REPUBLIC OF TURKEY
AKDENIZ UNIVERSITY

DEVELOPMENT OF IOT-BASED SOLAR WATER HEATING SYSTEM

Hüseyin GÖKALP

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DEPARTMENT OF COMPUTER ENGINEERING

MASTER THESIS

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This thesis unanimously accepted by the jury on 29/07/2023.
Prof. Melih GÜNAY (Supervisor)
Prof. Warren JASPER
Assoc. Prof. TANER DANIŞMAN

ÖZET

NESNELERİN İNTERNETİ TABANLI GÜNEŞ ENERJİLİ SU ISITMA SİSTEMİNİN GELİŞTİRMESİ

Hüseyin GÖKALP

Yüksek Lisans, Bilgisayar Mühendisliği Anabilim DalI

Danışman: Prof. Dr. Melih GÜNAY

Temmuz 2023; 68 sayfa

Güneş Enerjili Isıtma Sistemleri (SWHS), sundukları avantajlara rağmen, sıcak su talebinin öngörülemez doğası, işletmelerini optimize etme konusunda önemli bir engel oluşturmaktadır. Mevcut araştırmalarda, stokastik sıcak su talebinin tahmin edilmesi ve SWHS'lerin en iyi şekilde çalıştırılması konusunda belirgin bir boşluk gözlemlenmektedir. Birkaç çalışma, hacimsel sıcak su kullanımının tahmini ve talep tarafı tahminlerine dayalı su ısıtma sistemlerinin optimizasyonu konusunda ışık tutmuş olsa da, gelişmiş öğrenme tekniklerini ve Nesnelerin İnterneti (IoT) teknolojisini hem tahmin hem de optimizasyon için entegre eden kapsamlı bir yaklaşım büyük oranda araştırılmamıştır. Bu boşluk, SWHS'lerin, özellikle evsel ortamlarda, verimliliğini artırma fırsatını sunmaktadır. Bu çalışma, IoT tabanlı bir Güneş Enerjili Su Isıtma Sistemi geliştirerek ve esas olarak gün boyunca optimum sıcak su talebini sağlamak için IoT teknolojisinden, derin sinir ağlarından (DNN'ler) ve derin pekiştirmeli öğrenmeden (DRL) yararlanan 'Güneş Enerjili Su Isıtma Sistemi Denetleyici Ünitesi (SWHSCU)' olarak adlandırılan denetim biriminin ekseninde bu boşluğu doldurmayı amaçlamaktadır. Önerilen kontrol ünitesi, sadece stokastik sıcak su talebini genişletmekle kalmayıp, aynı zamanda bu tahminleri SWHS'lerin gerçek zamanlı işletilmesine entegre etmeyi hedefleyerek sistem verimliliğini ve işletme güvenilirliğini artırmayı hedeflemektedir. Geliştirme süreci üç ana aşamayı kapsamaktadır. İlk olarak, SWHS'lerin tasarımı ve kurulumu, her biri bir öncekisinden daha gelişmiş olan iki iterasyon geliştirilmiştir. İkinci olarak, IoT teknolojisi ve ileri programlama tekniklerini içeren SWHSCU'nun geliştirilmesi. Son olarak, zaman serisi verilerini etkili bir şekilde ele almak için Long Short-Term Memory (LSTM) yaklaşımını kullanan bir DRL algoritma çerçevesinin oluşturulması. Araştırma, gelişmiş AI ve IoT metodolojileri aracılığıyla sıcak su talebi tahminini optimize ederek konut tipi güneş su ısıtma sistemlerinin işletilmesini iyileştirmeye odaklanmaktadır. Bu ilerleme, güneş su ısıtma sistemlerinin enerji verimliliğinde önemli iyileştirmeleri tetikleyebilir, çevresel etkilerin ve enerji maliyetlerinin azalmasını sağlayabilir. Araştırma verileri, araştırmacı tarafından tasarlanan ve 2023 yılının 15 Mart ile 15 Haziran tarihleri arasında Antalya'nın Konyaaltı ilçesinde yeniden tasarlanan ikinci nesil güneş enerjili su ısıtma sisteminde kullanılan, kontrol ünitesine bağlı sensörler ve aktuatörlerin çalışma durumları aracılığıyla toplanan gerçek verilere dayanmaktadır. Ek olarak, veriler güneş enerjili su ısıtma sisteminin kurulduğu bölgedeki ilgili tarihler için mgm.gov.tr web sitesinden alınan meteorolojik bilgileri içermektedir. Bu alandaki gelecekteki çalışmalar, geliştirilen SWHS'nin uygulanabilirliğini ve güvenliğini daha da artıracak, maliyet azaltma ve veri güvenliği konularında ek bakış açıları sağlayacaktır. Bu çalışma, ileri yapay zeka ve Nesnelerin İnterneti (IoT) yöntemleri aracılığıyla evlerdeki güneş enerjisiyle çalışan sıcak su

sistemlerinin işleyişini optimize etmek için yeni bir yaklaşım sunarak literatüre katkıda bulunmaktadır.

ANAHTAR KELİMELER: Güneş enerjili su ısıtma sistemi, Nesnelerin interneti, Yapay zeka, Makine öğrenmesi, Microdenetleyici, ESP-NOW.

JÜRİ: Prof. Dr. Melih GÜNAY

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ABSTRACT

DEVELOPMENT OF IOT-BASED SOLAR WATER HEATING SYSTEM

Hüseyin GÖKALP

MSc Thesis in Computer Engineering

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Despite the advantages they offer, the unpredictable nature of hot water demand poses a significant impediment to optimizing their operation. There is an observable gap in existing research concerning the prediction of stochastic hot water demand and optimal operation of SWHSs. While several studies have shed light on the prediction of volumetric hot water usage and the optimization of water heating systems based on demand-side predictions, a comprehensive approach that integrates advanced learning techniques and the Internet of Things (IoT) for both prediction and optimization remains largely unexplored. This gap presents an opportunity to enhance the efficiency of SWHSs, especially in residential settings. This study aims to fill this lacuna by developing an IoT-based Solar Water Heating System and mainly on the axis of its supervising unit termed 'The Solar Water Heating System Controller Unit (SWHSCU)' that leverages IoT technology, deep neural networks (DNNs), and deep reinforcement learning (DRL) to ensure optimal hot water demand throughout the day. The proposed controller aims to not only expand the prediction of stochastic hot water demand but also integrate these predictions into the real-time operation of SWHSs, thereby enhancing system efficiency and operational reliability. The development process entails three core phases. Firstly, the design and installation of the SWHSs, during which two iterations were developed, each representing an advancement from its predecessor. Secondly, the development of the SWHSCU, incorporating IoT technology and advanced programming techniques. Lastly, the creation of a DRL algorithm framework supported by DNNs, utilizing a Long Short-Term Memory (LSTM) approach to handle time-series data effectively. The research focuses on enhancing the operation of residential solar water heating systems by optimizing hot water demand prediction through advanced AI and IoT methodologies. This advancement could catalyze significant improvements in the energy efficiency of solar water heating systems, resulting in the reduction of environmental impacts and energy costs. The research data is based on real data collected through sensors and the operating statuses of actuators connected to the controller unit of the second-generation solar water heating system, which was designed by the researcher and employed in the redesigned second-generation solar water heating system in the Konyaaltı district of Antalya, between March 15, 2023, and June 15, 2023. In addition, the data includes meteorological information obtained from the mgm.gov.tr website for the corresponding dates in the region where the solar water heating system was installed. Future work in this field will further enhance the viability and security of the developed SWHS, providing additional perspectives for cost reduction and data security. This study contributes to the literature by offering a novel approach to optimize the operation of residential SWHSs through advanced AI and IoT methodologies.

KEYWORDS: Solar water heater system, Internet of things, Artificial intelligence, Machine learning, Microcontroller, ESP-NOW.

COMMITTEE: Prof. Melih GÜNAY

Prof. Warren JASPER

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TEXT OF OATH

I declare that this study “Development of IoT-Based Solar Water Heating System”, which I present as master thesis, is in accordance with the academic rules and ethical conduct. I also declare that I cited and referenced all material and results that are not original to this work.

29/07/2023
Hüseyin GÖKALP

LIST OF ABBREVIATIONS

Abbreviations

AI	: Artificial Intelligence
ANN	: Artificial Neural Network
ANFIS	: Adaptive Neuro-Fuzzy Inference System / Adaptive Network-Based Fuzzy Inference System
DNN	: Deep Neural Network
DRL	: Deep Reinforcement Learning
FL	: Fuzzy Logic
IoT	: Internet of Things
LSTM	: Long Short-Term Memory
MCU	: Microcontroller Unit
ML	: Machine Learning
MQTT	: Message Queuing Telemetry Transport
RL	: Reinforcement Learning
RNN	: Recurrent Neural Network
SWH	: Solar Water Heater
SWHS	: Solar Water Heating System
SWHCU	: Solar Water Heating System Controller Unit

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1. INTRODUCTION

Solar water heating systems (SWHSs) exemplify an environmentally friendly and sustainable approach to heating water. By harnessing the sun's energy, these systems cater to a wide range of applications, including domestic and industrial use. In residential settings, they provide hot water for daily activities such as bathing, washing dishes, and laundry. By reducing reliance on electricity or gas-powered water heaters, solar water systems contribute to energy conservation and help reduce utility bills for homeowners.

Solar water heaters (SWHs) have a long history, dating back to around 200 BC when the concept was used by the Romans to heat their public baths. Over the centuries, solar water heating systems have evolved and with advancements in technology, they have become more efficient and affordable, making them suitable for use in various climates.

In recent years, the use of Internet of Things (IoT) and Artificial Intelligence (AI) in solar water heating systems has become an important research area to enhance their performance. The utilization of IoT and artificial technologies can enhance the efficiency of solar water heating systems and enable smarter system operation.

The unpredictable nature of hot water demand poses a significant challenge in optimizing the operation of solar water heating systems. At this point, for prediction of stochastic hot water demand and optimal operation of the solar water heating system suitable for the residential use by utilizing the right learning method via artificial intelligence, which considers usage habits and other environmental factors in conjunction with IoT, could provide an opportunity for significant improvements in the solar water heating systems.

The literature review reveals that there is a limited number of studies that have specifically addressed the prediction of stochastic hot water demand and optimal operation of water heating systems based on learning the demand. The available studies on prediction of stochastic hot water demand focused on the prediction of volumetric hot water use for hot water production. Another topic that has been focused on the literature is the optimization of water heating systems by considering demand-side predictions.

The research question at the heart of this thesis is whether it is possible to increase the working of the solar water heating system suitable for the residential use to ensure the optimum hot water demand during day by developed solar water heating system controller.

In this context, the integration of IoT, deep neural networks (DNNs), and deep reinforcement learning (DRL) provide a promising approach through real-time data collection and advanced predictive capabilities for predicting stochastic hot water demand and optimizing the operation of solar water heating systems.

This thesis covers the development an IoT-based Solar Water Heating System that increases the efficiency of the solar water heating system suitable for the residential use with IoT technology, deep neural networks, and a deep reinforcement learning algorithm framework to ensure the optimum hot water demand during the day.

To accomplish this, was aimed to development of an IoT-based Solar Water Heating System that increases the efficiency of the solar water heating system suitable for the residential use to ensure the optimum hot water demand during the day.

On the other hand, that was focused on:

1. Expanding the stochastic hot water demand prediction to encompass additional variables and leveraging advanced data analytics techniques.
2. Integrating the demand prediction into the real-time operation of solar water heating systems for better system efficiency and operational reliability.

The research data is based on real data collected through sensors and the operating statuses of actuators connected to the controller unit of the second-generation solar water heating system, which was designed by the researcher and employed in the redesigned second-generation solar water heating system in the Konyaaltı district of Antalya, between March 15, 2023, and June 15, 2023. In addition, the data includes meteorological information obtained from the mgm.gov.tr website for the corresponding dates in the region where the solar water heating system was installed.

2. LITERATURE REVIEW

2.1. Solar Water Heating System

2.1.1. The solar energy

The use of solar energy has reached a notable limit in recent years. Among all renewable energy sources, solar thermal energy stands out as the most abundant form and is available in both direct and indirect forms. Within a mere hour, the Earth receives an amount of solar energy surpassing the global annual energy consumption (Thirugnanasambandam, Inyan, & Goic, 2010).

Türkiye has a significant solar energy potential due to its geographical location (Solar, 2023). Figure 2.1 shows the general potential outlook found in Solar Energy Potential Map (SEM) of Türkiye prepared by Ministry of Energy and Natural Resources is presented below. According to the SEM, Türkiye has a total annual sunshine duration of 2,741 hours and an average of 7.51 hours of sunshine per day. In addition, the average annual total global radiation value is 1,527.46 kWh/m^2 (T.C. Enerji ve Tabii Kaynaklar Bakanlığı, 2023a).

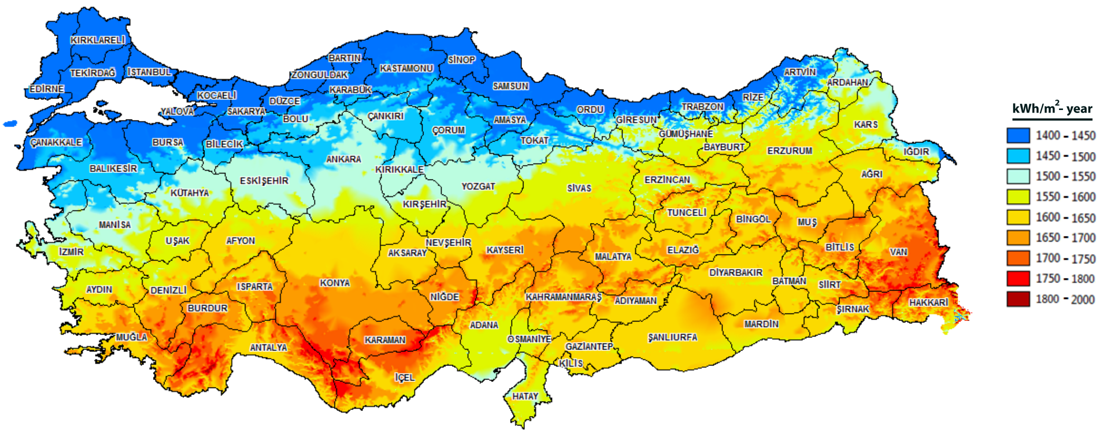


Figure 2.1. Solar Energy Potential Map (SEM) of Türkiye

Considering the location of Türkiye and the amount of solar radiation, it should be noted that it has an ideal level of sunshine (Babalıoğlu, Büyükpatpat, & Genç, 2023). Especially, Türkiye's Mediterranean Region is second largest region with the greatest potential to benefit from solar energy after Southeastern Anatolia Region (T.C. Enerji ve Tabii Kaynaklar Bakanlığı, 2023b). The province of Antalya, which is the subject of the research, is one of the provinces of the Mediterranean Region. Antalya province has radiation intensity and sunshine duration above the average of Türkiye throughout the year. Figure 2.2 shows the general potential outlook found in Solar Energy Potential Map (SEM) of Antalya province is presented below. Antalya province has a total annual sunshine duration of 3013 hours and an average of 8.26 hours of sunshine per day. In addition, the average annual total global radiation value is 1,650.25 kWh/m^2 (T.C. Enerji ve Tabii Kaynaklar Bakanlığı, 2023b).

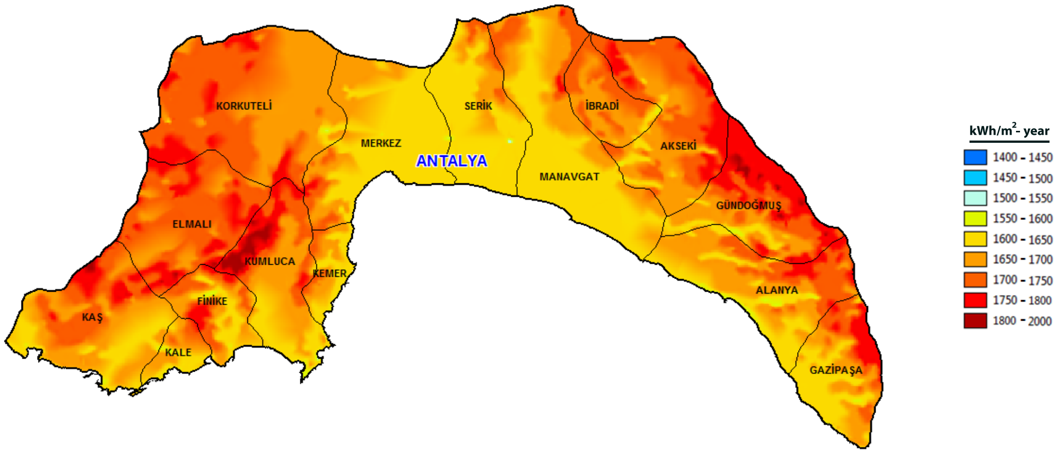


Figure 2.2. Solar Energy Potential Map (SEM) of Antalya

2.1.2. Solar water heating

Solar water heating is a well-known application of solar thermal technology that has proven to be cost-efficient for various domestic and industrial purposes (Islam, Sumathy, & Khan, 2013).

Solar water heaters have a long history, with their usage dating back to around 200 BC when the concept was employed by the Romans to heat their public baths. The development of SWH as a prototype occurred in 1767 when Swiss naturalist De Saussure trapped heat between two glass panes, a concept he called the "Hot Box." This invention had multiple applications, including cooking, heating, and producing hot water. The first commercially available SWH system, named Climax, was introduced in 1891 by Clarence Kemp. It was an integrated system where the metal tank served as both the collector and storage tank. Inspired by Kemp's work, researchers in the late 19th century focused on improving the efficiency and durability of solar water heating systems. In 1909, William Bailey introduced a new solar water heating system that separated the solar collector from the storage tank. This system utilized the thermosyphon principle, which involved circulating the water between the collector and storage tank (Gong & Sumathy, 2016).

2.1.3. Technical background of solar water heating systems

A solar water heating system consists of essential components such as solar collector(s), the storage tank where the heated water is collected, and the insulated pipes that provide the connection between these two parts, a working fluid, and if necessary, the elements that complete the system such as pump(s) and controller(s).

The system operates by transporting the fluid in contact with a dark surface, typically referred to as the solar collector, which is designed to absorb solar radiation and minimize heat loss. The purpose of the solar collector is to efficiently absorb the solar radiation and transfer its heat to the fluid. In solar water heating systems, the fluid can be water itself, which is heated directly and used for various purposes, or it can be a heat transfer fluid like a mixture of glycol and water. In the latter case, the heat transfer fluid passes through a heat-exchanger, where it transfers its heat to the water that will be utilized. A schematic diagram illustrating the process of heating water using solar energy can be seen in Figure 2.3 (Herez, Khaled, El Hage, Lemenand, & Ramadan, 2018).

Figure 2.3. Process of heating water using solar energy

2.1.4. Classification of solar water heating system

Solar water heating systems can be further categorized into passive circulation systems and active circulation systems based on the circulation of working fluids. Passive circulation systems rely on the thermosyphonic method, where the natural circulation of the fluid is induced by the density difference. In contrast, active circulation systems utilize a pump to facilitate the circulation of the working fluid.

Additionally, solar water heating systems can be broadly classified into two main categories based on the heat transfer process: direct systems and indirect systems. In direct systems, water is directly heated in the collector. In indirect systems, a heat transfer fluid is heated in the collector and then passed through a condenser or heat-exchanger to heat the water. Different techniques are employed in direct and indirect solar water heating systems to prevent the freezing of the working fluid during adverse weather conditions. These techniques involve recirculation or drain-down techniques for direct systems and the drain-back technique for indirect systems.

2.1.5. Project design process of solar water heating system

The project design process of a solar water heating system involves several key steps to ensure efficient and effective implementation. Firstly, a thorough assessment of the site and its solar resource potential is conducted, considering factors such as geographical location, solar radiation levels, and shading analysis. This information is then used to determine the appropriate type and size of solar collectors required for the system. Next, the design team evaluates the hot water demand of the intended users, considering factors like occupancy, usage patterns, and desired water temperature. This data is used to determine the storage capacity of the system, as well as the required heat-exchangers and pumps. Additionally, the design process involves careful consideration of the plumbing and piping layout, ensuring optimal flow rates and minimal heat loss. The overall system design is then reviewed and optimized to maximize energy efficiency and minimize environmental impact. Finally, a comprehensive cost analysis is conducted to assess the financial viability of the project, considering factors such as equipment costs, installation expenses, and potential savings from reduced energy consumption. Through this rigorous design process, a solar water heating system can be effectively tailored to meet the specific requirements of the site, while providing sustainable and cost-effective hot water solutions.

The proper sizing of solar water heating system is a highly complex problem due to its inclusion of both predictable factors such as the performance characteristics of collectors and other equipment, as well as unpredictable parameters like external environmental conditions. In this regard, numerous methods have been developed to model the performance of desired solar water heating systems. Among these methods, the f-chart method stands out as one of the most significant. Using the f-chart method, it is possible to estimate the proportion of the required water heating load that can be met by solar energy on a monthly and yearly basis for a specific type of collector and surface area (Bayramian, Günerhan, & Yalçınkaya, 2023) (Yiğit & Atmaca, 2018).

Additionally, a simplified model can be employed for calculations within a specific seasonal range, offering further utility in the design of solar water heating systems. A simplified method for calculating the required collector surface area, storage tank volume, and circulation rate as parameter-based considerations in the selection of solar water heating (SWH) system components for a middle-income 4-member family residing in Antalya province throughout the year has been detailed. This methodology is explained through a series of mathematical formulas, providing a comprehensive understanding of the process (Yiğit & Atmaca, 2018).

The formula for calculating the useful heat obtained for unit collector surface area is as follows:

$$Q_{useful} = \mathrm{H_T} \times \eta_{col} \times \eta_m \tag{3.1}$$

where,

Q_{useful} is useful heat.

$\mathrm{H_T}$ is monthly average daily solar radiation on collector surface per unit area.

η_{col} is the system efficiency excluding the collector(s). In small-scale installations, the overall system efficiency can be taken as 0.40-0.66, while in large-scale installations, it can be considered as 0.50-0.80.

η_m is the collector efficiency. The efficiency of a single-glazed absorber surface collector is 0.40 and a double-glazed absorber surface collector is 0.45 throughout the entire year. Additionally, the efficiency value for a single-glazed absorber surface collector during the months of June, July, and August is 0.65, whereas for a double-glazed absorber surface collector, it is 0.60. Furthermore, the efficiency value for a single-glazed absorber surface collector during the months of November to March is 0.25, whereas for a double-glazed absorber surface collector, it is 0.35.

The determination of the required thermal load for hot water demand can be done as follows:

$$Q_{need} = m \times c_p \times (\mathrm{T}_w - \mathrm{T}_m) \tag{3.2}$$

where,

Q_{need} is the required thermal load.

m is daily amount of hot water to be prepared. The daily amount of hot water to be prepared can be calculated by multiplying the daily per capita hot water consumption rate by the number of individuals in a family.

c_p is the specific heat of water (4190 J/kgK).

T_w is the minimum acceptable water temperature.

T_m is monthly average main supply water temperature.

The formula for determining the total collector surface area for a solar water heating system on an annual basis is as follows:

$$A_c = \sum_{i=1}^{12} Q_{useful} / \sum_{i=1}^{12} Q_{need} \tag{3.3}$$

The formula for calculating the number of collectors is as follows:

$$n = \frac{A_c}{S} \tag{3.4}$$

where,

n is the required number of collectors.

A_c is the total collector surface area (m^2).

S is the net surface area of the collector absorber.

Based on the net surface area of the selected collector absorber and the required number of collectors, the total collector surface area is recalculated. This value will be used to determine the required storage tank volume and the circulation rate in liters per minute for a specific unit of time.

The formula for recalculating the total collector surface area is as follows:

$$A_c = n \times S \tag{3.5}$$

where,

A_c is the total collector surface area (m^2).

n is the required number of collectors.

S is the net surface area of the collector absorber (m^2).

The required storage tank volume:

$$V = \beta_1 \times A_c \tag{3.6}$$

where,

V is the required storage tank volume (m^3).

