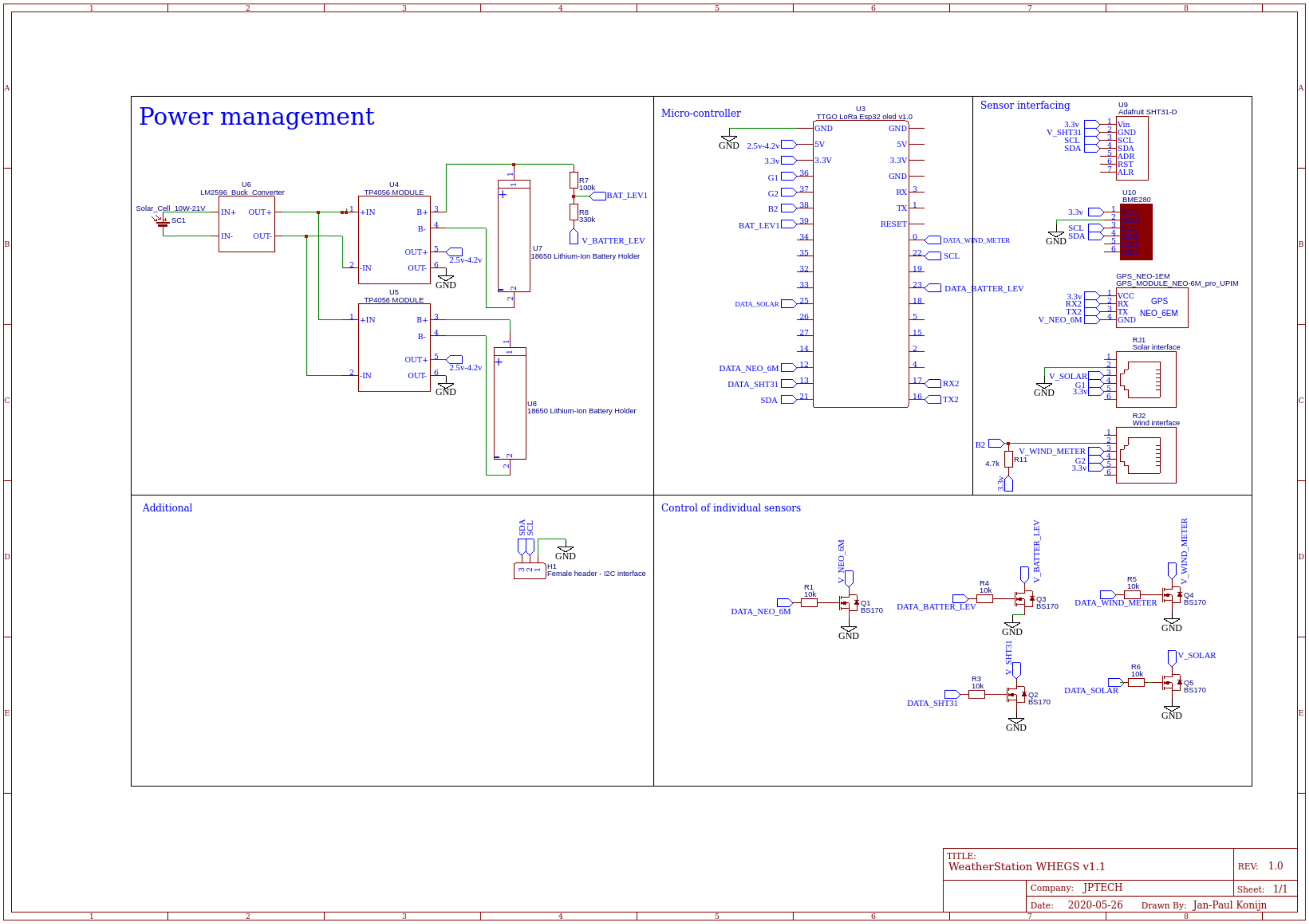
E Sensor survey overview

Manufacturer	sensor name	Type	Type 2	amount of parar	Price	Accuracy paramet	Accuracy parameter 2	Lower bound range	Upper bound range	Reliability	Resolution	Resolution 2	precision	Documentation	Price source:	Notes	Datasheet
Max Integrated	DS18B20	temp	none	1	4.5	0.5	none	-55	125		12-bit				https://www.kiwi-e	1 pin interface	https://datasheets.maximintegrated.com/en/ds/DS18B20.pdf
Texas Instrumen	HDC-1080	temp	humid	2	7.95	0.2	2										
unkown	DHT11	temp	humid	2	2										https://www.tinytronics.nl/shop/en/s		https://www.mouser.com/datasheet/2/758/DHT11-Technical-Data-Sheet-Translated-Version-1143054.pdf
AOSONG	DHT22	temp	humid	2	9.95	0.5	2	-40	80		0.1	0.1		moderate	https://www.kiwi-electronics.nl/DHT		https://www.sparkfun.com/datasheets/Sensors/Temperature/DHT22.pdf
Microship	MCP9809	temp		1	5	0.5					0.0625				https://www.adafr	has a selectable	http://ww1.microchip.com/downloads/en/DeviceDoc/MCP9808-0.5C-Maximum-Accuracy-Digital-Temperature-Sensor-Data-Sheet-DS20005095B.pdf
Sensirion	SHT-31	temp	humid	2	13.95	0.3	2					0.015			https://www.adafruit.com/product/2857		
Silicon labs	Si7021	temp	humid	2	7.95	0.4					A-D-C				https://www.kiwi-electronics.nl/spar		https://www.silabs.com/documents/public/data-sheets/Si7021-A20.pdf
RS	PT-500	temp		1	13.95	0.3		-50	600						https://nl.rs-online	Class B	
Bosch	BME-280	pressure	humid	3	4.5	1.7	3	300	1100		0.18	0.01		excellent	https://www.tinytr	Relative humidity	https://ae-bst.resource.bosch.com/media/_tech/media/datasheets/BST-BME280-DS002.pdf
Bosch	BMP180	pressure	temp	2	4	2		300	1100		16 bit			excellent	https://www.tinytronics.nl/shop/nl/s		https://www.tinytronics.nl/shop/image/data/Producten/Sensoren/Temperatuur-Lucht/BST-BMP180-FL000.pdf
Bosch	BME-680	pressure	temp	4	22.5	0.6	-1	300	1100						https://www.adafr	Relative humidity	https://www.bosch-sensortec.com/media/boschsensortec/downloads/datasheets/bst-bme680-ds001.pdf
	LPS35HW	pressure	temp	2	12.5	1	1.5		1						https://www.adafr	waterproof packa	https://pdf1.alldatasheet.com/datasheet-pdf/view/929262/STMICROELECTRONICS/LPS35HW.html
	https://www.froggit.de/product_info.php?info=p138_replacement-wind-speed-sensor-for-wh1080-1090-wh3080-wh4000.html																
Davis instrument	6410	w.speed	w.direction		175	1		1	89						https://www.weer	JT	https://www.davisinstruments.com/product_documents/weather/spec_sheets/6410_SS.pdf
unkown	Windmeter	w.speed			55									poor			
					28									poor	https://www.kiwi-electronics.nl/windmeter-windsnelheid-sensor-met-analoge-voltage-output		
unkown	windmeter ali express		w.speed											poor			https://nl.aliexpress.com/item/4000528991082.html?spm=a2g0o.productlist.0.0.622e195befg3yD&s=p&ad_pvid=20200523003731917486999620620015623832_3&algo_pvid=6d501e42-4ad4-4d91-ad10-76673dd59cd7&algo_expid=6d501e42-4a
wh1080	replacement sen:	w.speed	w.speed		17.99	?	?							poor	https://nl.aliexpress.com/item/4000528991082.html?spm=a2g0o.productlist.0.0.622e195befg3yD&s=p&ad_pvid=20200523003731917486999620620015623832_3&algo_pvid=6d501e42-4ad4-4d91-ad10-76673dd59cd7&algo_expid=6d501e42-4ad4-4d91-ad10-76673dd59cd7-25&b		
unkown	windvane ali express		w.direction		37.9	3								poor	https://nl.aliexpress.com/item/4000761101406.html?spm=a2g0o.productlist.0.0.489e12d5GOWTJv&algo_pvid=5bedce0c-9ec5-4f32-82ae-8a9cb30374e9&algo_expid=5bedce0c-9ec5-4f32-82ae-8a9cb30374e9-24&btsid=0be3743b15902254865012762eb007&ws_ab_test=searchw		

