END-TO-END IIOT AUTOMATION SYSTEM SOLUTION

Micro-CHP automation system with database and visualisation application integration

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TIIVISTELMÄ

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TIIVISTELMÄ

Hajautetut energiantuotantojärjestelmät edellyttävät pitkälle vietyä automaatiota ja optimointia, jotta niillä saavutettaisiin maksimaalinen hyöty. ”Vähähiilistä energiatehokkuutta mikro-CHP tekniikalla” (VEneCT) -tutkimusprojektin toimeksiantona oli suunnitella ja rakentaa automaatiojärjestelmä, joka optimoi vähähiilisen biomassan palamis- ja aurinkoenergian keräysprosessit. Lisäksi hybridienergiamoduuli integroitiin keskeiseen aikasarja-tietokantaan tiedonkeruuta varten. Lopuksi tutkielman tavoitteena oli kehittää käyttöliittymä prosessien visualisointiin ja etävalvontaan.

Energia-alan, automaatiotekniikan ja tietotekniikan asiantuntemus oli välttämätöntä tutkimuspohjaisen opinnäytetyön toteuttamiseksi. Biomassan palamisen, aurinkokeräimen ja aurinkosähkön perusperiaatteita tarkistettiin mikroyhteistuotannon lisäksi. Työssä edellytettiin osaamista kaikilla automaatiotekniikan osa-alueilla, mukaan lukien anturien ja toimilaitteiden tuntemus sekä ohjelmoitavat logiikkaohjainten ohjelmointitaitot. Tietojen käsittelyyn ja sovellusten kehittämiseen vaadittiin tietoa ja kykyä työskennellä moderneilla IIoT-tekniikoilla.

Kaiken kaikkiaan opinnäytetyö on tuottanut automaatiojärjestelmän, joka tarkkailee ja ohjaa mikrotason yhdistettyä lämmön- ja sähköntuotantoprosessia. Tietokantaan hankittiin reaaliaikaiset mittaukset ja valvonta edelleen analysointia ja parantamista varten. Käyttäjille ja operaattoreille tarjottiin alustojen välinen visualisointisovellus kattavaa etähavaintaa varten. Prototyyppiä voidaan pitää kehyksenä kokonaisvaltaiseen IIoT-automaatiojärjestelmäratkaisuun, joka on skaalattavissa eri kohteisiin. Järjestelmän parannuksia ja uusia strategioita on suunniteltu ja ne toteutetaan tulevaisuudessa.

Avainsanat automaatiotekniikka, datavisualisointi, IIoT, mikro-CHP, PLC

Sivut 35 sivua, joista liitteitä 0 sivua

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ABSTRACT

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ABSTRACT

The trend of decentralised energy-generating systems required well-designed automatic operations to unleash their full potentials and accomplish desired efficiencies. The commissioning for "Vähähiilistä energiatehokkuutta micro-CHP tekniikalla" (VEneCT) research project included designing and building an automation system that would optimise low-carbon biomass combustion and solar energy collecting processes. In addition to this, the hybrid energy module was integrated with the central time-series database for data acquisition. Finally, the thesis aimed to develop a user interface for process visualisation as well as remote supervision.

Expertise in energy industry, automation engineering, and computer sciences were all essential in conducting this research-based thesis. Fundamental operating principles of biomass combustion, a solar collector and photovoltaics were reviewed, in addition to the micro-cogeneration. The commissioning also involved the author's competence in all aspects of automation engineering, including sensors and actuator, and programming skills in programmable logic controller. Knowledge and abilities to work with state-of-the-art IIoT technologies were required for data processing and application development.

All in all, the thesis work has resulted in an automation system which monitors and controls a micro combined heat and power process. Real-time measurements and supervision were acquired to database for further analyses and improvement. Users and operators were provided with a cross-platform visualisation application for comprehensive remote observation. The prototype could be considered as a framework to the end-to-end IIoT automation system solution, which similar deployments and projects could adopt for their own uses. Improvements into the system and new strategies have been planned and will be conducted in the future.

Keywords automation engineering, data visualisation, IIoT, micro-CHP, PLC

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Writing a thesis is a personal process, but I would not be writing these words without the endless support from people whom I have met and worked with in the VEneCT project, and also at HAMK.

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To all my friends at HAMK, it was my honour to be friend and study with you.

To mom, dad, and sisters, I love you to the moon and back.

Valkeakoski,

October 21st 2019

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1 INTRODUCTION

1.1 Target and commissioning of the thesis

Environmental sustainability demands different approaches to resource usage and reduction of greenhouse gases (GHGs) to satisfy human necessities and needs while casting noxious wastes and shrinking the carbon profile. Having a significant influence on the environment, the energy industry must take action to qualify itself as a member of the resource-efficient and carbon-neutral circular economy (TEM, 2019). The global strategy for this revolution is taking advantage of renewable energy sources, refining energy-generating processes, decreasing transportation costs and advancing energy storage methods (YM, 2019). In the context of the Finnish economy, the government emphasised the importance of replacing conventional environment-exhausting power plants with decentralised renewable energy units (Finnish Government, 2019). In addition to that, energy processes should be optimised and precisely controlled to achieve as much efficient energy as possible (VTT, 2019). The bi-directional energy market is also encouraged to balance the demands and supplies during peak hours. By taking these procedures, small-scale energy systems can make uses of the most locally optimal resources, easily control the process according to weather conditions and other situations, at low transporting expenses and heat loss (Power Technology, 2018). Besides, local heat and electricity production helps sparsely populated areas to be energy self-sufficient and minimise the dependency on public supplies.

The Low-carbon energy efficiency with micro combined heat and power (CHP) technology (VEneCT) project was conducted by Häme University of Applied Sciences (HAMK) and HAMK Tech research unit. It was the sequel of the Energy efficiency with precise control (TOE) project (Heikkilä, 2019). The projects, following the aforementioned strategies, aimed to develop an energy production framework to be applied for single-family houses, small-scale farms or residential buildings. At the end of 2018, the TOE project resulted in a hybrid module utilising a bio-based combustion process, solar energy, and low-temperature phase-change materials. With that foundation, the VEneCT project focused on refining the existing module with the implementation of the organic Rankine cycle (ORC) and CHP technology, as well as Industrial Internet of Things (IIoT) automation system.

Consisting of four stages, or working packages, the project firstly optimises the automation system to perform automatic control over the combustion process, energy flows, and power generating systems. In the second stage, all organic Rankine cycle (ORC) options, their working principles, implementation, and installation are considered to find the most suitable and economical one for integration with the existing system. The third work package includes the examination of energy storage methods. The chosen techniques will be studied over a year, after which their storing capabilities will be found. The results, as well as research done during the project, will be published at international and national forums. They will also be introduced to prestigious seminars and discussed in workshops held around Finland, especially in the Pirkanmaa region. Through these methods, the advantages and possibilities of developing and integrating such energy hybrid module are explained hence encouraging companies to adopt these ideas into their projects and business. (Heikkilä & Mustonen, 2019.)

This thesis was commissioned to design a system infrastructure and develop an automation system for the VEneCT project. The thesis covers all the technical aspects in an automation system, from installing and connecting field instruments, developing supervisory logic for a programmable logic controller (PLC), to standardising the data scheme, processing data flows and building a measurement visualisation application. The work corresponds to the first three layers of the automation system hierarchy: the field level, the control level and the supervisory level, as shown in figure 1.

Figure 1. Automation system hierarchy (RealPars, n.d.)

In the first level, new field devices, including pumps, temperature and flow sensors, terminal cards were installed to the existing system and the electrical cabinets. The addition was explained by acquiring more information from and control over the automation system, so that the optimisation in the burning process could be achieved. In the second layer, new PLC programs were developed with the foundation being the system from TOE’s project. In detail, the stage included reorganising the project and data structure, developing precise control over the whole module, and building an open platform communication unified architecture (OPC UA) server to be used in the third layer. At the supervisory level, measured and controlled data were processed before being transferred to a database for storage and monitoring purposes. That meant the measurements and experiments in the process could be viewed, studied, and saved in more informative and user-friendly forms. The innovation of the commissioned automation system was that it took advantage of OPC UA and the IIoT technology by bringing traditional industrial processes closer to state-of-the-art applications, frameworks, and technologies. Therefore, data from the system can be easily accessed, monitored or acquired for any further development. Most of the work in the thesis belonged to the first work package; however, its results were the skeleton that defined the system infrastructure of the VEneCT project.

1.2 Automation system

In the scope of engineering and industry, “automation can generally be defined as the process of following a predetermined sequence of operations with little or no human labour, using specialised equipment and devices that perform and control manufacturing processes. Automation, in its full sense, is achieved through the use of a variety of devices, sensors, actuators, techniques, and equipment that are capable of observing the manufacturing process, making decisions concerning the changes that need to be made in operation, and controlling all aspects of it.” (Gupta, Arora, & Westcott, 2017. p.2.) Though automation was introduced in the mid-1940s, it was not until the middle of the 20^{th} century that it spread out and proved to be practical in the industry. That was thanks to the integration with computer and software engineering. With this advancement, sensors, actuators, and equipment could be monitored and controlled using pre-defined conditions by computer programs. It also eliminated potential human mistakes and cast the use of sophisticated electrical designs and wiring techniques.

The advantages that automation technologies bring to manufacturing industries or energy processes are undoubted. Firstly and most importantly, process operators no longer have to work in dangerous areas and environment, which reduce the fatal hazards in factories. Human safety and health are always the priority, not only in the industry but in any other aspect of life. Another great benefit when applying automation in manufacturing processes is that it improves product quantity and quality. Robots, conveyors, or welding machines can run uninterruptedly, hence giving significantly higher productivity than workers, at the same time, reducing overwork and fatigue. While handmade products are usually thought to be done with excellent workmanship and carefulness, low accuracy among them is inevitable. In professional big-scale manufacturers, such precision and uncertainty are undesirable. Besides, by changing controls over processes according to different conditions, energy and material efficiency can be achieved by automatic programs. More benefits from the use of the technology can be named; however, these factors are already convincing enough to imply automation is a must for modern industries.