β_1 is 0.06 m^3/m^2.

A_c is the total collector surface area (m^2).

The required circulation rate:

$$G = \beta_2 \times A_c \tag{3.7}$$

where,

G is the required circulation rate (L/min).

β_2 is 1L/min.

A_c is the total collector surface area (m^2).

The design of the hot water storage tank is a critical aspect that significantly influences the overall performance and efficiency of these systems. Several key considerations must be considered to ensure an optimized design and effective utilization of solar energy. One crucial consideration is the size and capacity of the hot water storage tank. The tank's capacity should be determined based on the anticipated hot water demand, considering factors such as household size, daily water usage patterns, and peak demand periods. Proper sizing prevents unnecessary energy losses due to overfilling or underutilization, maximizing the system's efficiency. Insulation plays a vital role in minimizing heat loss from the storage tank. Adequate insulation helps maintain the desired water temperature for an extended period, reducing energy wastage. Using high-quality insulation materials and employing effective insulation techniques, such as thermal blankets or foam insulation, can significantly reduce heat transfer through the tank walls. The orientation and location of the tank are also important factors to consider. Optimal placement of the tank in a well-insulated, accessible location with optimal exposure to solar radiation is essential. This positioning allows for maximum solar heat gain during daylight hours while minimizing shading from surrounding structures or vegetation. Additionally, aligning the tank's orientation with the local solar angles maximizes solar energy absorption and minimizes the need for auxiliary heating. Efficient heat exchange mechanisms within the tank facilitate the effective transfer of heat collected by the solar collectors to the stored water. These mechanisms can include internal heat-exchangers such as coils or heat transfer plates, which enhance thermal contact between the solar heat transfer fluid and the stored water. Efficient heat exchange systems optimize the utilization of solar energy and improve the overall performance of the solar water heating system. Careful selection of materials is crucial for constructing the storage tank. The tank must be constructed with materials that are corrosion-resistant, durable, and capable of withstanding operational pressures and temperatures. Common materials used include stainless steel, glass-lined or polymer-coated steel, and corrosion-resistant plastics. Proper material selection ensures the longevity and reliability of the storage tank, reducing maintenance requirements and extending the system's lifespan.

On the other hand, thermal stratification is another critical aspect in the design of the hot water storage tank in solar water heating systems. Thermal stratification refers to the natural separation of hot water from cold water in solar water heating systems. This phenomenon can be explained based on the laws of thermodynamics. One advantage of thermal stratification is its ability to enhance energy transfer efficiency. The hot water in the system tends to condense and accumulate in the upper layer, heating up more rapidly, while the tap water remains in the lower layer and warms up at a slower pace. As a result, the system becomes more efficient, and usable hot water can be obtained more quickly. Additionally, thermal stratification allows for better preservation of hot water in the storage tank, reducing energy losses. However, there are also disadvantages associated with thermal stratification. Firstly, it requires careful system design and adjustments. Without proper sizing, the stratification effect may not be adequately achieved, leading to reduced energy efficiency. Furthermore, the separation of the hot water upper layer can disrupt the homogeneous distribution of water, resulting in insufficient hot water in certain areas. This can negatively impact the overall system performance.

2.1.6. Automation of solar water heating system via IoT

Traditional SWH systems often lack intelligent control mechanisms, resulting in inefficient energy usage and limited user customization.

Moreover, automatic control is crucial in solar water heating systems. It is necessary to utilize the energy collected in the collector and transfer it to the storage tank as quickly as possible. The control of the active circulation solar water heating system is generally achieved using differential thermostats, which regulate the system based on the demand for hot water. Differential thermostats measure the temperature difference between the water in the collector outlet and the water in the storage tank. When the temperature in the collector outlet is higher than a predetermined value (temperature differential) compared to the storage tank temperature, the thermostat activates the circulation pump to initiate the circulation of hot water from the collector to the storage tank. Once the temperature in the storage tank reaches the desired set point, the thermostat detects this and deactivates the circulation pump. This prevents overheating and maintains the water in the storage tank at the desired temperature. When hot water is used, the temperature in the storage tank decreases, and the differential thermostat senses this temperature difference. It then activates the circulation pump again to transfer hot water from the collector to the storage tank until the desired temperature is reached (Yiğit & Atmaca, 2018).

Utilizing Internet of Things (IoT) technology to make automation systems in solar water heating systems more functional is an ideal solution. IoT presents potential avenues for improving efficiency of solar water heating systems. IoT enables users to monitor and control their solar water heating systems remotely through digital devices. This capability provides greater convenience and allows users to adjust the system settings based on their requirements. Through continuous monitoring, IoT devices can predict potential malfunctions or breakdowns, providing alerts for necessary maintenance. This predictive maintenance can prevent system damage and unexpected repair costs. IoT devices, such as sensors and actuators, are integrated to monitor various parameters and control the system. These devices collect data and send it to a central IoT gateway, which processes and transmits the data to a cloud server for further analysis and storage. While IoT offers numerous advantages, it also presents challenges. These include privacy and security concerns, potential technological malfunctions, and the requirement for constant internet connectivity. Therefore, careful consideration of these factors is vital when implementing IoT in solar water heating systems.

2.2. Artificial Intelligence

2.2.1. Introduction

The concept of artificial intelligence aims to simulate the human-like thinking, learning, decision-making, and problem-solving abilities of computer systems. Artificial intelligence techniques have the potential to outperform traditional methods in terms of providing superior, faster, and more practical predictions (Kalogirou & Şencan, 2010).

Machine learning, on the other hand, is a subfield of artificial intelligence and refers to the ability of computer systems to improve themselves by learning from data and experiences.

Machine learning is an umbrella term that refers to a diverse set of analytical algorithms (Seetharam, Brito, Farjo, & Sengupta, 2020). Machine learning algorithms can be mainly classified into four categories: supervised learning, unsupervised learning, semi-supervised learning, and reinforcement learning (Sarker, Furhad, & Nowrozy, 2021).

Supervised learning focuses on datasets that have labeled or annotated domains, where the algorithm learns from the provided labels. On the other hand, unsupervised learning explores unlabeled data points and is considered label-independent and agnostic. Semi-supervised learning combines characteristics of both supervised and unsupervised learning approaches. Lastly, reinforcement learning, which resembles human psychology, employs reward criteria to guide the algorithm in performing tasks within a dataset.

Artificial Neural Networks, also known as Neural Networks, are a mathematical model used in the field of artificial intelligence and machine learning. They aim to mimic the neural cells, or neurons, in the human brain.

Reinforcement learning and artificial neural networks are two distinct yet complementary concepts in the field of machine learning.

Deep learning is a particular type of machine learning that utilizes multi-layered artificial neural networks and can create powerful models capable of solving complex problems with large amounts of data.

Deep Reinforcement Learning is an integration of reinforcement learning and deep learning techniques, aimed at improving an agent's learning capabilities in interacting with an environment. In this approach, the agent observes states through its interactions with the environment, takes actions based on these states, and receives rewards or feedback as a result.

Deep neural networks are artificial neural networks capable of learning intricate patterns and representations from large datasets. The utilization of deep neural networks is a distinguishing aspect of deep reinforcement learning. This enables deep reinforcement learning algorithms to tackle complex and abstract tasks effectively while achieving high performance. It enables the agent to learn through trial and error, iteratively refining its decision-making process and improving its performance over time. By leveraging the power of deep neural networks, deep reinforcement learning offers promising opportunities for addressing challenging problems and advancing the capabilities of intelligent systems.

2.2.2. AI and IoT Collaboration

The advent of the IoT is undeniably revolutionizing numerous areas of human endeavor by enabling the interconnection of myriad devices on an unprecedented scale. IoT systems offer a unique capability to extract data from diverse sensors, execute real-time data processing, and control devices remotely, leading to significant advancements across multiple sectors. This review offers an insight into the fundamental principles underlying IoT, its broad array of applications, and the crucial challenges requiring resolution for IoT's sustainable evolution.

The linchpin of IoT technology is the network of interconnected devices that gather and exchange data. In the ambit of IoT, these devices can communicate amongst themselves and with humans, thus creating an intricate network that seamlessly integrates the physical and digital worlds. The architecture of an IoT system can be effectively elucidated through the five-layer model, comprising the Perception, the Network, the Middleware, the Application Layer, and the Business Layer. Each layer has specific roles and responsibilities within the IoT system, ranging from data collection to executing intricate tasks by leveraging artificial intelligence techniques.

Artificial intelligence plays a crucial role in the five-layer architecture of an IoT system. In the Perception Layer, artificial intelligence algorithms optimize the data collection process by improving the efficiency and accuracy of sensors and devices. Within the Network Layer, artificial intelligence techniques are employed to manage data transmission, ensuring optimal network performance, and minimizing latency. The Middleware Layer utilizes AI-powered analytics and edge computing to process and store data efficiently. In the Application Layer, artificial intelligence algorithms enhance user experience by analyzing user interactions and providing personalized services. Finally, the Business Layer benefits from AI-powered automation and decision-making processes, enabling efficient management and strategic decision support. This comprehensive integration of artificial intelligence across the IoT system's layers ensures enhanced data processing, intelligent decision-making, and improved overall system performance. It is important to note that real-world IoT implementations may require further customization and adaptation to suit specific use cases and requirements.

2.3. Studies

Artificial intelligence is being increasingly utilized in various fields, and one of these fields is the solar water heating system. Artificial intelligence and machine learning can be employed for data analysis and prediction of variables such as hot water production, hot water demand and hot water consumption, enabling the creation of models to forecast future to optimize system operation. Artificial neural networks can be utilized in solar water heater systems for the prediction problem-solving tasks. Deep learning can be utilized to optimize water heating processes. The utilization of these techniques can enhance the efficiency of solar water heating systems and enable smarter system operation.

Kalogirou et al. (1999) studied an ANN which was trained to predict the performance of a thermosiphon solar domestic water heating system. The network was trained using data from four different system types under various weather conditions to ensure it could handle diverse cases. The input data provided to the network included the storage tank heat loss coefficient, system type, storage volume, and readings from real experiments such as total daily solar radiation, total daily diffuse radiation, ambient air temperature, and initial water temperature in the storage tank. The network output consisted of the useful energy extracted from the system and the water temperature rise. During training, the network achieved high accuracy, with a statistical coefficient of multiple determination (R2-value) of 0.9914 for useful energy and 0.9808 for water temperature rise. These values indicate a strong mapping between inputs and outputs. To test the prediction accuracy, unknown data from all four systems were used, resulting in maximum deviations of 1 MJ and 2.2°C, respectively. Comparisons were also made between predictions using experimental measurements and those generated by the artificial neural network, and the results were found to be highly comparable. This suggests that the proposed method can effectively estimate the performance of the thermosiphon system under different configurations. One significant advantage of this model is its ability to continuously improve performance by learning from examples and incorporating experimental knowledge into the network. In summary, the study successfully trained an artificial neural network to predict the performance of a thermosiphon solar water heating system. The network demonstrated high accuracy and the ability to handle diverse scenarios, making it a promising approach for estimating system performance (Kalogirou, Panteliou, & Dentsoras, 1999).

A limited number of studies have focused on the prediction of stochastic hot water demand and optimal operation of water heating systems based on learning the demand. Existing research on prediction has primarily centered around either volumetric hot water use or energy use for hot water production (Heidari, Olsen, Mermod, Alahib, & Khovalyg, 2021). As an example, a study conducted by Maltais and Gosselin (2019) involved the development of a machine learning (ML) model to forecast the hourly volumetric hot water demand in a residential building located in Quebec City, Canada. Their analysis revealed that the hot water use profile contains a significant noise component. To address this, they employed a Sequential Multi-task ML model, incorporating a recurrent neural network to predict the filtered trend and a Random Forest (RF) to predict the noisy part (Maltais & Gosselin, 2019). Dmy et al. (2019) evaluated seven different statistical models and a Support Vector Machine for predicting hourly and daily hot water demand in a hotel in Oslo, Norway (Dmytro, et al., 2019). Gelažanskas and Gamage (2015a) explored the feasibility of forecasting volumetric hot water demand at the individual building level. They analyzed a dataset comprising hot water use in 120 residential buildings in the UK and employed various stochastic models, including exponential smoothing, seasonal autoregressive integrated moving average, seasonal decomposition, and their combinations, to forecast the demand 24 hours in advance (Gelažanskas & Gamage, 2015a). In another study by Gelažanskas and Gamage (2015b), the authors assessed the potential of an ANN in predicting the energy demand profile of individual water heaters. They analyzed data from a hundred dwellings using autocorrelation techniques, selected appropriate time lags, and compared different neural network topologies (Gelažanskas & Gamage, Forecasting Hot Water Consumption in Dwellings Using Artificial Neural Networks, 2015b). Delorme-Costil and Bezian (2017) utilized an ANN to predict energy use for domestic hot water production 8 and 64 minutes ahead. They analyzed three different neural network models with varying architectures and input parameters (Delorme-Costil & Bézian, 2017). Fischer et al. (2016) integrated behavioral and energy balance models to generate hourly profiles of space heating and hot water energy use in German households. These profiles were valuable for accurately sizing and operating thermal supply systems in buildings (Fischer, Wolf, Scherer, & Wille-Haussmann, 2016). Dong et al. (2018) evaluated three ML models, including Support Vector Machine, Gaussian Naive Bayes, and RF, to predict the power use of a 9-kW electric water heater. Predicting hot water energy use becomes more challenging when renewable energy sources are integrated into the system (Dong, Munk, Cui, Boudreaus, & Kuruganti, 2018). In such cases, energy demand is influenced by two stochastic factors: occupant behavior and renewable energy availability. To assess the feasibility of energy demand prediction in these systems, Heidari and Khovalyg (2020) evaluated the energy demand prediction of a solar-assisted heat pump. In their research, the authors developed an innovative neural network that integrated time series decomposition and attention mechanisms. This novel approach was compared to conventional models in order to evaluate its performance (Heidari & Khovalyg, 2020). Ritchie et al. (2021) developed a probabilistic simulator for hot water usage to generate hourly usage profiles. These profiles can be utilized in various applications, such as demand-side management (Ritchie, Engelbrecht, & Booysen, 2021).

Optimal control of the water heating systems considering the predictions of the demand side is another area of focus in the literature. Existing studies on optimal control of building energy systems based on demand learning primarily focus on either cost optimization to reduce total energy demand (Bünning, Huber, Heer, Aboudonia, & Lygeros, 2020) or cost optimization to shift the peak of energy demand (Luo, et al., 2020). However, limited research has been conducted on the optimal control of water heating systems to reduce total energy demand. For instance, Kazmi et al. (2018) developed a reinforcement learning model to optimize hot water production based on stochastic hot water demand. Their application of this model to 32 houses in the Netherlands resulted in approximately 20% energy savings for hot water production without compromising occupant comfort, defined as maintaining water supply temperature of at least 45°C

(Kazmi, Mehmood, Lodeweyckx, & Driesen, 2018). To address the risk of legionella growth in control systems, Kapsalis and Hadellis (2017) devised a control algorithm that combines a convolutional neural network for demand prediction with a cognitive supervisor considering legionella risk. This control system regulates the temperature of the storage tank to minimize bacterial formation while minimizing the increase in energy consumption (Kapsalis & Hadellis, 2017). Regarding the potential for energy storage in water heating systems, they present an interesting opportunity for load shifting in building systems. Therefore, a few studies have also explored the integration of dynamic pricing in optimization to enable load shifting of water heating systems. Kapsalis and Hadellis (2017) developed a scheduling algorithm based on Dijkstra's algorithm to optimize the energy cost of electric water heaters under dynamic pricing (Kapsalis & Hadellis, 2017). Furthermore, Ruelens et al. (2016) employed an auto-encoder network along with a well-established batch reinforcement learning algorithm called fitted Q-iteration to reduce the energy consumption cost of a 2.36 kW electric water heater by identifying an optimal control strategy. Compared to a default thermostat controller, their proposed method achieved a 24% reduction in energy cost using day-ahead prices and a 34% reduction using imbalance prices (Ruelens, et al., 2016). Despite the increasing significance of hot water energy demand and the advancements in AI and ML, the potential of implementing ML models to predict hot water usage behavior is still relatively unexplored. Early prediction of hot water usage behavior using ML has the potential to prevent energy wastage while ensuring occupant satisfaction (Heidari, Olsen, Mermod, Alahib, & Khovalyg, 2021).

As discussed in the literature, it is important to prediction of stochastic hot water demand and optimal operation of the solar water heating system suitable for the residential use using right artificial intelligence technique depending on usage habits and other environmental factors.

The unpredictable nature of hot water demand poses a significant challenge in optimizing the operation of solar water heating systems. Stochastic models are a potential tool to handle such unpredictability. Recently, the integration of IoT, deep neural networks, and deep reinforcement learning have shown substantial potential in improving these models, through real-time data collection and advanced predictive capabilities. IoT provides real-time monitoring capabilities for solar water heating systems. IoT devices can collect and transmit data on water usage, temperature changes, and other relevant parameters to the cloud, enhancing the timeliness and accuracy of data used in demand prediction. Deep neural networks can process a variety of inputs to produce outputs, making them suitable for predicting hot water demand. Deep neural networks can analyze data collected by IoT devices and use it to make accurate predictions about future hot water demand. Deep reinforcement learning can adapt to different scenarios and aims at reward maximization. In the context of solar water heating systems, deep reinforcement learning can optimize the operation by determining the most efficient operating parameters based on the predicted hot water demand.

3. MATERIAL AND METHOD

The material and method chapter structured into three main sections, each elaborating on different key aspects respectively as follows:

The Solar Water Heating System (SWHS): This part of the study delves into the processes involved in designing and installing a solar water heating system. The critical steps from system requirement assessment to the actual installation of the system components are discussed comprehensively. During this process, two solar water heating systems, namely the first-generation and the second-generation, were designed and installed due to the reasons outlined in Section 3.1.1 and Section 3.1.2. The research has progressed based on the first-generation solar water heating system and its more advanced version, the second-generation solar water heating system.

The Solar Water Heating System Controller Unit (SWHSCU): This section explores the design and installation of the solar water heating system's controller unit, with particular emphasis on the integration of IoT technologies and relevant programming. The detailed procedures in developing an IoT-compatible controller unit, as well as the necessary programming techniques, are thoroughly discussed. During this process, two solar water heating system controller unit, namely the first-generation and the second-generation, were designed and installed due to the reasons outlined in Section 3.2. The research has progressed based on the second-generation solar water heating system controller unit is an advanced and more complex version of the first-generation solar water heating system controller unit, utilizing the same hardware components and algorithmic logic. In the enhanced version, changes have been made to the communication protocols between hardware units, a user-friendly graphical interface has been developed, and additional features such as data storage on cloud platforms and artificial intelligence support have been incorporated. Therefore, detailed information about the first-generation controller unit will not be provided, but relevant brief notes may be shared if available.

Programming The Learning Algorithm Framework and the Data Analysis Process: This segment of the study focuses on the formulation of a deep reinforcement learning algorithm supported by deep neural networks. It provides an in-depth discussion on the algorithm's design, training process, and the subsequent data analysis aimed at evaluating and improving the algorithm's performance.

The research data is based on real data collected through sensors and the operating statuses of actuators connected to the controller unit of the second-generation solar water heating system, which was designed by the researcher and employed in the redesigned second-generation solar water heating system in the Konyaaltı district of Antalya, between March 15, 2023, and June 15, 2023. In addition, the data includes meteorological information obtained from the mgm.gov.tr website for the corresponding dates in the region where the solar water heating system was installed.

3.1. The Solar Water Heating (SWH) System

The designed first-generation solar water heating system which in Section 3.1.1 played a crucial role in achieving the research objectives by providing a foresight regarding system efficiency, system controller design, the selection of sensors, and other system components, as well as offering insights into the potential issues or malfunctions of the installed system. Shortly after the installation of this system, it has been redesigned due to the reasons that will be elaborated on in Section 3.1.2. This redesign involved incorporating additional features and making changes to system components. The research has been conducted based on this second-generation solar water heating system.

3.1.1. The First-Generation Solar Water Heating (SWH) System

The first-generation solar water heating system was conceptualized to meet the daily hot water requirement of a middle-income family comprising four individuals, in Antalya, Türkiye (36.87557, 30.64474). Each individual was aimed to allot a daily hot water quota of 60 liters, with the system ensuring a minimal water temperature of 55°C throughout the year. This system has been designed and implemented based on the principle of a closed-loop (indirect) active circulation solar water heating system.

The characteristics of the components which was needed in the first-generation solar water heating system design were calculated with the aid of the simplified method described in Section 2.1.5.

The collector surface area to be used for a single-glazed solar water heating system which is installed in Antalya, Türkiye that can meet the daily hot water demand of 60 liters per person 4-person middle-income family at a minimum water temperature of 55°C on an annual basis has been calculated. The total collector surface area has been calculated on an annual basis according to the formula 3.3 as follows:

$$A_c = \sum_{i=1}^{12} Q_{useful} \,/\, \sum_{i=1}^{12} Q_{need} \rightarrow A_c = \frac{237.925}{60.747} = 3.917\ m^2 \quad (3.8)$$

Given that one collector has a net surface area of 1,66 m², the number of collectors has been calculated according to the formula 3.4 as follows:

$$n = \frac{A_c}{S} \rightarrow n = \frac{3.917}{1.66} \cong 2.35 \rightarrow 3 \text{ pieces} \quad (3.9)$$

Based on the net surface area of the selected collector absorber and the required number of collectors, the total collector surface area is recalculated. This value will be used to determine the required storage tank volume and the circulation rate in liters per minute for a specific unit of time. Based on the net surface area of the selected collector absorber and the required number of collectors, the total collector surface area has been recalculated according to the formula 3.5 as follows:

$$A_c = n \times S \ \rightarrow A_c = 3 \times 1.66 = 4.98\ m^2 \quad (3.10)$$

This value was used to determine the required storage tank volume and the circulation rate in liters per minute for a specific unit of time.

The required storage tank volume has been calculated according to the formula 3.6 as follows:

$$V = \beta_1 \times A_c \rightarrow V = 0.06 \times 4.98 = 0.299\ m^3 \quad (3.11)$$

The required circulation rate has been calculated according to the formula 3.7 as follows:

$$G = \beta_2 \times A_c \rightarrow G = 1 \times 4.98 = 4.98\ liters/min \quad (3.12)$$

The design and operation of the system are as follows:

A circulation line, facilitated by a circulation pump, is established between the collectors mounted on the roof and a hot water storage tank situated at a lower level. Through the use of a heat exchanger, the heat exchanger fluid circulating within the line enables the heating of the water in the tank. However, due to the design requirements, this heat transfer fluid is distinct from the water intended for domestic use in the tank. System control is handled by a controller unit, designed based on a specific algorithmic logic. Between sunrise and sunset, the system circulates at regular intervals, and the decision to operate the circulation pump is made by the controller unit, based on the efficiency of the solar water heating system. This decision relies on factors such as the placement of temperature sensors at the inlet and outlet of the heat exchanger, proximity to the hot water intake point of the tank, and other parameters. The water level in the hot water storage tank is variable, managed by adding water into the tank through a solenoid valve. The reasoning for this alteration in water level is tied to factors such as consumption needs prediction, potential solar energy heat production of the solar water heating system, and other reasons identified prior to the preparation phase of the hot water storage tank. To increase the pressure at the hot water outlet of the tank, a booster pump is employed. When the water level in the tank reaches a critical point, the booster pump is automatically shut down by the controller unit and mains water adding via solenoid valve to reach threshold water level at the same time. The schematic diagram of the first-generation solar water heating system is presented below in Figure 3.1.