temp in
humid in %
pressure in hPA



F Circuit designs


Power management
U6
LM2596_Buck_Converter
Solar_Cell_10W-21V
SC1
IN+
OUT+
IN-
OUT-
U4
TP4056 MODULE
+IN
-IN
B+
B-
OUT+
OUT-
2.5v-4.2v
GND
U5
TP4056 MODULE
U7
18650 Lithium-Ion Battery Holder
U8
18650 Lithium-Ion Battery Holder
R7
100k
R8
330k
BAT_LEV1
V_BATTER_LEV
Micro-controller
U3
TTGO LoRa Esp32 oled v1.0
GND
5V
3.3V
RX
TX
RESET
2.5v-4.2v
3.3v
G1
G2
B2
BAT_LEV1
DATA_SOLAR
DATA_NEO_6M
DATA_SHT31
SDA
DATA_WIND_METER
SCL
DATA_BATTER_LEV
RX2
TX2
Sensor interfacing
U9
Adafruit SHT31-D
Vin
GND
SCL
SDA
ADR
RST
ALR
3.3v
V_SHT31
U10
BME280
GPS_NEO-1EM
GPS_MODULE_NEO-6M_pro_UPIM
VCC
RX
TX
GND
GPS
NEO_6EM
V_NEO_6M
RJ1
Solar interface
V_SOLAR
RJ2
Wind interface
V_WIND_METER
R11
4.7k
Additional
H1
Female header - I2C interface
Control of individual sensors
R1
10k
Q1
BS170
R3
10k
Q2
BS170
R4
10k
Q3
BS170
R5
10k
Q4
BS170
R6
10k
Q5
BS170
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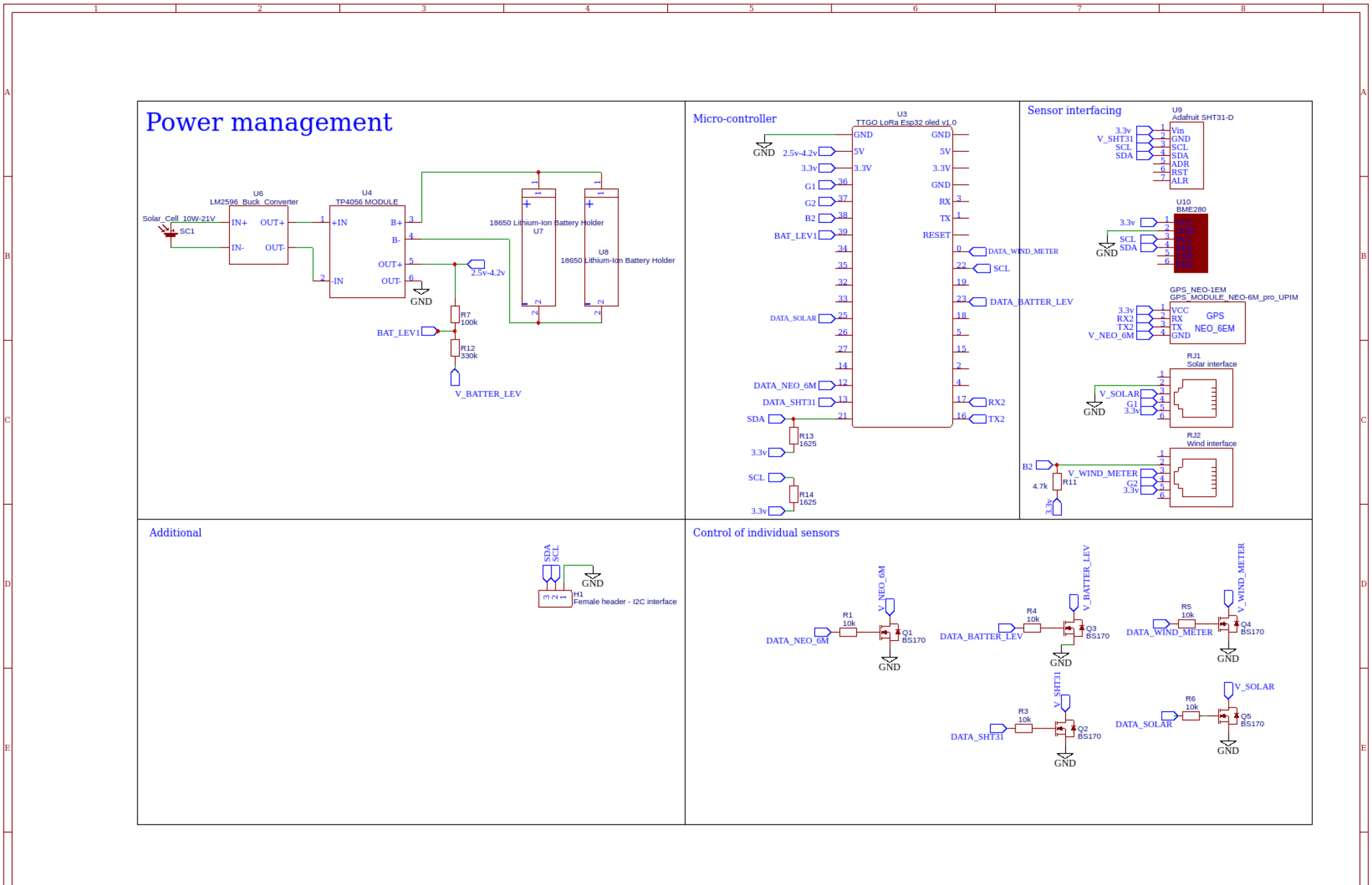
WeatherStation WHEGS v1.1
REV: 1.0
Company: JPTECH
Sheet: 1/1
Date: 2020-05-26
Drawn By: Jan-Paul Konijn



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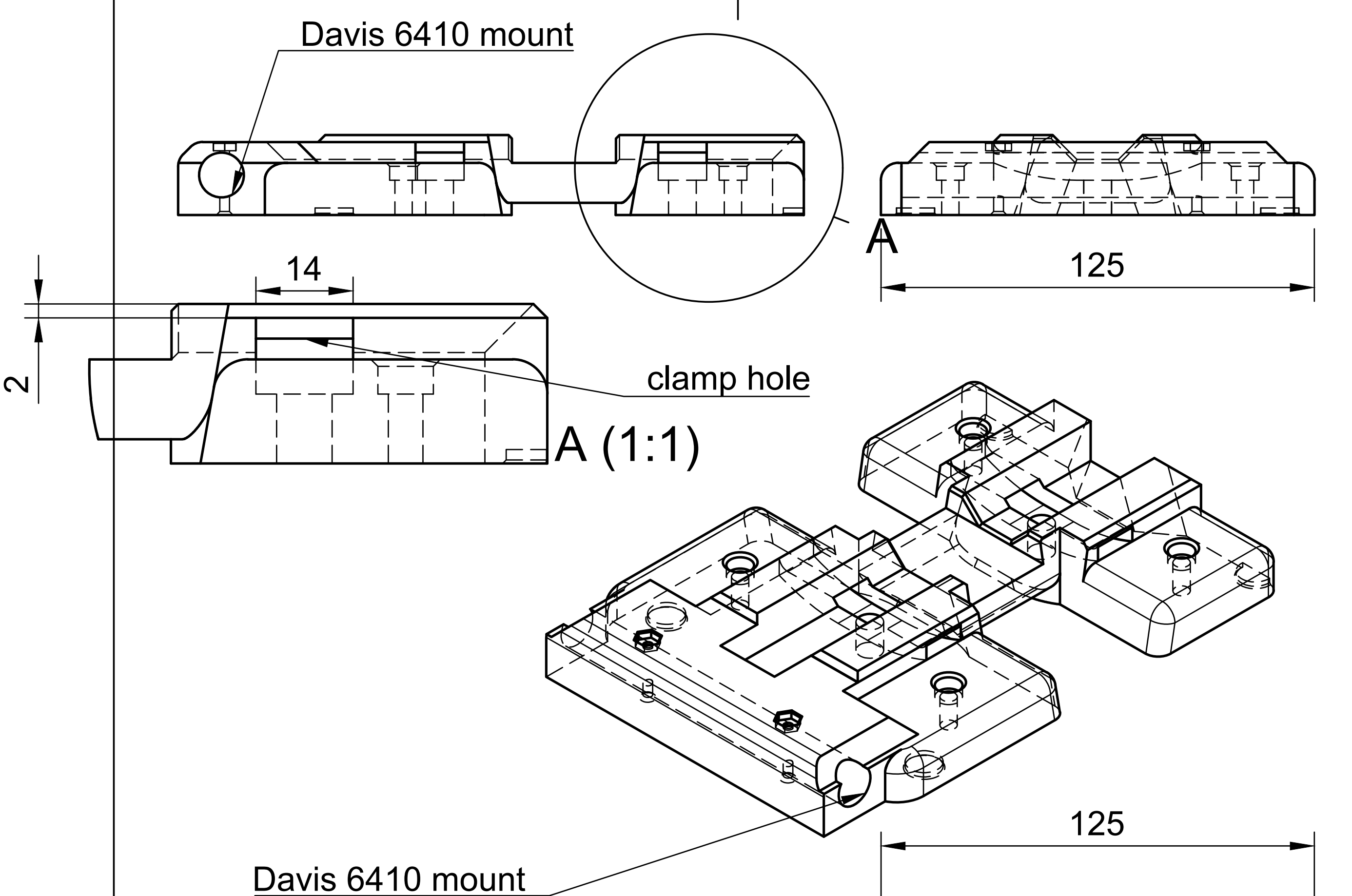
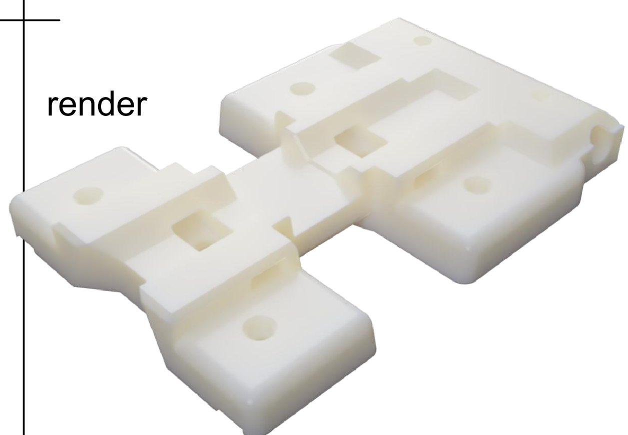
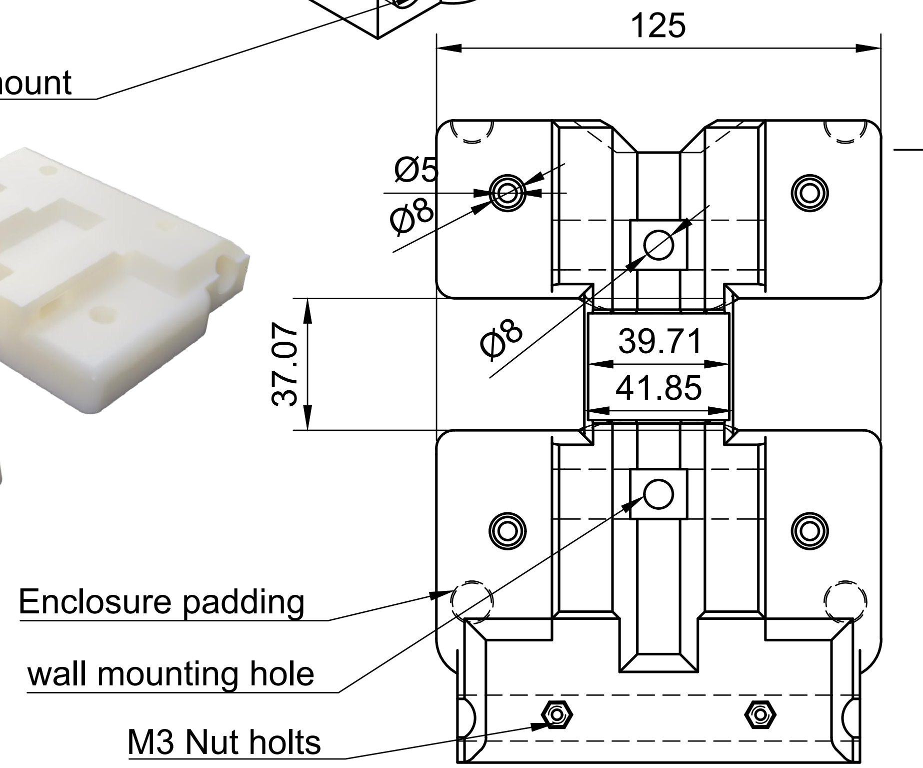
	Company: Creative Technology	Sheet: 1/1
	Date: 2020-05-26 Drawn By: Jan-Paul Konijn	

