AUTOMATION SYSTEM TO PRODUCE BIOCHAR FROM PYROLYSIS USING LOCALLY ACQUIRED BIOMASS

HÄMEEN AMMATTIKORKEAKOULU
HÄME UNIVERSITY OF APPLIED SCIENCES

Bachelor's thesis

Electrical and Automation Engineering

Spring 2023

Daniel Kelly

HÄMEEN AMMATTIKORKEAKOULU
HÄME UNIVERSITY OF APPLIED SCIENCES

Sähkö ja automaatiotekniikka		Tiivistelmä
Tekijä	Daniel R. Kelly	Vuosi 2023
Työn nimi	Automaatiojärjestelmä tuottamaan biohiiltä pyrolyysistä käyttämällä paikallisesti hankittua biomassaa	
Ohjaaja	Juhani Henttonen	

Opinnäytetyön tekijä on ollut kiinnostunut ohjelmoitavista logiikkaohjainjärjestelmistä siitä lähtien, kun hän tuli yliopistoon, joten oli etukäteen suunniteltu, että opinnäytetyön aihe käsittelee jotakin, joka liittyy tällaisen järjestelmän käyttöön. Tarkka aihe oli silti epäselvä, ja toimeksiantaja HAMK Tech mahdollisti aiheen valinnan palaverissa.

Opinnäytetyön tavoitteena oli saada biohiilen tuotanto jatkuvaksi ja tuottaa tasalaatuista biohiiltä, joka täyttää kemiallisten ja fysikaalisten ominaisuuksien kriteerit. Tämä tavoite saavutettiin, sillä tuote sisälsi keskimäärin noin 83 % hiiltä massaprosentteina ja muita alkuaineita, kuten vetyä (2,5 %) ja typpeä (0,1 %), mikä osoittaa, että kyseessä on biohiili.

Sisältö alkaa luvussa kaksi biohiilen historiasta, määritelmistä ja vaikutuksista ja päättyy pyrolyysin historiaan. Seuraavissa luvuissa määritellään automaatiojärjestelmä ja tutkitaan sen käyttökelpoisuutta tässä skenaariossa, käsitellään myös ohjausjärjestelmän arkkitehtuuria ja asiaankuuluvia algoritmeja sekä perustellaan ne. Tutkielman loppupuolella keskusteltiin toteutuksesta, esiteltiin tulokset ja analysoitiin niitä.

Toimeksiantona tehdyn opinnäytetyön tavoite on toteutunut, sillä paikallisesti tuotetun biomassan pyrolyysin automatisoidun järjestelmän luominen ja käyttö biohiilen tuottamiseksi on osoittautunut onnistuneeksi. Vähentämällä tarvittavan ihmistyön määrää, vähentämällä virheiden mahdollisuutta ja hyödyntämällä käytettävissä olevia resursseja parhaalla mahdollisella tavalla automatisoitu järjestelmä on täyttänyt tarkoituksensa lisätä biohiilen valmistusprosessin tehokkuutta ja vaikuttavuutta.Tiivistelmän pituus on 1 sivu.

Avainsanat	Pyrolyysi, automaatiojärjestelmä, biohiili, Ohjelmoitava logiikkaohjain
Sivut	62 sivua ja liitteitä 2 sivua

HÄMEEN AMMATTIKORKEAKOULU
HÄME UNIVERSITY OF APPLIED SCIENCES

Electrical and Automation Engineering Abstract
Author Daniel R. Kelly Year 2023
Subject Automation system to produce biochar from pyrolysis using locally acquired biomass.

Supervisor Juhani Henttonen

The author of the thesis has had an interest in programmable logic controller systems since the day he entered this university, hence it was likely that the thesis topic would be about something that involves the use of such a system. Still, the exact topic was unclear and the commissioning party HAMK Tech made the topic selection process possible during a meeting.

The purpose of this thesis was to make the production of biochar continuous and to produce biochar of a consistent quality that meets the criteria for chemical and physical properties. This aim has been met since the product contained roughly 83% carbon on average by mass percent and other elements such as hydrogen (2.5%) and nitrogen (0.1%) which indicates that it is considered biochar.

Biochar was covered extensively in chapter two with the history of biochar, its definitions, and its effects, and ends with the history of pyrolysis. In subsequent chapters, the automation system is defined and explored in terms of its usefulness for this scenario, the control system architecture and the relevant algorithms were also discussed as well as justified. At the latter part of the thesis, the implementation will be discussed, and the results will be presented and analyzed.

The aim of this commissioned thesis work has been realized since the creation and use of an automated system for the pyrolysis of locally obtained biomass to produce biochar has proved successful. By lowering the amount of human labor required, decreasing the chance of mistakes, and making the best use of available resources, the automated system has fulfilled its intended purpose to increase the efficiency and efficacy of the biochar manufacturing process.