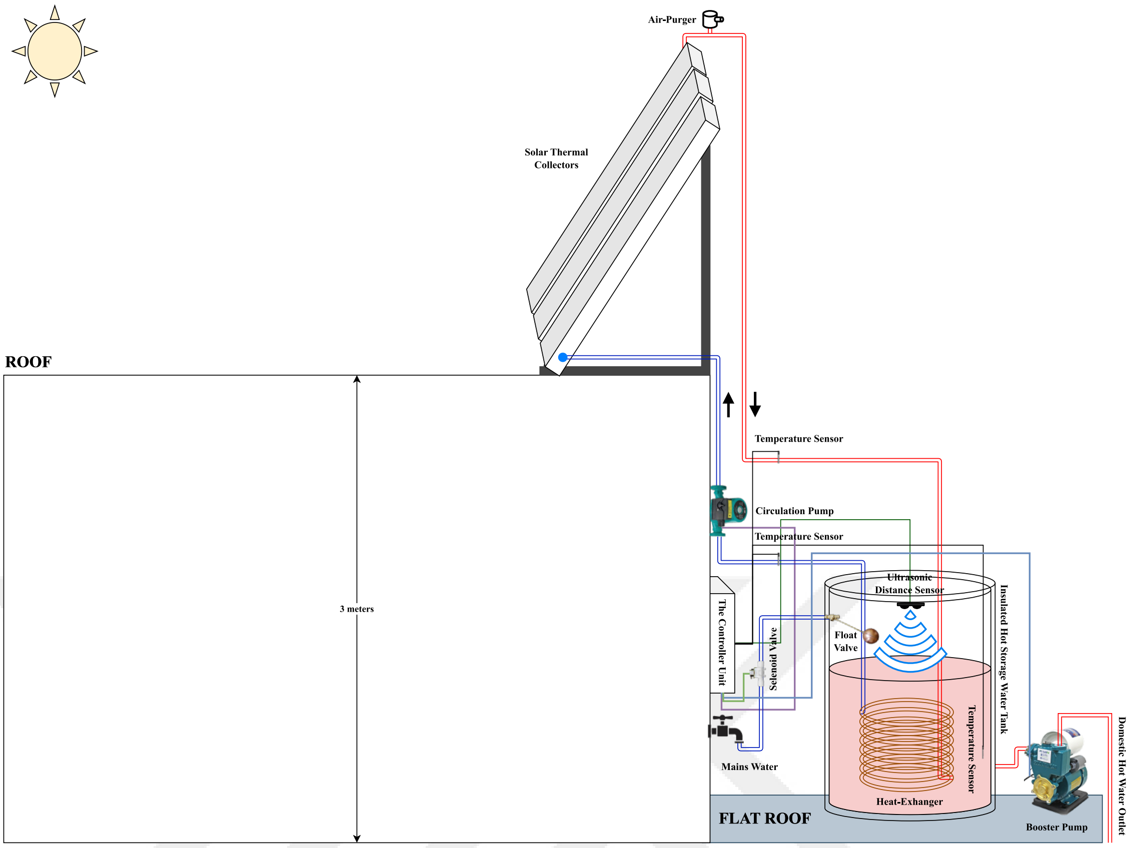


Figure 3.1. The schematic diagram of the first-generation SWH system.

The components that constitute the first-generation solar water heating system are the solar collectors, hot water storage tank, circulation pump, booster pump (hydrofor), air-purger, water tank float valve, valves (solenoid valve, etc.), piping components, and the first-generation solar water heating system controller unit.

The solar collectors are a device that absorbs solar radiation and converts it into thermal energy. Typically mounted on rooftops, it captures solar energy to heat either water or a heat transfer fluid within the system. A total of three units of the Uluçay GK-94-BO Galvanize Piped Solar Collector model, manufactured by Uluçay Metal, were utilized as solar collectors in the system. The interior panel utilized is made of aluminum. In the implemented system, the solar collectors have been interconnected in a series configuration. This arrangement involves connecting the outlets of the collectors to one another, thereby facilitating the circulation of water throughout the series circuit. With the series connection, as water traverses each collector, it undergoes a heating process before advancing to the subsequent collectors, thus ensuring the continuous transfer of thermal energy. Consequently, the overall flow rate remains constant while the temperature of the water passing through each collector progressively rises.

The hot water storage tank serves as a reservoir for the heated water. It is insulated to minimize heat loss and ensures a ready supply of hot water for use. The temperature of the water stored in solar water heating systems is contingent upon a variety of factors such as the intensity of solar irradiance, environmental conditions, and the rate of water consumption. Designing hot water storage tanks for solar water heating systems requires careful consideration of various factors to optimize performance and efficiency. Proper sizing, insulation, positioning, heat exchange mechanisms, and material selection are all essential considerations. By incorporating these factors into the design process, solar water heating systems can efficiently utilize solar energy, reduce energy costs, and contribute to a more sustainable approach to water heating.

During periods of no hot water production, notably during nighttime and under cloudy weather conditions, an increase in water consumption can lead to a rapid decrease in the temperature of the water within the storage hot water tank. This phenomenon constitutes one of the primary challenges associated with the operation of solar water heating systems. To counterbalance the variability in solar irradiance, these systems commonly incorporate an auxiliary heating unit, often powered by electricity or gas. This auxiliary system ensures the continuous availability of hot water even during periods of insufficient solar input. These solutions introduce additional levels of complexity and costs to the operation of solar water heating systems. Therefore, they should be thoroughly considered during the design and implementation phases of a solar water heating system. Ideally, a customized solar water heating system design that considers local climatic conditions, demand for hot water, and other relevant factors would be most beneficial for ensuring optimal system performance and efficiency.

Furthermore, due to thermal stratification, a natural process that occurs in water storage tanks where hot water rises to the top, and colder, denser water sinks to the bottom. This happens because of the differences in water density at various temperatures: hot water is less dense and hence floats over colder, denser water. In a solar water heating system, the solar collector heats a fluid which transfers its heat to the water in the storage tank. This heated water naturally rises to the top of the tank due to its lower density. As a result, it makes sense to draw the domestic hot water supply from a point near the top of the tank, where the water is hottest. Similarly, the tap water, which will need heating, is introduced at the bottom of the tank, where the water is cooler. This ensures a more efficient heat exchange and aids the natural thermal stratification in the tank, further improving the efficiency of the system. Proper design and management of the thermal stratification in the tank can significantly improve the efficiency and performance of the solar water heating system. This is one of the reasons why solar water heaters can provide a substantial percentage of a household's hot water demand, particularly in regions with abundant sunlight. However, there are also disadvantages associated with thermal stratification. These can negatively impact the overall system performance. Firstly, it requires careful system design and adjustments. Without proper sizing, the stratification effect may not be adequately achieved, leading to reduced energy efficiency. Furthermore, the separation of the hot water upper layer can disrupt the homogeneous distribution of water, resulting in insufficient hot water in certain areas. Moreover, despite the basic principle of thermal stratification, where warmer water rises to the top and cooler water sinks to the bottom, in practice, the temperature distribution in a hot water storage tank is not perfectly uniform in the vertical direction (Yiğit & Atmaca, 2018). There are several reasons for this. Factors such as heat losses from the tank walls, turbulence caused by water inflows and outflows, the specific geometry and insulation of the tank, the nature of the heat-exchanger and the characteristics of the heating and cooling cycles can all create variations in temperature distribution within the tank. This means that while the general pattern of warmer water being on top and cooler water on the bottom will generally hold true, there will be fluctuations and variations in temperature at different points within the tank. Recognizing and understanding these variations is crucial for optimizing the performance of a solar water heating system.

The controlled addition of tap water could be an effective method to mitigate the disadvantages brought by thermal stratification in solar water heating systems. In essence, by strategically adding tap water to the system at particular times, you can help to disrupt the thermal stratification and more evenly distribute the heat within the storage tank. This can help to avoid situations where the water at the top of the tank becomes too hot (potentially leading to problems like overheating or excessive heat loss), while the water at the bottom of the tank remains too cold. However, this must be carefully managed. The system needs to be designed and controlled to ensure the proper amount and timing of the tap water addition. If too much tap water is added, or if it's added at the wrong time, it could lead to inefficiencies and reduce the overall performance of the system. The key is to achieve a balance where the benefits of disrupting the thermal stratification (i.e., more even heat distribution and prevention of overheating) outweigh the potential disadvantages (i.e., inefficiencies and loss of heat). Achieving this balance will enable the system to operate in an efficient and effective manner, providing reliable and cost-effective hot water supply. Such a strategy would require a sophisticated control system that could monitor the temperatures at various levels within the tank and adjust the amount and timing of the main water addition accordingly. But with the right design and control mechanisms, this could be an effective method to optimize the performance of solar water heating systems.

In a variable water level hot water storage tank, the delivery of water is a pivotal aspect that necessitates meticulous supervision. Fluctuations in the tank's water level can be attributed to a variety of factors such as consumption rate, heating rate, and the speed at which tap water is added to the system. In high-demand scenarios, the water content in the tank can diminish quickly. This may lead to situations where the hot water needed surpasses the system's ability to supply it, especially if the water heating speed is slower than the rate of consumption. Contrarily, during times of diminished demand, the water level in the tank might swell. If left unchecked, this could cause the water level to surpass the tank's maximum limit, triggering potential overflow problems. Hence, water supply management for a variable-level hot water storage tank is vital to maintain the water level within an ideal bracket. This strategy will guarantee the system's ability to satisfy the hot water needs while simultaneously averting potential overflow complications.

The critical question to address in the context of a variable-level hot water tank is not concerned with the introduction of cold water, as that typically presents no issues. The more urgent issue to consider is pinpointing the optimal location for obtaining the hot water intended for use. The focus should be on identifying the most efficient and strategic point in the system to ensure an uninterrupted and efficient supply of heated water to its end users.

Assuming the water within the hot water storage tank can maintain homogeneity, acquiring hot water from the tank's lower portion shouldn't pose an issue. This concept rests on the presupposition that the heating mechanism of the tank diffuses heat uniformly, resulting in a constant temperature throughout the water mass. Nevertheless, the natural phenomenon of thermal stratification in practice implies that heated water gravitates upwards in the tank, while cooler water moves downward. Therefore, to ensure a genuinely consistent water temperature, specific methods, such as the use of a mixing valve or a recirculation system, would need to be implemented within the tank.

In line with the preceding discussions, a hot water tank has been designed for use in the first-generation solar water heating system. The tank was positioned 3 meters below the collector level. The hot water storage tank features a galvanized sheet metal inner tank for water storage, complemented by an outer tank crafted from galvanized sheet metal to ensure protection. The interstitial space between these intertwined two tanks is insulated with a 5 cm thick layer of fiberglass. Moreover, to prevent potential water overflow or wetting due to evaporation within the boiler and to ensure that the insulation properties of the fiberglass insulation material remain intact, the insulation material between the nested inner and outer tanks has been coated with epoxy foam, thereby affording improved insulation properties. The tank is of cylindrical shape and is intended for vertical positioning. It incorporates insulation between two walls, utilizing 5 cm thick fiberglass material, thus ensuring effective heat preservation. Moreover, to prevent potential water overflow or wetting due to evaporation within the boiler and to ensure that the insulation properties of the fiberglass insulation material remain intact, the insulation material between the nested inner and outer tanks has been coated with epoxy foam. The tank boasts a capacity of 300 liters, making it adequately large to meet significant hot water requirements and allowing the system to adeptly handle periods of high demand. In terms of configuration, the hot water outlet has been situated 15 cm above the bottom of the tank. Conversely, the tap water inlet is located 5 cm from the top, arranged to facilitate the introduction of tap water into the tank.

The heat-exchanger is a component used to transfer the heat energy obtained from the solar collector to the water. The heat transfer fluid passing through the solar collector transfers its heat to the water through the heat exchanger. The power of the heat exchanger has been calculated and designed to ensure the attainment of the minimum necessary thermal capacity. In order to enable the warming of water inside the tank, a helically wound heat exchanger, constructed from copper tubing with DN20 dimension, was inserted via the tank's upper aperture. The decision to utilize copper in the construction of the heat exchanger stems from its exceptional thermal conductivity - one of the most proficient among metallic substances. Additionally, the merits of copper include its robust nature, convenience in installation, and resilience against microbial proliferation. The strategic design of the helical coil increases the overall surface area of the heat exchanger, thereby optimizing the process of heat transfer within the confines of the tank.

The circulation pump facilitates the movement of the heat transfer fluid, or water, between the solar collector and the water storage tank. The LEO LRP-15-60/130 model, manufactured by LEO Group, was utilized as a circulation pump. It was used for ensuring the efficient heat transfer and maintaining the flow within the system.

The booster pump (hydrofor) is a device that pressurizes the water from the storage tank to supply pressurized water to the user points. The Gold Ak Milan Solar Energy Booster Pump, and the Hot Water Booster Pump GA-133JBE model, manufactured by Gold Ak Milan, was utilized as a booster pump. It was used for pumping the water as needed and maintains the desired water pressure.

Valves are integral to the system, controlling the flow and direction of the heat transfer fluid or water. They were used for allowing for regulating the flow rate, diverting the flow, and isolating specific sections of the system as needed. The solenoid valve in the system was operated through the controller unit of the first-generation solar water heating system, while the remaining valves were manually controlled.

The air purger is employed to eliminate air pockets and air bubbles within the system. It was used for ensuring the optimal flow and circulation of the heat transfer fluid or water, enhancing system efficiency.

A water tank float valve, also known as a water tank float mechanism or water tank float assembly, is a device used for monitoring and controlling the water level in a water tank. It consists of a float, typically made of buoyant materials such as plastic or foam, and a valve mechanism. It was used for obstructing the water overflow from the hot water storage tank.

Within the context of the plumbing infrastructure, the system of conduits, commonly referred to as piping, establishes a connection among diverse components of the solar water heating apparatus. This encompasses elements such as the solar collector - responsible for harnessing solar energy, the storage tank - designed for thermal energy storage, the circulation pump - instrumental in fluid movement, and the booster pump (hydrofor) - a key player in maintaining water pressure. In the system, PPR-C (Random Copolymer Polypropylene) water pipes and fittings with DN20 dimensions have been used.

The first-generation solar water heating system controller unit is a component used for controlling and optimizing the operation of a solar water heating system. It was worked in conjunction with other components such as the sensors for measuring the water in tank level, water temperatures, solenoid valve and pumps.

3.1.2. The Second-Generation Solar Water Heating (SWH) System

The need for a new solar water heating design arose due to several factors that coincided, including a growing user base of solar water heating system, a potential rise in hot water demand throughout the day, and inherent limitations in the existing primary system such as overflow problems and inadequate tank efficiency. These challenges prompted the development of a novel solar water heating system design characterized by increased storage capacity, advanced safety features, and improved efficiency. This system has been designed and implemented analogously to the first system, grounded in the principle of a closed-loop (indirect) active circulation solar water heating system.

The design and operation of the system are as follows:

A circulation line, facilitated by a circulation pump, is established between the collectors mounted on the roof and a hot water storage tank situated at a same level. Through the use of a heat exchanger, the heat exchanger fluid circulating within the line enables the heating of the water in the tank. However, due to the design requirements, this heat transfer fluid is distinct from the water intended for domestic use in the tank. System control is handled by a controller unit, designed based on a specific algorithmic logic. Between start time and stop time, the system circulates at regular intervals, and the decision to operate the circulation pump is made by the controller unit, based on the efficiency of the solar water heating system. This decision relies on factors such as the placement of temperature sensors at the inlet and outlet of the heat exchanger, proximity to the hot water intake point of the tank, and other parameters. The water level in the hot water storage tank is variable, managed by adding water into the tank through a solenoid valve. The reasoning for this alteration in water level is tied to factors such as consumption needs prediction, potential solar energy heat production of the solar water heating system, and other reasons identified prior to the preparation phase of the hot water storage tank. To increase the pressure at the hot water outlet of the tank, a booster pump is employed. When the water level in the tank reaches a critical point, the booster pump is automatically shut down by the controller unit via sensor-driver unit. The hot water outlet of the tank and combi hot water outlet and mains water are integrated into the domestic hot water outlet via a mixing valve. When the volume of water in the tank is sufficient to meet demand, its release from the system is permitted and it serves as the sole source of water consumption. If the water temperature falls below the desired level, or if the volume of water remaining in the system falls below a critical threshold, a solenoid valve allows the boiler system to automatically engage by the controller unit via combi-driver unit. Additionally, the determination of the water level within the tank is achieved using an external measurement technique designed according to the principle of communicating vessels. Close to the tank and prior to the booster pump, a measuring tube of suitable diameter and equivalent to the tank's height is added to the hot water outlet pipe. Subsequently, with an ultrasonic distance sensor mounted on this tube, the water level outside the tank is calculated by the controller unit. Finally, to control water overflow, a float valve has been manually implemented at the water inlet.

In order to recalibrate the second-generation solar water heating system for a six-person household with demographic characteristics analogous to the previously evaluated four-person middle-income family, a new calculation was executed employing with the help of simplified method described in Section 2.1.5.

As a consequence of the recalculation, a more robust circulation pump was incorporated into the system, thereby enabling stable water circulation and improved energy harvesting potential along with the circulation line was re-established with the DN25 dimension PPRC piping. Moreover, the power of the heat exchanger has been recalculated to ensure the attainment of the minimum necessary thermal capacity. Additionally, the number of collectors was increased to four. These modifications were aimed at enhancing the system's capacity to circulate larger volumes of water at a quicker pace, thereby escalating its overall energy collection potential. Furthermore, the provision of increased tank storage capacity allows for extended periods of hot water access for users. With these advancements, the second-generation solar water heating system can more effectively and securely produce and store hot water, thus offering enhanced performance, efficiency, and safety.

The schematic diagram of the second-generation solar water heating system is presented below in Figure 3.2.

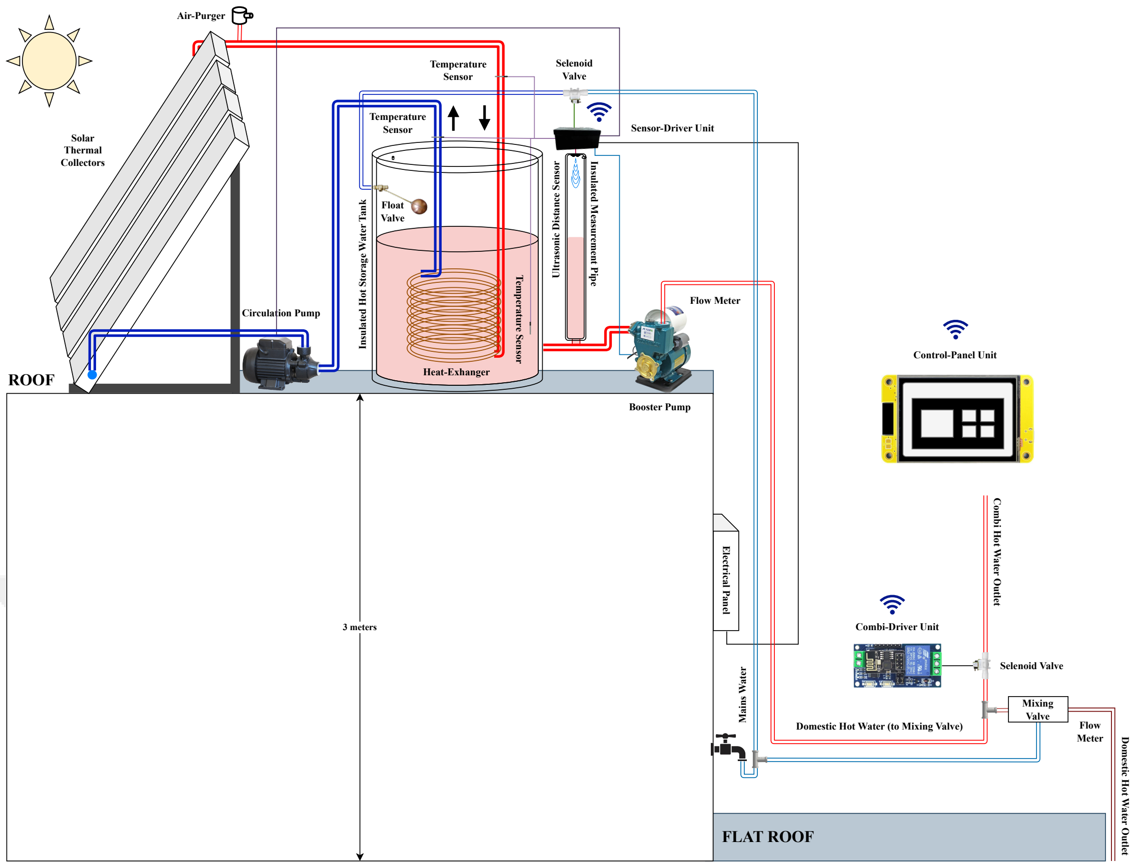


Figure 3.2. The schematic diagram of the second-generation SWH system.

The components that constitute the second-generation solar water heating system are the solar collectors, hot water storage tank, circulation pump, booster pump (hydrofor), air-purger, water tank float valve, valves (solenoid valve, etc.), piping components, and the second-generation solar water heating system controller unit.

The solar collectors are a device that absorbs solar radiation and converts it into thermal energy. Typically mounted on rooftops, it captures solar energy to heat either water or a heat transfer fluid within the system. As a consequence of the recalculation, a total of four units of the Uluçay GK-94-BO Galvanize Piped Solar Collector model, manufactured by Uluçay Metal, were utilized as solar collectors in the system. In the implemented system, the solar collectors have been interconnected in a series configuration. This arrangement involves connecting the outlets of the collectors to one another, thereby facilitating the circulation of water throughout the series circuit. With the series connection, as water traverses each collector, it undergoes a heating process before advancing to the subsequent collectors, thus ensuring the continuous transfer of thermal energy. Consequently, the overall flow rate remains constant while the temperature of the water passing through each collector progressively rises.

The hot water storage tank serves as a reservoir for the heated water. It is insulated to minimize heat loss and ensures a ready supply of hot water for use. In line with the preceding discussions in previous section which is Section 3.1.1, as a consequence of the recalculation, a 500-liter new hot water storage tank with enhanced insulation was implemented in lieu of the aforementioned first hot water storage tank within the system. The first-generation's hot water storage tank was initially positioned 3 meters below the collector level. However, in the revised design, the new hot water storage tank was relocated to the roof, resulting in a reduced length of the circulation line connecting the collector and the hot water storage tank. This upgraded hot water storage tank features a plastic inner tank for water storage, complemented by an outer tank crafted from galvanized sheet metal to ensure protection. The interstitial space between these intertwined two tanks is insulating with a 10 cm thick layer of stone wool and epoxy foam, thereby affording improved insulation properties. Regarding its configuration, the positioning of the hot water outlet remains consistent, situated 5 cm above the tank bottom. This strategic placement aims to mitigate the potential accumulation of sediment at the base, reducing the risk of clogging over time. In contrast, the tap water inlet is positioned 5 cm below the tank top, strategically facilitating the introduction of tap water into the tank. Furthermore, a safety valve has been integrated into the system to preemptively address the possibility of water overflow within the tank resulting from excessive water intake. This safety measure is vital in averting potential damage or flooding incidents. The implementation of these design modifications ensures the new system boasts enhanced thermal efficiency and durability. The utilization of a plastic inner tank, galvanized sheet metal outer tank, and a substantial insulation layer further contribute to minimizing heat loss and optimizing the system's performance.

The heat-exchanger is a component used to transfer the heat energy obtained from the solar collector to the water. The heat transfer fluid passing through the solar collector transfers its heat to the water through the heat exchanger. The power of the heat exchanger has been calculated and designed to ensure the attainment of the minimum necessary thermal capacity. In order to enable the warming of water inside the tank, a helically wound heat exchanger, constructed from cooper tubing with DN25 dimension, was inserted via the tank's upper aperture like as the first-generation solar water heating system's heat-exchanger. The decision to utilize copper in the construction of the heat exchanger stems from its exceptional thermal conductivity - one of the most proficient among metallic substances. Additionally, the merits of copper include its robust nature, convenience in installation, and resilience against microbial proliferation. The strategic design of the helical coil increases the overall surface area of the heat exchanger, thereby optimizing the process of heat transfer within the confines of the tank.

The circulation pump facilitates the movement of the heat transfer fluid, or water, between the solar collector and the water storage tank. As a consequence of the recalculation, a more robust circulation pump was incorporated into the new system, thereby enabling stable water circulation and improved energy harvesting potential. The QB60K-1 model, manufactured by İmpo, was utilized as a circulation pump. It was used for ensuring the efficient heat transfer and maintaining the flow within the system.

The booster pump (hydrofor) is a device that pressurizes the water from the storage tank to supply pressurized water to the user points. The booster pump used in the previous system has also been utilized in the new system. It was used for pumping the water as needed and maintains the desired water pressure.