G Technical drawing parts

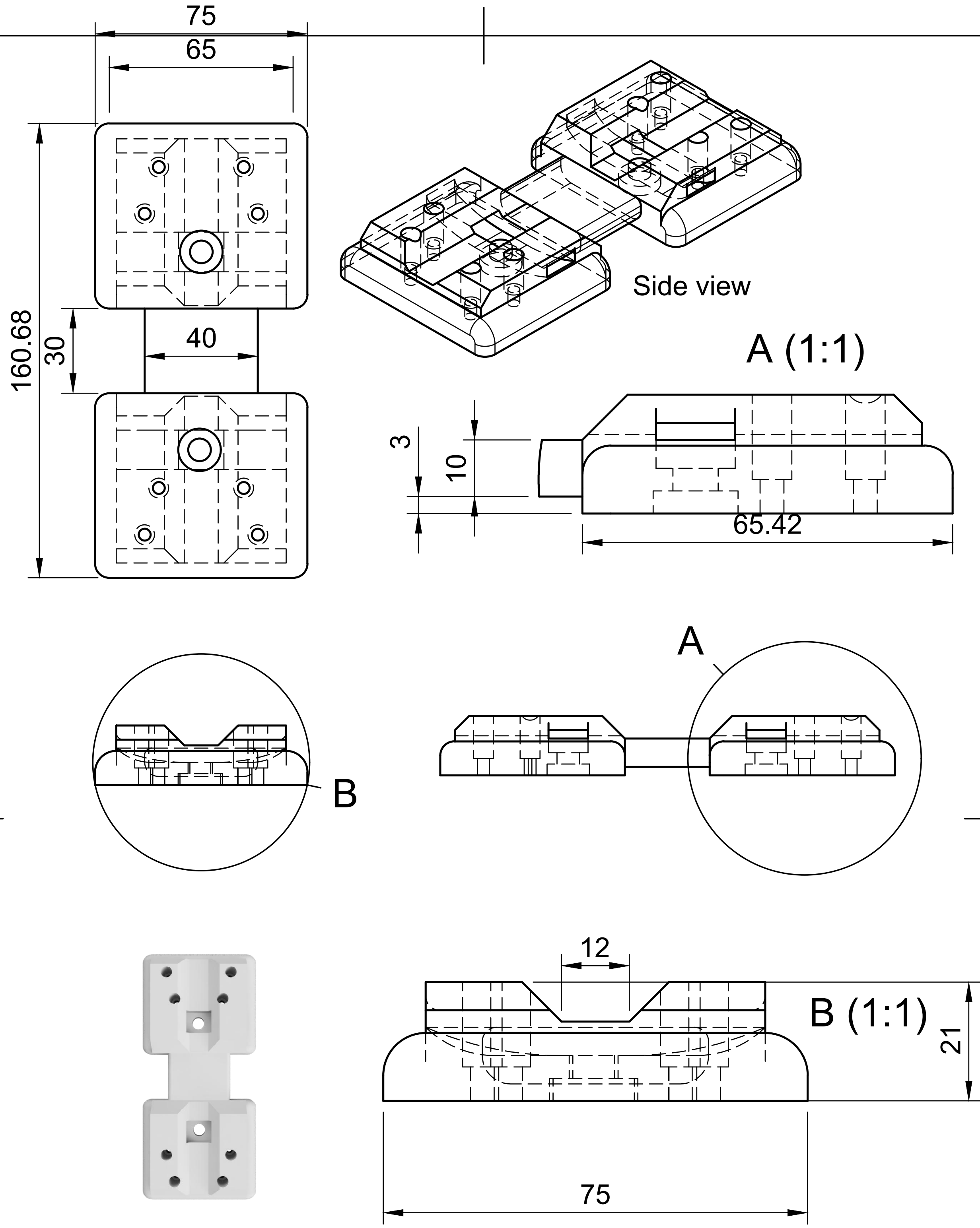


render

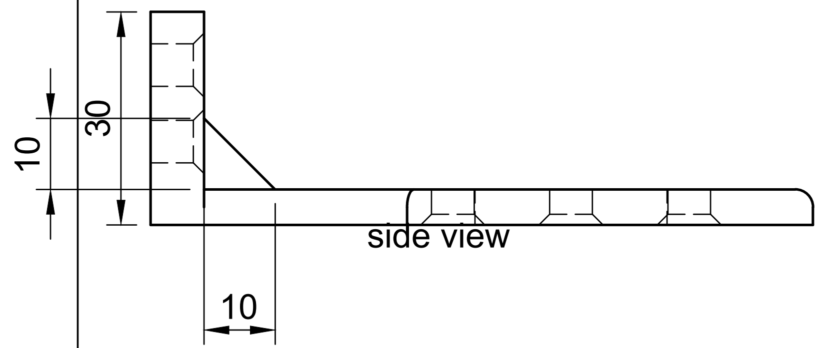




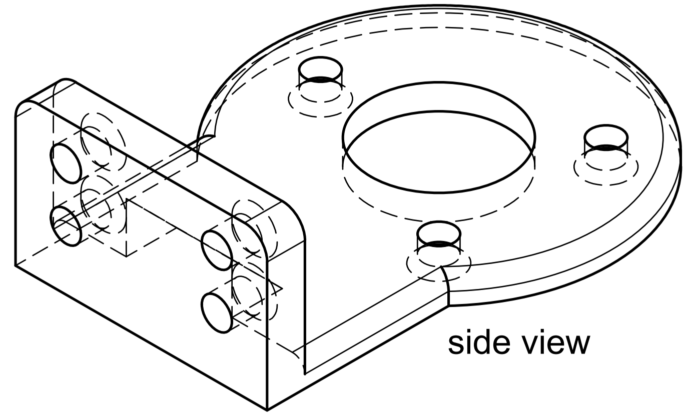
Dept.	Technical reference	Created by Jan-Paul Konijn 02/07/2020	Approved by
		Document type specification	Document status Final
		Title **mount** Mount enclosure, and Davis 6410	DWG No.
			Rev. / Date of issue / Sheet 1/1



Dept.	Technical reference	Created by Jan-Paul Konijn 02/07/2020	Approved by		
		Document type specification	Document status Final		
		Title mount new side v1.1 - solar mount version	DWG No.		
			Rev.	Date of issue	Sheet 1/1