Keywords pyrolysis, automation system, biochar, Programmable Logic Controller
Pages 62 pages and appendices 2 pages

Content

1 INTRODUCTION 1

1.1 Background 1

1.2 Objectives of the automation system 2

2 Pyrolysis-Based Biochar Production 3

2.1 Fundamentals of Biochar 3

2.1.1 Terra Preta 4

2.1.2 Biochar’s functional group content 7

2.2 Definitions of Biochar 9

2.3 The Effects of Biochar 10

2.3.1 Effects of different biochar types on Agriculture 10

2.3.2 The effects of biochar on some plant types 12

2.3.3 Using Biochar to reduce organic and inorganic contaminants 13

2.3.4 Effects of Biochar on greenhouse gas emissions 16

2.4 Pyrolysis 18

2.4.1 Types of Pyrolysis 22

2.4.2 Slow pyrolysis 24

2.4.3 Fast pyrolysis 25

2.4.4 Flash Pyrolysis 25

2.4.5 Ultra-rapid pyrolysis 26

2.5 Challenges of the traditional pyrolysis methods 26

2.6 Advantages of using an automation system for pyrolysis 27

3 Automation System Design 28

3.1 What is an automation system? 28

3.1.1 Levels of an automation system 29

3.1.2 Advantages of an automation system 29

3.2 Components of the automation system 30

3.2.1 Hardware 30

3.2.2 Software 33

3.2.3 Process flowchart 34

3.2.4 Design Considerations and trade-offs 35

3.2.5 Sensors and actuators used in the System 36

4 Control System Architecture 39

4.1 Control System Definition 39

4.1.1 Open-loop and closed-loop control system 40

4.1.2 Deadtime 41

4.2 Control algorithms 41

4.2.1 Feedforward control 41

4.2.2 Automatic Feedforward Control 42

4.2.3 Manual Feedforward Control 43

4.2.4 Selection and implementation of the control system 44

4.2.5 Variables in the System 44

5 Implementation details 46

5.1 System implementation details 46

5.1.1 Cabinet selection 46

5.1.2 Device selection criteria 46

5.1.3 Connections 49

5.2 PLC Program 49

5.2.1 Data Unit Type 51

5.2.2 Global Variables (GVL) 51

5.2.3 Sequential Function Chart 52

6 Results 56

6.1 Temperature tests 56

6.2 Quality of biochar produced by the automation system 58

7 Conclusion 60

7.1 Benefits and limitations of the automation system 60

7.2 Future Works and Improvements 61

7.3 Concluding remarks 62

References 63

List of figures and tables

Figure 1. Composition of Biochar (Yong Sik Ok et al, 2015, p. 4) 4

Figure 2. Pyrolysis products 19

Figure 3. Schematic layout of a pyrolysis plant 20

Figure 4. Beehive oven as a fixed pyrolyzer for charcoal production 25

Figure 5. Cabinet layout 32

Figure 6. Veto-60 Kw biomass boiler 33

Figure 7. Automation system flowchart 35

Figure 8. Schematic of a sensor. 37

Figure 9. RS PRO Type K thermocouple. 38

Figure 10. RS PT100 Temperature Transmitter. 39

Figure 11. closed-loop control block diagram. 40

Figure 12. Automatic Feedforward control. 42

Figure 13. Manual Feedforward control. 43

Figure 14. Air inlet fan for the combustion of fuel 45

Figure 15. Humimeter BP1 measuring the moisture of 280 grams of wood pellets 46

Figure 16. IEC 61131-3 programming languages..50

Figure 17. Data unit Type "ATV_Status" 51

Figure 18. Global variable list “Drive” 52

Figure 19. Sequential function chart program for the 3-phase motor control..............54

Figure 20. TempFallDelay step 55

Figure 21. Reactor pipe with bend 56

Figure 22. Temperature test 1...57

Figure 23. Temperature test 6...58

Figure 24. Char formed at the “bend” of the reactor 59

Table 1. Comparisons of different pyrolysis processes 23

Appendices

Appendix 1. Circuit diagram

1 INTRODUCTION

1.1 Background

In this section, the reason for selecting a topic of this nature will be discussed as well as the motivation behind it. At the Häme University of Applied Sciences, there are several research units, one of which is known as HAMK Tech. The HAMK Tech unit commissions projects that are aimed at developing sustainable technology solutions. The unit combines expertise from its different departments to focus on research directed toward the metal and building industry. On a societal level, the overall objective is to utilize the opportunities provided by ecological technology solutions, with the hope of boosting societal well-being by promoting the effective and sustainable use of natural resources. (*HAMK Tech – Technology for the Future*, n.d)

When this thesis was written, there was a project called Fiksuhilli (Wise Carbon) in HAMK Tech. This project aimed to modify a factory-made, low-capacity boiler into a continuous-flow biochar-producing boiler. As far as possible, the project aimed to reduce the cost of modifying the boiler by using the default factory-made parts. The project will examine the boiler's efficiency with various fuels and examine whether regional side streams made of biomass are suitable for making biochar. The research will also look at potential commercial plans for small-scale regional biochar production. This analysis is crucial because the hybrid boiler is a device that is not offered on the Finnish market due to its size and technology. To guarantee that the outcomes may be applied moving forward, the project is also creating follow-up measures. Based on the findings, a larger hybrid boiler might be modified, say for use in farming or by an operator of a similar scale. Since some industrial side-streams and waste by-products are difficult to recycle, it has been made a long-term goal of the unit to use biochar production as a medium to promote the sustainable use of these materials. (*FiksuHiili*, n.d.)