Valves are integral to the system, controlling the flow and direction of the heat transfer fluid or water. They were used for allowing for regulating the flow rate, diverting the flow, and isolating specific sections of the system as needed. The solenoid valve in the system was operated through the controller unit of the second-generation solar water heating system, while the remaining valves were manually controlled. Regardless of certain changes in terms of quantity and technical specifications depending on the plumbing system, all types of valves used in the previous system have been retained and utilized in the new system as well.

The air purger is employed to eliminate air pockets and air bubbles within the system. It was used for ensuring the optimal flow and circulation of the heat transfer fluid or water, enhancing system efficiency. The air purger used in the previous system has also been utilized in the new system.

A water tank float valve, also known as a water tank float mechanism or water tank float assembly, is a device used for monitoring and controlling the water level in a water tank. It consists of a float, typically made of buoyant materials such as plastic or foam, and a valve mechanism. It was used for obstructing the water overflow from the hot water storage tank. The water tank float valve used in the previous system has also been utilized in the new system.

Within the context of the plumbing infrastructure, the system of conduits, commonly referred to as piping, establishes a connection among diverse components of the solar water heating apparatus. This encompasses elements such as the solar collector - responsible for harnessing solar energy, the storage tank - designed for thermal energy storage, the circulation pump - instrumental in fluid movement, and the booster pump (hydrofor) - a key player in maintaining water pressure. In the system, PPR-C (Random Copolymer Polypropylene) water pipes and fittings with DN20 dimensions and with DN25 dimensions have been used together.

The second-generation solar water heating system controller unit is a component used for controlling and optimizing the operation of a solar water heating system. It was worked in conjunction with other components such as the sensors for measuring the water in tank level, water temperatures, solenoid valve and pumps. The second-generation solar water heating system controller unit is an advanced and more complex version of the first-generation solar water heating system controller unit, utilizing the same hardware components and algorithmic logic. In the enhanced version, changes have been made to the communication protocols between hardware units, a user-friendly graphical interface has been developed, and additional features such as data storage on cloud platforms and artificial intelligence support have been incorporated. Detailed information about the controller unit will be given in Section 3.2.

3.2. The Solar Water Heating System Controller Unit (SWHSCU)

The efficacy of traditional solar water heating systems often hinges on the application of intelligent control mechanisms. Solar water heating system controller units are integral components in the design of solar water heating systems, serving as central units for managing and optimizing system operations. These units are responsible for monitoring and controlling the flow of heat transfer fluid between the solar collectors and storage tanks. The primary function of a solar water heating system controller unit is to continuously measure and regulate various parameters critical to system performance.

These parameters include the temperature of the heat transfer fluid, ambient temperature, and solar radiation intensity. By analyzing these measurements, the controller unit can adjust the operation of pumps, valves, and auxiliary heating sources to maximize energy collection from the solar collectors and ensure efficient heat transfer to the storage tank. Furthermore, advanced algorithms and control logic are incorporated into the controller unit to enable intelligent decision-making processes. These processes involve analyzing temperature differentials, managing thermal stratification, preventing freezing, and avoiding overheating. By leveraging the collected data and implementing appropriate control strategies, the controller unit ensures safe and optimal operation of the system. In addition to its control functions, the solar water heating system controller unit provides a user-friendly interface for monitoring system performance and facilitating user interaction. This interface allows users to adjust temperature settings, access diagnostic information, and monitor the overall system operation. Some controller units also offer communication capabilities for remote monitoring and control of the system. The integration of a centralized controller unit into solar water heating systems offers several advantages. It enhances system efficiency by optimizing energy collection and heat transfer processes. Additionally, it ensures safe and reliable operation through the implementation of advanced control algorithms and preventive measures. The utilization of a central controller unit is essential in achieving improved system performance, energy savings, and user-friendly operation in solar water heating system designs.

The incorporation of IoT technology offers a viable solution for enhancing the functionality of automation systems within solar water heating systems. IoT has the potential to improve the efficiency of solar water heating systems by allowing remote monitoring and control of the systems via digital devices. This flexibility provides greater convenience and permits users to adjust system settings based on their individual needs. Continuous monitoring capabilities of IoT devices allow for the prediction of potential malfunctions and timely alerts for necessary maintenance. This predictive maintenance can prevent system damage and reduce unexpected repair costs. IoT devices, such as sensors and actuators, are integrated into the system to monitor various parameters and control the system. These devices collect data and transmit it to a centralized IoT gateway, which then processes the data for further analysis and storage on a cloud server. However, the implementation of IoT also presents challenges, such as privacy and security issues, potential technological malfunctions, and the requirement for constant internet connectivity. Therefore, it is vital to consider these factors carefully when integrating IoT into solar water heating systems.

The second-generation solar water heating system controller unit represents a sophisticated evolution of the first-generation controller unit, retaining the same hardware components and algorithmic logic. Enhancements in the second-generation version include alterations to the communication protocols between hardware units, the creation of a user-friendly graphical interface, and the addition of features such as cloud-based data storage and artificial intelligence support. As a result, detailed information regarding the first-generation controller unit will not be provided; however, relevant concise notes may be shared if available. Henceforth, the term "the controller unit" will be utilized to refer to the second-generation version.

The integration of IoT and artificial intelligence technologies, specifically deep reinforcement learning and deep neural networks, has been critical in the development of the solar water heating system controller unit. This integration follows a five-layer IoT architectural model which described in Section 2.2.2., guiding the planning, design, and development stages of the controller unit.

The methodology delineated in this section is organized into two distinct phases. In the initial phase, the emphasis is on the selection and features of the hardware components that constitute the controller unit. The subsequent phase involves the creation and refinement of the controller unit's programming.

3.2.1. Hardware

The controller unit is architecturally comprised of three hardware segments: the control-panel unit, the sensor-driver unit, and the combi-driver unit. In addition to these units, a compact single-board computer has been employed to integrate artificial intelligence support into the controller unit. The Raspberry Pi compact single-board computer serves as the AI-hub of the controller unit.

Mounted on a wall within the residence, the control-panel unit (as seen in Figure 3.3.a), due to its ergonomic design, affords users the capacity to monitor and manipulate the system's status. Providing an integrated display panel and a web-based remote-control interface, it furnishes users with comprehensive possibilities for system observation and management. Within this unit, a series of parallel processing services, including a remote dashboard, embedded dashboard, cloud storage operations, and system administration, are executed for user convenience. Additionally, the control-panel unit, linked to artificial intelligence support via the cloud storage service, relays commands or suggestions from a computer, denoted as the AI-Hub, through the same cloud storage service to the sensor-driver unit and the combi-driver unit, thereby enabling autonomous operation of the system.

The sensor-driver unit (as seen in Figure 3.3.b) has been installed on a measurement pipe arrangement on the hot water outlet pipeline of the hot water storage tank belonging to the solar water heating system located on the roof. Its primary function is to gather data concerning the solar water heating system via sensors connected to its sockets and transmit this data to the control panel unit. Additionally, it has the responsibility to manage the operation or cessation of the circulation pump, the booster pump, and the solenoid valve which facilitates water inflow to the hot water storage tank based on commands received from the control panel unit; these components are also connected via sockets. The execution of these tasks is coordinated with the control-panel unit through a peer-to-peer network established between them.

Similar to the role of the sensor-driver unit in controlling the output devices, the combi-driver unit (as seen in Figure 3.3.c) is responsible for controlling the entry of hot water coming from the boiler into the mixing valve by opening and closing it through a solenoid valve. The combi- driver unit has been installed in a location close to the boiler, and in a place where it can communicate with the control-panel unit.

a) **b)** **c)**

Figure 3.3. a) The control-panel unit (DirencNet, 2023a); b) The back-view of the sensor-driver unit; c) The combi-driver unit (DirencNet, 2023b).

The advanced second-generation controller unit, incorporating a connectionless communication protocol developed by Espressif, forms a peer-to-peer network between the control-panel, the sensor-driver, and the combi-driver units. This protocol allows multiple devices to communicate seamlessly without the need for the existing Wi-Fi network. Serving as a rapid communication protocol, it facilitates the exchange of succinct messages (up to 250 bytes) between ESP32 and ESP8266 boards with a range in open field up to 220 meters (Santos & Santos, ESP-NOW Two-Way Communication Between ESP32 Boards, 2020). This innovative approach mitigates challenges originating from the location-specific installation of the first-generation controller unit, particularly those pertaining to extending the IoT network to remote locations like rooftops, and the associated financial burdens. Consequently, it offers a more efficient and flexible system for contemporary domestic users. The types of communication protocols established between these units have been schematized in Figure 3.4 below.

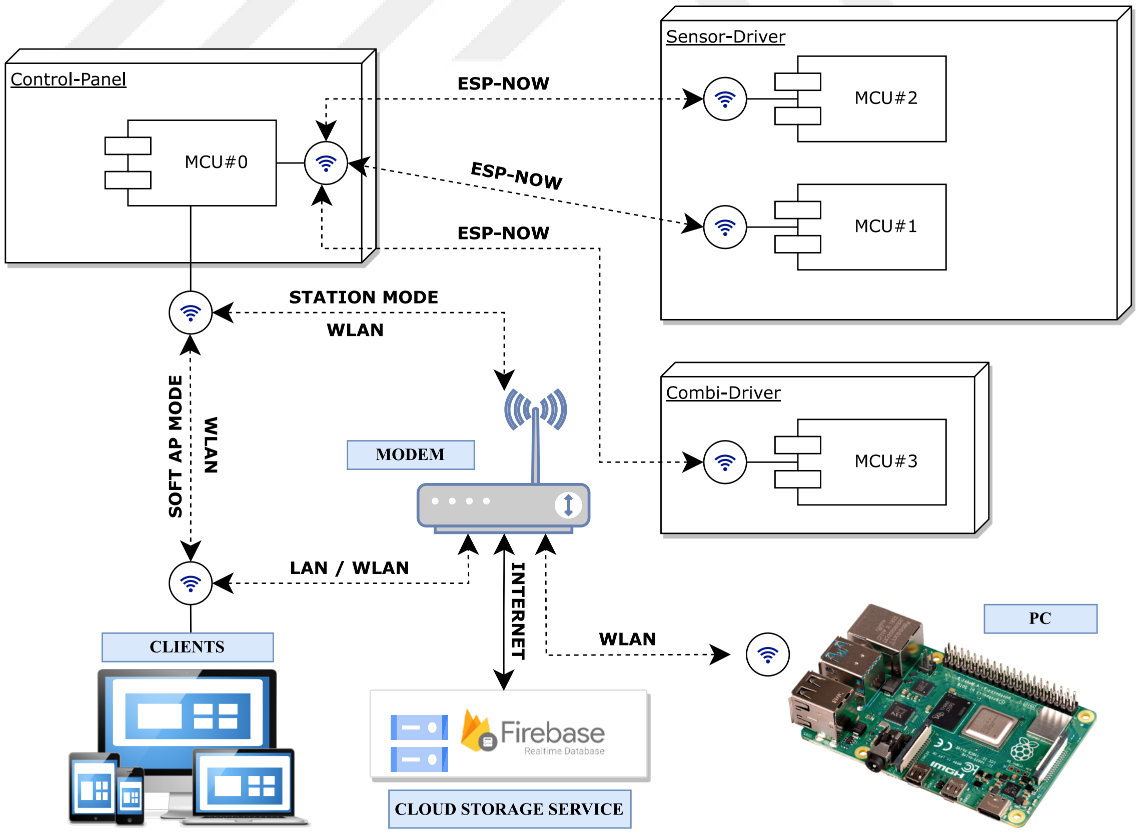


Figure 3.4. The block diagram of the communication protocols of the controller unit.

The components pertaining to the control-panel unit, the sensor-driver unit, and the combi-driver unit are enumerated in Table 3.1, Table 3.2, and Table 3.3 respectively. Data cables, power cables, jumper cables, and the other components constitute the additional elements utilized within these units.

Table 3.1. The components of the control-panel unit.

Component
1 x ESP32-WROOM Arduino LVGL Wi-Fi Bluetooth 2.8 Inch LCD TFT Touchscreen Development Board (ESP32-2432S028R)
1 x Universal 5V 2A USB Charger Adapter

Table 3.2. The components of the sensor-driver unit.

Component
2 x NodeMCU V3 ESP8266 ESP-12E (CP2102) Development Board
2 x ESP-12E L293D Motor Shield
1 x HL-52S V1.0 2-Channel 5V Relay Module with Optocoupler
1 x IRF520 MOS Driver Module
1 x DS18B20 Pluggable Terminal Module
3 x 3m/9.8ft DS18B20 Waterproof Temperature Sensor Stainless Steel Probe
1 x DFRobot A02YYUW Waterproof Ultrasonic Sensor
1 x Laser Distance Sensor GY-VL53L0XV2 (With Lens)
1 x DHT11 Temp and Humidity Sensor
1 x 12V Brushless DC Cooling Fan
2 x Noas YL20-0036 12V 3A 36W Slim Led Driver
1 x Adjustable 3A Step-Down Voltage Regulator LM2596 With 7 Segment Displays

Table 3.3. The components of the combi-driver unit.

Component
1 x ESP8266 ESP-01 WiFi Module
1 x ESP8266 1 Channel 12V ESP-01 WiFi Relay Module
1 x Noas YL20-0036 12V 3A 36W Slim Led Driver

Figure 3.5 presents a comprehensive overview of the controller unit's hardware components, including their functionalities, and the environment in which they operate and communicate.

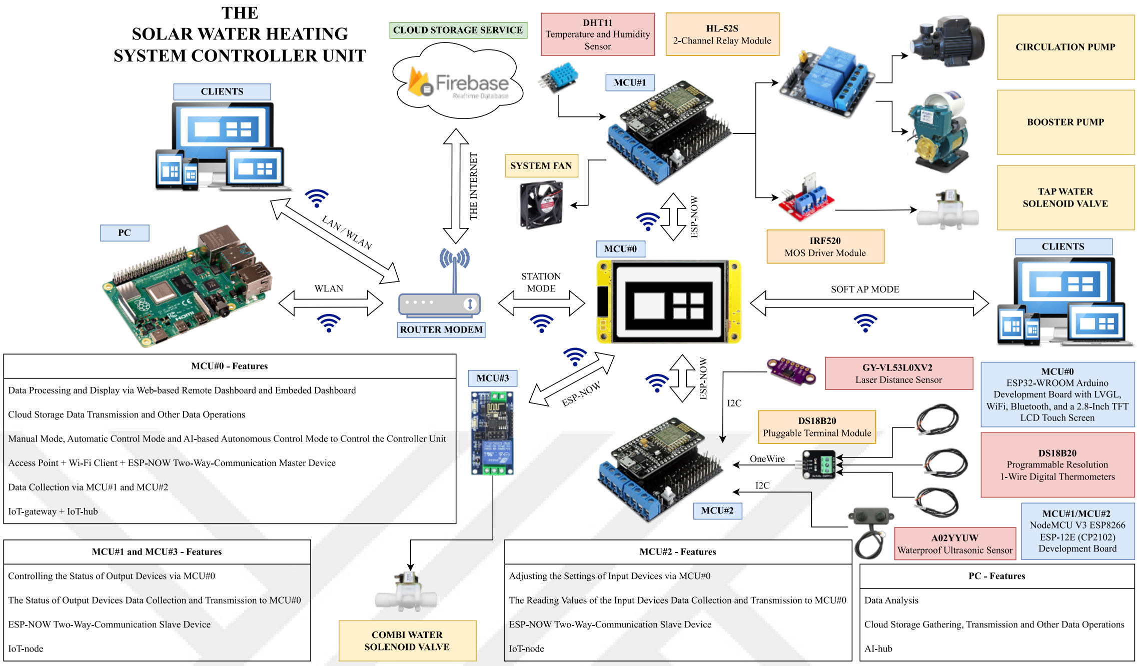


Figure 3.5. The block diagram of the hardware components of the controller unit.

Printed circuit boards have been designed for the control-panel, the sensor-driver, and the combi-driver units of the controller unit. However, due to ongoing patent work related to the hardware and software of the aforementioned controller unit, three distinct development boards and a module have been employed in the research. These boards and module, which emulate all functionalities of the aforementioned boards and serve as inspiration for their designs, are utilized in conjunction with expansion boards. This arrangement facilitates the use of sensor and driver modules in tandem, providing flexibility and convenience in their connections. That development boards and the module used in the controller unit segments are listed in Table 3.4.

Table 3.4. The development boards and a module of the controller unit

ID	Development Board	Located in
MCU#0	ESP32-WROOM Arduino LVGL Wi-Fi Bluetooth 2.8 Inch LCD TFT Touchscreen Development Board (ESP32-2432S028R)	Control-Panel Unit
MCU#1 MCU#2	NodeMCU V3 ESP8266 ESP-12E (CP2102) Development Board	Sensor-Driver Unit
MCU#3	ESP8266 ESP-01 WiFi Module	Combi-Driver

The ESP32 and the ESP8266, produced by Espressif Systems, represent an advancement in the realm of low-cost, power-efficient microcontrollers. Both systems, originating from Shanghai, China, exhibit distinct features making them particularly appealing to certain applications. The ESP32 can be characterized as an affordable System on a Chip (SoC) microcontroller. Its unique selling point lies in its integrated WiFi and Bluetooth capabilities. Due to its robust architecture and performance potential, the ESP32 tends to be the more favorable option when the requirement for computational power outweighs other considerations. On the other hand, the ESP8266 stands out due to its singular features. It is not merely a cost-effective Wi-Fi microchip. It also boasts a full Transmission Control Protocol/Internet Protocol (TCP/IP) stack and inherent microcontroller functionality. These attributes make it an ideal choice for users seeking a user-friendly microcontroller with seamless Wi-Fi capabilities. In conclusion, when deciding between the two microcontrollers, the context and the specific needs of the project play a vital role. The ESP8266 could be the optimal choice when the ease of use and Wi-Fi functionalities are primary concerns. Conversely, the ESP32 could be the preferred option when the project necessitates a high-performance microcontroller (Gray, 2023).

The ESP32-WROOM Arduino Development Board, identified as MCU#0, serves as an IoT-hub, and IoT-gateway component within a control-panel unit. The device's core feature, the ESP32-WROOM chip, offers integrated Wi-Fi and Bluetooth capabilities, enhancing wireless communication. The board supports several Wi-Fi operation modes, such as Station (STA) mode and Soft Access Point (Soft AP) mode, providing network configuration flexibility. It is compatible with the ESP-NOW communication protocol, enabling swift and energy-efficient communication between ESP32 and ESP8266 devices, which is critical in IoT applications. The board also includes a 2.8-inch TFT LCD touchscreen, powered by the Light and Versatile Graphics Library (LVGL), offering a user-friendly interface. Furthermore, the device extends its user interface via its web server functionality, allowing applications to be controlled remotely over a network. The main controller, the ESP32-WROOM-32, features a dual-core MCU with an operational frequency of up to 240MHz. It incorporates 520KB SRAM, 448KB ROM, and 4MB Flash size, boosting processing and storage capacity. The display unit supports a 240x320 resolution with resistive touch technology. The design encompasses comprehensive circuitry, including LCD display, backlight control, touchscreen control, speaker drive, photosensitive systems, and RGB-LED control circuits. The module includes multiple interfaces such as a TF card interface, serial interface, a temperature, and humidity sensor interface (compatible with DHT11), and additional IO port interfaces. This provides the ability to connect with various devices and sensors. The device supports multiple development environments such as Arduino IDE, ESP IDE, Micropython, and Mixly, providing a versatile platform for a wide range of IoT applications. These features position the development board as an ideal main controller for the controller unit.

In the control-panel unit, a multitude of parallel processing services such as a web-based remote dashboard, embedded dashboard, cloud storage operations, and system management are executed for the users. However, these conditions are not applicable to the sensor-driver and the combi-driver units. Firstly, the computational requirements of these units are less intensive when compared to the control-panel unit, hence a single-core solution like the ESP8266 is deemed sufficient. Secondly, the superior energy efficiency of the ESP8266 positions it as a more sustainable choice for this particular application. Lastly, the cost-effectiveness of the ESP8266 plays a crucial role in hardware selection, particularly for projects constrained by budgetary considerations.

In the initial phase of designing the sensor-driver unit, the NodeMCU V3 ESP8266 ESP-12E (CP2102) development board was employed as a single entity in the first-generation controller unit. From a theoretical standpoint, this board possesses the capability to efficiently manage sensors and drivers connected to it, due to its notable technical features, such as adjustable clock speed, integrated 10-bit ADC, versatile GPIO pins, and support for various communication protocols like SPI and I²C. Moreover, it can facilitate wireless internet connectivity due to its built-in ESP8266EX Wi-Fi module, allowing seamless interaction with connected devices. Despite these features, practical implementation revealed a few constraints with the initial setup in the first-generation controller unit, necessitating an alternative approach for the second-generation controller unit. The primary issue pertained to the provision of power through the combined setup of the development and expansion boards, which resulted in irregular sensor data readings, booting issues, and intermittent connectivity losses. Consequently, the design was revised to increase the development boards to two, with one managing the sensors and the other managing the drivers. This decision was further influenced by challenges encountered with certain pins on the development board, especially during firmware uploading processes. The technical intricacies of the NodeMCU V3 ESP8266 ESP-12E (CP2102) board necessitated this division to ensure efficient operation and effective handling of sensors and drivers.

As displayed in Figure 3.6, the NodeMCU V3 ESP8266 ESP-12E (CP2102) development board is characterized by a specific pinout structure. Santos (2019), on the Random Nerd Tutorials website, offers an authoritative guideline delineating the optimum usage of GPIO pins for the ESP8266. This robust and empirical guide is consolidated in Figure 3.7, assisting in the application of GPIO pins (Santos & Santos, ESP8266 Pinout Reference: Which GPIO pins should you use?, 2019).

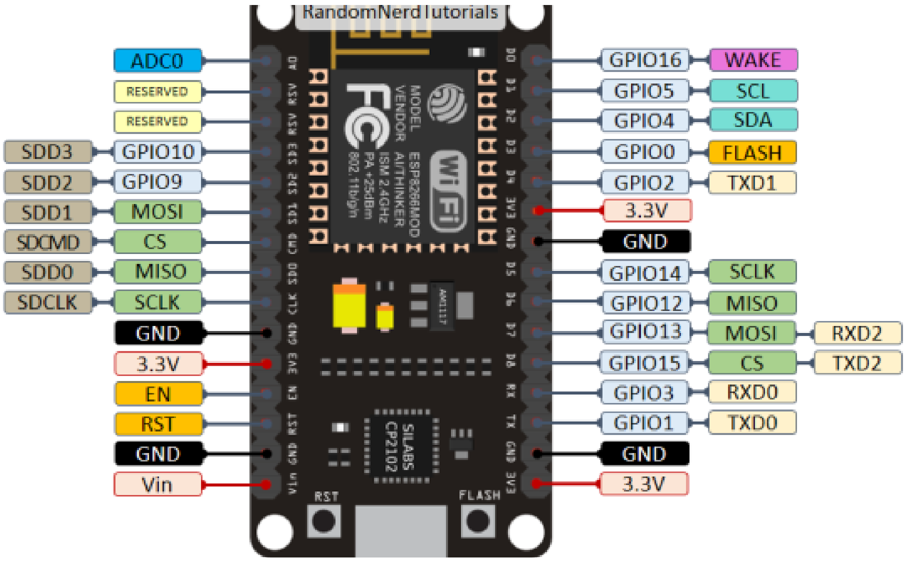
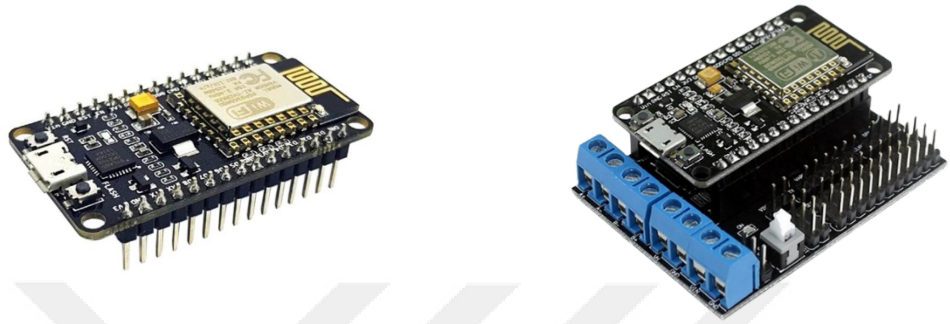


Figure 3.6. The pinout diagram of the NodeMCU V3 ESP8266 ESP-12E (CP2102) (Random Nerd Tutorials, 2019).