An automation system consists typically of field devices, PLCs, supervisory control and data acquisition (SCADA) systems, and potentially manufacturing execution system (MES) and enterprise resource planning (ERP) application. Each of those includes smaller components. Field devices may refer to any physical elements on floor areas, such as sensors, motors, pipes, pumps, valves, etc. These instruments send signals to and receive signals from PLCs. In cabinets, PLCs are connected to input and output (I/O) cards, terminals and other electrical devices. Cabinets are commonly installed on walls of factory sites. In more significant projects where multiples PLCs are used, a SCADA system is required to control and acquire data from them. In medium to big companies, MES and ERP are needed to monitor manufacturing statistics as well as other business and human resources aspects. Since the thesis focuses on the technical prospect of an automation system, the implementation of MES and ERP for the automation system will not be conducted.

1.3 Industrial Internet of Things (IIoT)

Industrial Internet of Things (IIoT), a subset of Internet of Things (IoT), refers to industrial field devices and PLCs that have, preferably individual, connectivity to automation programs and applications. By this connectivity, machines can exchange, process, monitor, analyse real-time measurements and controls with supervisory programs, hence improving the efficiency of the system, technically and economically. The possibility is thanks to the rapid developments of hardware and software in the 21st century. Semiconductor devices development advanced in terms of density, computational capabilities and energy efficiency. Therefore, manufacturers can integrate them into smaller devices, thus enabling them with more capabilities. Whereas, information technology and software developments are more accessible and evolving than ever, with the growth of the internet around the world. Open-source frameworks and technologies allow everyone to join and contribute to the joint development of data communication, the heart of IoT.

In an IoT solution, IoT devices can be sensors, actuators, PLCs, phones, watches, light fixtures, or any devices that generate data. Though IoT devices appear to produce discrete and meaningless information, there would not be smart homes, artificial intelligence, autonomous factories, or Industry 4.0 with them. It is the first node of a network, where actions are taken, and data are collected for other applications and technologies. Other Industry 4.0 technologies include cloud computing, edge computing, machine learning, big data, etc. In figure 2, IoT devices' role in IoT solution was illustrated. Data from devices would be transferred through cloud gateway, or directly to a server, via standardised protocols. Common IoT protocols and standards include message queuing telemetry transport (MQTT), advanced message queuing protocol (AMQP), Wi-Fi, Bluetooth, Zigbee, constrained application protocol (CoAP), radio frequency identification (RFID), EnOcean. An IoT broker will use the data as input for other applications, depending in on the demands of each solution. Reversely, data may come from on-the-cloud applications and supervise IoT devices to take corresponding actions.

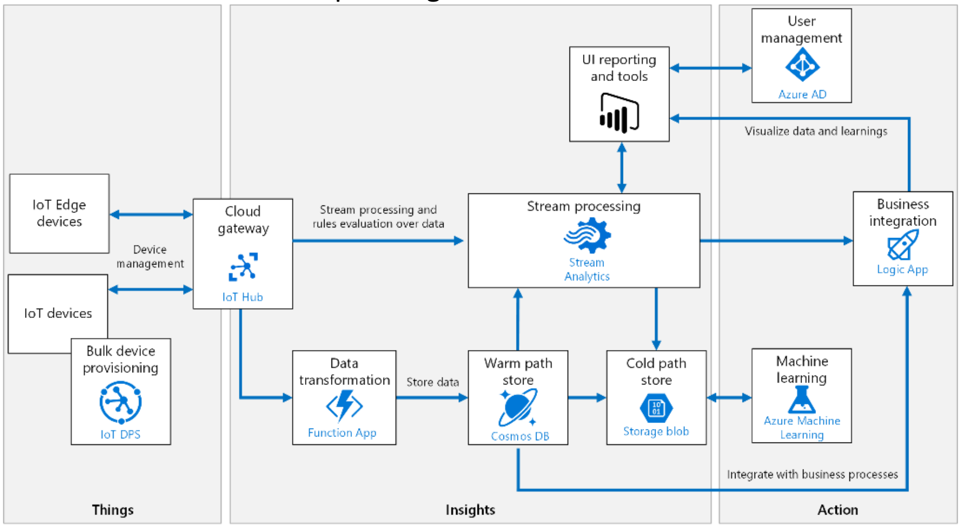

Figure 2. IoT solution architecture (Azure IoT reference architecture, 2019)

In the context of the automation industry, data exchanges usually take place between IoT field devices, PLCs and cloud services, or applications. As more and more field devices are IoT-enabled, the current majority is that a PLC and their old-fashion controlled devices are considered as an IoT device or end-point. In other words, a PLC can be seen as a sophisticated and multi-tasking IoT device. Once a PLC's data are available on the broker, any further applications can have access and control over it, without having to make any physical or logic changes on the floor level and in PLC programs. This was also the orientation of the commission for the VEneCT project that is to make process variables in the hybrid module to be accessible and controllable on a server, which application can be built upon to monitor and control them.

In general, the implementation of IIoT, giving insights to all devices, their data, and metadata, would bring significant benefits to a business or merely an automation system. Enormous amounts of data can be analysed to plan the production according to resources and needs, reduce downtime of a system, or arrange proactive maintenance. Concerning the VEneCT project, IIoT solution would help to notify burning material refills, predict energy needs in certain peak hours and carry out demand-response energy. Data collection is also essential in such a research project or further developments and analyses of the hybrid module.

2 FUNDAMENTALS OF ENERGY SYSTEMS

2.1 Low-carbon biomass combustion

Biomass combustion is a process in which fuel and oxygen (O_2) react at high temperatures resulting in carbon dioxide (CO_2), vapour, and heat. Besides thermal energy, biomass combustion is also used to generate electricity and produce energy carriers by implementing thermochemical and biochemical conversion technologies (Kondratiev, 2019). It is one of the earliest methods used to create fire and still being applied in many energy applications nowadays, thanks to its high efficiency. As many as biomass combustion processes, small-scale and factory-size, functioning all around the world, there have not been significant developments in reducing carbon emissions. That is why the processes have lost popularity in the energy industry to other renewable resources and energy-generating techniques such as solar energy, heat pumps, district heating, etc. Therefore, to optimise the potential of biomass combustion, automation and process engineering should be applied to cast the carbon footprint.

As discussed by Lindgren in his research concerning optimising autopilot for bio boiler in hybrid heating system, the optimisation of the combustion processes can be considered from four different perspectives, including economic, ecological, emission-oriented, and minimal maintenance. If economic constraints are the critical factor, the operation aims to produce heat with the possibly lowest functioning costs. On the other hand, ecological-focused units will make use of available fuels, to preserve the exhausted unrenewable sources. With respect to emission-oriented optimisation, the third option is to improve the burning processes so that they will release as less GHGs as possible. The last option is to concentrate on designing and building an energy system that lasts for years without special maintenance and changes in automation programs. It is hard to meet all four requirements simultaneously; thus, designers must compromise and find a balanced setup, with one being the main optimising target. From the perspective of automation engineering, too many parameters in processes make the system’s programs unnecessarily complicated and uncontrollable. (Lindgren, 2019.)

Since one of the targets of the VEneCT project is to build a hybrid energy module that produces energy at near-zero emission, the combustion process optimisation will focus on carbon and by-product reduction. By adjusting the fuel to combustion-air ratio, clean combustion and efficient thermal energy can be achieved. Typical biomass combustion results in undesired unburned gases such as nitrogen (N_2), carbon dioxide (CO_2), carbon monoxide (CO), which are harmful to the environment. Therefore, by applying real-time measurements and automation, the gases can be burned to achieve a non-emission target. Furthermore, lambda sensors will be used to measure the amount of unburned gas in the flue, and then the secondary fan will supply corresponding amount of O_2 to do the second combustion, which leaves with no GHGs. Because the composition and properties of the biofuel vary, the control values of the combustion process should be adjustable according to situations, to maintain high-efficiency level. (Sauvé & Eng, 2014.)

2.2 Solar heat collectors

Solar energy is undoubtedly the cleanest, most accessible and most abundant resource of all (Solar Energy Industries Association, 2019). As the movements in protecting the environments and preserving fossil fuel resources have gone actively in the 2010s, solar energy has been deployed, not only in industrial-scale but also in domestic applications. This is also thanks to the development of solar technologies that have improved solar power systems' performance and reduced installation costs. The efficiency of solar energy systems is heavily dependent on the locations and weather situations in the areas, so it is highly recommended that solar energy system operates in conjunction with some other sources of energy. Besides easy integration, CO_2 reduction, free charge, and potential financial benefits are features that help solar energy outweigh other non-renewable and also renewable resources.

For utilization of solar radiation, two common forms of energy production solutions are solar heat generation and photovoltaic systems. With respect to solar heat, the technology collects energy from solar radiation and heats domestic and space-heating water through collectors. There are two types of solar collectors: flat-plate and evacuated tube. Each of them has its advantages and disadvantages; however, their working principles are similar. Flat-plate collector, as the name tells, has a wide, flat, dark-colour absorber surface. It absorbs solar radiation and transfers the heat to circulating fluid underneath. It also consists of an insulating layer, generally made out of rock wool or polyurethane foam, that helps to lower heat losses to the environment. Flat-plate collectors have low listing prices and maintenance costs, but also a low-efficiency level. On the other hand, evacuated tubes' high efficiency offers systems the ability to integrate with high-temperature heating units with smaller footprints. When sunlight hits absorbing material of the tubes, it boils the fluid inside the tubes. Fluid's vapour flows to condenser bulb, where thermal energy is extracted to main water flow. The steam then condenses and flows back to the tubes. Figure 3 demonstrates more clearly the energy flow in evacuated tube solar collectors.