The project had been distributed into six work packages, referred to as “TP” from here going forward. TP1 focused on the planning and implementation of the hybrid boiler which included but is not limited to removing parts of the container in which the boiler was kept to accommodate the increase in size, removing a metal tank that was used in the previous project to accommodate size increase, designing a reactor pipe and making modifications to the front door of the boiler. TP2 focused on testing the performance of the modified boiler which included but was not limited to the testing of the operational boundary conditions using wood pellets and other regional side streams. TP3 focused on reducing emissions through pyrolysis. The objective, according to the website, was to “examine and find the impact of pyrolysis on emissions from low-energy production.” TP4 handled the creation and promotion of new business models aimed at small-scale biochar production. TP5 aimed to increase the interest in local small-scale production of biochar among equipment manufacturers and the public. TP6 aimed to secure the possibility of future scalability. Ultimately, the thesis was commissioned by HAMK Tech to investigate the topic that I had chosen. (*FiksuHiili*, n.d.)

1.2 Objectives of the automation system

The automation system aimed to make the production of biochar continuous in such a way that minimal human input was required. Since, based on history, the process of producing biochar has been tedious and time-consuming, the system was designed with this in mind. The automation system was aimed at producing biochar of a consistent quality, which ensures that the product meets certain standards for chemical and physical properties. The automation system aimed to optimize production efficiency thus reducing waste and increasing output. Another important objective was safety. The system was designed to facilitate the safety of the environment and the worker simultaneously. The Possible risks associated with the production process were also taken into consideration on the grounds of safety and the automated system mitigated these possible risks as much as possible. The cost-effectiveness of the system was also taken into consideration when designing it.

The system aimed to reduce production costs which would lead to more affordable biochar production that can compete with other soil amendments. The system aimed to be environmentally sustainable, reducing carbon emissions, minimizing waste, and potentially utilizing biomass waste streams that might otherwise be discarded. To accommodate increases in production volume and satisfy the rising demand for biochar, the system was made to be scalable.

2 Pyrolysis-Based Biochar Production

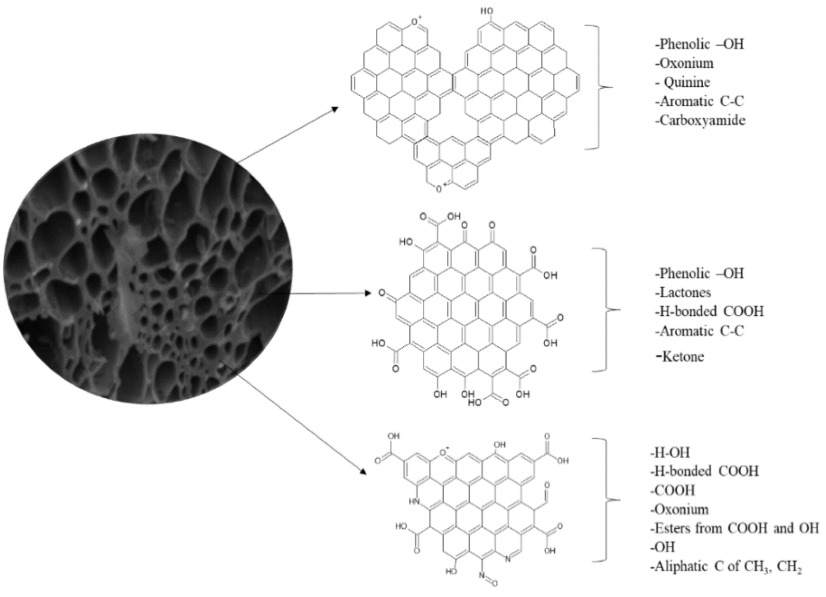
2.1 Fundamentals of Biochar

In the year 2022, an event took place that caught the world by surprise, which was the invasion of Russia into Ukraine. Since then, there has been an energy crisis in the European region and biochar has risen as a topic of interest thereafter. The prospects and applications of biochar must be properly understood from the perspective of environmental management and energy production. Biochar is an aid for carbon sequestration, greenhouse gas reduction, and soil fertilization. (Yong Sik Ok et al, 2015, p. 4)

An ideal platform for pollutant removal is provided by biochar’s complex and heterogeneous chemical and physical makeup (Figure 1). It is challenging to pinpoint the precise chemical makeup of biochar since the chemical composition of biochar relies on the type of feedstock and pyrolysis parameters, such as residence time, temperature, heating rate, and reactor type (Lehmann & Joseph, 2009, p. 16). Carbon dominates the composition of biochar. Depending on the type of feedstock used, the inorganic portion of biochar primarily contains minerals including calcium, magnesium, and potassium as well as inorganic carbonates i.e., carbonate ions. Within the organic composition of biochar, there is a high presence of carbon. Graphite does not develop significantly at the temperature required to make biochar, nor do aromatic rings. As opposed to graphite, which has aromatic rings packed and aligned in flawless sheets, biochar does not. With the creation of biochar, further asymmetrical arrangements of carbon are generated, and these contain Oxygen and Hydrogen. (Lehmann & Joseph, 2009, pp. 1—2)

In some circumstances, the type of feedstock affects mineral formation. Biochar typically comprises carbonized and noncarbonized phases because it is not fully carbonized. When biochar is added to soil, water infiltration, soil water retention, ion exchange capacity, and nutrient retention all increase (Ayodele et al, 2009; Laird et al, 2010, pp. 436—442; Lehmann et al, 2003, pp. 405, 416).