Label	GPIO	Input	Output	Notes
D0	GPIO16	no interrupt	no PWM or I2C support	HIGH at boot used to wake up from deep sleep
D1	GPIO5	OK	OK	often used as SCL (I2C)
D2	GPIO4	OK	OK	often used as SDA (I2C)
D3	GPIO0	pulled up	OK	connected to FLASH button, boot fails if pulled LOW
D4	GPIO2	pulled up	OK	HIGH at boot connected to on-board LED, boot fails if pulled LOW
D5	GPIO14	OK	OK	SPI (SCLK)
D6	GPIO12	OK	OK	SPI (MISO)
D7	GPIO13	OK	OK	SPI (MOSI)
D8	GPIO15	pulled to GND	OK	SPI (CS) Boot fails if pulled HIGH
RX	GPIO3	OK	RX pin	HIGH at boot
TX	GPIO1	TX pin	OK	HIGH at boot debug output at boot, boot fails if pulled LOW
A0	ADC0	Analog Input	X	

Figure 3.7. What pins are the best to use in the NodeMCU (Santos & Santos, 2019).

The first NodeMCU V3 ESP8266 ESP-12E (CP2102) (as seen in Figure 3.8.a), identified as MCU#1, serves as an IoT-node component within a sensor-driver unit. This development board, which possesses a compact and dense form, is a versatile IoT device endowed with Wi-Fi network capabilities. The development board utilizes the ESP8266 Wi-Fi Module chip, which is widely recognized for its popularity, and features the ESP-12 SMD footprint. The implementation of the CP2102 USB-UART bridge controller facilitates a seamless connection to the computer for programming and debugging purposes. Furthermore, it supports over-the-air (OTA) updates necessary for firmware enhancements. The performance of this development board is enhanced when it is utilized in conjunction with the ESP-12E L293D motor shield (as seen in Figure 3.8.b). This hardware combination assures the efficient functioning of the system's cooling fan. In addition, the control of circulation and booster pumps, as well as the solenoid valve, has been facilely achieved through the connection points on the board via relays and mosfet driver modules. This development board is tasked with synchronously implementing alterations in the statuses of the output devices, based on instructions received from MCU#0. Moreover, to sustain the feedback loop concerning these real-time status changes of the output devices, it has established an effective communication channel using the ESP-NOW protocol. Consequently, this arrangement ensures two-way-communication between the NodeMCU V3 ESP8266 ESP-12E (CP2102) development board and MCU#0, thereby guaranteeing timely and accurate data transmission and reception.



a) **b)**

Figure 3.8. a) The NodeMCU V3 ESP8266 ESP-12E (CP2102) development board (DirencNet, 2023c); b) The combined usage of the NodeMCU V3 ESP8266 ESP-12E (CP2102) development board and the ESP-12E L293D motor shield (Kompent, 2023).

Another NodeMCU V3 ESP8266 ESP-12E (CP2102) (as seen in Figure 3.8.a), identified as MCU#2, serves as an IoT-node component within a sensor-driver unit, which differentiates it from the initial unit owing to its distinct assigned task. Although this development board, like first-one, has been used in conjunction with the ESP-12E L293D motor shield expansion board (as seen in Figure 3.8.b), the integrated L293D motor driver feature in this unit has not been employed. It was chosen solely to provide an interface for the connection of input devices. This development board has established an effective two-way-communication channel using the ESP-NOW protocol with a twofold purpose: first, to synchronously transmit reading values from the input devices, commonly referred to as sensors, to MCU#0, and second, to adjustment the settings of the necessary parameters for the sensors based on data received from MCU#0.

The components that constitute the hardware of the sensor-driver unit components were listed in Table 3.2. Additionally, the roles and connection methods of these components within the controller unit were schematized in detail in Figure 3.5.

The system's components in sensor-driver unit energy requirements are met by utilizing an Adjustable 3A Step-Down Voltage Regulator to reduce the voltage level to 5V via the Noas brand YL20-0036 model LED driver. This power is used for the MCU#1, MCU#2, the expansion boards and their connected interface modules and sensors in sensor-driver unit.

The MCU#1, under the supervision of MCU#0, is entrusted with the regulation of operations for the pumps, valves, and system cooling fan components that are part of the solar water heating system. This execution is carried out by utilizing the LD293D motor driver module located on the expansion board to which MCU#1 is connected, as well as the interface modules.

For the optimal functionality of the solar water heating system, it is mandatory to ensure the effective control of the circulation pump and booster pump components. This regulation process is implemented by employing the HL-52S V1.0 optocoupler relay module. This interface module is extensively adopted in such projects due to its capacity to provide electrical isolation between low-power control signals and high-power devices. Control signals are transmitted through the GPIO pins on the ESP-12E L293D Motor Shield in conjunction with MCU#1. The energy required to operate this interface module is supplied through the 5V and GND pins on the ESP-12E L293D Motor Shield in conjunction with MCU#1.

Moreover, the IRF520 MOS Driver Module has been chosen for managing the solenoid valve that facilitates the controlled introduction of tap water to the hot storage water tank. This module serves as another intermediary module, possessing the ability to control high-power devices using low-power control signals. Control signal is transmitted through the GPIO pins on the ESP-12E L293D Motor Shield in conjunction with MCU#1. The energy required to operate this interface module is supplied through the 3V3 and GND pins on the ESP-12E L293D Motor Shield in conjunction with MCU#1. The energy required to operate the solenoid valve is supplied from the Noas brand YL20-0036 model LED driver via IRF520 MOS Driver.

Furthermore, especially during hot weather, to preempt factors related to overheating, a 12V Brushless DC Cooling Fan is used to maintain the stability of system component performance. This fan is managed by MCU#1 via the LD293D motor driver embedded on the expansion board. Control signals are transmitted through the GPIO pins on the ESP-12E L293D Motor Shield in conjunction with MCU#1. The energy required to operate the system cooling fan is supplied from the Noas brand YL20-0036 model LED driver via the ESP-12E L293D Motor Shield.

Lastly, on MCU#1, the sole sensor deployed for the control of the system fan is the DHT11 temperature and humidity sensor. The data obtained from this sensor has not been incorporated into the process of data analysis. It is vital to mention that the energy supply required to operate this sensor comes from the 5V and GND pins present on the ESP-12E L293D Motor Shield, which operates in conjunction with the MCU#1.

The MCU#2, under the supervision of MCU#0, is entrusted with the responsibility of monitoring the solar water heating system by reading temperature, and distance values through sensors. This operation is conducted using sensor modules connected to the expansion board that MCU#2 is affiliated with, via the sockets on the sensor-driver unit, as well as directly.

For optimal operation of a solar water heating system, maintaining an accurate measurement of the water level within the hot water storage tank is crucial. The ability to monitor the tank level in real time allows for efficient addition of tap water, thereby preventing potential overflow issues. Notably, the most critical need for such measurements arises in the context of adjusting the quantity of water within the tank. The A02YYUW Waterproof Ultrasonic Sensor is selected for this task due to its ability to calculate the water level and volume within the hot water storage tank. This sensor is a commercial-grade module produced by DFRobot that simplifies measurement by assessing the distance to a target, which, in this case, is the water surface in the tank. This calculation is based on the time delay between the emission and reception of an ultrasonic pulse. The A02YYUW sensor is designed with a waterproof and dustproof closed-separated probe, which makes it suitable for use in harsh and moist environments that can typically be found within a hot water storage tank. All of the signal processing units are integrated within the module itself, simplifying its use and reducing the need for external devices. The distance value is readily obtained via the Asynchronous Serial Interface, resulting in a straightforward and efficient measurement process. The communication between the A02YYUW and the MCU#2 occurs at a band rate of 9600 bits per second. This high-speed data transfer facilitates shorter development cycles and more immediate updates on the tank's water level. It is vital to mention that the energy supply required to operate this sensor comes from the 5V and GND pins present on the ESP-12E L293D Motor Shield, which operates in conjunction with the MCU#2.

Errors have arisen in the water level measurements of the hot water storage tank due to the humidification resulting from evaporation, notwithstanding the waterproof feature of the ultrasonic distance sensor positioned under the tank lid, which observes the water directly from the center. This situation necessitated the design of an alternative measurement system grounded in the principle of the communicating vessels law. The law of communicating vessels, also known as the law of interconnected vessels, states that the levels of liquid in connected vessels will equilibrate, and this level is associated with the balance of pressure. In such a case, in a system with multiple interconnected vessels, the liquid levels in these vessels will balance each other out. The pressure within the vessel is directly proportional to the height of the liquid, and this pressure fluctuates as the liquid level changes. Utilizing this principle, an external measurement apparatus has been developed to measure water levels.

A measurement tube, which won't obstruct the water flow and matches the height of the hot water storage tank, has been connected to the hot water outlet of the hot water storage tank via a connection apparatus. This tube is also insulated like the hot water tank. According to the law of communicating vessels, this tube constitutes the second open-ended vessel, while the hot water storage tank forms the first open-ended vessel. The small hole of 1 mm in diameter situated at the top of the hot water storage tank ensures that the hot water storage tank is also open-ended, and this condition doesn't inhibit the hot water storage tank from cooling. The sensor has been mounted on the measurement tube.

The Laser Distance Sensor GY-VL53L0XV2, as known as Time-of-Flight (ToF) sensor technology, has been utilized as an alternative to the A02YYUW sensor, taking advantage of external measurement. This choice and calibration process have been employed during sensor selection and calibration, offering distinct benefits. This sensor operates at a wavelength of 940nm. This sensor offers a significant advantage in accurately measuring distances within a range of up to 2 meters with a precision of 1mm. It is considered a highly valuable module due to its operational voltage range spanning from 2.8 volts to 5.5 volts, and its compatibility with the I^2C connection protocol. It is vital to mention that the energy supply required to operate this sensor comes from the

3V3 and GND pins present on the ESP-12E L293D Motor Shield, which operates in conjunction with the MCU#2.

Throughout this experimental phase, both the ultrasonic and ToF sensors exhibited commendable performance. However, the ultrasonic sensor's waterproof nature allowed for a smooth installation on the measurement tube, presenting an obstacle for the ToF sensor. To overcome this, the ToF sensor was strategically installed within the mid-lower section of the sensor-driver unit, facilitating easy measurement of the tank's water level. Precise quantification of the water level is crucial for calculating the instantaneous hot water demand parameter, a key component of the learning algorithm to be discussed later. This critical process of accurate measurement and reliable data acquisition was considered during the sensor selection and calibration stage, though the acquired data in this phase were not included in the final analysis. The research data is confined to the real-world data collected by A02YYUW sensor.

On the other hand, to ensure the optimal operation of a solar water heating system, it is paramount to incessantly monitor and compare the temperatures within the circulation line and the hot water storage tank. Consequently, the waterproof variant of DS18B20 sensors has been chosen for this application. Renowned for its significant flexibility and precision, the DS18B20 digital temperature sensor utilizes a 1-Wire communication system. This characteristic allows for multiple DS18B20s to be connected to a single digital pin of a microcontroller, thereby enabling the acquisition of parallel temperature readings from distinct locations. Its operational power supply range, spanning from 3.0V to 5.5V, confirms compatibility with a broad array of microcontrollers and single-board computers. The DS18B20 boasts an extensive operational temperature range from -55ºC to +125ºC, thus covering a majority of practical applications. In terms of accuracy, the sensor offers a maximum deviation of 0.5ºC within the -10ºC to 85ºC range. The DS18B20 digital temperature sensors, mounted at the determined points of the solar water heating system, were interfaced with MCU#2 via the DS18B20 Pluggable Terminal Module. It is vital to mention that the energy supply required to operate these sensors comes from the 3V3 and GND pins present on the ESP-12E L293D Motor Shield, which operates in conjunction with the MCU#2 via the DS18B20 Pluggable Terminal Module.

The components that constitute the hardware of the combi-driver unit components were listed in Table 3.3. Additionally, the roles and connection methods of these components within the unit were schematized in detail in Figure 3.5.

The microcontroller module, identified as MCU#3, incorporates an ESP8266 core processor within the ESP01 Wi-Fi module that with the relay module as seen in Figure 3.3.c was used in combi-driver unit. This module was developed by the Ai-thinker Team (Ai-Thinker, 2017) and is classified not as a development board but as a module. Serving as an IoT-node component within the combi-driver unit, this module provides an unparalleled ability to incorporate Wi-Fi capabilities within other systems or operate as an independent application, all achieved with minimal cost and spatial requirements. The control of the water inflow from the combi to the mixing valve is executed through the solenoid valve connected to the relay on the ESP8266 1 Channel 12V ESP-01 WiFi Relay Module (as seen in Figure 3.3.c), under the supervision of the ESP-01 module. Based on instructions from MCU#0, the module undertakes the task of implementing synchronous changes in the status of the solenoid valve. Furthermore, to sustain the feedback loop concerning real-time status changes of this output device, it establishes an effective communication channel using the ESP-NOW. Consequently, this arrangement assures bidirectional communication between ESP-01 WiFi and MCU#0, thereby guaranteeing the timely and accurate transmission and reception of data. Lastly, the power requirements for MCU#3, the interconnected interface module, and the solenoid valve within the combi-driver unit are catered to through the use of the Noas brand YL20-0036 model LED driver.

3.2.2. Software

A significant portion of this study is devoted to the design and creation of an IoT-based Solar Water Heating System and its supervising unit, termed 'the-controller unit'. This unit employs the framework of deep neural networks and a deep learning algorithm, capitalizing on the benefits provided by the IoT ecosystem. The objective of this system is to enhance the efficiency of solar water heating systems utilized in residential settings and simultaneously ensure optimal hot water supply throughout the day. This is achieved through the use of not only hardware technologies but also software technologies and the data analyses. Data analysis related studies will be discussed in detail in Section 3.3.

The Arduino Integrated Development Environment (IDE) represents a sophisticated software development platform specifically designed to cater to the needs of Arduino kits. This versatile system facilitates the process of code writing, compilation, and the subsequent transfer of these compiled codes directly to an Arduino kit that is connected via the computer's USB port. In essence, the Arduino IDE plays a key role in bridging the gap between conceptual code development and actual implementation in the hardware. Its design and functionality are tailored to assist users in crafting commands in a simplified, yet powerful programming environment. Through its intuitive interface, programmers are enabled to write and verify their code - a vital step known as compilation. In the broader perspective of the digital programming sphere, the Arduino IDE provides a unique contribution. Its ability to facilitate the direct transfer of developed and compiled codes onto an Arduino kit has made it a critical tool in digital programming. This direct transmission system, which utilizes the USB port of a computer, minimizes complications and inefficiencies associated with manual code input or intermediate transfer stages. Therefore, the Arduino IDE has significantly streamlined the coding process for Arduino kits, ushering in a more efficient, effective and user-friendly approach to software development for these devices. By doing so, it has become an indispensable tool for developers working with Arduino kits, as it affords them greater flexibility and control over the entire developmental process. The Arduino Integrated Development Environment (IDE) serves as an instrumental tool in the programming and utilization of ESP modules. The universal design of the Arduino IDE allows users to code across various microcontrollers, which implies that it is feasible to employ the Arduino IDE in programming ESP modules. Users can craft code for ESP modules, compile this code, and upload the compiled code to ESP modules, all via the Arduino IDE. Hence, the Arduino IDE software has been employed in the programming of microcontroller units (MCUs) utilized in the controller unit.

The coding associated with the microcontroller units within the sub-components of the 'controller unit', those located in the 'control-panel', 'sensor-driver', and 'combi-driver' units, is delineated sequentially below in the context of their respective functions.

The MCU#0 performs a critical role within the IoT-based control panel system, utilized within the control-panel unit. The outlined responsibilities of MCU#0 within this system are as follows: 1. Serving the Operations in Multiple Wi-Fi Networks, 2. Inter-device Communication & Data Collection Process, 3. Web Server & User Interface, 4. Cloud Connectivity & Data Transfer, 5.AI-Mode Operation. The coding for MCU#0 was accomplished within the Arduino IDE environment using the C++ language like the other MCUs in the controller unit.

S*erving the Operations in Multiple Wi-Fi Networks:* MCU#0 possesses the functionality to operate in a hybrid mode termed as Access Point and Station Mode (WIFI_AP_STA) (Santos & Santos, 2021). This unique mode facilitates MCU#0 in concurrently creating its own Wi-Fi network and forming a connection with a pre-existing access point.

Inter-device Communication & Data Collection Process: Utilizing the ESP-NOW protocol (as seen in Figure 3.4), MCU#0 establishes bidirectional communication via ESP-NOW communication channel with other MCUs, thereby serving as the main device for effective control within the IoT network. This arrangement ensures that the local network traffic, established through the home router, does not become congested due to the continuous data transfers between devices within the IoT ecosystem. Concurrently, it facilitates a seamless and reliable data collection process by remotely obtaining accurate data from the sensors and information regarding the operational status of the motors and valves. Furthermore, it ensures operational efficiency in controlling the system's motors and valves.

Web Server & User Interface: In today's digital landscape, the pursuit of ease of use and usability is paramount as users interact with web and mobile applications. Graphic User Interface (GUI) design plays a crucial role in meeting these demands. A Graphic User Interface (GUI) refers to the interface through which users interact with an application or website. Well-designed GUI enables users to navigate the application easily, achieve their goals quickly, and have a positive experience. Bootstrap is a popular CSS framework that has a significant impact on GUI design. Bootstrap offers a range of CSS and JavaScript components that empower developers to create rapid and impressive GUI designs. It offers a responsive grid system, pre-designed styles, and interactive elements, allowing for rapid prototyping and consistent design across different devices. The ESP32 and Bootstrap integration offers numerous potential applications in IoT, smart home automation, industrial monitoring, and data visualization. The powerful capabilities of the ESP32 combined with the design flexibility of Bootstrap open up possibilities for innovative and user-centric web interface development. Serving as a web server in Station Mode, MCU#0 facilitates users' access to system information and its management through a web-based dashboard user interface (as seen in Figure 3.9), utilizing the network they are connected to. Concurrently, in Soft-AP mode, it provides this service through an access point it generates, granting users control over the system. The web-based user interface effectively serves users across both desktop and mobile devices. Additionally, MCU#0 offers users the ability to retrieve system information and manage the system using the built-in touch screen dashboard user interface (as seen in Figure 3.10).

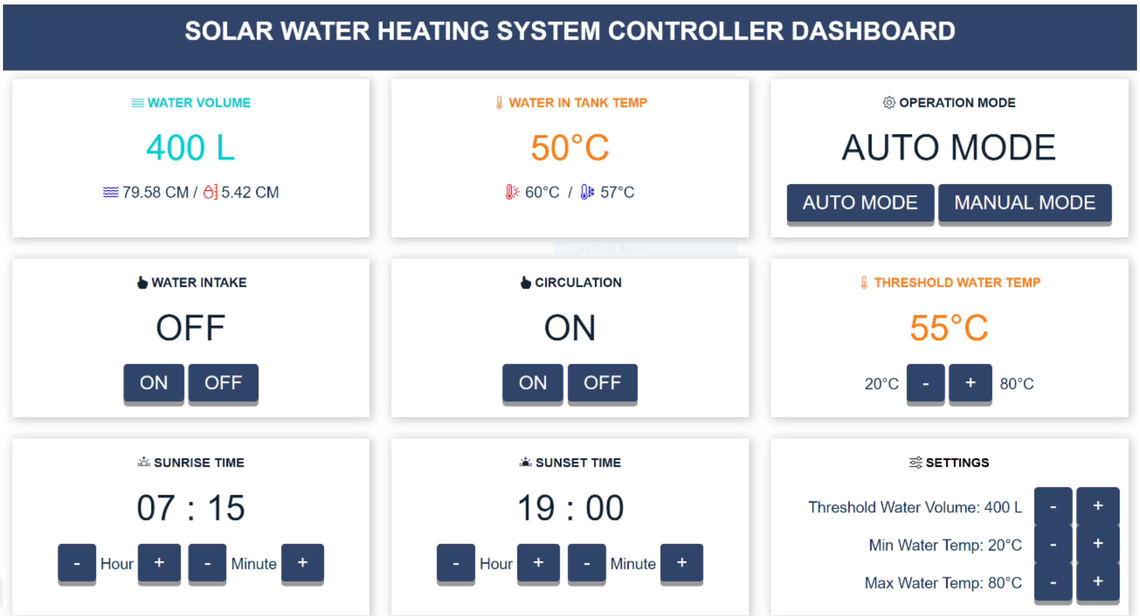


Figure 3.9. The web-based dashboard UI of the SWHSCU.

Figure 3.10. The built-in dashboard UI of the SWHSCU.

Cloud Connectivity & Data Transfer: In Station Mode, MCU#0 establishes a connection with the cloud storage server, thereby facilitating a mutual data transfer service between itself and the server.

AI-Mode Operation: MCU#0 is to operate the system in Auto-Mode as a Super-User Mode based on the data received from the AI-Hub through cloud storage.

The programming flow for MCU#0, as depicted in Figure 3.11, provides a comprehensive schematic overview of its intricate coding structure and sequence.

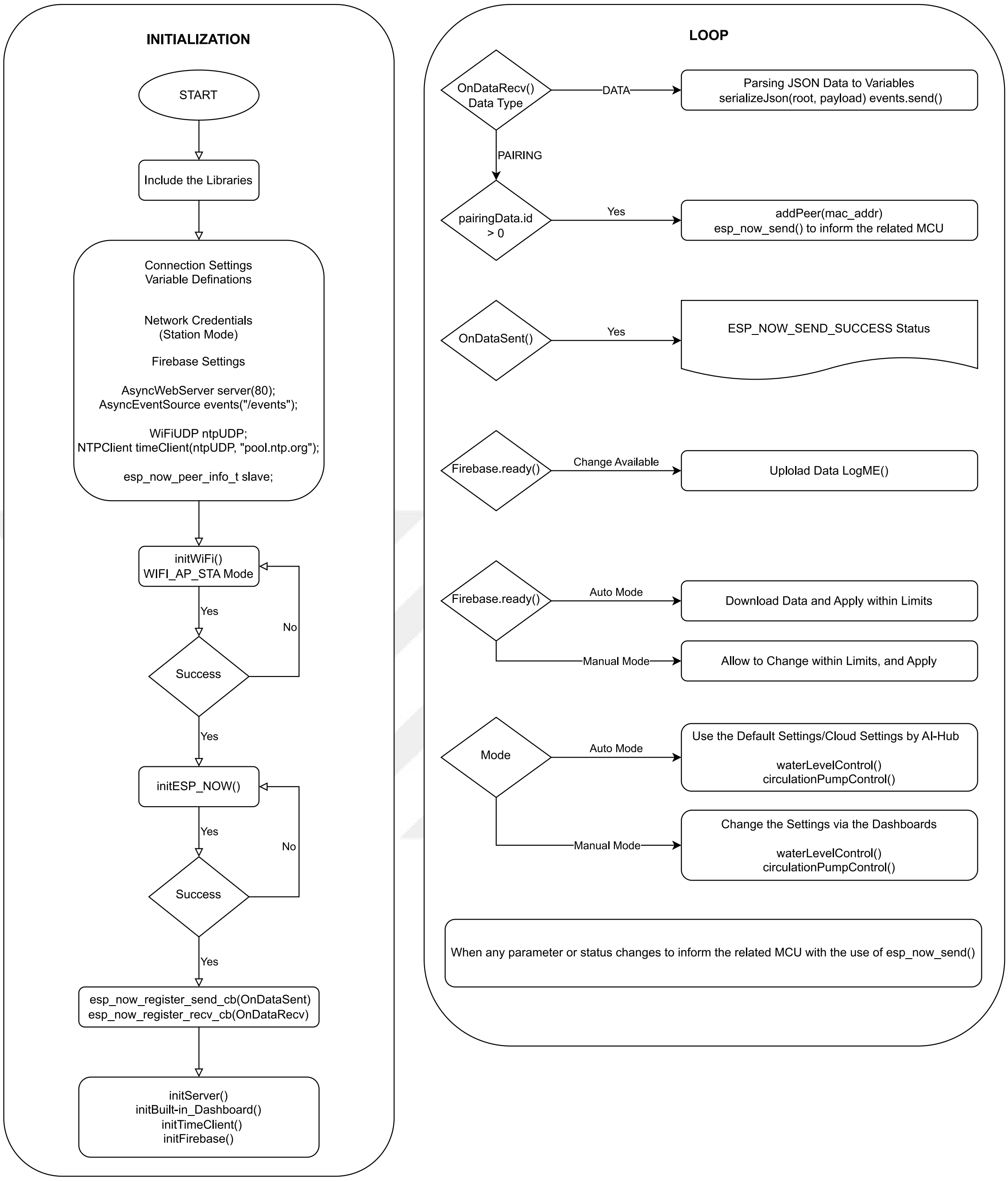


Figure 3.11. The schematic of the MCU#0's programming flow.