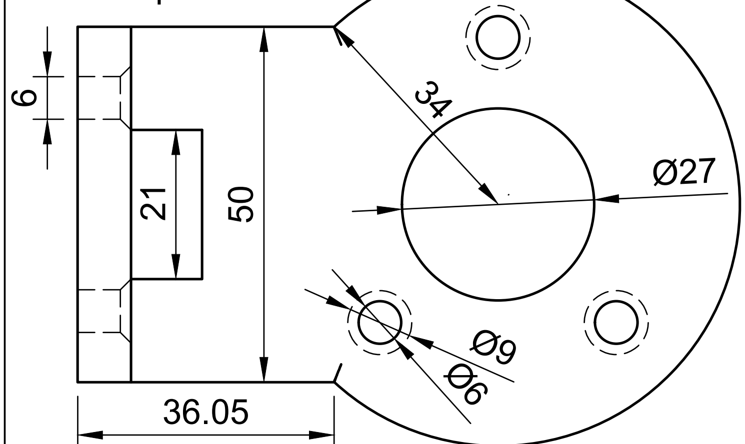


side view



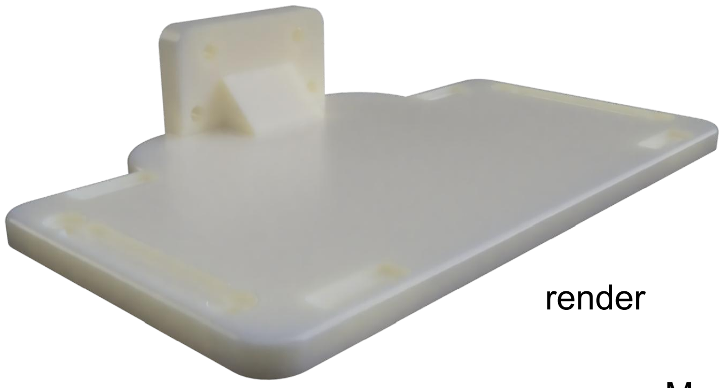
side view

top view

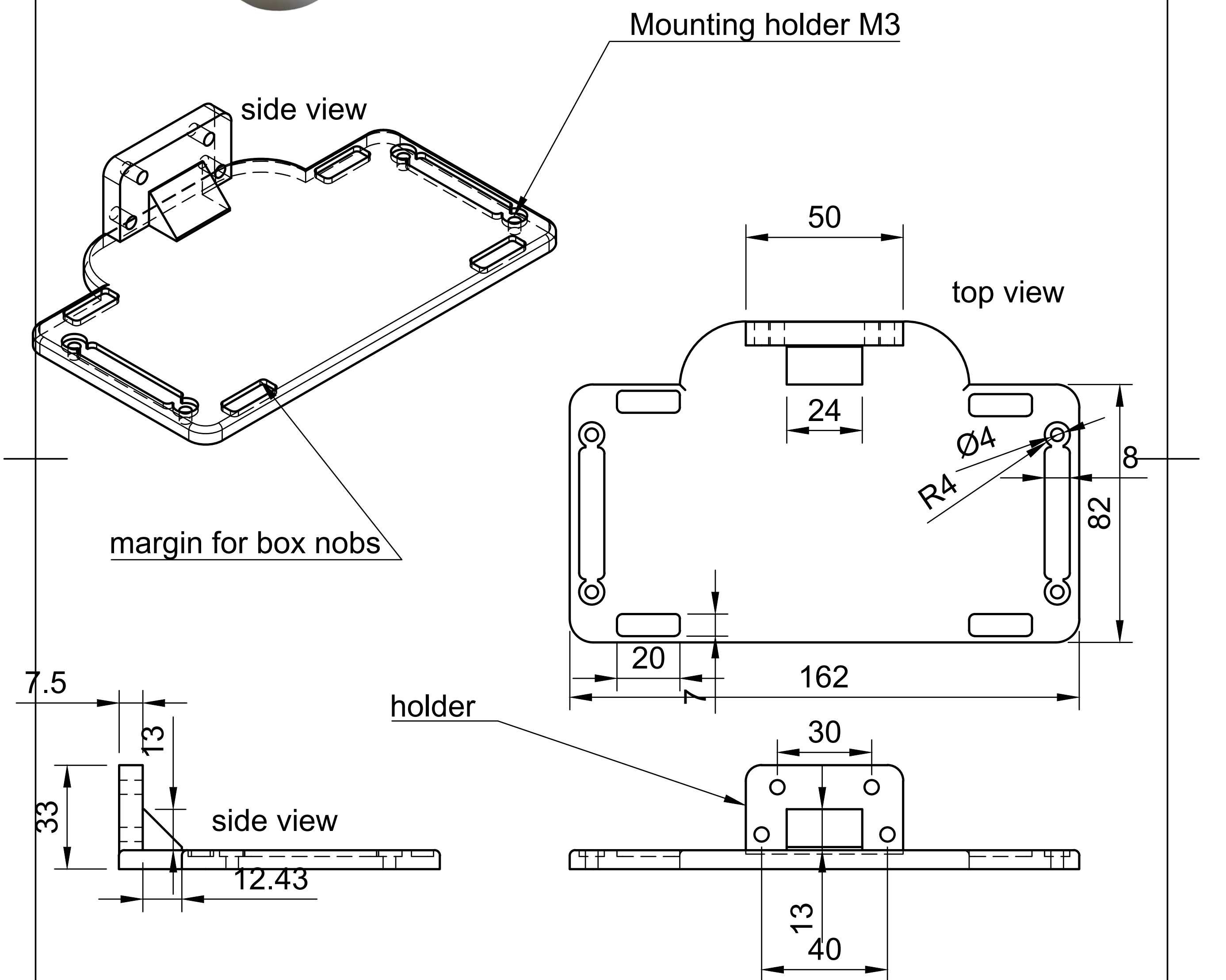


render

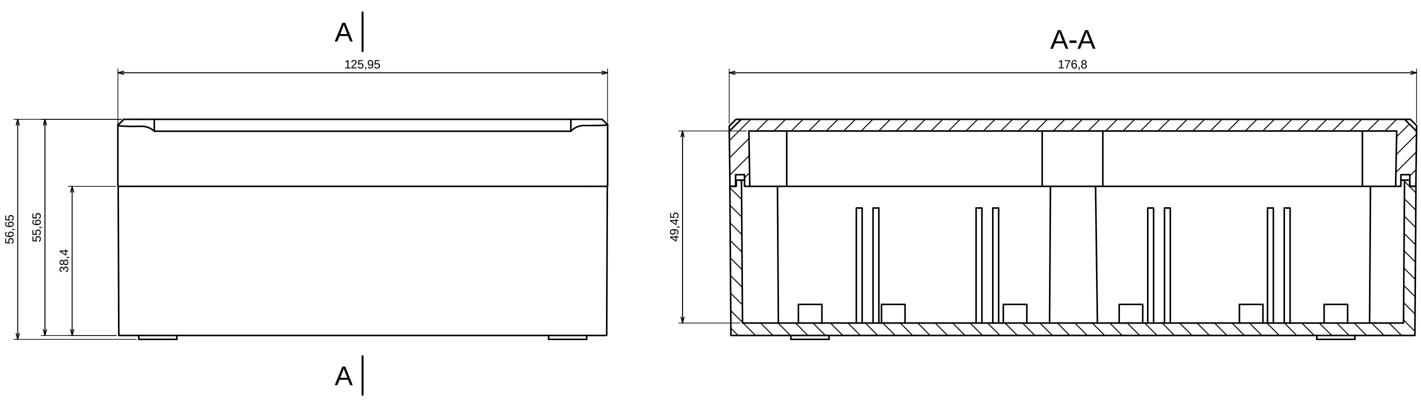
Dept.	Technical reference	Created by Jan-Paul Konijn 02/07/2020	Approved by
		Document type specification	Document status Final
		Title pyranometer mount v1.0	DWG No.
			Rev. | Date of issue | Sheet 1/1



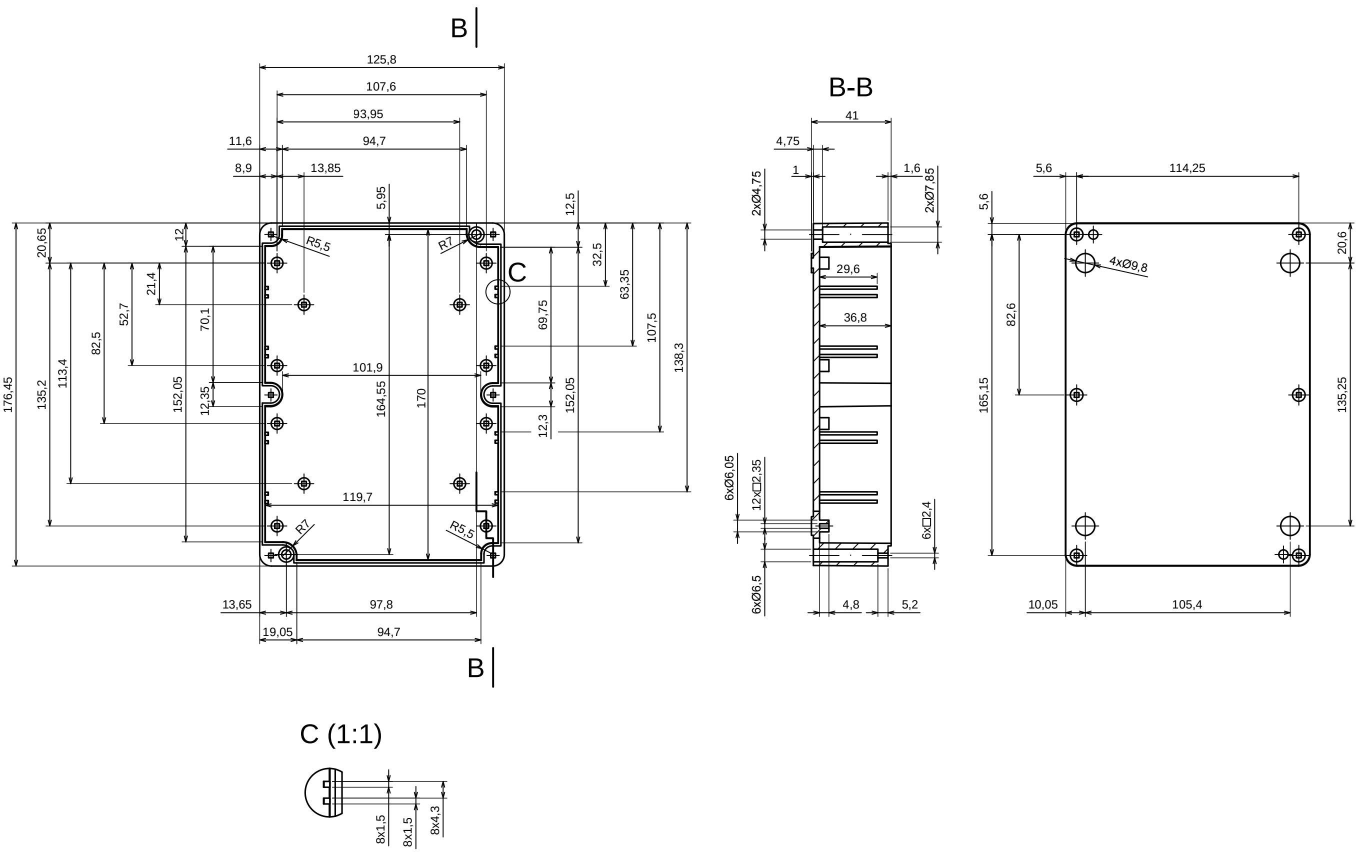
render



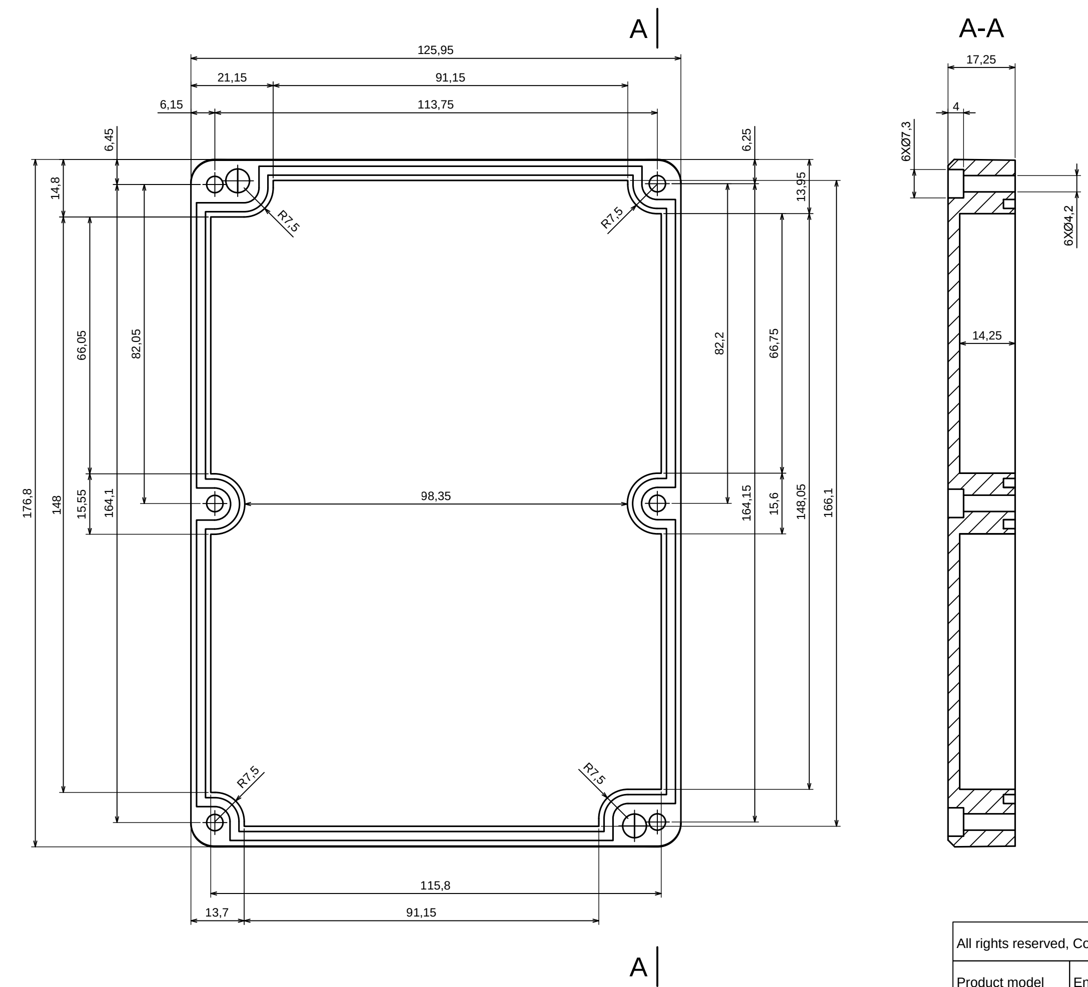
Dept.	Technical reference	Created by Jan-Paul Konijn 02/07/2020	Approved by
		Document type specification	Document status Final
		Title mount pyrano peter	DWG No.
			Rev. / Date of issue / Sheet 1/1