Figure 1. Composition of Biochar (Yong Sik Ok et al, 2015, p. 4)



According to Lehmann & Joseph (2009, p.14), biochar’s discovery dates as far back as the pre-Columbian era, during which period the ancient Amerindian communities existing in the Brazilian Amazon region created dark earth soils known as terra preta, through the slash-and-burn method. As a result of utilizing this method, there was a change in the composition of the carbon content of the soil that was noticed apparently by the people of that time. The soil was noted to be comprised of a high carbon content of 150 g of Carbon per kilogram of soil while the surrounding soils were noted to be comprised of a much lower quantity of Carbon with 20 – 30 grams of Carbon per kilogram of soil (Glaser et al, 2002, pp. 226—227; Smith, 1980, pp. 556 —557). After centuries, the high carbon content is still found in the same location even though the soil was abandoned and has not encountered active agricultural work since then. In one way or another, this is proof of the persistence of the carbon content in the dark earth soil (Yong Sik Ok et al., 2015, p. 6).

2.1.1 Terra Preta

The discovery of thousands of elevated platforms with black, extremely rich soil patches in the Amazon River basin by the explorer Herbert Smith in 1879 is linked to the creation of biochar (Marris, 2006, p.624). The soil was given the moniker “Terra Preta de Índio” due to its dark color and place of origin (black earth of the Indian). Today, even the addition of chemical fertilizers cannot maintain agricultural yields into a third consecutive growing season, although this dark earth had preserved their fertility for generations. As a result, studies have concentrated on terra preta's physical, chemical, and cultural characteristics. Field research has demonstrated that slash-and-burn methods were used to generate terra preta (Lehmann & Joseph 2009, pp. 1—9). Additionally, studies have quantified and proven that incomplete combustion was the cause of the carbonized organic materials in the terra preta. Similarly, it is generally established that terra preta contains burnt plant matter known as biochar (Glaser et al. 2001). Since biochar can be made from nearly any type of natural organic material, a lot of research is currently being done to replicate the development of terra preta by producing biochar using various methods of heating plant detritus without oxygen (Yong Sik Ok et al., 2015, p. 19).

According to the results from previous studies done on terra preta, it was noted that it consists of a great amount of carbon and considerably lower amounts of nitrogen, calcium, and phosphorus. It was discovered that the cation exchange capacity, pH and base saturation of terra preta was noticeably greater than those same characteristics in the neighboring soil areas. During that time, ongoing experiments proved that a hectare of meter-deep terra preta could store as high as 250 tons of carbon when compared to the lower limit of 100 tons in neighboring soils which resulted in the darker color of the earth. (Glaser et al, 2001, pp. 37— 40).

Two factors that reduce the durability of organic material in the real-world environment are biological decomposition and chemical oxidation which are naturally occurring processes. Biological decomposition concerns the breakdown of the material into simpler organic or inorganic matter by abiotic or biotic processes (Smith, 2023). Oxidation is a chemical process during which atoms lose electrons such as hydrogen and gain oxygen electrons (Raman, 2016). With these two points being established, the reason for the durability of the biochar throughout centuries can be attributed to its polycyclic aromatic structure which in effect, hinders these processes to a great extent (Glaser et al, 2001, p.39). The negatively charged carboxylate groups, also known as carbon and oxygen atom groups, are highly concentrated on the surface of biochar. The improved ability of terra preta to store nutrients may be due to the carboxylate groups that result during surface oxidation (Kim et al, 2007, pp. 684,685).

A significant characteristic of biochar is its relatively high organic carbon (C org) content, which is largely kept in condensed aromatic rings with some reactive functional groups (Xue et al, 2012, pp. 674,675). Its composition is essential to the concept of biochar as a Carbon sequestration method. In recent years, there has been substantial support for the use of biochar as a soil supplement to mitigate climate change by increasing carbon storage in soils and decreasing net carbon dioxide (CO_2) emissions. However, not all biochar carbon is resistant, and a labile portion is often released shortly after soil assimilation (Atkinson et al. 2010, pp. 4—7). Although biochar can bind this and other native forms of carbon in soils, it is the carbon that is "preserved" in highly concentrated forms that makes biochar a potential strategy for raising carbon stocks. When considering biochar Carbon, it is essential to distinguish between total carbon (TC) content (mixed inorganic and organic Carbon) and organic carbon (C organic). (Yong Sik Ok et al., 2015, p.70) Traditionally, the carbon content in biochar studies has been measured by total carbon, which is commonly obtained by complete combustion. However, it has been maintained that organic carbon is a more accurate estimate of biochar carbon because, after pyrolysis, certain biochar has a high carbonate component due to their high ash content. This causes biochar carbon content to be overestimated, which has repercussions for elemental ratios used to infer properties such as aromaticity (H/C), stability (O/C), and possible N immobilization (C/N). A research analysis found that total carbon and organic carbon depend on the charcoal feedstock and the highest treatment temperature (HTT). (Yong Sik Ok et al., 2015, p.70)