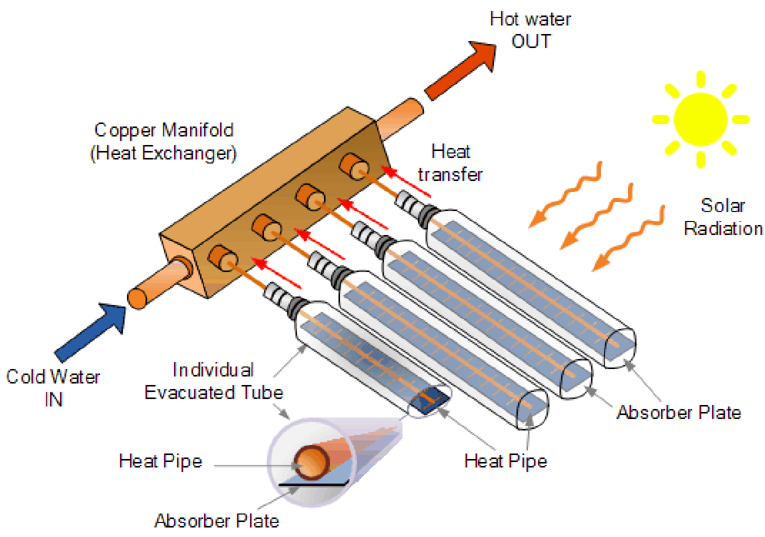

Figure 3. Evacuated tube collector working principle (Alternative Energy Tutorials, 2019)

2.3 Photovoltaic

Solar photovoltaic (PV) uses semiconductors to convert solar radiation into direct current (DC) electricity. Different types of semiconductor materials are used to manufacture solar panels, arrays of solar cells. The choice of material determines the efficiency of solar panels, hence the whole PV system. Generally, commercial PV panels convert around 18-25% of the energy they receive from the sun. These performances are achieved from enormous numbers of researches on improving PV technology for the last decades. Even though the efficiency is not as high as other power plants', PV technology is capable of supplying enough electricity for the whole world's demands, thanks to the abundant and accessible sources.

There are three widely-known types of solar cells, monocrystalline, polycrystalline, and thin film. Each of them is made out of distinct semiconductor materials, has its characteristics, advantages and disadvantageous. However, their working principles are ordinarily similar. The construction of a single solar cell includes doped semiconductor regions, N-type and P-type, and a layer called junction lying in the middle, shown in figure 4. N-type regions contain mostly free electrons and the P-type region contains primarily free holes. The difference creates an electrical field, preventing particles from moving between layers. Whereas, sunlight is the wave of energy-containing particles called photons. When sunlight hits solar cells, the energy breaks electrical bonds and free the electrons. Taking advantage of the electrons trying to get to the other layer, an external connection between N-type and P-type regions can be made, helping electrons to flow, which is current. This current is weak, so, to strengthen it, solar cells are serialised in arrays and modules, to make solar panels, of which power is higher. Usually, a solar panel consists of 60 or 72 cells. Harnessed electricity is direct current. Therefore, to use it for household appliances, a PV system must have inverters or microinverters to convert it into alternating current (AC). The latter has been getting more and more popular in PV system thanks to its ability to monitor and optimise individual panels' performances.

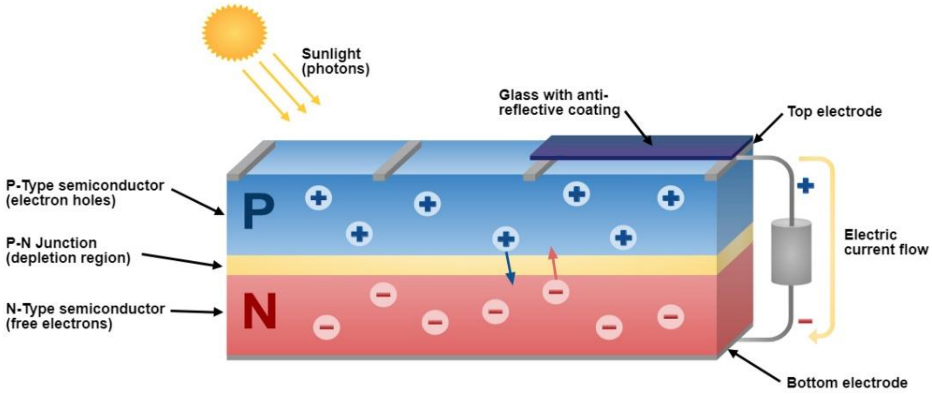

Figure 4. Solar cell construction (Apricus, 2019)

In the VEneCT project, besides solar collectors, solar energy is also harnessed to generate a small amount of electricity. The PV system was deployed as rather for experimental purposes than a central power-producing unit. Four solar panels were installed on the wall outside of the hybrid module. The system, from Ruukki, covered an area of approximately 3.2m^2 and faced to southwest direction. The panels were connected with a conventional string converter, SMA Sunny Boy. The smart inverter makes all measurements on the system, from incoming DC, alternative current (AC) on three lines, to internal temperature and DC side insulation resistance. Data from the inverter is integrated into the automation system through the industrial protocol Modbus, which will be explained in detail in section 5.2.1.

2.4 Combined heat and power (CHP)

Combined heat and power (CHP), or cogeneration, refers to power engines and energy plants that simultaneously generate two forms of energy, heat, and electricity, from a single fuel source. Usually, CHPs refine conventional systems by recovering otherwise-wasted energy for advantageous uses. A system adopting CHP can reach energy efficiency of up to 85%. (Bhatia, 2014.) Increasing the amount of useable energy produced also means a reduction in fossil fuel harnessing and use, hence preserving the fossil fuels, protecting the exhausted environment, and contributing to sustainable development.

Directive 2004/8/EC defined micro-CHP (mCHP) as CHP plant of which maximum capacity is not higher than 50kWe. Its most significant advantage compared to big-size CHP is that it eliminates heat losses due to long-distance transportation and heat transfer in district heating. A mCHP system can produce electricity as the main product and utilise heat as an additional energy form, or vice versa. Either way, the overall efficiency of the whole system is improved by 30 to 60 per cent. However, as the amount of energy loss in heat transportation is higher than in electricity distribution, mCHP or CHP plants are commonly constructed close to where thermal energy will be used. In case of mCHP, those are small commercial and residential buildings. Because the production of heat and electricity is simultaneous, CHP plants' operators must take into consideration excessive by-product energy when responding to the primary energy form's demand, and also the other way around. For example, if the "side-effect" heat generated from a mCHP system is more than needs, and there are no methods to store or dispose them, input fuel must be reduced, which, at the same time, lowers electricity production. Therefore, these factors should be taken into account carefully when designing a CHP plant.

The challenge for the energy industry in Finland is the different demands throughout a year (Statistics Finland, 2019). In the summertime, the demand is low because the air temperature is high, and days are longer. On the other hand, extreme coldness in the winter requires great amount of heating energy. At the same time, longer nights result in more electricity needs for lighting purposes. Renewable resources such as solar and wind are dependent on the weather situations; thus, energy plants cannot guarantee to meet the demands. Therefore, they cannot act as the primary but supportive energy unit to the biomass combustion process, which is more independent and controllable. The VEneCT hybrid energy module consists of a biomass combustion process, small solar PV system, solar collectors, and ORC. The last technology will be deployed in the later stages of the project; thus, its implementation will not be discussed in the scope of the thesis (Heikkilä & Mustonen, 2019).

3 SYSTEM INFRASTRUCTURE

As mentioned earlier, the commissioned automation system could be divided into three layers: field level, control level, and supervisory level. In the first layer, field devices have primary responsibilities of transferring machines and processes data to the control level for monitoring and analysis (Hibbard, 2019). The field devices were sensors and actuators. Besides the PLC as the central controller, there were also two independent devices, Resol and PV, collecting data for the system. Three primary field devices, PLC, Resol and PV, communicated to each other via Modbus and message queuing telemetry transport (MQTT) protocol. Data from the instruments were then exchanged with PLC programs, which belonged to the second layer, through open platform communications unified architecture (OPC UA). In the control level, the PLC could monitor real-time process measurements and control actuators accordingly, so that the energy efficiency was maximised and GHGs level was minimised. The continuous supervision was automatic because PLC was programmed with predefined algorithms. OPC UA also connected with another MQTT application, which publishes critical data to the remote central server. The server and all of its application fell to the third layer of the automation system. This layer included a database, a metrics visualisation application, and a web application. The database stored all data coming to the central server for further analyses. Instantly, data were queried from the database for metrics visualisation. All queried data were expressed in forms of graphs to emphasise their changes over time. The last application was a web app, which displayed simplified process diagram with corresponding data points. All the mentioned applications constituted the VEneCT automation system, which was the key to energy efficiency. Figure 5 illustrated the system architecture.

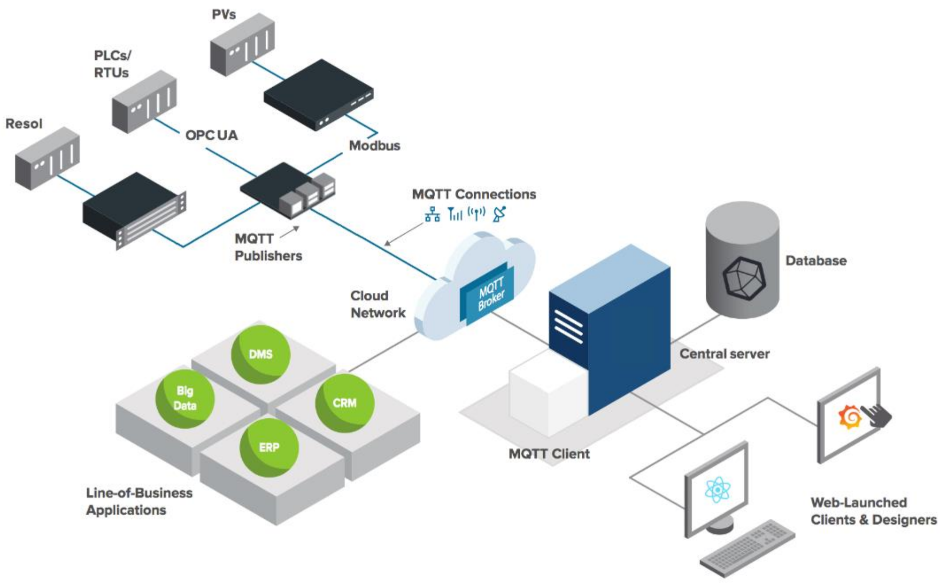

Figure 5. System architecture (Inductive Automation, 2019)

Every layer in an automation system is as essential as one another. Missing a layer would make a whole system unworkable. In chapter 4, 5, and 6, each level of the VEneCT automation system will be explained in detail: what is their contribution to systems, how do they operate, which components are included, how data is collected, processed, and monitored, specifically in the scope of the VEneCT project.