Product model	Enclosure Z74 - assembly
Format: A3	Material: PS, ABS
Scale 1:1	Tolerance: +/- 0.5

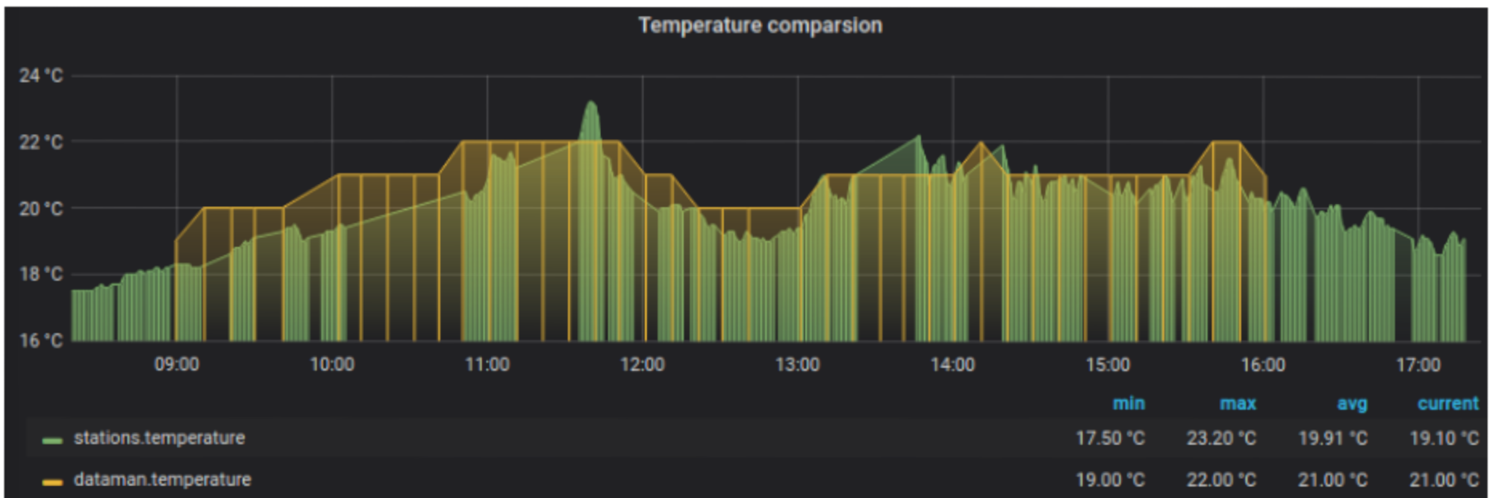


Product model	Enclosure Z74 - base	
Format: A3	Material: PS, ABS	
Scale 1:2	Tolerance: +/- 0.5	

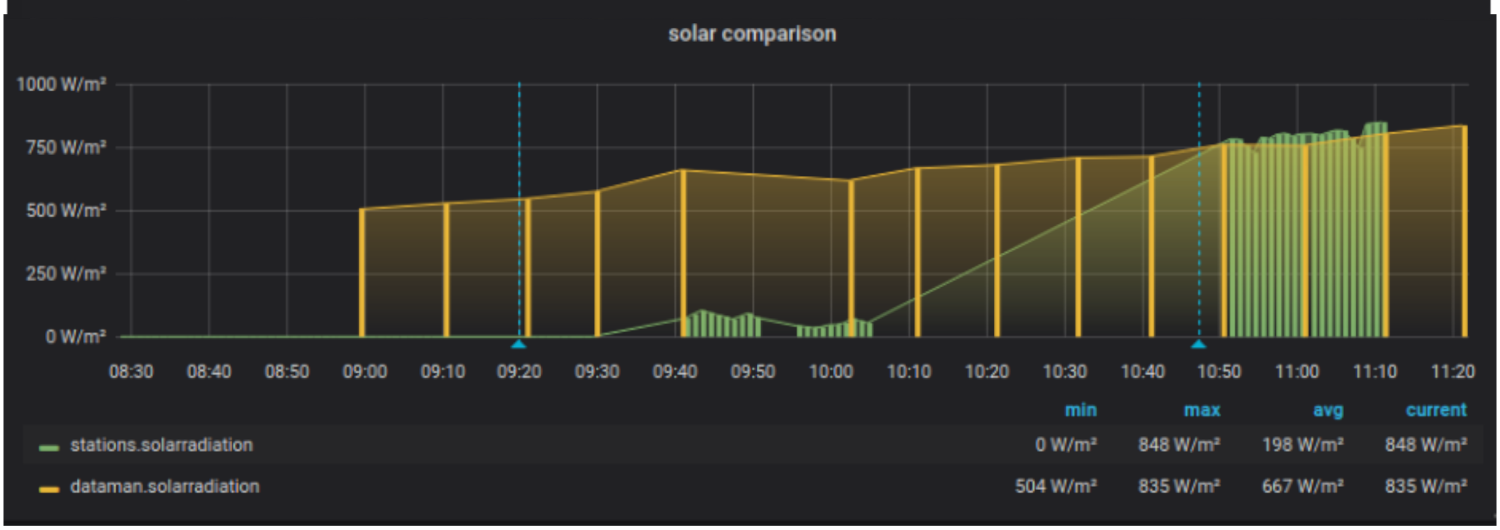


Product model	Enclosure Z74 - cover	
Format: A3	Material: PS, ABS	
Scale 1:1	Tolerance: +/- 0.5	