Depending on the feedstock, the carbon percentage of biochar can range from 36 to 94%, with the carbon content increasing with greater pyrolysis temperatures (Keiluweit et al, 2010, pp. 1247 — 1250; Novak et al, 2009, pp. 195 — 201). According to information from the UC Davis Biochar Database, the total carbon for lower temperature biochars ranges from 60 to 95% for feedstocks like wood and from 50 to 70% for feedstocks like nutshells (Mukome & Parikh 2013).

Biochar's organic carbon concentration is proportional to both the feedstock and pyrolysis conditions (Mukome et al, 2013, p. 2197, 2198). Based on the raw material and pyrolysis circumstances, biochar can store up to 50% of the feedstock's organic carbon (Sohi et al. 2010, pp. 47 — 82). Hence, this thermal conversion technique enhances the organic carbon storage when compared to allowing the biomass to decay through natural routes. Furthermore, although biochar's organic carbon is sometimes categorized as resistant, it is not a permanent carbon storage mechanism. The C structure in biochar degrades with time, and some biochar is less stable than others. Biochar's long-term durability depends on both the biochar material and the way it interacts with and is stabilized by soil minerals. In addition, climate and various species influence the longevity of biochar organic carbon in the soil. (Yong Sik Ok et al., 2015, p.71)

2.1.2 Biochar’s functional group content

To forecast and comprehend how a given biochar would react in the soil, it is essential to have in-depth knowledge of the chemistry of biochar functional groups. It has been demonstrated that the addition of biochar to soil increases the sorption of a variety of heavy metals (Johanson & Edgar, 2006, pp. 50 — 56), pesticides (Spokas et al, 2009, pp. 574 — 579), and PAHs (Zhang et al, 2010, pp. 2822 — 2824). To forecast which biochar is best suited for binding types of chemicals and a comprehensive characterization of the material is necessary. The functional group composition of biochar is essential for analyzing adsorption processes as part of this characterization. Although elemental analysis is vital, it fails to offer direct information about the order of elements inside a sample. Typically, a range of spectroscopic analytical methods is employed to gain information on the molecular bonds within biochar. The most prevalent of these analytical techniques are Fourier transform infrared (FTIR), Raman, and nuclear magnetic resonance (NMR) spectroscopies. Both FTIR and Raman spectroscopies are vibrational spectroscopies that are frequently used to examine soil and biochar samples, and they offer complementary spectra with peaks corresponding to the chemical vibrations of molecular bonds. Using the magnetic characteristics of elements, nuclear magnetic resonance (NMR) spectroscopy provides information on the chemical surroundings of organic molecules.

Examination of FTIR spectroscopy data demonstrates that increasing pyrolysis temperature and length of biochar synthesis leads to spectra with decreased C– O, O– H, and aliphatic C–H peaks and increased aromatic C– H peaks (Keiluweit et al, 2010, p. 1249; Peng et al, 2011, pp. 160 — 165). This effect of pyrolysis temperature can be explained as follows: initial dehydration reduces O– H bands; elevated temperatures increase peaks corresponding to C=C, C=O, C– O, and C– H of lignin and cellulose; and, at extremely high temperatures, there is a general decrease in peaks as the carbon becomes condensed into aromatic ring structures. Since FTIR spectroscopy offers information mainly on chemical bonds with dipole moments, the spectra of strongly aromatic biochar lack prominent peaks. Either Raman or NMR spectroscopy is favored for determining the aromaticity of biochar. Raman spectroscopy demonstrates that during biochar production, the Raman bands associated with disordered carbon decrease in comparison to aromatic and other forms of recalcitrant carbon (Chia et al. 2012; Wu et al. 2009). Dispersive Raman spectroscopy has also demonstrated the effect of biochar feedstock on the disordered carbon fraction (sp^2:sp^3 ratio) (Jawhari et al, 1995, pp. 1562 — 1564; Mukome et al, 2013, pp. 2197, 2200). In addition, the NMR results demonstrate that aromaticity and condensation increase with increasing pyrolysis duration and temperature, with variances between the various feedstocks (Brewer et al, 2009, pp. 386 — 390; McBeath et al, 2014, pp 121 — 126).