4 FIELD LEVEL

The field level is the lowest layer of automation in the automation hierarchy. This layer is where the real-time physical world is translated into the digital world. It is also the most recognisable layer of all because this level includes most of the hardware of a system. Components of the field level could be switches, buttons, conveyors, pumps, motors, etc. In automation and process engineering, based on their functionalities in the system, these components or devices are generally divided into two groups: sensors and actuators. Sensors are devices that measure physical attributes of a process and send the measurement, in the form of electricity, to PLCs. The measurements and signals from sensors are the arguments for predefined PLC programs to decide what actions should be taken. Said actions are done by actuators. Devices classified as actuators receive signals from PLCs and translate them into real-world by movements such as turning lights on, rotating motors faster, stopping conveyors, etc. The relation between sensors, actuators, and computer controllers is illustrated in figure 6. (Gupta, Arora, & Westcott, 2017.)

Figure 6. Sensors, actuators, and controller’s relation

Though the classification is clear, a device can be both sensors and actuators. That is because modern devices can act upon signals from PLC and measure other related attributes at the same time. For example, a pump can push fluids through pipes and measure flows’ pressure, volumetric flow rate, or temperature. Besides, wires are also considered in field level since they provide power and communicating medium between sensors and actuators with PLCs.

4.1 Sensors

In automation engineering, a sensor is a device or module that measure physical phenomena and send data to computer controllers, which can be PLC, remote terminal unit (RTU), distributed control system (DCS), supervisory control and data acquisition (SCADA), etc. Sensors’ working principles depend on the attributes that they monitor. For example, a sensor can measure temperature by sense resistance changes in a Wheatstone bridge, or, measure proximity by the interruption in the infrared beam. However, regardless of types, they are all based on proven physics laws and equations.

The quality of a sensor is determined its suitability, accuracy, precision, speed and other minor factors. A good sensor is not an expensive sensor but an informative sensor. Depending on different industries and applications, distinctive types of sensors with varying principles of functioning can be used. For example, turbine flow meters are recommended in sanitary and clean fluid measurements but should not be used in dirty fluids because they might damage the sensors. If the sensor is not suitable for the phenomena and process that it measures, that may lead to incorrect information and unwanted accidents. Likewise, the compatibility refers to the communication between the sensors and terminal I/O cards in particular and PLC. The connected cards must support the data structure that sensors produce so that the information will be translated correctly and do not make any electrical faults. In some other cases, where sensors use specific protocols, PLCs should have programs or libraries to accurately interprets data frames coming from sensors.

In addition to suitability and compatibility, accuracy, precision, sensitivity, and speed are the key factors to assess sensors. Accuracy refers to how close the measurement and the real value of an attribute. High accuracy means the measurement is correct, hence helping PLC to give suitable corresponding actions. Precision, or repeatability, refers to a sensor’s ability to produce the same results under the same measuring conditions. If precision is low, it means the system and sensor itself is not trusty. Sensitivity, or resolution, of a sensor indicates the smallest changes in the physical phenomena the sensor can detect. Sensors with high sensitivity produce more accurate information, given that its accuracy and precision are also high. It is worthy of mentioning that sensitivity is different from accuracy and precision. A sensor might be sensitive to quantity changes, but that does not mean the measurements are accurate. Therefore, accuracy, precision, and sensitivity are critical requirements in automation systems, especially in applications where meticulousness is needed. Last but not least is the sensing speed of sensors. It can be understood as the time from when the changes in attributes happen to when the sensors detect the changes and send new data to PLCs. Sometimes, it is only known as the time sensors take to send data to controllers. Nevertheless, this characteristic shows how fast data can be transferred and updated, thus making proactive actions to the process.

When it comes to classifying sensors, there are two features: based on their output types and based on the physical phenomena that they measure. By the first method, a sensor can be either analog or digital. By the second method, a sensor can be categorised in temperature, humidity, flow, volume, proximity, etc. Typically, the former is more widely used because sensors are chosen depending on quantities needs measuring. However, in this research, sensors will be explained according to their output signal, by which all types of sensors will be covered. An analog sensor produces a continuous analog signal that represents the quantity it measures. The magnitude of analog outputs is generally proportionally to the physical phenomena, commonly temperature, sound wave, strain gauges, etc. Most of the outputs of analog sensors are translated into electric pulses of varying amplitudes. The amplitude must be within an available range, which defines the maximum and minimum value that a sensor can sense. Analog sensors were popular in the automation industry for years until the introduction and significant development of digital sensors. Compared to digitalised sensing devices, analog sensors appear to have more shortcomings than strengths. Their signals are easily affected by noise, thus losing accuracy and precision. In addition to that, data coming from analog sensors do not have error checking frame, so it is impossible to verify if the measurements are correct. Besides, these devices require more wiring and draw more power than their competitors.

On the other hand, digital sensors, which generate discontinuous signals, have been gaining praise for their abilities to deliver accurate data at high transmission speeds and small profiles. Data from these sensors are discretized and transmitted in binary messages. Even though the data is discrete, represented information can be either continuous or discontinuous, thanks to the advancement of information technology. The advantages of digital sensors are that they can be implemented seamlessly with other computing and digital electronics, use low-power electricity, and provide error checking. Even though sensors are classified clearly into categories of output signals and their physical phenomena, it is recommended to follow their specific information in their datasheet. Sensing principles, power supplies, communication interfaces, ingress protection (IP) ratings, and many other characteristics may vary within products of same categories. These are what determine which sensors are of high quality and suitable for specific applications.

In energy sectors, mostly all conventional ambient sensors are required in processes to measure critical attributes, shown in table 1.

Table 1. Common measurements and their units

Types	**Units**
Temperature	°C or K
Relative humidity	%
Volumetric flow rate	m^3/s, l/s
Pressure	Pa, bar
Level	m
Mass	kg
Concentration	kg/m^3, ppm

The TOE automation system was installed with essential temperature sensors to monitor the water temperature level in storage tanks. Except for those, new sensors were installed during the VEneCT project to acquire more information for burning process optimisation. More sensors of the same manufacturer were placed in the burning chamber, pipes, flue to study and control temperature changes during burning experiments. The sensors were model AKS 12 084N0036 from Danfoss.

Table 2. Temperature sensors

Sensors' IDs	Locations	Variables names
LS_TE001	Loop 2 boiler out	fTE[1]
AK_TE002	Loop 1 solar collector	fTE[2]
LS_TE003	Loop 1 heat exchanger in	fTE[3]
LS_TE004	Loop 1 heat exchanger out	fTE[4]
K_TE005	Loop 3 boiler out	fTE[5]
VV1_TE006	Tank 1 In	fTE[6]
VV2_TE007	Tank 2 In	fTE[7]
VV3_TE008	Tank 3 In	fTE[8]
VV1_TE009	Tank 1 Up Out	fTE[9]
VV1_TE010	Tank 1 Low Out	fTE[10]
VV2_TE011	Tank 2 Up Out	fTE[11]
VV2_TE012	Tank 2 Low Out	fTE[12]
VV3_TE013	Tank 3 Up Out	fTE[13]
VV3_TE014	Tank 3 Low out	fTE[14]
J_TE015	Out to load	fTE[15]
J_TE016	Return from load	fTE[16]
K_TE017	Water inside the boiler	fTE[17]
K_TE018	Loop 2 boiler out	fTE[18]
K_TE019	Exhaust temp from boiler	fTE[19]

They were connected to terminal cards EL3214 and KL3204, which support 3-wire and 2-wire connection technique, respectively. EL3214 was installed with EK1914 EtherCAT coupler, in a star topology from EK1122 2-port EtherCAT junction. KL3204, on the other hand, was connected with EK1100 EtherCAT coupler on another end of the star topology from EK1122. The terminals are shown in appendix baobao.

In addition to temperature sensors, flow sensors were installed in the primary and secondary fan to monitor and control the amount of air, especially O_2, supplied for the burning process. The sensors were model D6F P0010A2 from Omron. Table 3 describe flow sensors' process name, locations, and variable names. They were connected with terminal KL3064, in JB2, shown in appendix baobao.

Table 3. Flow sensors

Process ID	Location	Variable name
F1_FE	Primary fan	PrimaryFan.fFE
F2_FE	Secondary fan	SecondaryFan.fFE

4.2 **Actuators**

Actuators translate signals from computer controllers into real-world movements or actions. All actuators need control signals and power sources. Control signals may be electricity, hydraulics, pneumatics, etc. Electrical control signals can be either digital or analog. Digital signals mostly represent Boolean values such as 0 and 1 or true and false. These values are applied to components that only have either state, for example, two-state light, conveyor, motor. However, digital signals may also appear in devices that support industrial protocols such as Modbus, CANopen, BACnet, etc. Analog signals are getting less and less popular due to their sophisticated wiring and limited accuracy. The signals are usually used to control speed or different stages of devices.
Similarly, the power source for the final control elements may come from the mentioned sources. Electrical actuators' popularity is thanks to the availability of electricity all around the world. Besides, these types of actuators have the highest precision in movements, adaptivity to network and programming changes, no noises and few environmental hazards. Pneumatic actuators have small profiles yet manage to deliver motions at high speeds. Moreover, they can be used in extreme temperature applications.