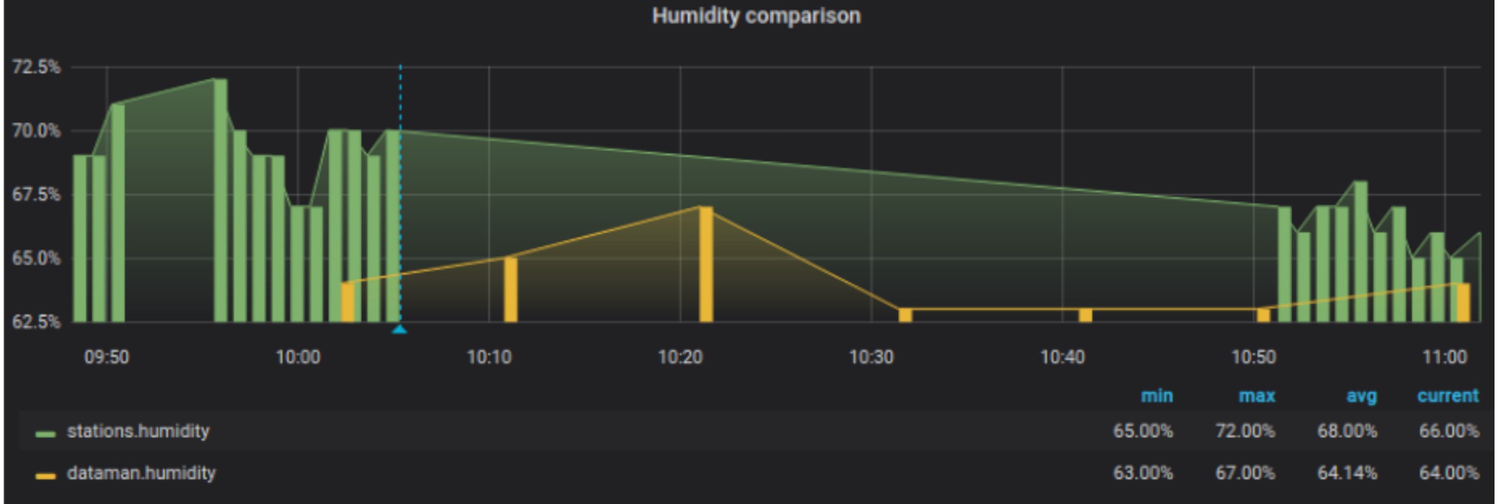
H Results June 19 2020

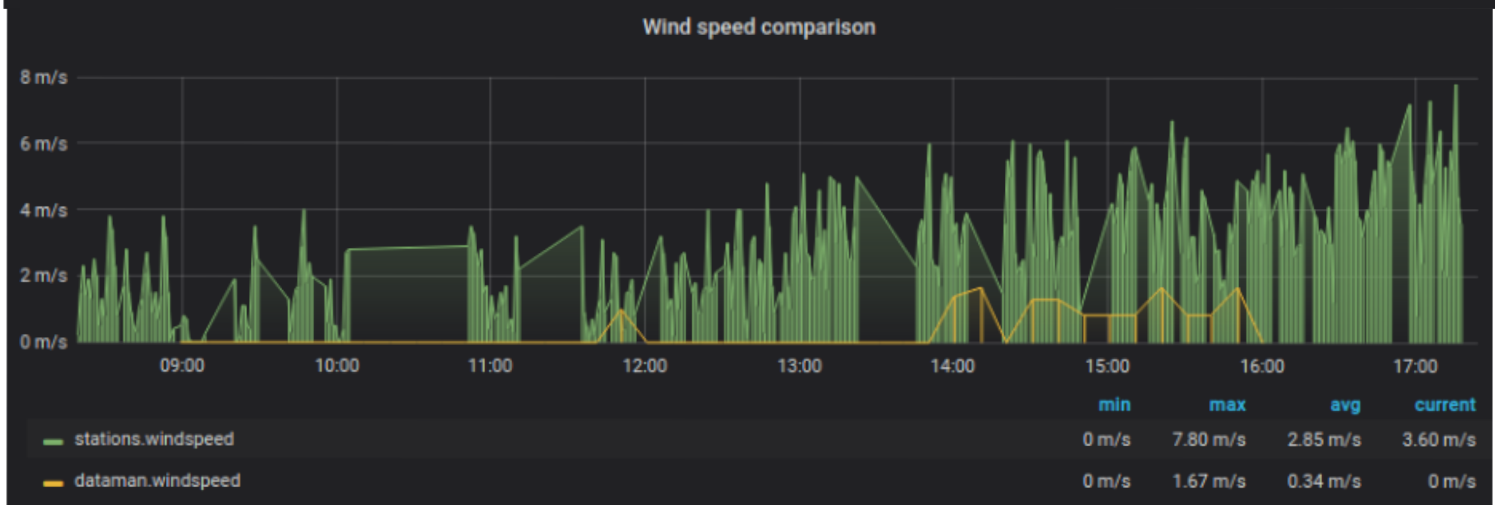


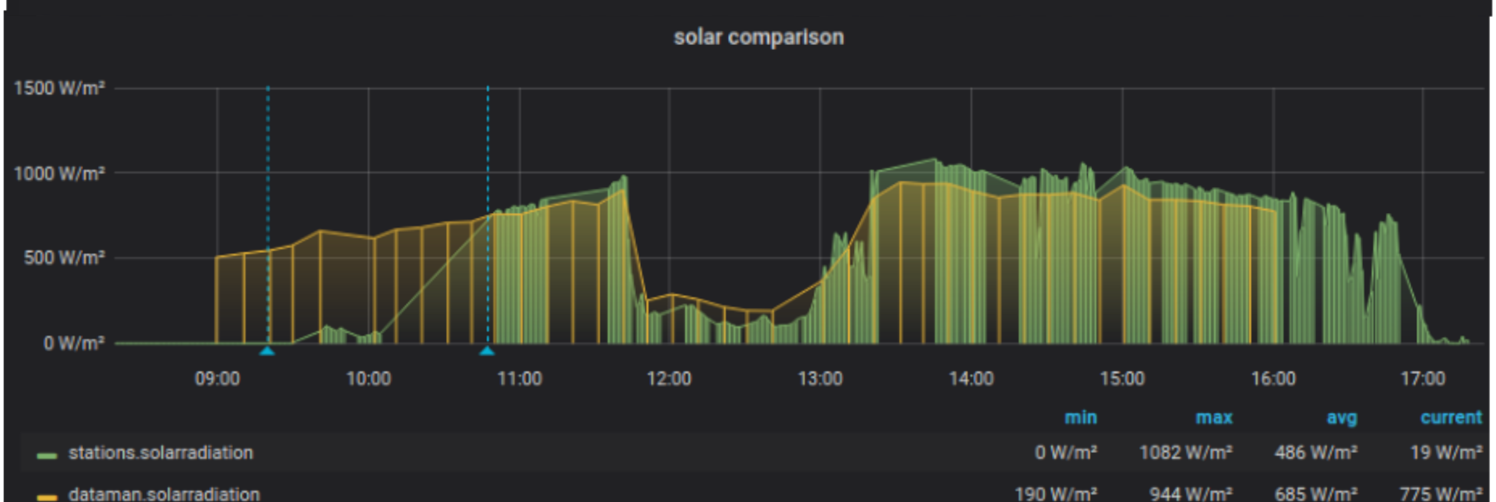
Temperature comparsion
24 °C
22 °C
20 °C
18 °C
16 °C
09:00
10:00
11:00
12:00
13:00
14:00
15:00
16:00
17:00
min
max
avg
current
stations.temperature 17.50 °C 23.20 °C 19.91 °C 19.10 °C
dataman.temperature 19.00 °C 22.00 °C 21.00 °C 21.00 °C

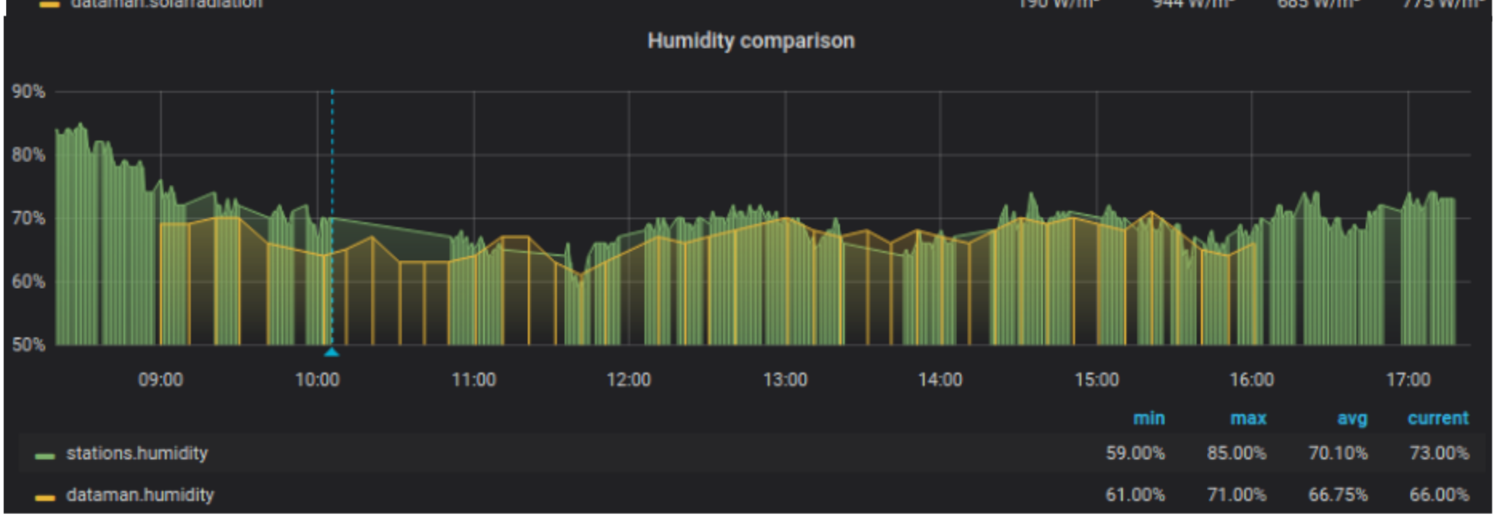


solar comparison
1000 W/m²
750 W/m²
500 W/m²
250 W/m²
0 W/m²
08:30
08:40
08:50
09:00
09:10
09:20
09:30
09:40
09:50
10:00
10:10
10:20
10:30
10:40
10:50
11:00
11:10
11:20
min
max
avg
current
stations.solarradiation 0 W/m² 848 W/m² 198 W/m² 848 W/m²
dataman.solarradiation 504 W/m² 835 W/m² 667 W/m² 835 W/m²

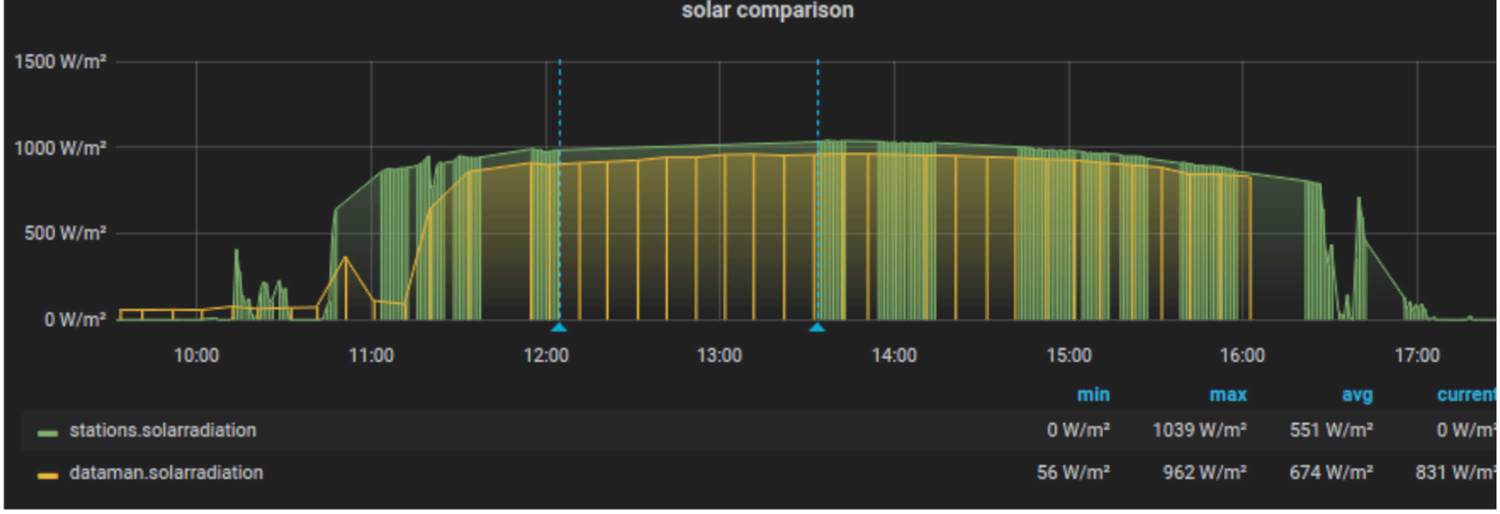

Humidity comparison
72.5%
70.0%
67.5%
65.0%
62.5%
09:50
10:00
10:10
10:20
10:30
10:40
10:50
11:00
min max avg current
stations.humidity 65.00% 72.00% 68.00% 66.00%
dataman.humidity 63.00% 67.00% 64.14% 64.00%