The data produced from these spectroscopic techniques is essential for comprehending how biochar added to soils would affect soil pH and interact with inorganic and organic components. Biochar containing considerable amounts of carboxyl and hydroxyl groups, for instance, will have a greater CEC and sorption capacity for cations and metals. Highly aromatic biochar will be more hydrophobic and have a high attraction for a broad spectrum of organic molecules, especially those with limited solubility in water. Similarly, the functional group content determines how biochar will interact with H+ in soil, and consequently how they will affect soil pH. Even though biochar normally produces an increase in soil pH, biochar with multiple oxygen-rich functional groups gives some buffering capability, and pH increases are typically less severe. With an understanding of the functional groups present, biochar may be selected for a variety of agronomic or environmental effects. (Yong Sik Ok et al., 2015, p.88)

2.2 Definitions of Biochar

Throughout the years in the domain of science, researchers and like-minded professionals have created a variety of definitions for the term biochar (Yong Sik Ok et al., 2015, p. 9). The definition of biochar can vary depending on the pyrolysis conditions and the application to soil (Ahmad et al, 2014, pp. 150 — 156). According to *About Biochar* (n.d.) biochar is the solid material obtained when biomass has been thermochemically converted in an oxygen-limited environment at temperatures lower than 800 degrees Celsius. When biomass, such as wood, manure, or leaves, is heated in a closed container with little to no air, the result is a carbon-rich product (Lehmann & Joseph, 2009). Sohi et al (2009, p.55) state that biochar is defined as the “solid carbon-rich residue yield in the thermal decomposition of plant-derived biomass under the partial or total absence of oxygen”. Verheijen et al (2010) define it in a more sophisticated way by saying that biochar is the substance that after undergoing pyrolysis in an oxygen-free reactor, is applied to the soil at a particular site and is anticipated to sustainably mitigate climate change while simultaneously improving soil functions under present and potential administration while avoiding both immediate and long-term negative effects on the broader natural world and mankind's wellbeing. When incomplete combustion of biomass occurs in a reactor, biochar is the solid residue as a by-product (Keiluweit et al, 2010, pp. 1247 — 1249). Beesley et al (2011, pp. 3269 — 3280) define it as the porous carbon-rich product that is achieved after combustion inside a controlled anti-oxygen environment. An even more complex definition is provided by Shackley et al (2012, p. 49), which states that biochar is the porous solid that is made when organic materials are changed thermochemically in an atmosphere with little oxygen. It has physical and chemical properties that make it a good place to store carbon in the environment for a long time and in a safe way.

An analysis of these definitions provided by these expert scientists, reveals that there is one central principle within them. The fact is that biochar is produced in one way only, and that is when biomass is heated until there are solid remains. No matter which way someone wants to define biochar, it stands proven that it must be created through heating at a specific range of temperatures. This gives us the certainty that heat, of whatever source, is a key player in this process as well as the type of biomass. From the days of terra preta which occurred centuries ago until now, the principle of making biochar has been in practice thereby indicating that it will likely remain the same for centuries to come. Of course, definitions are dynamic and that means that if somehow a new way of producing this resource without heat or by utilizing heat in a new way is discovered then the definitions will follow suit and undergo a change as well.

2.3 The Effects of Biochar

2.3.1 Effects of different biochar types on Agriculture

Biochar properties, such as elemental ingredient concentrations, density, porosity, and hardness, are determined by the types of biomaterials used for production, for example woody biomass, agricultural residues, grasses, etc. (Spokas et al, 2012, pp. 974 — 978). It may be necessary to select biomaterial, a pyrolysis production process, and production circumstances to generate biochar with certain properties to optimize biochar for a given use. Biochar made from three feedstocks that were pyrolyzed at varied temperatures is described in a research paper by Kloss et al. (2012). Compared to the two woody-based biochar, straw-based biochar generally had higher concentrations of soluble elements, but their nutritional contents were not sufficient to encourage their direct application as a soil amendment.

Raising the pyrolysis temperature increased the surface area of biochar explicitly, which may benefit sandy soils by boosting absorption locations or may enhance the preservation of nonpolar contaminants in soils. The authors additionally demonstrate how biochar's polycyclic aromatic hydrocarbon (PAH) content was affected by increasing pyrolysis temperatures. PAHs are very resistant and possibly dangerous aromatic hydrocarbons that are produced during incomplete combustion. Based on research the PAH content of wood-based biochar tends to lessen with rising temperature, but the PAH content of straw-based biochar rose when increasing pyrolysis temperatures. (Kloss et al, 2012)

To develop a minimal diagnostic dataset for investigating the prospective utilization of biochar as a soil amender and for carbon capture, Schimmelpfennig & Glaser (2012, pp.

1001 — 1009) utilized 16 distinct biofuel materials to generate 66 forms of biochar produced from five different pyrolytic methods such as conventional charcoal stack, rotary kiln, Pyreg reactor, wood gasifier, and hydrothermal carbonization. Based on their findings, Schimmelpfennig & Glaser (2012) concluded that soil applications of biochar comprising of the following will be effective carbon isolation agents. The oxygen to carbon to hydrogen ratio is an indicator of the level of carbonization that impacts the long-term viability of biochar in soil. The presence of black carbon should be more than 15%. They also offer other criteria, such as N2 -Brunauer-Emmett-Teller surface area of more than 100 m2 g1 (which might aid in predicting the impact of biochar on soil moisture levels) and advise that biochar PAHs be below safe levels in soils for use as a soil supplement (Schimmelpfennig & Glaser, 2012, pp. 1011 — 1012).