During programming, MCU#0 employs a series of libraries to accomplish specific functions, ensuring the optimal operation of a solar water heating system. The WiFi.h library takes on a pivotal role in managing operations across multiple Wi-Fi networks. Inter-device communication and data collection processes are executed via the esp_now.h library. The ESPAsyncWebServer.h and AsyncTCP.h libraries are used for web server capabilities and creating a web-based user interface. The ArduinoJson.h library plays a crucial role in parsing data transmitted via ESP-NOW from MCUs to the web-based user interface. Embedded user interface requirements are catered to by the lvgl.h and LovyanGFX.hpp libraries. Time synchronization tasks are handled by the NTPClient.h and WiFiUdp.h libraries. The AsyncElegantOTA.h library takes on an important role in conducting Over-The-Air (OTA) updates for MCU#0. Finally, cloud connectivity and data transfer are managed via the Firebase_ESP_Client.h, addons/TokenHelper.h, and addons/RTDBHelper.h libraries.

MCU#1, responsible for driving the output devices located in the sensor driver unit, and MCU#2, responsible for reading the sensors, along with MCU#3 in the combi-driver unit, which has a role similar to MCU#1 in managing output devices, have fewer and less complex tasks compared to MCU#0. The connection between these units employs ESP-NOW two-way communication channel, known for its low-power communication capabilities. This facilitates the establishment of bidirectional communication channel between MCU#0 and other MCUs, thus creating an effective and efficient network aimed at optimizing performance while minimizing power consumption and in order not to occupy the existing local network in the IoT ecosystem.

During the programming of MCU#1, MCU#2, and MCU#3, the ESP8266WiFi.h library and espnow.h library file have been integrated at the inception of the program in lieu of the WiFi.h library and esp_now.h library file, respectively. This decision was made to enable communication with MCU#0 via the ESP-NOW two-way communication system, a constituent of the IoT network. For MCU#2, the OneWire protocol is utilized to read the data from the DS18B20 sensors, which are read via same GPIO. To implement this protocol, the OneWire.h library is incorporated at the beginning of the program. Further, on the same MCU, sensor data is read through the DallasTemperature.h library. Finally, for the A02UYYW ultrasonic distance sensor, which is employed to determine the water level in the tank, the SoftwareSerial.h library is included at the start of the program.

The programming flow for MCU#1, as depicted in Figure 3.12, provides a comprehensive schematic overview of its intricate coding structure and sequence.

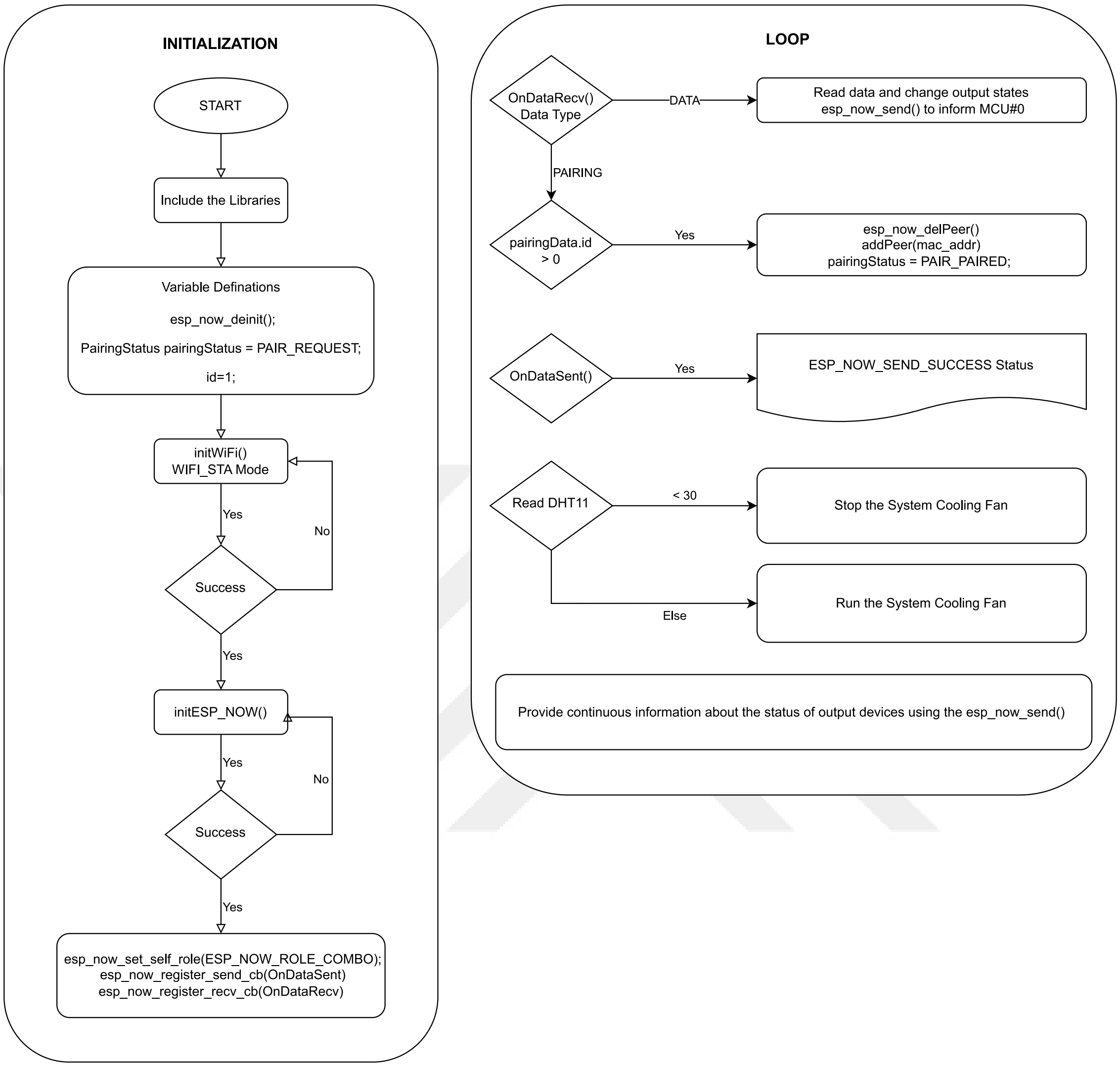


Figure 3.12. The schematic of the MCU#1's programming flow.

The programming flow for MCU#2, as depicted in Figure 3.13, provides a comprehensive schematic overview of its intricate coding structure and sequence.

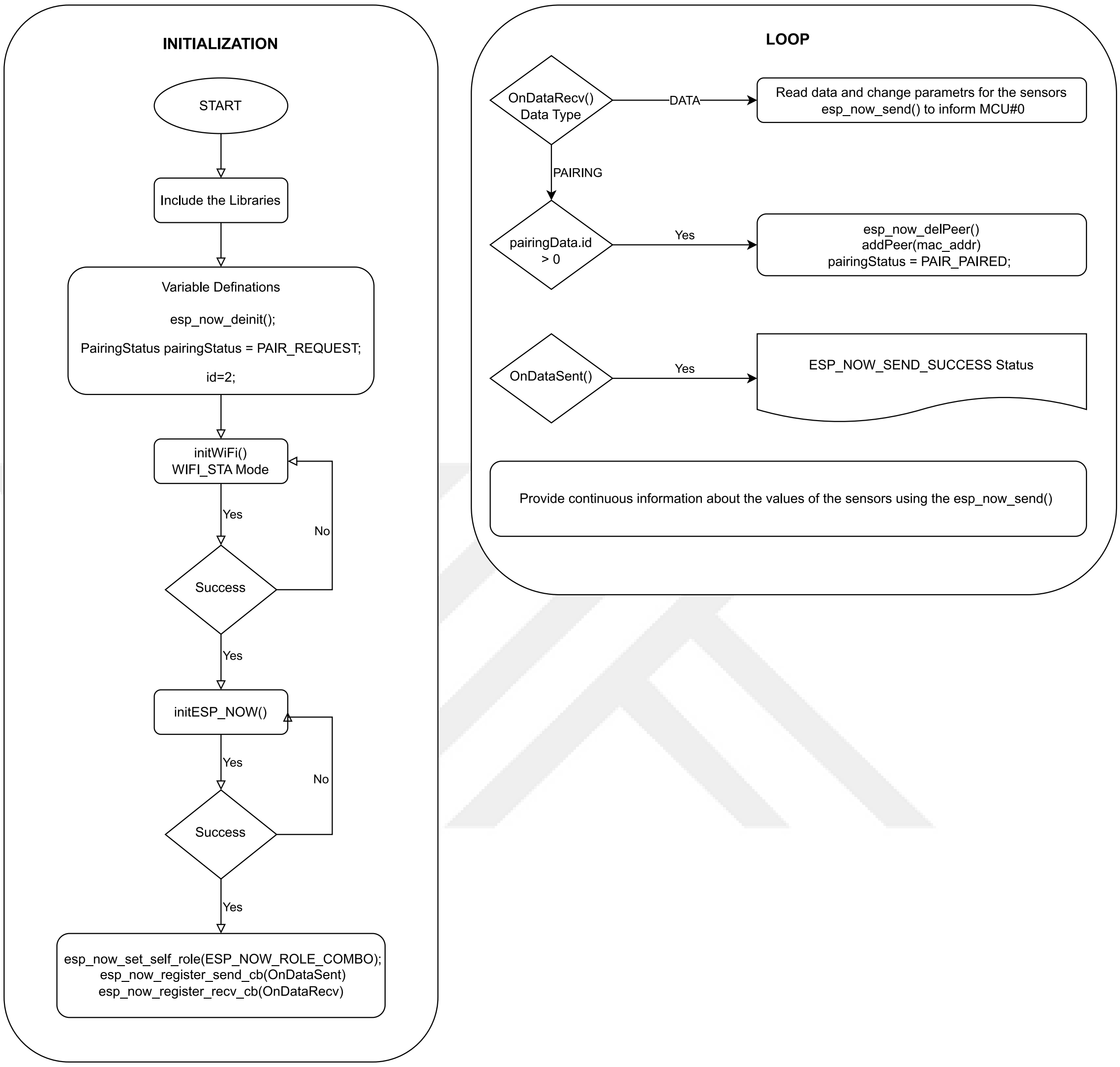


Figure 3.13. The schematic of the MCU#2's programming flow.

The programming flow for MCU#3, as depicted in Figure 3.14, provides a comprehensive schematic overview of its intricate coding structure and sequence.

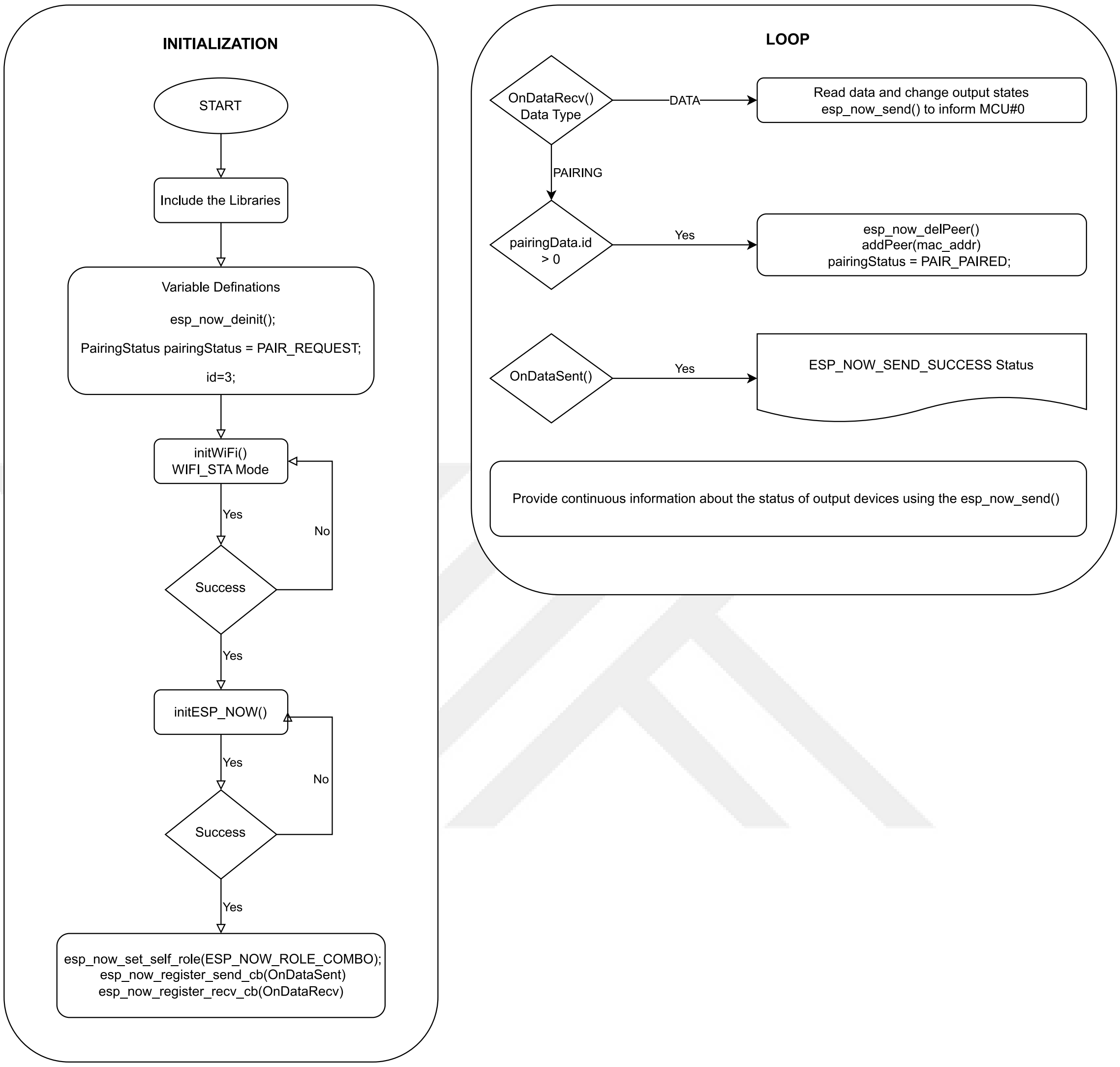


Figure 3.14. The schematic of the MCU#3's programming flow.

The AI-Hub, a quintessential component of the controller unit in a solar water heating system, serves as a pivotal element in facilitating the system's autonomous operation. Functioning as a bespoke computing system, the AI-Hub continuously retrieves archival performance records pertaining to the system's status, transmitted by MCU#0, the principal component of the control-panel unit, from a cloud-based storage service. To enhance system performance, it employs a learning algorithm specifically designed using Python programming language, with the support of the Keras library and other essential libraries, realized on the DataSpell IDE. The objective of this algorithm is to augment the efficiency of the solar water heating system through effective operational scheduling tailored to meet immediate hot water demand. This goal is achieved by taking into account variable parameters such as water usage, threshold water temperature, threshold water level within the tank, and temporal meteorological data. By analyzing historical trends and patterns, the algorithm makes predictive inferences about the system's preparatory measures for future stages. In aiming to endow the system with an autonomous structure, the algorithm establishes the operational scenario at a specific time based on these inferences. Subsequent to this learning process, the AI-Hub establishes itself as a decision-making nucleus, indirectly integrating into the controller unit via cloud storage. Additionally, the AI-Hub effectively leverages the cloud storage service to transmit instructions or recommendations to the control-panel unit and units under the control-panel's supervision, such as the sensor-driver and the combi-driver units. Thus, the AI-Hub, with its sophisticated decision-making capabilities, emerges as a crucial component within the system's architectural framework and operational functionality, fostering efficient and autonomous operation of the system. Details about the learning algorithm and its programming will be provided in Section 3.3.

In summary, the operation of the system mentioned above is implemented through the roles and relationships of the microcontrollers within the control-panel unit, the sensor-driver unit, and the combi-driver unit, in conjunction with the AI-Hub integrated via the Internet through Cloud Storage Service, all within the context of the controller unit and facilitated by software protocols. Interoperability between these components is orchestrated through an IoT network (as seen in Figure 3.4). Fundamentally, the system operates in two modes: automatic mode (auto mode) and manual mode. In the auto mode, the system functions with default settings, while in the manual mode, the system operates based on user-defined settings. Furthermore, there exists a super-user mode that functions according to a learning algorithm framework, introducing a form of autonomous structure that has the capability to make system operation decisions by the AI-Hub. As the performance of the learning algorithm improves, its impact on the system correspondingly increases. In this context, the system operates in super-user mode via a cloud storage platform, optimizing system settings for a more efficient user experience. This mode also assists the decision-making process within the auto mode. The system is initiated by MCU#0, connects to the existing network, and links to other units via ESP-NOW. Concurrently, its internal web server provides two dashboard services with the web-based user interface and the built-in touch screen dashboard user interface, allowing for monitoring and management of the overall system status. During this period, sensor readings and driver statuses controlled by MCU#1 and MCU#2 in the sensor-driver unit, and MCU#3 in the combi-driver unit, are time-stamped and saved to a cloud storage environment. These data are collected and transferred to a cloud storage service by the MCU#0 for system manipulation purposes by the AI-Hub. Following this, the data are downloaded and processed in the auto mode. Throughout this process, the super-user can customize the parameters of the auto mode with the new data. In manual mode, users are permitted to adjust system parameters according to their needs, without the support of artificial intelligence. This approach allows users to customize the system to suit their specific needs.

3.3. The Learning Algorithm Framework and the Data Analysis Process

The unpredictable nature of hot water demand poses a significant challenge in optimizing the operation of solar water heating systems. Stochastic models are a potential tool to handle such unpredictability. Recently, the integration of IoT, deep neural networks, and deep reinforcement learning have shown substantial potential in improving these models, through real-time data collection and advanced predictive capabilities. IoT provides real-time monitoring capabilities for solar water heating systems. IoT devices can collect and transmit data on water usage, temperature changes, and other relevant parameters to the cloud, enhancing the timeliness and accuracy of data used in demand prediction. Deep neural networks can process a variety of inputs to produce outputs, making them suitable for predicting hot water demand. Deep neural networks can analyze data collected by IoT devices and use it to make accurate predictions about future hot water demand. Deep reinforcement learning can adapt to different scenarios and aims at reward maximization. In the context of solar water heating systems, deep reinforcement learning can optimize the operation by determining the most efficient operating parameters based on the predicted hot water demand.

Python, a high-level language designed in the early 1990s by Guido van Rossum, plays a pivotal role in this research. Initially conceived as a scripting language, Python has garnered a vast user base and ecosystem over time. Currently, Python is widely employed across multiple applications including data analysis, scientific computation, web development, and automation. In recent years, Python's popularity has surged in the realm of machine learning and deep learning. The language has been augmented with a myriad of libraries and tools to facilitate the use of these technologies. Libraries such as TensorFlow, PyTorch, and Keras have enabled the implementation of complex algorithms like deep learning and deep neural networks. Within the process of data analysis, Python's broad array of features is commonly employed in conjunction with deep learning and deep neural network algorithms. These libraries offer extensive capabilities and afford the opportunity to utilize Graphics Processing Units (GPUs) to expedite the training of complex algorithms. The Keras library, in particular, further simplifies the construction and training of deep neural networks. Nevertheless, languages like C++ and Java can be employed in scenarios where quick runtime performance is prioritized. However, these languages generally entail more complexity in their use compared to Python and offer fewer machine learning and deep learning libraries. Python is considered a more accessible and user-friendly option for such applications due to its extensive library support and ease of use. These factors have contributed to the continued popularity of Python in the fields of deep learning and machine learning.

DataSpell, designed by JetBrains, serves as an amalgamation of artificial intelligence and data science, making it an advantageous tool in scholarly research endeavors. It draws inspiration from Jupyter notebooks, thereby providing an avenue for users to sequentially execute Python code while simultaneously viewing the results. The integral feature of DataSpell lies in its ability to assist researchers with data analysis and model development through the provision of readily available machine learning and deep learning algorithms. Thus, it streamlines several academic tasks ranging from data exploration to experimental design, from result visualization to the creation of scholarly manuscripts. The inherent strengths of DataSpell can be encapsulated in the following quintessential aspects: it provides an Interactive Working Environment, facilitates Data Preprocessing and Feature Engineering, enables Model Training and Evaluation, fosters Collaboration and Sharing, and encompasses Integrated Artificial Intelligence Capabilities. In essence, DataSpell serves as an instrumental platform, equipping researchers with an interactive environment that enhances efficiency in data analysis and modeling undertakings.

It is important to prediction of stochastic hot water demand and optimal operation of the solar water heating system suitable for the residential use using right artificial intelligence technique depending on usage habits and other environmental factors. In this context, a learning algorithm has been designed using the Python programming language, with the aid of the Keras library and other necessary libraries, implemented on the DataSpell IDE. The objective of this algorithm is to optimize the efficiency of the solar water heating system by effectively scheduling the system's operation to meet immediate hot water demand. This is achieved by considering varying parameters such as water usage, threshold water temperature, threshold water level in the tank, and meteorological data over time. Through the analysis of past trends and patterns, the algorithm makes inferences about how the system should be prepared for future stages. This approach aims to endow the system with an autonomous structure by determining the operational scenario at a given time based on these inferences.

In order to achieve the goal of the study, a deep reinforcement learning algorithm framework was developed, bolstered by deep neural networks. This framework utilizes realistic sensor data obtained through IoT technology, which delivers precise, real-time information on the environmental conditions of the solar water heating system. This data-driven approach enables the system to adapt and optimize its operations based on real-world conditions, ultimately improving its efficiency and performance.

The design of the aforementioned learning algorithm was executed using a methodology Reinforcement Learning with specifically tailored for time-series data, namely Long Short-Term Memory (LSTM), a variant subclass of Recurrent Neural Networks (RNNs) under the broader category of Deep Neural Networks (DNNs). This algorithm, grounded in Deep Neural Networks (DNNs) and Deep Reinforcement Learning (DRL), particularly employs a Long Short-Term Memory (LSTM) approach, a subclass of Recurrent Neural Networks (RNNs) adept at handling time-series data. The objective is to develop autonomous systems capable of making informed operational decisions based on data patterns and trends.

The proposed algorithm is applied to a real-world case study of optimizing a solar water heating system for residential use. The framework is employed to identify the optimal operation schedules based on action-reward feedback for household demand. Deep neural networks (DNNs) play a crucial role in handling big data, primarily due to their exceptional ability to extract complex patterns and trends from large datasets. Moreover, deep neural networks provide the "deep" in deep reinforcement learning, allowing the algorithms to handle large, complex tasks and making them a distinguishing feature of deep reinforcement learning. Implementing deep neural networks and deep reinforcement learning in tandem could significantly enhance the performance of solar water heating systems. With no prior information about the hot water system or the household occupants, the deep reinforcement learning agent, complemented by deep neural networks, begins to learn and adapt. Over time, and as more data are collected and analyzed, the performance of the solar water heating system improves. This adaptive, learning-focused approach underscores the immense potential of integrating DRL, and DNNs in enhancing the efficiency of solar water heating systems.