The characteristics that determine the quality of an actuator include suitability, speed, force, energy efficiency and other minor aspects. The most crucial factor is that the motor is compatible with the PLCs and processes. No matter how expensive an engine is, if it requires an analog control signal while PLC sends digital, it will never run. Therefore, when choosing an actuator for the system, one must consider the sides, power supply, moving limits, working environments and so on. The next trait to be considered is speed or force, or both. Depending on the application, speed or force might be the dominant factor. For example, in intensive production lines, speed is more important as it affects directly the amount of good produced. Whereas, in mining or construction sites, big machines with powerful actuators may be needed to load, move big objects between places. Then, because most of nowadays actuators are electricity-driven, energy efficiency is more and more influential. An actuator with a high-efficiency level not only saves remarkable electricity bills but also reduces the burden on overload grids.

Thanks to the development of software and hardware engineering, actuators are now controlled by significantly smaller and more powerful processors. They also offer the ability to integrate more measurements to improve the performance of actuators. Simply put, this means a device may have an actuator and several sensors. Commonly, these kinds of devices are known for their actuator's purpose, because integrating multiple sensors into an actuator is easier than the other way around. Nevertheless, this advancement brings a lot of benefits to the automation and process industry. In the era of information, the more data, the better.

Therefore, having insights into the smallest parts of devices and processes will bring full control to the automation systems. In addition to that, having multiples measurements done by a device will reduce significant amounts of space, wires and working hours.

The actuators used in the VEneCT project include lights, valves, pumps, the fuel feeder, cooling systems, and igniter. Digital addressable lighting interface (DALI) light-emitting diode (LED) panels were used to provide lightness to the closed energy hybrid module. The usage and implementation of these actuators will be explained in later. 2-way and 3-way valves were used to control water flow between the burning chamber, storage tanks, and cooling system. The valves, model Sirai L113, are described in table 4, together with their position and variable names.

Table 4. Valves

Valves ID	Position	PLC varibles
VV1_HV-001	Tank 1 In Valve	bHV[1]
VV1_HV-002	Tank 1 Low Out Valve	bHV[2]
VV1_HV-003	Tank 1 Up Out Valve	bHV[3]
VV2_HV-004	Tank 2 In Valve	bHV[4]
VV2_HV-005	Tank 2 Low Out Valve	bHV[5]
VV2_HV-006	Tank 2 Up Out Valve	bHV[6]
VV3_HV-007	Tank 3 In Valve	bHV[7]
VV3_HV-008	Tank 3 Low Out Valve	bHV[8]
VV3_HV-009	Tank 3 Up Out Valve	bHV[9]
J_HV-010	Output to the cooling system	bHV[10]
J_HV-011	Return from the cooling system	bHV[11]

Three smart pumps were deployed in the project to drive water from burning chamber to tanks for storage, from tanks to cooling system to unload the heat, and then back to the system. They are great examples of field devices that have actuators and sensors built in the same devices. The pumps provide measurements on flows' volumetric flow rates, pressure, temperature, motor speed, etc. Similarly, the fuel feeder, which loads pallets from stocker to chamber, was driven by a variable-speed drive (VSD), which gives detailed information on the motor. Data communication, from and to pumps and fuel feeder, is done by the industrial protocol Modbus. Since each protocol has distinctive characteristics affecting wiring techniques, the installation and implementation of pumps and VSD will be explained along with their protocol in chapter 5.2.1.

5 CONTROL LEVEL

5.1 Programmable logic controllers (PLC)

5.1.1 Programming structure

"Programs should be written for people to read, and only incidentally for machines to execute" (Abelson & Sussman, 1996). A well-structured project not only improves the overall performance of the automation system but also helps programmers to follow and modify codes easily. Figure 7 showed PLC project structure of the VEneCT hybrid energy module. It consists of four sub-folders, naming BurningProcess, CommunicationPrograms, EnergyFlow, and Lights, and two separate programs, MAIN and ModbusCommunication. MAIN program, either directly or indirectly, ran other programs. It also included algorithms and conditions that affected multiple programs. ModbusCommunication program took responsibility for controlling pumps and the fuel feeder. Because Modbus channel could only handle a request from slave devices at a time, the program used CASE function to switch between communication with multiples Modbus-based field devices. Like MAIN program, ModbusCommunication used and controlled variables in different sub-programs, hence leaving the program in the main folder remained a common practice.

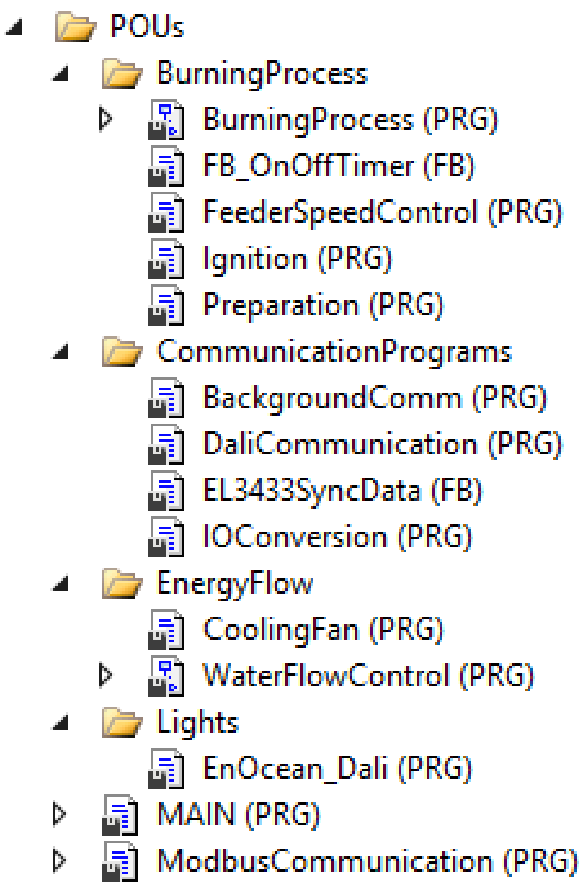

Figure 7. Project structure (Tran, 2019A)

BurningProcess program, which was considered the most important program in the project, monitored sensors' parameters and controlled biomass combustion, based on predefined rules. Its aim was to maintain the thermal energy level in storage tanks and to the load, which was the cooling system. Detailed of the program can be found in appendix baobao.

CommunicationPrograms contained program tasks that run by PLC to exchange data with terminal cards. Field devices that have single variables were read to IOConversion task. Modbus data was read separately through another task called BackgroundComm. DaliCommunication was used to control DALI panels. EL3433SyncData task was to read electricity consumption in the module.

EnergyFlow included CoolingFan program, which controlled water circulation between storage tanks and cooling system, and WaterFlowControl, which controlled water flow between the burning chamber and tanks as well as a heat exchanger. These were critical programs because water circulation affected directly to energy save and loss.

Lights folder comprised EnOcean_Dali program, which held up the communication and controlling algorithms between the two different protocols. In the future, when motion sensors are added to the system to control Dali instead of switches, the program will be included in this folder.

5.1.2 Variable structure

Similar to the program structure, logically arranged variables are easy to read, understand, and manage. Instead of writing all the system variables in a common file, splitting them into smaller groups, based on their functions, improves the programs' comprehension and efficacy. In automation engineering in general and Beckhoff PLC programming in particular, there are two objects containing variables, data unit type (DUT) and global variable list (GVL). While DUT is used to define users' own data structure, GVL contains global variables that can be accessed from any program of the project.

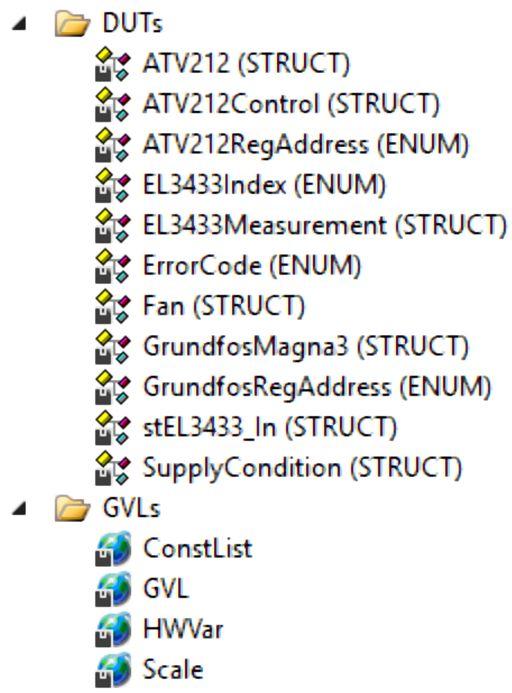

Figure 8. Variable structure (Tran, 2019A)

Figure 8 showed the variable structure in the hybrid energy module's PLC project. DUTs folder consisted of DUT objects that constructed structures storing Modbus, electricity consumption data, and error codes. GVLs folder contained ConstList, GVL, HWVar, and Scale. ConstList, as the name said, contained constant variables. GVL included all variables that would be available for access through the OPC UA server. HWVar had variables that are linked directly to terminal cards. Most of them were unique structures defined by Beckhoff standard libraries. Last but not least, Scale included numbers to be multiplied with data from Modbus to give correct measurement values.

5.1.3 PLC programming languages

PLC programming languages (PLs) are used to program PLCs for industrial automation and process applications. The standard PLC PLs are specified in the IEC 61131-3 standard. They include structured text (ST), instruction list (IL), function block diagram (FBD), ladder diagram (LD), and sequential flow chart (SFC). The first two languages are known as textual languages, and the next two are called graphic languages. The last one is "defined for structuring the internal organisation of programmable controller programs and function blocks". (IEC, 2013.)