To detect biochar that includes phytotoxic chemicals, Rogovska et al (2012) employed aqueous biochar extracts to carry out conventional germination experiments including analyses of seedling stage development. They conducted experiments on maize and found that biochar generated by high-temperature gasification and pyrolysis decreased the shoot length and root length of the maize, whereas biochar pyrolyzed at lower temperatures did not. The authors postulate that the inclusion of the discovered PAHs, especially naphthalene, that was present within the biochar isolates of high-temperature biochar was likely what caused the reduction in stem and root length. The findings from Schimmelpfennig & Glaser (2012) and Rogovska et al (2012) support each other for the development of low-cost, quick biotoxicity tests that may be used to spot biochars that have harmful impacts. In four quick toxicity evaluation tests that lasted less than two weeks, the authors used one biochar and one hydrochar, materials created by hydrothermal carbonization of biomass in an aqueous suspension with reasonable pressure levels and higher temperatures (Funke and Ziegler, 2010, pp. 160 — 175). The tests involved the evaluation of earthworm avoidance, barley plant growth and re-growth, lettuce sprouting, and capsicum germination. Apart from the hydrochar, which had poor results in all four experiments, detrimental consequences were not seen with the biochar. The findings are encouraging since they were based on rapid, simple, and reasonably priced techniques that may be utilized by manufacturers and other consumers globally.

2.3.2 The effects of biochar on some plant types

The effects of biochar on plant development are discussed in the paragraphs that follow. In the trials of Ippolito et al (2014) during which they administered a single sample of hardwood biochar to an arid soil at a rate of 22.4 Mg ha^{-1}, noting no difference in maize silage production compared to control after 1 year, but a 36% output decline in year 2 compared to the controls. According to the nutrient concentrations in corn, the decreased production was caused by either a decrease in the availability or absorption of nutrients such as nitrogen, sulphur, and Magnesium. The reaction was comparable to a priming effect seen in soils with low levels of organic carbon (Zimmerman et al, 2011, pp. 1169 — 1177). In this case, the biochar may have caused a decrease in soil carbon decomposition, which in turn inhibited the availability of at least soil nitrogen and sulphur.

Schnell et al. (2012, pp. 1044 —1050) added up to 3 Mg ha-1 of biochar made from sorghum to an Alfisol before growing the crop for 45 days. Because of the low application rates of biochar, there was no difference in biomass output between the control and biochar treatments. According to Spokas et al. (2012), the authors speculate that a lack of yield response may have been caused by inadequate nutrient recovery in plants cultivated in biochar-treated soil. Based on the findings of Kammann et al (2012, pp. 1053 —1065), The author set out to grow ryegrass, then injected 50 Mg ha^{-1} of biochar made from peanut hulls to a German Luvisol. As compared to controls, the authors saw a significant increase in biomass output. Unknown factors may have contributed to the increase in yield, including decreased nitrogen loss to denitrification and higher N absorption by plants cultivated near biochar. According to Gaji & Koch (2012), they also used a German Luvisol to grow sugar beet on soil that had been treated with either 10 Mg ha^{-1} of hydrochar made from beer draff or sugar beet pulp. In all trials, plant development abruptly stopped or significantly decreased after emergence and final crop yield was lower than that of the control. The authors conducted a comparable trial using hydrochar administered at 30 Mg ha^{-1}, a German Cambisol, with identical outcomes (Gajić & Koch, 2012, p. 1069).

The findings of this study are in line with those of other studies (Lehmann et al, 2011, pp. 1812 — 1834; Hilber et al, 2012, pp. 3042 — 3048; Kuzyakov and Bol, 2006, pp. 747 —757), which imply that materials with significant levels of bioavailable carbon (such as hydro char) might reduce plant accessible nitrogen and yields owing to immobilization. These findings suggest that although certain biochar and hydrochar might boost agricultural yields, others can reduce crop yields. What is missing is a thorough scientific knowledge of how different types of biochar affect yields, either negatively or positively. To create production processes that result in biochar that is optimal for certain crop-soil-environmental systems, future research should concentrate on a deeper understanding of the interactions between biochar and plants.

2.3.3 Using Biochar to reduce organic and inorganic contaminants

Aqueous systems have traditionally been purified using charcoal (Ippolito et al, 2012, pp. 967—971). Considering this, a study examined how biochar may be used as a medium for the absorption of heavy metals, phosphorus, and antibiotics. According to Uchimiya et al (2012, pp. 5035—5040), metals must interact with biochar through electrostatic interactions, cation and electron exchange, adsorption via proton exchange, or ligand binding for stabilization to take place.