The research data is based on real data collected through sensors and the operating statuses of actuators connected to the controller unit of the second-generation solar water heating system, which was designed by the researcher and employed in the redesigned second-generation solar water heating system in the Konyaaltı district of Antalya, between March 15, 2023, and June 15, 2023. In addition, the data includes meteorological information obtained from the mgm.gov.tr website for the corresponding dates in the region where the solar water heating system was installed.

4. RESULTS, DISCUSSION AND CONCLUSION

The first-generation solar water heating system, initially designed to meet the hot water demands of a middle-income four-person household in Antalya, Turkey, was pivotal in achieving the study's objectives by offering insights into system efficiency, controller design, sensor selection, and potential system issues. Operating based on the principle of a closed-loop (indirect) active circulation solar water heating system, this design employed a heat-exchanger and circulation line, a distinct heat transfer fluid, a controller unit, and variable water level managed through a solenoid valve. To measure the water level in the tank, an ultrasonic distance sensor was utilized, and a booster pump increased the pressure at the hot water outlet. Due to increasing demand and system limitations, such as overflow problems and inefficient tank performance, a second-generation solar water heating system was developed, retaining the same basic operating principles but incorporating enhanced features for safety, efficiency, and storage capacity.

In considering the design of hot water storage tanks with variable water levels, the location from which the hot water is extracted is of paramount importance. It has been postulated that a uniform temperature distribution within the tank could overcome this challenge. In this context, the designed tank was observed to have a negligible temperature differential of approximately +3°C between the lowest and highest points within the tank. This was measured during various experimental trials under comparable environmental conditions at different levels. Consequently, it has been suggested that by drawing water from a point near the base of the tank and introducing cold water from the top, it could facilitate a more uniform temperature distribution within the tank. The veracity of this approach has been corroborated through data analysis post March 15, 2023, indicating a successful implementation of the system under this design premise.

This study utilized the A02YYUW Waterproof Ultrasonic Sensor for real-time monitoring of water levels in solar water heating systems, however, humidity-related errors necessitated an alternative approach. A system utilizing the principle of communicating vessels was developed, employing a measurement tube and the relocation of the A02YYUW sensor. Additionally, the GY-VL53L0XV2 Laser Distance Sensor, based on Time-of-Flight technology, was introduced as an alternative, providing precise measurements. Although both sensors performed satisfactorily in experimental testing, careful positioning of the ToF sensor was necessary due to its vulnerability to water. Accurate water level measurement is crucial for computing the instantaneous hot water demand parameter, a key element of the system's learning algorithm. Furthermore, for optimized operation, continuous comparison of temperatures within the circulation line and tank was facilitated using the DS18B20 digital temperature sensors, interfaced with the second microcontroller unit via the DS18B20 Pluggable Terminal Module.

The present study extensively explores the development and implementation of an IoT-based Solar Water Heating System, including its chief supervising entity referred to as 'the-controller unit'. This sophisticated system leverages deep neural networks, deep learning algorithms, and benefits from an Internet of Things (IoT) environment. The primary objective of this system is to enhance the efficiency and performance of solar water heating systems in domestic applications while simultaneously ensuring a steady supply of hot water throughout the day. The system achieves this objective by utilizing both hardware and software technologies, and extensive data analysis.

The advancement in the solar water heating systems technology has been greatly facilitated by the introduction of intelligent control mechanisms. These control mechanisms, predominantly embodied in the form of solar water heating system controller units, are crucial in optimizing the operational functionality of the solar systems. The controller units are tasked with regulating the transfer of heat between solar collectors and storage tanks. They continuously monitor and adjust several critical parameters such as the temperature of the heat transfer fluid, the ambient temperature, and the intensity of solar radiation. The integration of advanced algorithms and control logic within these units allows for intelligent decision-making processes based on the collected data. These processes involve regulating temperature differentials, managing thermal stratification, and preventing freezing and overheating, all aimed at achieving maximum system efficiency. Additionally, the controller units offer a user-friendly interface for monitoring and controlling the system, and some even provide remote access capabilities. Despite the advantages of these controller units, the implementation of Internet of Things (IoT) technology presents a viable strategy for further enhancing the functionality of solar water heating systems. IoT allows for remote monitoring and control of the system, facilitates predictive maintenance, and adds to the overall convenience of operation. However, the introduction of IoT also brings about challenges related to privacy, security, potential technological glitches, and the necessity for reliable internet connectivity. The transition to the second-generation solar water heating system controller unit marked a significant step in the evolution of this technology, with additions such as a user-friendly graphical interface, cloud-based data storage, and artificial intelligence support. The development of the second-generation unit has greatly benefited from the integration of IoT and artificial intelligence technologies, including deep reinforcement learning and deep neural networks, following a five-layer IoT architectural model. The methodology applied in the creation of this controller unit was divided into two primary phases: hardware selection and programming. The architectural layout of the controller unit for a solar water heating system involves three significant hardware divisions: the control-panel unit, the sensor-driver unit, and the combi-driver unit, enhanced by the integration of a Raspberry Pi compact single-board computer serving as the AI-hub. The control-panel unit is wall-mounted and offers an interactive interface for users to monitor and manipulate system operations, thanks to its integrated display panel and web-based remote-control interface. It provides various parallel processing services and communicates with the sensor-driver unit and the combi-driver unit through a cloud storage service, which is also linked to the AI-hub. The sensor-driver unit is installed on a measurement pipe arrangement for the solar water heating system and is responsible for data acquisition and management of various system components. In contrast, the combi-driver unit, installed near the boiler, regulates the entry of hot water into the mixing valve. The second-generation controller unit employs a connectionless communication protocol developed by Espressif, enabling communication between various units without the need for an existing Wi-Fi network. Central to the study is the implementation of a deep learning algorithm within an IoT ecosystem to enhance the efficiency of the solar water heating system. Various microcontrollers perform different roles within the system, with MCU#0 serving multiple functions within the control-panel unit and facilitating data collection and transfer, MCU#1 and MCU#2 managing output devices and reading sensors, respectively, and MCU#3 in the combi-driver unit controlling output devices. The AI-Hub, integrated via cloud storage, is critical to the system's autonomous operation by continuously retrieving archival performance records and making predictive inferences to enhance system performance. The system operates in three modes: automatic mode with default settings, manual mode with user-defined settings, and super-user mode, which is guided by a learning algorithm framework. As the algorithm's performance improves, its impact on the system increases, and the system operates in the super-user mode via a cloud storage platform for optimal system settings and efficient user experience.

The web-based user interface (as seen in Figure 3.9) effectively serves users on both desktop and mobile platforms. Additionally, MCU#0 offers users the ability to retrieve system information and manage the system using the built-in touch screen dashboard user interface (as seen in Figure 3.10). A mobile application, may be planned for future development, will allow system administration to be conducted specifically over the Internet.

The integration of Internet of Things (IoT), deep neural networks (DNNs), and deep reinforcement learning (DRL) introduces a new paradigm in optimizing solar water heating systems, by addressing the inherent unpredictability of hot water demand. IoT enables real-time data collection and monitoring of various system parameters, like water usage and temperature changes, thereby improving the accuracy of demand prediction. DNNs are employed to process this diverse set of input data, extracting complex patterns to accurately forecast future hot water demand. The adaptability of DRL, driven by its reward maximization strategy, optimizes the operation of the system based on the demand predictions. Specifically, the design of the proposed learning algorithm employs Long Short-Term Memory (LSTM), a variant of Recurrent Neural Networks (RNNs) under DNNs, optimized for handling time-series data. The objective is to create autonomous systems that can make well-informed decisions based on detected data trends and patterns. This algorithm, applied to a real-world case study of a residential solar water heating system, identifies the optimal operation schedules utilizing the action-reward feedback mechanism. The "deep" aspect of DRL, provided by the DNNs, enables handling of large, complex tasks, recognizing patterns within voluminous datasets, and hence, differentiating DRL from conventional reinforcement learning. The deep reinforcement learning agent, devoid of prior information about the household occupants or the hot water system, progressively learns and adapts, leading to performance enhancement of the solar water heating system over time. Thus, the combination of DRL and DNNs signifies a promising solution to increase the efficiency of solar water heating systems, further emphasizing the potential of these technologies when applied in unison.

In this study, was used the integrated use of Deep Reinforcement Learning (DRL) and Long Short-Term Memory (LSTM). It leverages the abilities of both methods to navigate complex environments and manage long-term dependencies in sequential data. The algorithm employed learns optimal policies by utilizing stored previous experiences and constantly interacting with the environment. For instance, past usage patterns on Saturday mornings and other environmental factors are collectively analyzed, and a prediction is provided to determine the average amount of water to be used that next Saturday, ensuring the autonomous operation of the solar water heating system. However, in the period from March 15, 2023, to June 15, 2023, despite a gradual uptrend in accuracy, the performance of the learning algorithm was deficient. This inadequacy was due to the constrained policy of the cloud storage service, which limited access to and storage of data on specific days of the month. Additionally, the preponderance of manual mode use in sensor readings and the inadequacy of the selected hyperparameters affected the results. This limited selection resulted in inadequate fitting and underscored the necessity for reevaluating the hyperparameters during the model's training and optimization phases. Furthermore, there emerged a requirement for robust data, gathered over a broader temporal range.

The study suggests that as a future work more reliable results can be achieved with a larger data set, or adopting a different learning model that requires less data might make it possible to reach a more autonomous decision-making structure. An alternative path that prefers autonomous system structuring can also be chosen.

In many situations, it is not possible to obtain precise mathematical model of a system due to its complexity. In such case of vague, ill-defined, and complex system models, the one impressive solution is fuzzy logic (FL) modelling. In this context, in comparison to artificial neural networks, fuzzy models consistently outperforming in predicting output(s) even with reduced datasets. For instance, Kishor et al. (2010) aimed to enhance prediction accuracy for thermosyphon solar water heating (SWH) systems using a fuzzy modeling approach. In comparison to neural network techniques, the study found that a fuzzy model with three inputs (inlet water temperature, ambient temperature, solar irradiance) showed improved prediction performance for outlet water temperature. Employing the “anfis” function in MATLAB, the research considered various input variables and demonstrated that the proposed fuzzy model outperformed artificial neural networks in predicting outlet water temperature, offering a promising alternative for assessing SWH system performance. Even when dealing with a reduced dataset, the fuzzy model consistently outperformed artificial neural network models in forecasting outlet water temperature.

Fuzzy logic, which is mentioned above, is designed as a mathematical paradigm to address complexities in reasoning and decision-making within contexts characterized by uncertainty, ambiguity, and vagueness. Fuzzy logic finds applications in automation, control systems, artificial intelligence, and many other fields. This approach extends the limitations of traditional binary logic to handle intricate and uncertain situations effectively. Diverging from the strictness of classical binary logic, fuzzy logic utilizes membership degrees between 0 and 1 to capture the nuanced nature of partial truth, thereby accommodating intricate concepts surpassing simplistic binary classifications. Rooted in the foundational principle of fuzzy sets, this framework allocates membership values based on the degree of inclusion, finding broad utility in domains including control systems and expert systems, offering a versatile and adaptable methodology for modeling uncertain and ambiguous information. Its capacity to mirror human decision-making by accounting for a wide range of possibilities between absolute truth and falsehood is particularly relevant in real-world scenarios where definitively ascertaining the veracity of a statement is challenging. Following Lotfi Zadeh's introduction of fuzzy logic, it has ushered a paradigm shift in the conception of adaptive control, indicating the feasibility of adaptive control without strict reliance on precise numerical data. This comprehensive framework finds careful application across diverse domains, including the management and optimization of solar water heating systems, which prominently underscores the integration of the Adaptive Neuro-Fuzzy Inference System or Adaptive Network-Based Fuzzy Inference System (ANFIS). By amalgamating fuzzy logic principles with neural network principles, ANFIS exemplifies a nuanced approach to capturing complex data relationships. In the context of solar water heating system control, ANFIS integration accommodates variations in required water consumption, addresses fluctuations arising from environmental conditions, reduces the necessity for secondary water heater such as combi, and enhances efficiency by ensuring that the predicted water temperature and volume of water within the tank remain above a specified threshold. This integration reinforces the inherent adaptability of fuzzy logic principles in addressing intricate and uncertain real-world scenarios, further underscoring its pivotal role in decision support and control applications.

Furthermore, in the architectural design of the IoT network (as seen in Figure 3.4), the controller unit holds a crucial position in facilitating seamless communication and operational efficiency among the constituent elements. However, the need to enhance data security and to circumvent the pricing policies of cloud storage services may necessitate the adoption of alternative methodologies for the reconfiguration of the IoT network. The first such approach involves the use of the local storage services with synchronize the data via MQTT (Message Queuing Telemetry Transport) protocol as a replacement for the cloud storage service, establishing a connection over the existing Wi-Fi network between the MCU#0 and the local AI-Hub, with data storage maintained within the same computer system. Concurrently, a hybrid design that incorporates a fog computing structure can serve as an alternative IoT network, reducing the volume of data stored in the cloud and enhance data security. Leveraging the AI-Hub, more accurate learning algorithms can be developed to improve decision-making efficacy, thus enhancing the overall performance of the system.

The first-generation system provided valuable insights but had limitations, leading to the development of the second-generation system with enhanced safety, efficiency, and storage capacity. One of the most critical issues, for instance, was related to the ultrasonic distance sensor with waterproof capability, which was used to measure the water level inside the tank; however, it was prone to erroneous readings due to fogging caused by the heating of the water within the tank. In the second-generation system, the water level within the tank is determined using an external measurement technique based on the principle of communicating vessels. However, during water usage, the water level in the measurement pipe decreases more rapidly compared to the water level within the tank. Although this method proves to be more effective than internal measurements, it exhibits greater stability and accuracy when there is no water usage. The solution to overcome this issue is rather straightforward. The measurement pipe can be connected to a different point on the tank, for example, just above the water outlet, rather than directly to the tank's water outlet.

Based on the aforementioned recommendations, the second-generation solar water heating system, architectural design of the IoT network, and the controller unit have been revised as a result of research. This system is referred to as the next-generation solar water heating system.

The design and operation of the system are as like as the second-generation solar water heating system. However, unlike the second system, one flowmeter is connected to the booster pump outlet and one flowmeter is connected to the mixing valve outlet as a more effective solution in determining the total hot water demand parameters met and consumed from the solar water heating system. Hot water volume data received over the

SWH system is collected by MCU#2 in the sensor-driver unit and transmitted to MCU#0 in the control-panel unit. Total consumed hot water volume data is collected by MCU#3 in the combi-driver unit and transmitted to MCU#0. The schematic diagram of the next-generation solar water heating system is presented below in Figure 4.1.

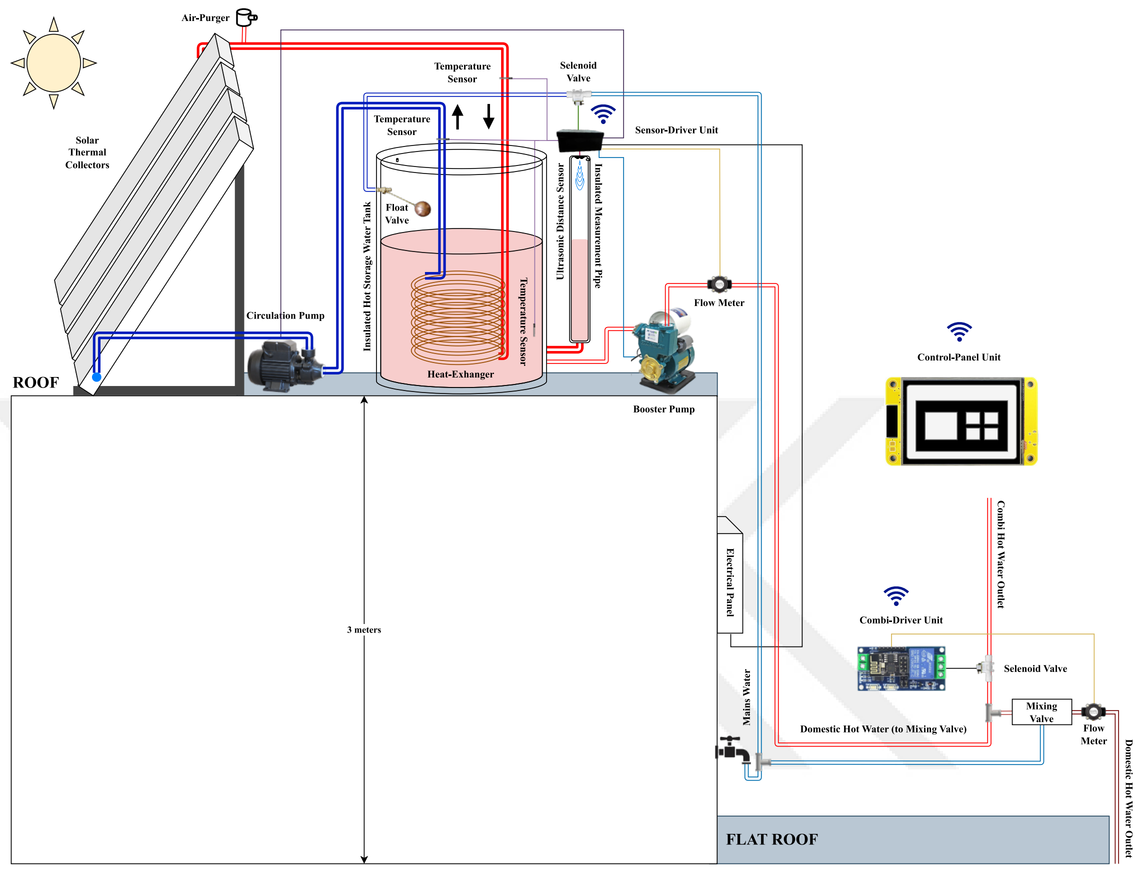


Figure 4.1. The schematic diagram of the next-generation SWH system.

The architectural design of the IoT network has been reconfigured to increase data security in the process and circumvent pricing policies of cloud storage services. The novel architectural design of the IoT network enables the synchronization of data through the MQTT protocol, allowing for a connection between MCU#0 (MQTT-Client) and the local AI-Hub (MQTT-Broker) over the existing Wi-Fi network, thereby replacing cloud storage services with local storage service options. Data storage is maintained within the same computer system. Additionally, a hybrid design incorporating a fog computing structure reduces the volume of data stored in the cloud and enhances data security. Consequently, leveraging the capabilities of the AI-Hub enables the development of more accurate learning algorithms to enhance decision-making efficacy and improve the overall performance of the system. The daily storage of system-related data is stored on the SD card storage because it is used as a second backup unit to minimize data loss by preventing a negative situation to the local storage service on the AI-Hub. For this reason, it is aimed to benefit from these data in order to complete possible missing data in the development of the learning algorithm. On the other hand, while the data about the system is stored in the local storage unit, the possibility of accessing the graphics of some statistical data via the ThingSpeak IoT platform on the Internet is included in this network architecture. ThingSpeak is an Internet of Things (IoT) platform that allows you to collect, analyze, and visualize sensor data from connected devices. It provides an easy-to-use interface for storing and retrieving data, as well as a variety of tools for data analysis and visualization. Finally, ESP-NOW communication protocol continues to be used inter-device communication and data collection processes among the MCUs.

The types of communication protocols established between these units have been schematized in Figure 4.2 below.

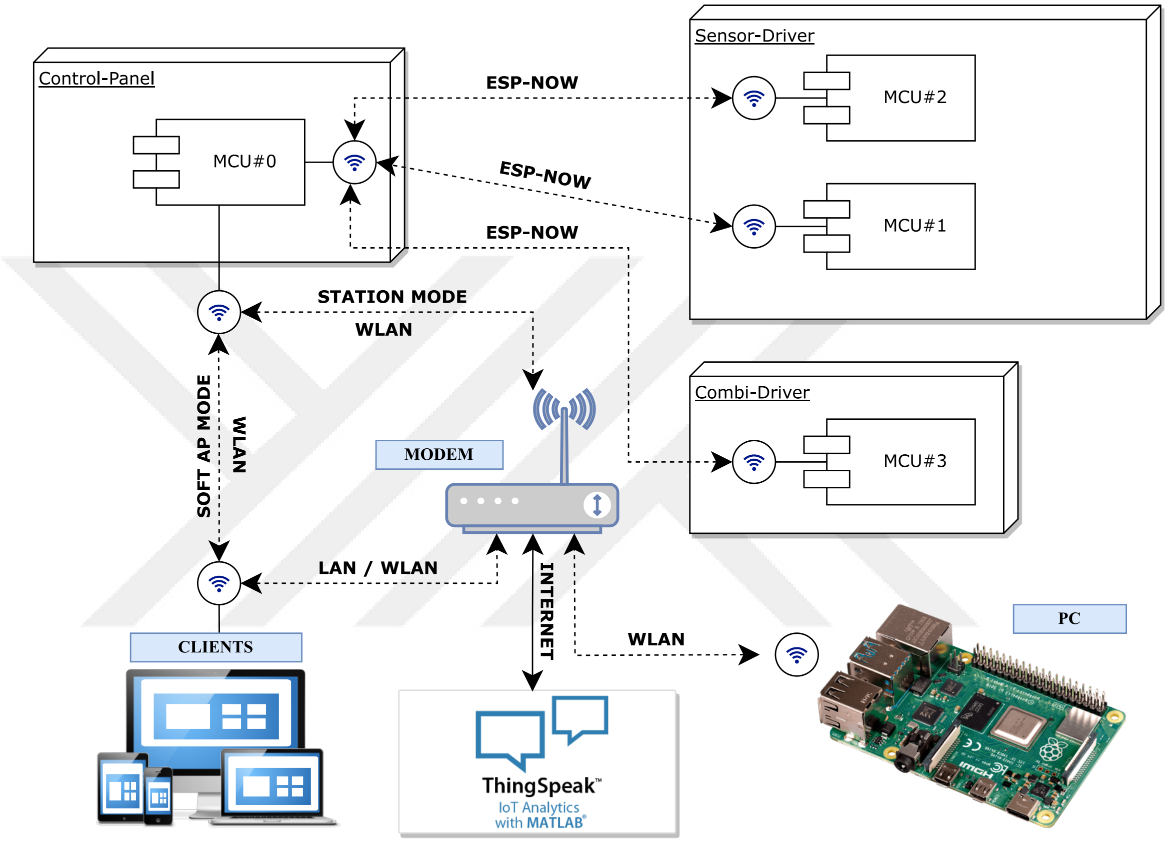


Figure 4.2. The block diagram of the communication protocols of the next-generation controller unit.

Figure 4.3 presents a comprehensive overview of the next-generation controller unit's hardware components, including their functionalities, and the environment in which they operate and communicate.

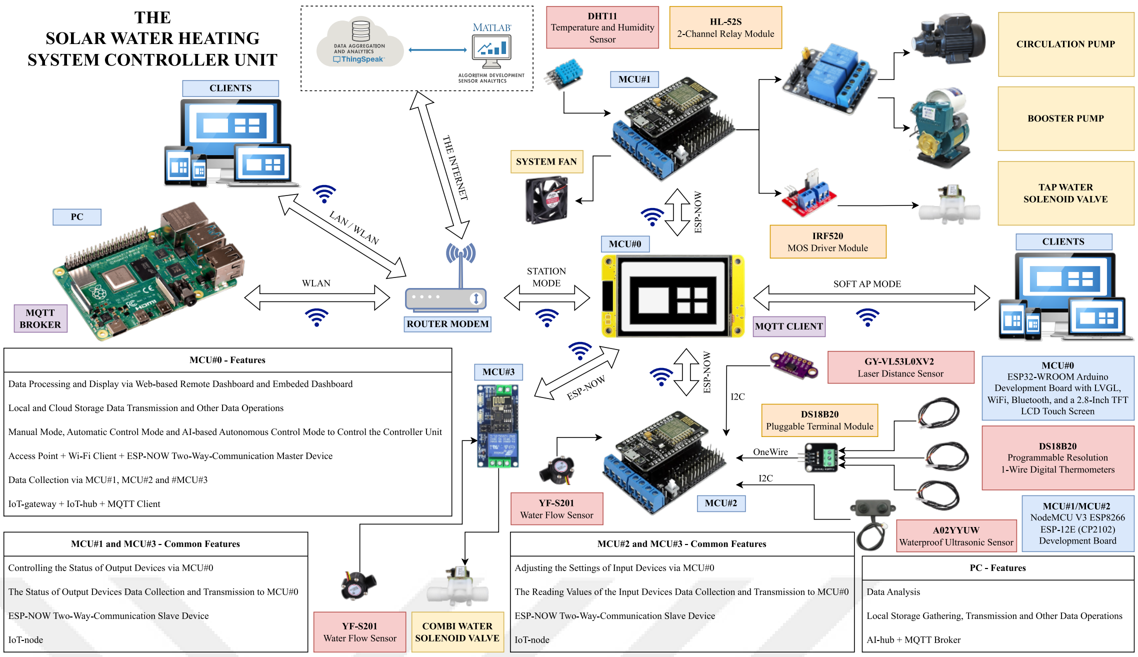


Figure 4.3. The block diagram of the hardware components of the next-generation controller unit.