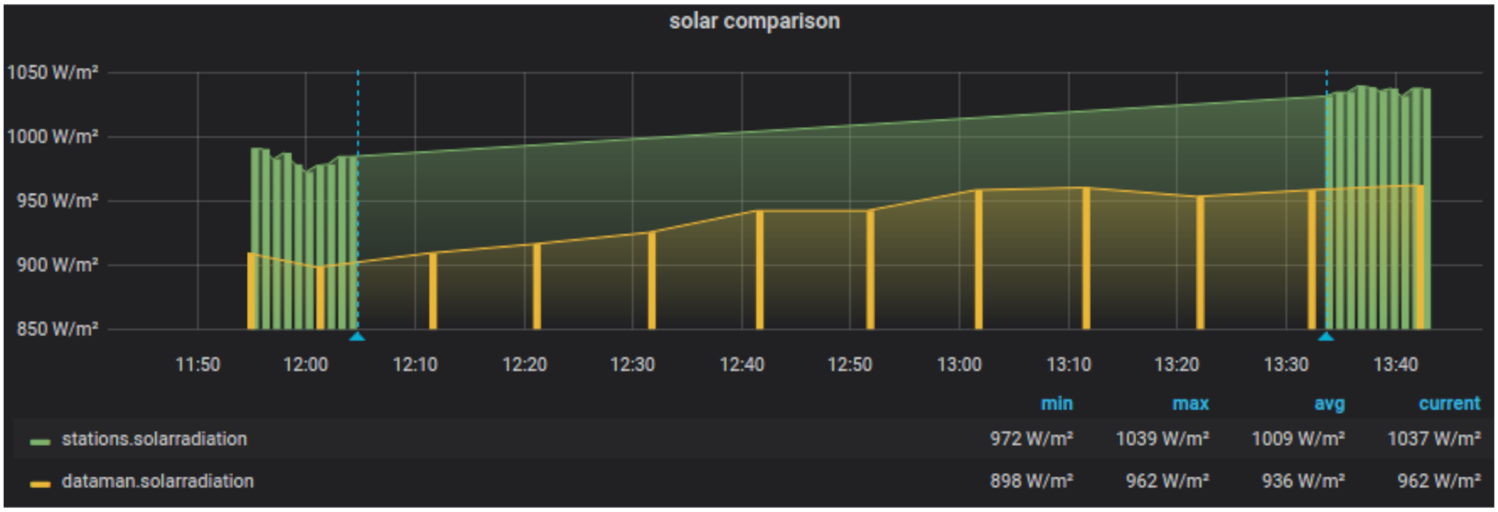

Wind speed comparison
8 m/s
6 m/s
4 m/s
2 m/s
0 m/s
09:00
10:00
11:00
12:00
13:00
14:00
15:00
16:00
17:00
min max avg current
stations.windspeed 0 m/s 7.80 m/s 2.85 m/s 3.60 m/s
dataman.windspeed 0 m/s 1.67 m/s 0.34 m/s 0 m/s

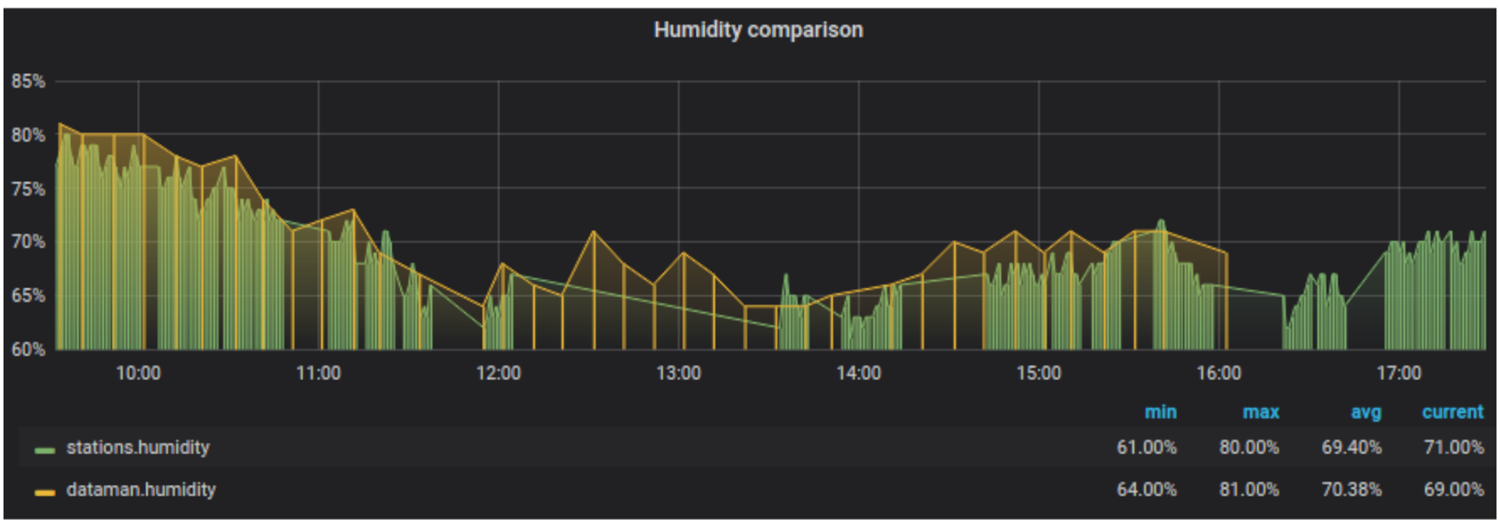

solar comparison
1500 W/m²
1000 W/m²
500 W/m²
0 W/m²
09:00
10:00
11:00
12:00
13:00
14:00
15:00
16:00
17:00
min max avg current
stations.solarradiation 0 W/m² 1082 W/m² 486 W/m² 19 W/m²
dataman.solarradiation 190 W/m² 944 W/m² 685 W/m² 775 W/m²

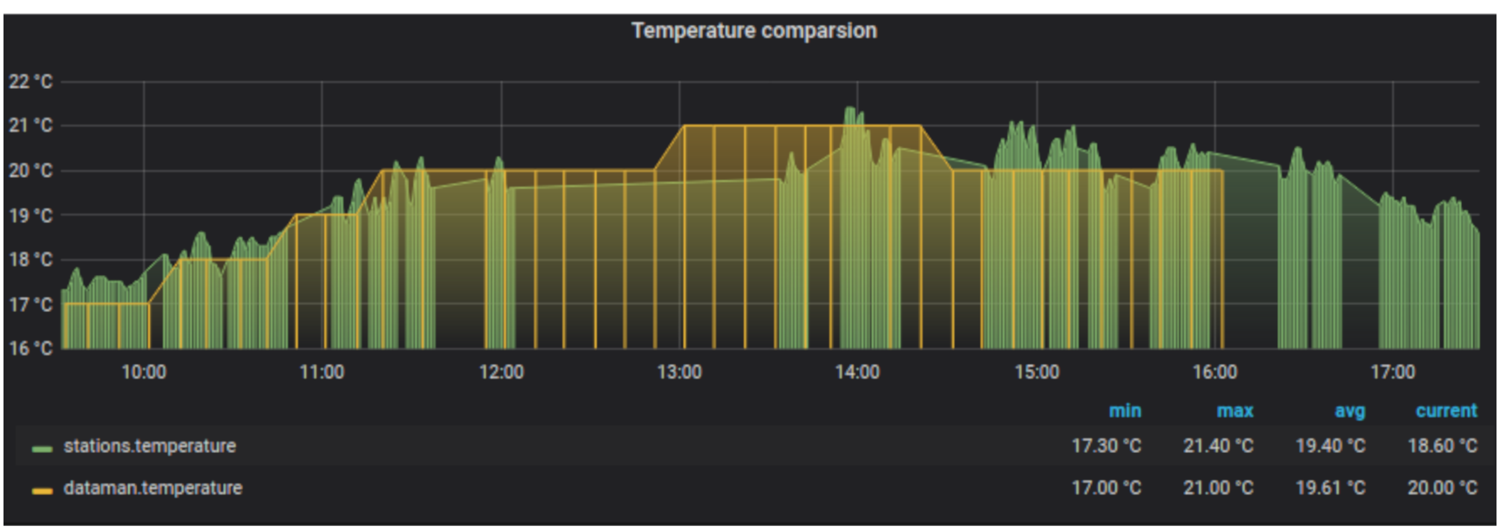

Humidity comparison
90%
80%
70%
60%
50%
09:00
10:00
11:00
12:00
13:00
14:00
15:00
16:00
17:00
min max avg current
stations.humidity 59.00% 85.00% 70.10% 73.00%
dataman.humidity 61.00% 71.00% 66.75% 66.00%

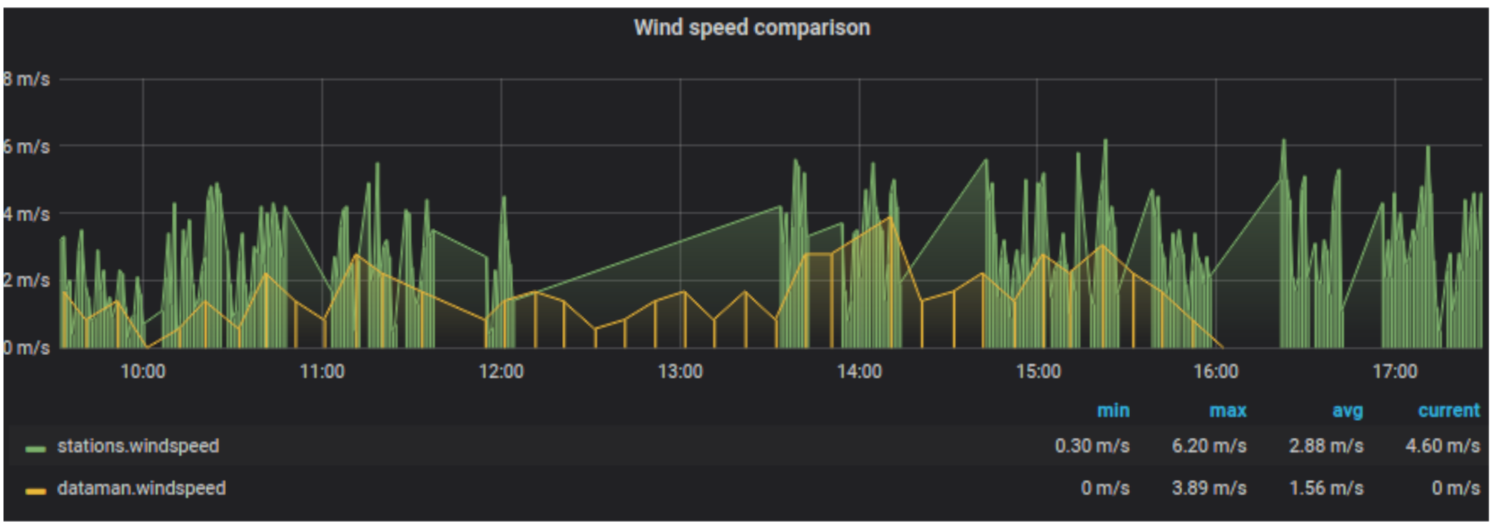
I Results June 20 2020


solar comparison
1500 W/m²
1000 W/m²
500 W/m²
0 W/m²
10:00
11:00
12:00
13:00
14:00
15:00
16:00
17:00
min
max
avg
current
stations.solarradiation
0 W/m²
1039 W/m²
551 W/m²
0 W/m²
dataman.solarradiation
56 W/m²
962 W/m²
674 W/m²
831 W/m²


solar comparison
1050 W/m²
1000 W/m²
950 W/m²
900 W/m²
850 W/m²
11:50
12:00
12:10
12:20
12:30
12:40
12:50
13:00
13:10
13:20
13:30
13:40
min
max
avg
current
stations.solarradiation
972 W/m²
1039 W/m²
1009 W/m²
1037 W/m²
dataman.solarradiation
898 W/m²
962 W/m²
936 W/m²
962 W/m²