Even though IEC does not define which PLs should be used in specific applications, their characteristics have proved to be more advantageous than others in different cases. ST is a high-level language that uses statements, algorithms and mathematical functions. With experiences, programmers can manipulate programs easily with this language because it offers more abilities to control codes than others. From the author’s point of view, ST is suitable for mathematical calculation computation and intensive data processing. IL is a basic microcontroller programming that uses mnemonic codes. Its best application is for programs that require lean and compact codes, leading to high execution speed. However, because of that, IL-based programs might be confusing and hard to debug. FBD uses blocks that take inputs on one side, processes them, and gives output to the other. Each block has its function and can be system-defined or user-defined. Either way, this graphical-oriented feature makes FBD popular in the automation industry because it is more visualised and easier to understand. LD, which adheres the idea of relay-logic, is the most popular PL in PLC programming. It eliminates the use of physical devices like timer and counter with blocks. The blocks are connected with inputs and outputs on rails, representing control circuits. At the same time, rails connect to rungs which can be seen as a power supply to the devices and circuits. LDs are highly straightforward, which helps automation engineers and electricians work smoothly together. Nonetheless, LDs are not suitable for programs having complex data outputs. SFC is inspired by flow charts. It consists of multiples steps connecting through transitions. When a step is called, actions belonging to that step will be executed. Actions can be written in different languages, but LD is mostly used. Transitions are statements that return Boolean values. When the transition after a step returns true, the program moves on to the next steps and executes new actions. The flow continues until it reaches the end or returns to the initial state. SFCs are fast-written, comprehensive, and easy to troubleshoot.

5.2 Industrial protocols and communication

5.2.1 Modbus

Modbus is an internationally standardised industrial protocol introduced the first time by Modicon in the late 1970s. As old as it is compared to new-born technologies and protocols, Modbus is still widely used in many control automation applications. That is due to its industry-friendliness, open-source characteristic, simplicity in deploy and maintenance, and manufacturer-independence.

Depending on application purposes, references, and possibilities provided by vendors, different versions of Modbus such as Modbus RTU, Modbus TCP/IP, Modbus Plus, Modbus ASCII, etc. can be implemented. The choice also defines the physical layer for the Modbus network. Commonly, RS-232, RS-485, and RJ45 can manufacturers as a connection in the Modbus application.

Based on serial communication, devices in a Modbus network transmit and receive data as roles of master and slaves. As much as 247 unique IDs for each slave, there could be only one master, which initiates conversations with devices by sending a request. That being said, slaves only send messages if they get requests from master. That being said, slave-to-slave communication is not possible without passing messages through the master. Every Modbus messages share commons structure, also known as an application data unit, including address, function code, data, and error check. Even so, depending on Modbus variants, message frames might be different in length. Either physical switches or software can configure an address of a Modbus device. The configuration might also include rate bits, parity, time out, and other options. Typically, when a Modbus product is delivered to a customer, vendor documentation is provided along with it. The documentation describes how the product is configured, what function code it supports, and how the data scheme is like (Thompson & Shaw, 2016, p. 275). In Modbus, a single-bit physical input is called discrete input, while a single-bit physical output is known as coil. Register is a temporary address that desired data can be assign to. When a master device sends a request to a specific register address, corresponding assigned data will be returned. The step of mapping physical data with register can be done manually during the configuration step or by broadcasting to all devices with configurative data. At the end of a Modbus message lies an error check, which uses different error-detecting codes in types of Modbus. For example, cyclic redundancy check (CRC) is used in Modbus RTU, while Modbus ASCII adopts a longitudinal redundancy check (LRC).

In the VEneCT project, Modbus RTU was implemented to monitor and control smart pumps, and variable-speed drive (VSD) manipulating pallet feeder. Whereas, solar panels connected to SMA Sunny Boy inverter utilising Modbus TCP. Their addresses are shown in table 5.

Table 5. Modbus addresses of field devices

Field devices	Address
Pump 1	2
Pump 2	4
Pump 3	6
Inverter (solar panels)	3
Speed drive (pallet feeder)	5

The pumps were Grundfos Magna3, which was designed to circulate liquids in heating, energy conversing systems with various control modes. In this project, the mode was set to AUTO$_{ADAPT}$ to automatically analyse flows and switch pumps to the most optimal settings to give the highest performance and the lowest energy consumption. The communication between each pump with the Modbus network was handled by accompanying communication interface modules (CIM). They were mounted directly to the control board of the pumps and connected to PLC by twisted pair cable. The reason for using PLC instead of RTU was that the automation system had PLC implemented already; hence, new RTU purchase would have been financially and technically unreasonable. This was a common situation in the automation industry since many SCADA and RTU vendors are no longer on the market, and that PLC was a more economical choice (Thompson & Shaw, 2016, p. 276). Three pumps were programmed similarly, though, their functioning conditions are different. Control, status, and data register block were used in this application. (Grundfos, 2019, pp. 18-25.)

The VSD used in the project was model ATV212HU55N4 from Schneider Electric. The device provided two connection options, RJ45 and Open Style. The latter was chosen to be daisy-chained with other pumps using twisted pair cable. Like Grundfos pumps, the configuration step was done by using HMI on the device. Bit rate was set at 19 200 bits per second (bps). Time out was configured to be 100 seconds during the development phase to avoid communication error; when being deployed, it might be set to lower value for safety and security reasons. Control, status, and monitor register blocks were utilised to operate the device. (Schneider, 2019.)

On the other hand, inverter for solar panels monitored its data via Modbus TCP. The inverter itself ran an application from which data were acquired using Node-RED app running on Raspberry Pi. Node-RED provided a palette that was tailored specifically for communication with Modbus-based devices. Figure 9 was the JSON format of a message sent to Modbus Flex Getter node to require data from the inverter.


```
▾payload: object
    value: 1571637791687
    fc: 3
    unitid: 3
    address: 30225
    quantity: 2
```


Figure 9. Modbus TCP request

Value of “value” property was timestamp at the moment message was sent. “fc” standing for function code indicated the action user wanted to make with the Modbus device. “unitid” was the identification number of a device in a Modbus connection, in this case, it was 3 as aforementioned above. “address” property was the address of specific data that was desired to be read from. If the function was to be applied for multiples register blocks, “address” would be of the first one. “quantity” would be used to indicate how many blocks were to be read. The node would send this message to a specific device and then output response as in figure 10.

```
topic: "393032a.053bace"
▾payload: object
    30225: 65535
    30226: 65535
_msgid: "5fff60f0.dfd47"
messageId: "5dad4af633a59eef8b480698"
```


Figure 10. Modbus TCP response

Because request message required for two register blocks' data, starting address 30225, preprocessed response message consisted of two properties, which were required register blocks, with their corresponding data. The application on Node-RED was programmed to read AC side measured values, DC side insulation resistance, DC and AC measurement, AC line currents, and internal temperature from the inverter. All sending and receiving message conformed to the explained structure.

5.2.2 EnOcean and digital addressable lighting interface (DALI)

Since its foundation in 2001, EnOcean and its energy harvesting technology has been gaining significant popularity in the automation industry, especially in smart building applications. The company focuses on manufacturing sensors and devices that collect energy from mechanical motions and environmental changes, instead of battery and live power. The devices function on an extremely low level of energy, at around 50µWs per telegram (EnOcean, 2016). Collected energy will be used to transmit sensors' data wirelessly to EnOcean gateways, which can be up to 30m away indoor and 300m away outdoor. The amount of data to be sent, however, is modest because of limited energy. This, in a way, is suitable for building automation applications because they are not data-intensive but rather emphasise on economic and smooth integration. EnOcean devices do not require any wiring or complicated installation, but just to be mounted on any wall or door to work at their finest. This makes EnOcean products competitively compact and economical, yet informative in terms of data. Due to advanced characteristics, EnOcean Alliance was founded in 2008 and has snowballed with the join of big companies and associates. The alliance is not profitable but aims to develop the technology and get benefits from the growth of the building automation industry.

Another front-runner in the building automation protocol race is DALI. DALI-compatible products are widely used in smart homes, building automation applications, and Industry 4.0 factories, thanks to their energy-saving and dimmable characteristics. A DALI lighting system is a network of power supply, a controller and up to 64 individual devices. Controller and devices are also known as master and slaves. Each DALI ballast, driver or dimmer in a network is assigned with a unique ID, ranging from 0 to 63, through which they are controlled. Data communication between master and slaves is done by bus of two wires named DALI+ and DALI-. This connectivity enables data to be exchanged half-duplex and asynchronously, at a bit rate of 1200 bauds. As being mentioned, the advantage of DALI compared to other lighting systems is controllability. It offers integration with automation systems, which change the brightness according to human occupancy, schedule, environmental conditions, etc. The integration allows lighting systems to function smoothly while significantly improving building energy efficiency.

In the VEneCT energy hybrid module, EnOcean and DALI were not used in either the burning process or energy-storing loops but were to improve the health of the module itself. Since the goal of the project is to produce clean energy and enhance efficiency level, not only the energy-generating processes but also all activities related to it must be optimised energy-wise. The first action was to use LEDs instead of bulbs. The United States Department of Energy's (DOE) suggested that using a 60 watts LED panels would save 75-80% of energy, compared to an equivalent-power incandescent bulb (The U.S Department of Energy, n.d.). Even though the replacement would also mean losing by-product energy from traditional light bulbs, the energy saved by using DALI LEDs were still more beneficial. The second step was to control LEDs' states in correspondence with specific circumstances. The two LEDs inside the module had been left on regardless of time in a day, so the initial plan was to use EnOcean switches to control them. The switches could turn LEDs on and off and dim them by pressing and holding the turn-on buttons. Besides, a timer of 45 minutes was set to dim lights by 50% brightness, and switch them off two minutes after that, in case users had left and forgotten doing so. If people were still working in the module, they could reset the timer by turning the LEDs on again. In the future, motion detection sensors would replace current switches for even better user experience.