Changes have been made to the web-based dashboard user interface (as seen in Figure 4.4) based on programming modifications. The controller unit's web-based dashboard user interface includes four operating modes: AI Mode, Default Mode, User Mode, and Service Mode, replacing the previous Auto Mode and Manual Mode. AI Mode encompasses the operation of the system by applying data received from AI-Hub through the MQTT protocol within the defined limits of the system. Default Mode involves running the system based on predefined standard data. User Mode allows users to manually operate the system within the limits of the system. Service Mode is the extended User Mode which running the system within the defined limits of the system.

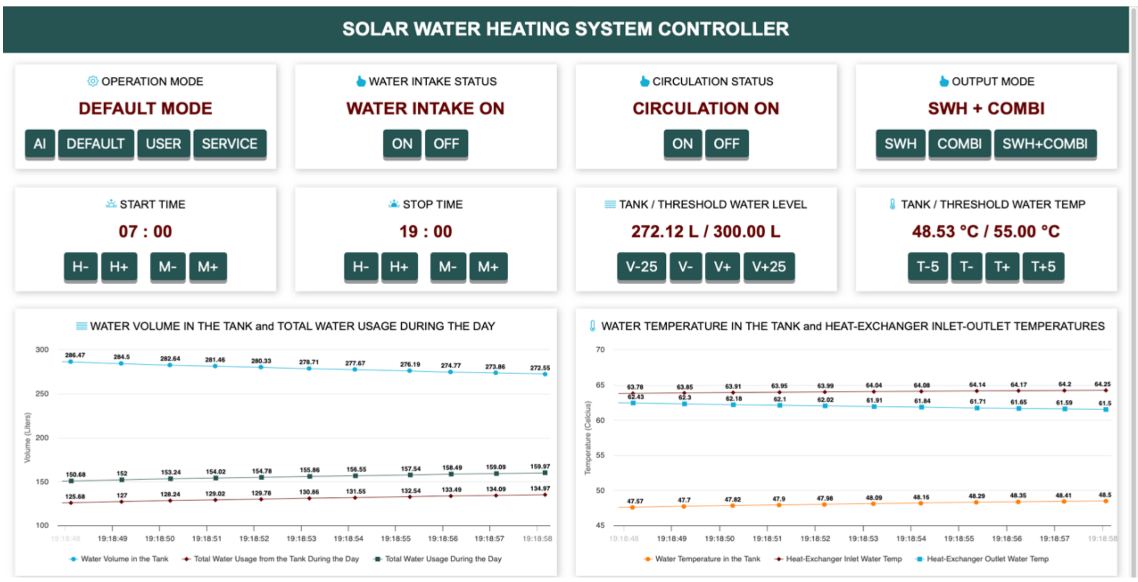


Figure 4.4. The web-based dashboard UI of the next-generation SWHSCU.

Several programming modifications have been implemented in MCU#0. Firstly, a significant change involves the daily permanent storage of system-related data. This is achieved by utilizing the SD Memory Card module present on the development board. The implementation of this functionality relies on the utilization of specific libraries such as FS.h for efficient file handling, SD.h for seamless microSD card interfacing, and SPI.h for communication through the SPI protocol. Another notable alteration pertains to the integration of the preferences.h library. Its primary purpose is to enable the system to resume its operations from the previous state, even in the event of factors such as a system reset. By utilizing the preferences.h library, the microcontroller's flash memory can effectively store and retrieve persistent data in the form of key-value pairs. This library offers a convenient and straightforward approach to preserve settings, configuration parameters, and other types of persistent data that need to persist across power cycles. However, it is important to note that the Arduino implementation of Preferences does not provide a method for completely removing a namespace. Consequently, over the course of several projects, the non-volatile storage (nvs) Preferences partition in ESP32 may become full. To address this issue, the nvs_flash.h library is utilized to fully erase and reformat the NVS memory used by Preferences. Furthermore, the PubSubClient.h library has been incorporated to facilitate essential functions and classes for establishing MQTT connections, publishing messages, and subscribing to topics. This library provides access to the necessary functionality, allowing for seamless integration with the MQTT protocol. Lastly, the ThingSpeak.h library has been introduced to provide access to functions and classes offered by the ThingSpeak library. This particular library enables the transmission of data to ThingSpeak channels, retrieval of data from channels, and other operations relevant to the ThingSpeak IoT platform.

The programming flow for MCU#0, as depicted in Figure 4.5 provides a comprehensive schematic overview of its intricate coding structure and sequence.

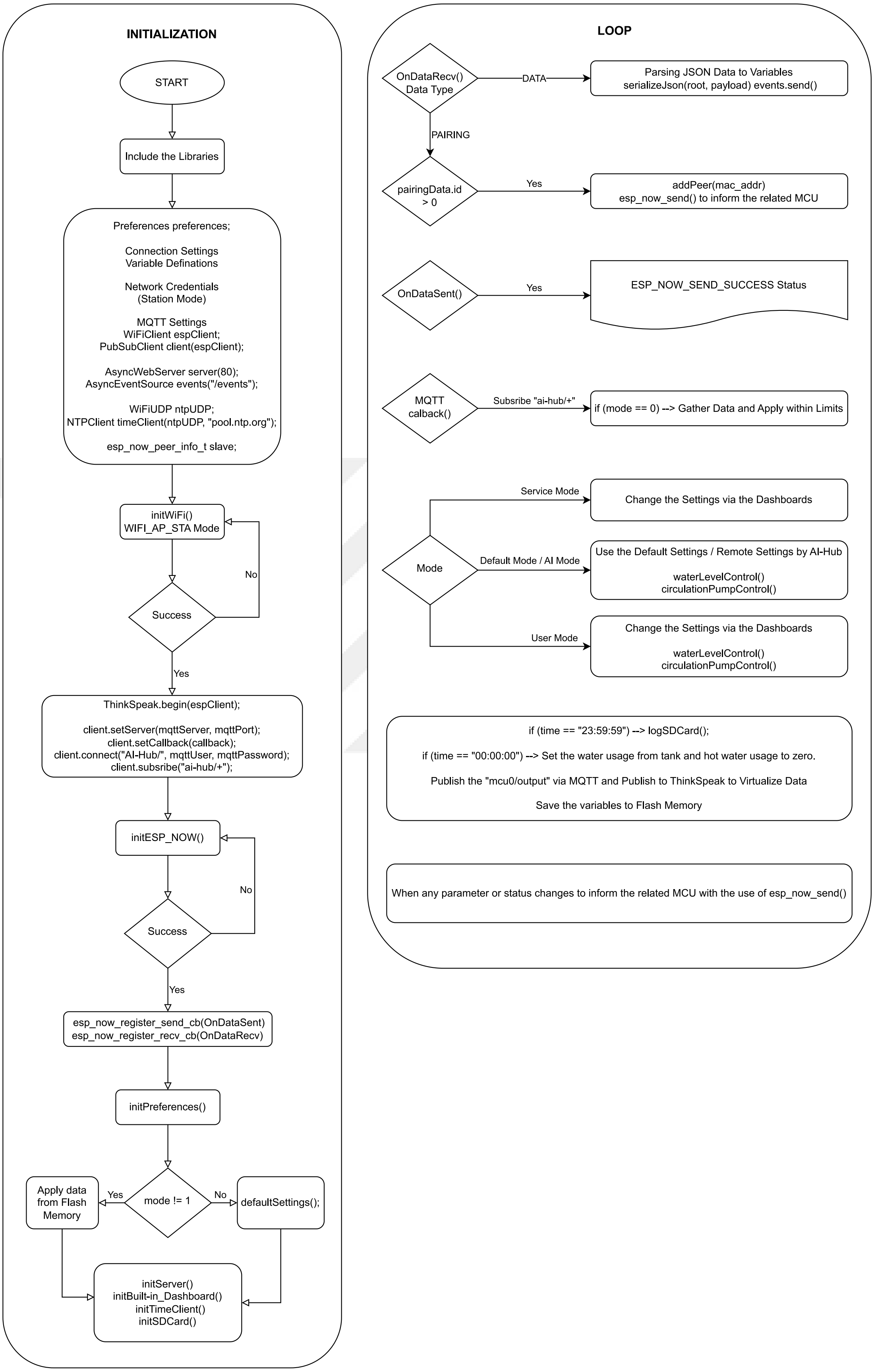


Figure 4.5. The schematic of the next-generation MCU#0's programming flow.

The programming flow for MCU#1, as depicted in Figure 4.6, provides a comprehensive schematic overview of its intricate coding structure and sequence.

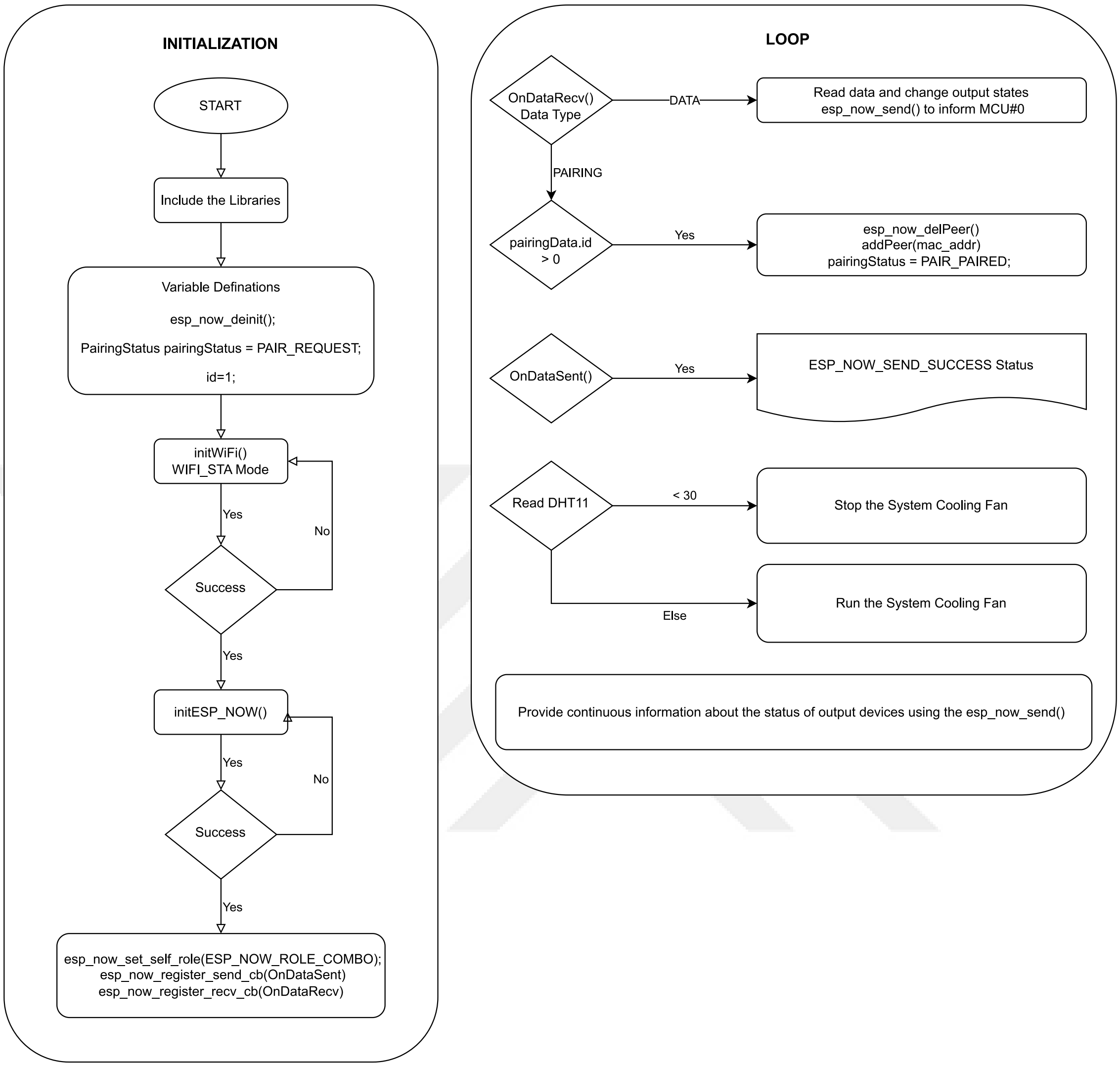


Figure 4.6. The schematic of the next-generation MCU#1's programming flow.

The programming flow for MCU#2, as depicted in Figure 4.7, provides a comprehensive schematic overview of its intricate coding structure and sequence.

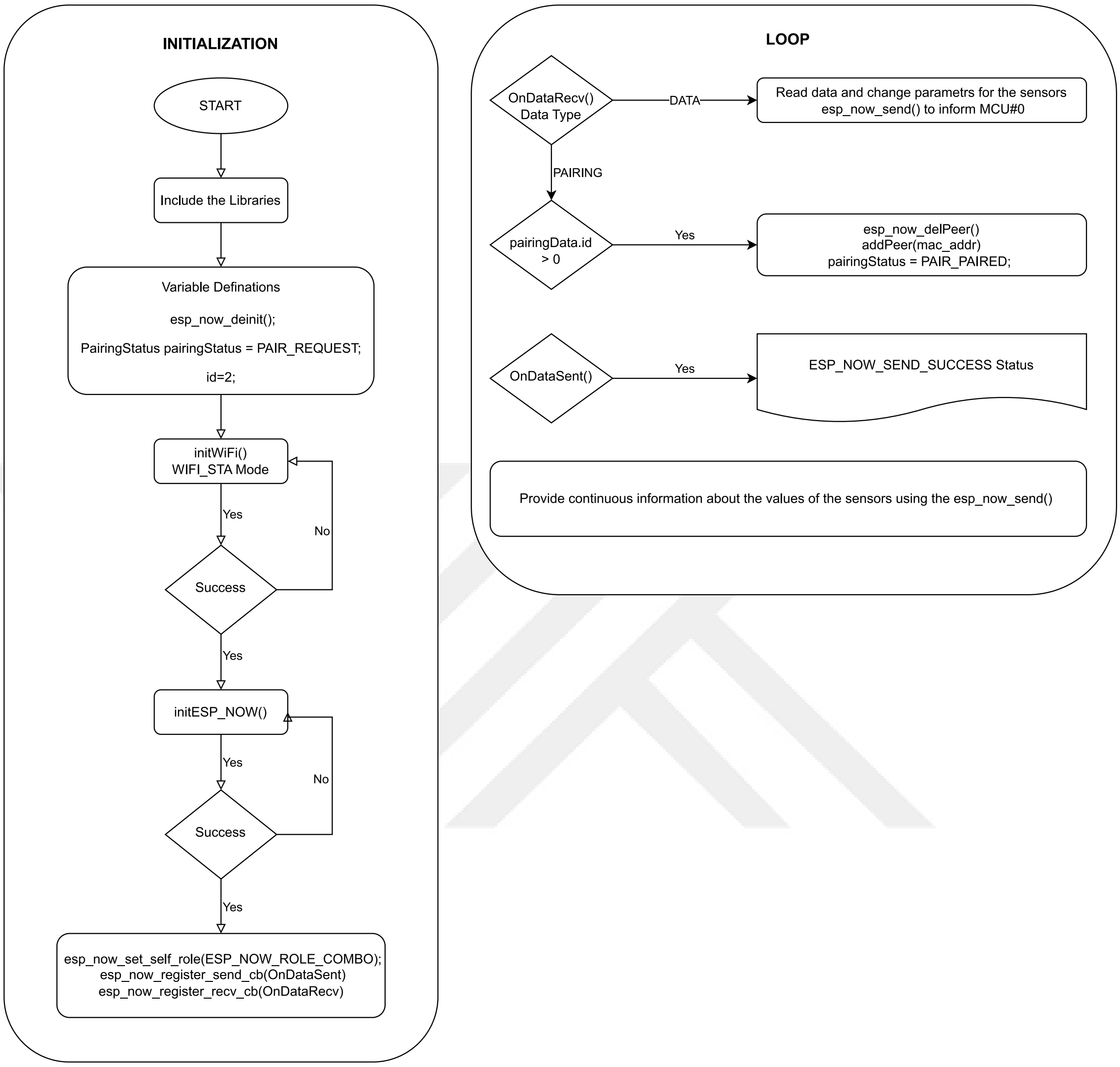


Figure 4.7. The schematic of the next-generation MCU#2's programming flow.

The programming flow for MCU#3, as depicted in Figure 4.8, provides a comprehensive schematic overview of its intricate coding structure and sequence.

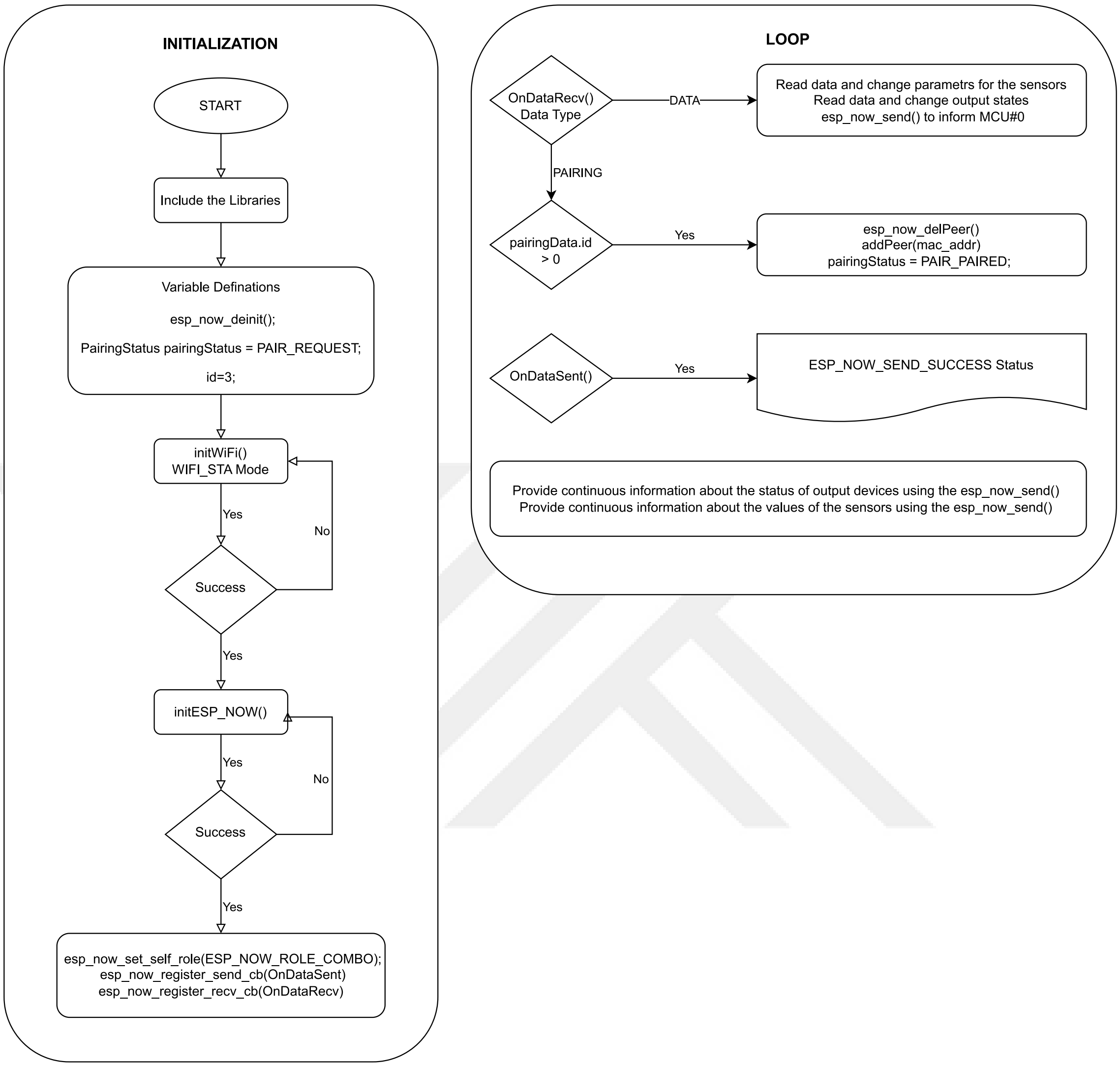


Figure 4.8. The schematic of the next-generation MCU#3's programming flow.

The AI-Hub, a quintessential component of the controller unit in a solar water heating system, serves as a pivotal element in facilitating the system's autonomous operation. Functioning as a bespoke computing system, the AI-Hub continuously retrieves archival performance records pertaining to the system's status, transmitted by MCU#0, the principal component of the control-panel unit, from a local storage service. To enhance system performance, it employs a learning algorithm specifically designed using Python programming language, with the support of the essential libraries, realized on the DataSpell IDE. The objective of this algorithm is to augment the efficiency of the solar water heating system through effective operational scheduling tailored to meet immediate hot water demand. This goal is achieved by taking into account variable parameters such as water usage, threshold water temperature, threshold water level within the tank, and temporal meteorological data. By analyzing historical trends and patterns, the algorithm makes predictive inferences about the system's preparatory measures for future stages. In aiming to endow the system with an autonomous structure, the algorithm establishes the operational scenario at a specific time based on these inferences. Subsequent to this learning process, the AI-Hub establishes itself as a decision-making nucleus, indirectly integrating into the controller unit via local storage. Additionally, the AI-Hub effectively leverages the local storage service to transmit instructions or recommendations to the control-panel unit and units under the control-panel's supervision, such as the sensor-driver and the combi-driver units. Thus, the AI-Hub, with its sophisticated decision-making capabilities, emerges as a crucial component within the system's architectural framework and operational functionality, fostering efficient and autonomous operation of the system.

In summary, the operation of the system mentioned above is implemented through the roles and relationships of the microcontrollers within the control-panel unit, the sensor-driver unit, and the combi-driver unit, in conjunction with the AI-Hub integrated via the local network through MQTT service, all within the context of the controller unit and facilitated by software protocols. Interoperability between these components is orchestrated through an IoT network (as seen in Figure 4.2). Fundamentally, the system operates in four modes: AI mode, default mode, user mode and service mode. In the default mode, the system functions with default settings, while in the user mode, the system operates based on user-defined settings within the limits of the system. The AI mode that functions according to a learning algorithm framework, introducing a form of autonomous structure that has the capability to make system operation decisions by the AI-Hub. As the performance of the learning algorithm improves, its impact on the system correspondingly increases. In this context, the system operates in AI mode via a MQTT protocol, optimizing system settings for a more efficient user experience. Service mode is the extended user mode which running the system within the defined limits of the system. The system is initiated by MCU#0, connects to the existing network, and links to other units via ESP-NOW. Concurrently, its internal web server provides two dashboard services with the web-based user interface and the built-in touch screen dashboard user interface, allowing for monitoring and management of the overall system status. During this period, sensor readings and driver statuses controlled by MCU#1 and MCU#2 in the sensor-driver unit, and MCU#3 in the combi-driver unit, are time-stamped and saved to a local storage environment. These data are collected and transferred to a local storage service by the MCU#0 for system manipulation purposes by the AI-Hub. Following this, the data are gathered and processed in the AI mode. AI mode encompasses the operation of the system by applying data received from AI-Hub through the MQTT protocol within the defined limits of the system.

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