Humidity comparison
85%
80%
75%
70%
65%
60%
10:00
11:00
12:00
13:00
14:00
15:00
16:00
17:00
min
max
avg
current
stations.humidity
61.00%
80.00%
69.40%
71.00%
dataman.humidity
64.00%
81.00%
70.38%
69.00%

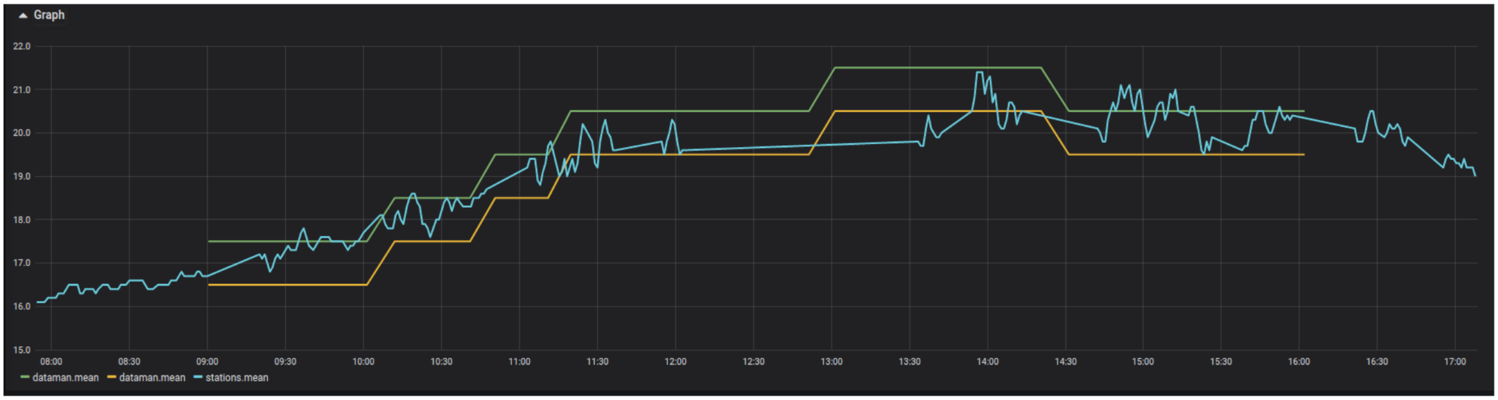

Temperature comparsion
22 °C
21 °C
20 °C
19 °C
18 °C
17 °C
16 °C
10:00
11:00
12:00
13:00
14:00
15:00
16:00
17:00
min
max
avg
current
stations.temperature
17.30 °C
21.40 °C
19.40 °C
18.60 °C
dataman.temperature
17.00 °C
21.00 °C
19.61 °C
20.00 °C

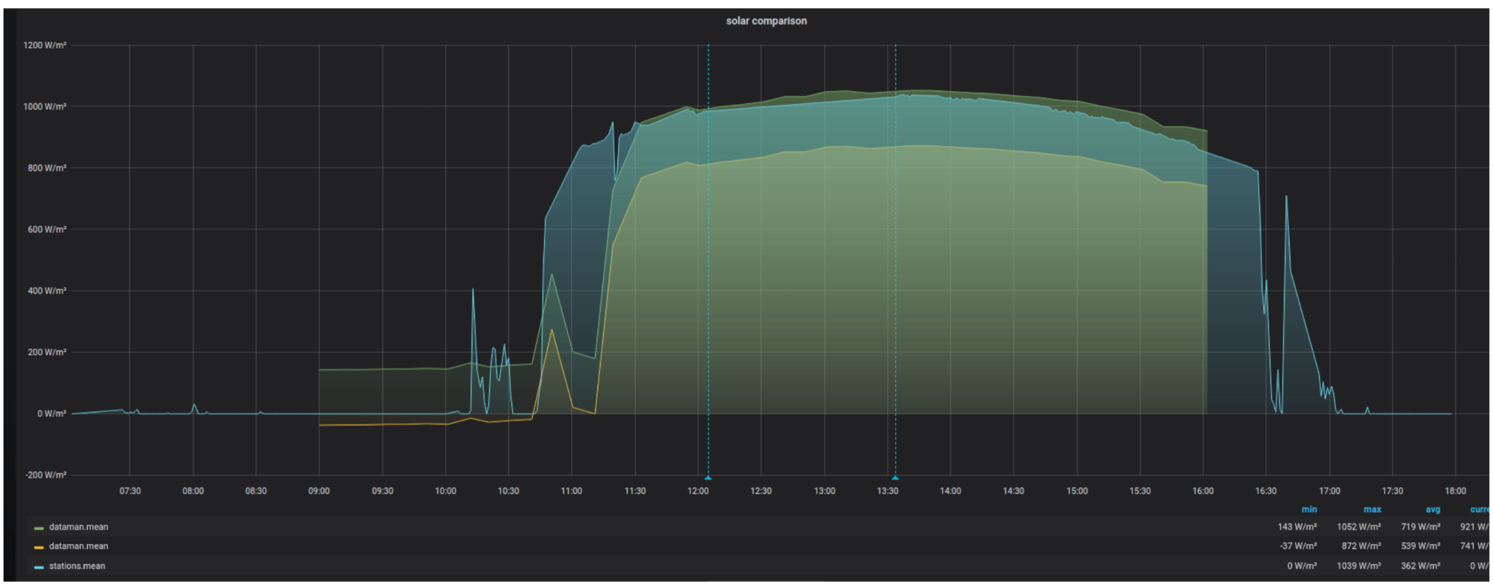


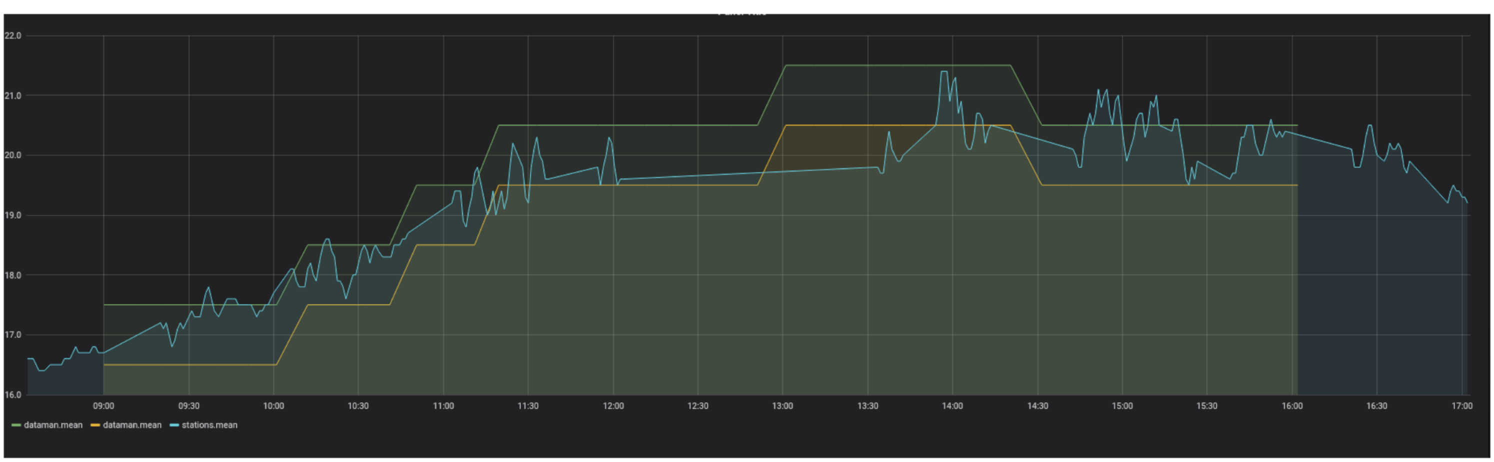
Wind speed comparison
8 m/s
6 m/s
4 m/s
2 m/s
0 m/s
10:00
11:00
12:00
13:00
14:00
15:00
16:00
17:00
min
max
avg
current
stations.windspeed 0.30 m/s 6.20 m/s 2.88 m/s 4.60 m/s
dataman.windspeed 0 m/s 3.89 m/s 1.56 m/s 0 m/s

J Results Accuracies June 20 2020


Wind speed comparison
8 m/s
6 m/s
4 m/s
2 m/s
0 m/s
-2 m/s
6/19 04:00
6/19 06:00
6/19 08:00
6/19 10:00
6/19 12:00
6/19 14:00
6/19 16:00
6/19 18:00
6/19 20:00
6/19 22:00
6/20 00:00
6/20 02:00
6/20 04:00
6/20 06:00
6/20 08:00
6/20 10:00
6/20 12:00
6/20 14:00
6/20 16:00
6/20 18:00
6/20 20:00
min max avg current
dataman.mean 0.20 m/s 4.09 m/s 1.12 m/s 0.20 m/s
dataman.mean -0.20 m/s 3.69 m/s 0.72 m/s -0.20 m/s
stations.mean 0 m/s 7.20 m/s 2.17 m/s 0 m/s


Graph
22.0
21.0
20.0
19.0
18.0
17.0
16.0
15.0
08:00
08:30
09:00
09:30
10:00
10:30
11:00
11:30
12:00
12:30
13:00
13:30
14:00
14:30
15:00
15:30
16:00
16:30
17:00
dataman.mean
dataman.mean
stations.mean


solar comparison
1200 W/m²
1000 W/m²
800 W/m²
600 W/m²
400 W/m²
200 W/m²
0 W/m²
-200 W/m²
07:30
08:00
08:30
09:00
09:30
10:00
10:30
11:00
11:30
12:00
12:30
13:00
13:30
14:00
14:30
15:00
15:30
16:00
16:30
17:00
17:30
18:00
min max avg
dataman.mean 143 W/m² 1052 W/m² 719 W/m² 921 W/
dataman.mean -37 W/m² 872 W/m² 539 W/m² 741 W/
stations.mean 0 W/m² 1039 W/m² 362 W/m² 0 W/


22.0
21.0
20.0
19.0
18.0
17.0
16.0
09:00
09:30
10:00
10:30
11:00
11:30
12:00
12:30
13:00
13:30
14:00
14:30
15:00
15:30
16:00
16:30
17:00
dataman.mean
dataman.mean
stations.mean