Being a member of both EnOcean and DALI alliance, Beckhoff has developed bus terminals allowing communication between its own PLCs and EnOcean and DALI products. Beckhoff's KL6583 enables data exchange with EnOcean sensors and switches; then data are monitored and controlled by PLC programs via KL6581 master terminal. Whereas, DALI LEDs are controlled via KL6811 master and power supply terminal. Beckhoff also provides supporting libraries for the technologies, making the experience integrating them with the module effortless. A KL6581 terminal offers a bus for up to eight KL6583 transmitter and receiver modules. KL6811 terminal was connected with DALI devices via two-wire DALI bus. Both terminals were linked together and with other cards of the PLC in the main cabinet of the hybrid module.

5.2.3 Open platform communications unified architecture (OPC UA)

According to OPC Foundation, OPC UA is a platform-independent service-oriented architecture that integrates all the functionality of the individual OPC Classic specifications into one extensible framework. It was developed based on the idea of OPC but left out the dependence on Microsoft's object linking and embedding (OLE) and distributed component object model (DCOM). OPC UA functions in machine-to-machine, server-client architecture, which means multiple client applications can connect and exchange data with an OPC UA server. Similar to Modbus, the communication between server and clients only starts with clients sending requests, which may be read, write, listen, discover, etc. Normally, an OPC UA server stays in a wait state. When it receives a request from a client, it responds with corresponding data, or takes actions from the command, then goes back to wait state. An OPC UA stack may have multiple OPC UA protocols. The underlying protocols include data access (DA), alarm and event (AE), historical data access (HA), extensible markup language (XML) DA, and data exchange (DX). Among those, DA and AE are mostly used. (Novotek, 2019.)

OPC UA is undoubtedly one of the most successful, forward-looking, advanced standards in the history of the computer. Its characteristics bring significant benefits to all sectors of the information and technology industry. In automation engineering, the benefits of applying OPC UA include platform-independence, scalability, complex data structure and method calls support, data communication without data loss, and security. It is worth emphasising the platform-independence feature on OPC UA because it offers devices, applications with different operating systems (OS) the possibility to communicate and exchange data. That means Window-, Linux-, Android-, iOS-based applications can connect, monitor, and control data, as long as they obey the OPC UA standard. At the same time, the characteristic helps organisations and companies scale the automation systems quickly without worrying about vendors and compatibility. Because OPC UA uses are spread in all industrial industries, it provides the ability to define and handle complex data structures so that any data from any application can be exchanged seamlessly. Before, client applications can only request the server to send variables' values in an interval. If variables' values vary faster than the cyclical update, data will be lost. Also, if a physical connection is interrupted, data during dysconnectivity cannot be recovered. With OPC UA, clients can request a server to send data when variables' values change. This way, data will not lose, yet clients do not have to receive too much unnecessary information. Besides, when a physical connection breaks, the server and client automatically search and connect. For security, OPC UA uses file-based certificates to identify servers and clients. Its encryption protect data in all aspects of the design and implementation of OPC UA applications. (Lange, Iwanitz, & Burke, 2010.)

The purpose of deploying the OPC UA server in the VEneCT automation system was for open data access. As mentioned, data available on an OPC UA server can be accessed from clients with different platforms. Since the VEneCT was a research project, data collected from the automation system was highly essential and would be used for further analyses. Therefore, they should offer other applications the easy integration in the future. In another scenario is where MES and ERP applications are implemented, they can connect to the OPC UA server and read information from there as well.

In the scope of the thesis, OPC UA was used as a gateway between the TwinCAT runtime and the data server. As an active member of OPC Foundation, Beckhoff provides free OPC UA server and client in its functions. OPC UA server was integrated into the industrial PC. OPC UA client application running on a central server connected to the OPC UA server and subscribed to available data. The scenario was illustrated in figure 11.

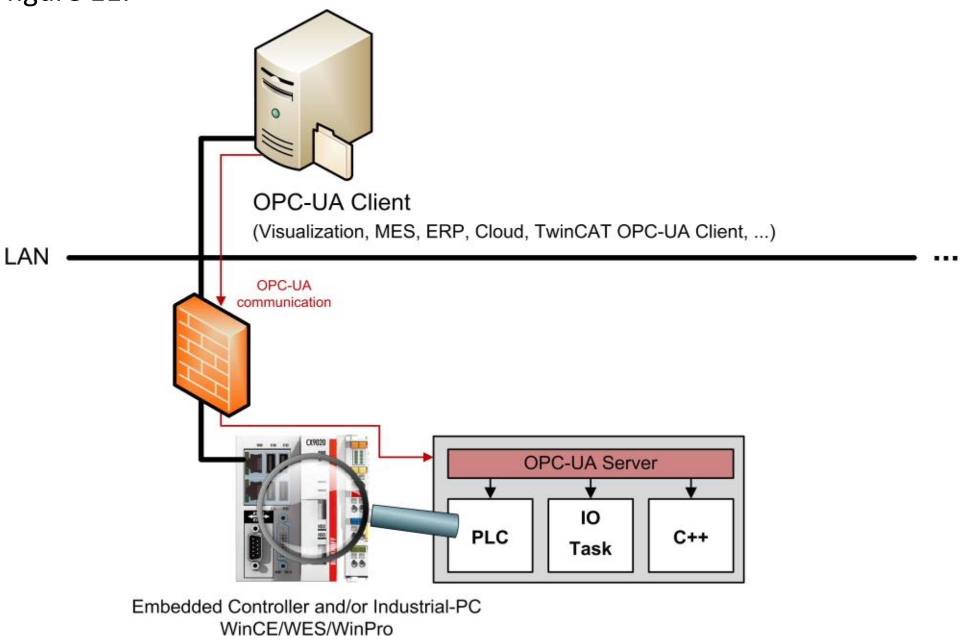

Figure 11. OPC UA architecture (Manual TC3 OPC UA, 2019)

The configuration of the OPC UA server on TwinCAT PLC includes configuring variables for data access, configuring namespace, and establishing a connection. To choose which PLC variables will be accessed on OPC UA server, a comment {attribute 'OPC.UA.DA' := '1'} must be written before the variables' declarations. This way, programmers had control over the data access, not letting confidential or unnecessary data be published. For namespace configuration, OPC UA server connected to the first PLC on the same system and used its trace message control (.tmc) file to configure the namespace. Then, the connection between the OPC UA server and client was made by accessing the URL with the format opc.<protocol>//<ip or name>:port

in which, “protocol“ was the transport to the OPC UA server. <ip or name> is the identification of the PLC in the network. “port” is the port on which OPC UA server was opened. Follow the format, the VEneCT PLC OPC UA server URL is:

opc.tcp://CX-2AFFDE:4840

6 SUPERVISORY LEVEL

6.1 Data process and storage

6.1.1 IoT protocol: Message queuing telemetry transport (MQTT)

Message queuing telemetry transport (MQTT) is a machine-to-machine protocol that is based on the publish-subscribe mechanism. An MQTT application consists of a broker and one or several client devices. Client devices can be publishers, subscribers or both. Publishing devices send data under topics, to which other devices can subscribe to receive data. Once being sent by a device, the message must go through the broker, before being received by any devices. This behaviour is because the broker manages the MQTT network. It keeps track of devices and topics that they subscribe to. When the broker receives a message, it forwards the message to corresponding client devices. Figure 12 is an example of data exchanges between clients in an MQTT application. The sensor continuously senses changes in relative humidity level and publishes the measurement to the broker under the topic “humidity”. Simultaneously, on-premise analytics and cloud analytics applications subscribe to the same topic. When a message is sent from the sensor, MQTT broker receives and forwards it to subscribers.

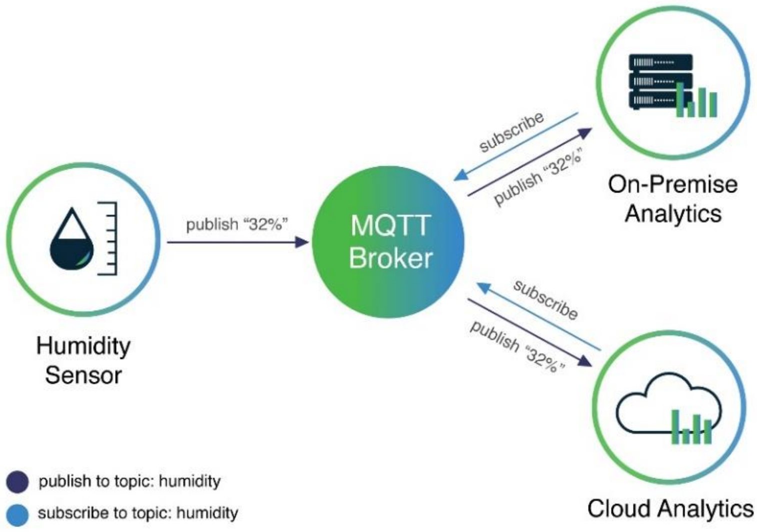

Figure 12. MQTT architecture example (Behrtech, 2019)

MQTT, based on TCP/IP, is one of the most popular protocols in IoT applications thanks to the lightweight and easy implementation characteristics. Therefore, it was deployed as the gateway between the local network and the central server in the VEneCT automation system. Data from OPC UA clients were processed and sent to MQTT broker by Node-RED application. Data were transported under different topics, depending on their locations and functions, as shown in appendix baobao. The MQTT broker ran on the central server, also known as "iot.research.hamk.fi". It also hosted another application acting as the MQTT subscriber, processing data and sending them to the database. Exchanged messages were expressed in JavaScript object notation (JSON) format, with variables or measurements being attributes and their data being values. Data can be sent separately or together in a JSON object. For example, measurements of running fuel feer were expressed as in figure 13.


```
▾payload: object
    fMotorSpeed: 1500
    fOutputFrequency: 50
    fOutputCurrent: 84.77999877929688
    fOutputVoltage: 93.54999542236328
  topic: "hamk/iot/valkeakoski/kontti/Feeder"
  _msgid: "1771d33b.0eb47d"
```


Figure 13. MQTT message

6.1.2 Time series database: InfluxDB

A time-series database (TSDB) is a database that is specifically used to manage and store values of variables that vary over time. Time-series data can be process measurements, triggers, and alarms, system and application metrics, business turnovers. They appear in every aspect of life, hence the need for tracking, monitoring, processing, and aggregating them is adequate. However, because variables' values continuously fluctuate, a database must meet specific requirements to be able to handle such a vast amount of data. Writing speed must be significantly high to keep track with a big chunk of data sent to the server every second, or even milliseconds. In addition to that, TSDB should have a high capacity, and potential scalability since the amount of data expands quickly over time. Also, it gives fast access to real-time analytics, which is mostly used in trendy machine learning applications. In-memory support, ingest performance, SQL support, compression is few other characteristics affecting the performance of a TSDB. (Smith, 2019.)

Time series analysis includes three different types of data, including time-series data, cross-sectional data, and pooled data, which is a combination of the first two types. Time series data is defined as a set of values of a variable; on the other hand, cross-sectional data examines the relationship between variables in an interval. (Brockwell & Davis, 1987.) This approach of grouping data applied to the optimisation of low-carbon biomass combustion. All process measurements must be monitored and controlled throughout a day to produce energy with a high-efficiency level. Besides, multiples experiments would be made to find nearly-ideal tuning parameters for the process. Time-stamped data grouped as cross-sectional data would help to observe the relevances between variables. Empirically, Influx database (InfluxDB) was hosted on the central server. After receiving messages from MQTT broker, the application would arrange data into a JSON object with pre-defined format, which was demonstrated in figure 14, and inject them into the database. In the future, Node-RED application will be replaced by Telegraf, which is a server agent for collecting and reporting metrics. The benefits of implementing the agent are minimal memory footprint, high reliability, easy integration with a wide variety of systems, and flexibility in adding new inputs to and outputs from the database (InfluxData, 2019).

```
▾payload: array[1]
  ▾0: object
     measurement: "VEneCT"
     timestamp: "2019-10-14T11:15:40.376Z"
    ▾tags: object
       location: "kontti"
       type: "Grundfos_1"
    ▾fields: object
       fHead: 0.1469999998807907
       fVolumeFlow: 0.30000001192092896
       fRelativePerformance: 25.979999542236328
```


Figure 14. InfluxDB data format

6.2 Data visualisation and supervision

6.2.1 Metrics visualisation: Grafana

Data visualisation is the act of representing information and data in the form of graphical components such as graphs, charts, histograms, gauges, geographic maps, etc. Data visualisation helps users to grasp the significance, patterns, and correlation of information by displaying raw data more intelligibly. Besides, visualised data convey concepts and ideas in a universal manner, which is essential in an internationalised world. With data visualisation, data analyses have evolved from tedious spreadsheets and reports into attractive and informative dashboards. Therefore, a metrics visualisation application was essential to demonstrating process measurements, performances of the hybrid energy module, through which the low-carbon biomass combustion optimisation would be achieved. (Rouse, 2017.)

Grafana is the analytics platform for visualising a wide variety of data types from different databases and operating systems. Being an open-source platform, Grafana offers developers abilities to discuss, share experiences, and together contribute to the common goal that is improving the data analysis sector. Thanks to that, Grafana provides hundreds of libraries and plugins, which are customised for almost every situation. Grafana also allows developers and analysers to make triggers for critical data, share data and dashboards across teams, or integrate it into their organisations' systems. (Grafana, 2019.)

Due to the advantages mentioned above, Grafana was made use for the third layer of VEneCT automation system. The most decisive values of the system were visualised in graphs for better understanding of the relationships between process variables. Being provided tools to work with InfluxDB, the integration between the database with the metrics visualisation was done effortlessly. After the database ingests data from on-site processes, they were instantly fed to the platform for viewing. As shown in figure 15, each process variable had its dashboards displaying their fluctuations in periods. Moreover, alerts were added to the most crucial variables such as water temperature and pumps' operations, to notify operators if the system did not function properly. Each metrics visualisation had a JSON object describing its configuration, from names, dimensions, tags to colours, owner organisations, and thresholds. One of the properties of a graph was "id", stood for identification, which distinguished itself among other graphs in the same dashboard. This property would be used to map the metrics visualisation with the process visualisation, which would be explained in the next chapter.

Figure 15. Grafana analytics platform

6.2.2 Web application: React

Human-machine interfaces (HMI) have been a standard in the automation industry for a long time. They present process variables in simple diagrams and provide operators with the ability to control them through screens and monitors. Most of the time, HMI is available near the actual process or in control rooms, on the factory floor. Besides, an only small amount of data can be viewed remotely in SCADA, MES, or ERP systems. However, with the thrive of information technology and especially web and native applications (app), users need more than just a plain, usable interface. Data visualised effectively and beautifully helps operators to grasp information more efficiently, hence act quickly on the process when required. In addition to that, in the time when data are the focus of every talk, they are expected to be user-friendly and accessible from anywhere in the world. Therefore, it was decided that a web app visualising the hybrid energy module's process variables was essential.

React, also known as ReactJS, is a JavaScript library for developing interactive user interfaces (UI) on web and progressive web apps. The main concept of React emphasises the use of reusable UI components. With components, React can manage states of apps and re-render corresponding part of their UIs when changes happen, without the need of requesting new views from remote servers. Because of its built-in flexibility, React was considered appropriate for the VEneCT process visualisation. To handle and display intensive data flows from the database, an app should not reload the whole page every time new data come. Instead, it had to be able to keep track of all variables' values separately and only update those that had changed. This method would improve not only the performance of the application but also user experience.

The home page of the app displayed "Energy cycles", which consisted of thermal energy loop and electricity loop. Users could switch between two tabs to see the cycles separately, as shown in figure 16. Each cycle represented an actual process by its diagram with sensors and actuators' real-time values attached to their corresponding positions. Clicking on a figure would trigger a popup showing the metric visualisation for the last six hours. The graphs fetched from Grafana would help users to keep track of the system's operations smoothly. When navigating to "About" page, information on the project could be found. Last but not least was the "Controlling" page which, after authorisation, would allow users to control the processes remotely from their browsers. In the scope of the thesis, the last page was not conducted due to time limitations. However, the feature will be implemented as the project carries on.

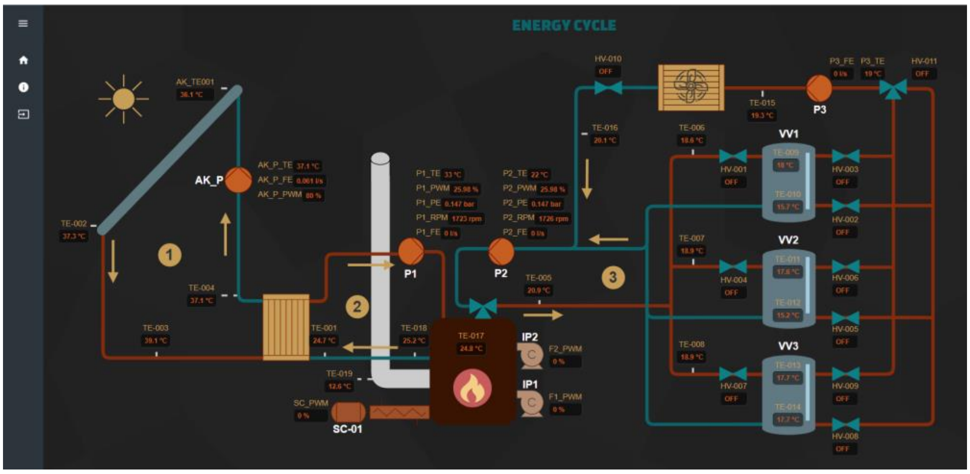

Figure 16. Web application

7 CONCLUSION

This thesis has depicted a framework of building a small-scale IIoT automation system, with the case study being a hybrid energy module. Based on the information given here, other research projects or small businesses can study and apply the knowledge for their cases.

The solution described the automation system at three levels including the field level, the control level and the supervisory level. At the field level, new temperature and flow sensors, pumps, EnOcean switches, and terminal cards were installed. At the control level, new programs controlling the combustion process, water circulation, and lighting system were added to the existing projects. The project structure was also modified to improve the performance of the system as well as the programming experience. Process variables were made accessible through an OPC UA server running on TwinCAT runtime. With the OPC UA, new applications from different platforms can easily have access to monitor and control the processes in the future. The supervisory level consisted of a gateway application, a database, metrics visualisation, and a web application. The gateway held up the data communication between an on-site PLC and remote central database. Every data point was saved on the database with corresponding tags and a timestamp. Metrics visualisation and web application were developed to illustrate the real-time operation of the processes. Through the diagram, both general users and professional engineers could quickly grasp detailed information on the performance of the process.

There are also improvements that could have been made in the implementation of the thesis. Firstly, the gateway between the second and third layer was hosted by a micro-computer Raspberry Pi. From the author’s perspective, the device was not appropriate for the industrial environment neither physically or technically. Therefore, applications running on Raspberry Pi will be moved to the PLC’s operating system. Secondly, the data communication between MQTT and InfluxDB was deployed on a Node-RED application, which was not stable and efficient. In the future, a Telegraf server-agent is suggested to replace the mentioned application to collect metrics for the database. Thirdly, the current data structure on the supervisory level was confusing due to misunderstands between engineers from two projects. The data structure should re-defined and carefully documented to improve comprehension. Finally, users could only monitor process variables through a web application at the time this thesis was finished. The feature, through which operators can control the process, will be developed hereafter.

In conclusion, the target of designing the framework was achieved, as the automation system used in the case study was proven applicable. An experiment conducted in September 2019 showed that the combustion was consistent and energy-efficient. Besides, no GHGs were detected in the flue during the burning. The water temperature in three storage tanks reached values of approximate 80°C. In addition to that, the visualisation applications behaved as expected and gave a thorough view of the test. Further experiments and development have been planned and will be carried out in the next stages of the project.

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