The researchers evaluated the absorption of Lead, Copper, Nickel, and Cadmium to an Ultisol in South Carolina that had been modified using five distinct forms of manure biochar such as dairy, asphalt feedlot, swine solids, chicken litter, and turkey litter and exposed to high temperatures at either 350 or 700 degrees Celsius. Applying biochar to this type of soil improved the preservation of heavy metals as determined by the amounts in steady state aqueous extracts, which were significantly lower for Lead, Copper, and Cadmium or barely lower for Nickel than metal levels in aqueous extract of the regulated soils, soil without biochar (Ippolito et al., 2012). Ultisols, which get their name from the Latin ultimus, or "last," are acidic, heavily leached forest soils with a poor natural fertility. They are mostly found on older, stable landscapes in moist temperate and tropical regions of the globe. (*Ultisols*, n.d.)

An experiment was conducted in which quinoa was cultivated on sandy soil with 0, 50, or 200 mg of copper per kilogram, as well as 0, 2, or 4% by weight of biochar made from green waste from harvested forests. Without biochar, plants had significant stress signs at 50 mg of copper per kilogram and were dead at 200 mg. The quantity of biochar was increased, which decreased plant stress and plant uptake of copper Ions. Plant biomass with amounts of 4% (80 Mg ha^{-1}) biochar and 200 mg Cu kg^{-1} was almost as high as that of the controlled soils. According to the authors, the improvement in plant growth was brought about by a decrease in copper toxicity, which was most likely caused by copper binding to negatively charged carboxylic acid groups in biochar, a rise in soil pH, or a rise in the volumetric soil water content, all of which essentially diluted the soil solution's copper concentrations. (Buss et al, 2012, pp. 1157 —1164)

Streubel et al. (2011, pp. 1402—1412) exploited biochar to remove phosphorus from dairy lagoon wastewater that was produced by pyrolyzing dairy fiber from anaerobic digesters. They continually circulated wastewater over pelletized biochar using a closed loop system; the biochar removed 380 mg P L^{-1} (the original dairy lagoon wastewater phosphorus content was around 550 mg L1). This was equivalent to a decrease in phosphorus content in the wastewater of almost 70%. Also, the Phosphorus preserved on the biochar was a mixture of adsorbed orthophosphate and Ca-PO_4 precipitates, suggesting that biochar wastewater filters might help retrieve Phosphorus in forms that are accessible to plants. (Streubel et al, 2011, pp. 1410 —1412)

A study was conducted where it was investigated how biochar affected the transformation of the bioavailable and dangerous form of chromium, Cr(VI), into the highly bound and harmless form, Cr(III). The scientists evaluated the outcomes between acid-activated black carbon from a weedy plant and biochar made from chicken dung. In two different soils, 0 or 50 mg kg1 of biochar or activated black carbon and 0 or 500 mg kg1 Cr were added (VI). For up to 14 days, soils were nurtured at full field capacity. The findings demonstrate that chicken dung biochar lowered between 198 and 219 mg kg1 over the course of the 14-day incubation, whereas activated black carbon converted all of the Cr (VI) to Cr (III) within six to ten days. The anticipated half-life for Cr (VI) reduction by biochar was between 10.7 and 11.4 days. While the study's time limit did not allow for a complete reduction of Cr (VI) to Cr (III) by biochar, the findings suggest that both biochar and acid-activated black carbons may be able to contribute to the reduction of Chromium (VI) in polluted soils. (Choppala et al, 2012, pp. 1175 —1183)

Livestock manures may contain significant amounts of antibiotics that have not yet been metabolized and up to 90% of the constituent compounds may be expelled; Sarmah et al, 2010, pp. 648—657); using these manures as natural fertilizers may result in the emergence of soil microbes resistant to antibiotics. Tylosin, a popular veterinary antibiotic, is known to travel through soils, however, according to the findings of Paik et al (2012, pp. 55 - 60), it was demonstrated that both hardwood and softwood biochar treatments greatly reduced this mobility. When the biochar additions grew from 0 to 10% by weight, the quantity of tylosin that was leached from forests and cornfield soils decreased. The amount of tylosin released from the soils decreased as the rate of biochar application increased, potentially as a result of tylosin's permanent surface bonding or trapping inside biochar nanoparticles (Spokas et al, 2009, pp. 974—987).

The findings mentioned above imply that biochar may be useful for collecting and recycling elements in wastewater streams as well as for isolating bio-based metals and antibiotics from polluted soils. It is necessary to do further study on a wide range of soil types affected by environmental deterioration. Custom-made biochar might trap mobile organic phases or absorb less readily stable metals like Cadmium and Nickel (Ippolito et al, 2012, p. 970). Commenting further on the findings, Ippolito et al (2012, p. 968—971) believe that before the large-scale potential application of biochar in contaminated soil start, it is necessary to identify the sorption processes and dynamics of pollutants, quantify the loading capacities of biochar, and record the outcome of pollutants in biochar-amended soils. It would be beneficial to compare the price and effectiveness of biochar with other pollutant mitigation techniques.

2.3.4 Effects of Biochar on greenhouse gas emissions

For soils, biochar is a powerful tool for sequestering carbon. Although some organic carbon is present in hydro char and low-temperature biochar, this carbon is typically more stable in soils than the carbon found in the original biomass; the carbon in biochar produced by moderate and high-temperature pyrolysis is very secure against biodegradation and will thus remain for centuries or even thousands of years in soils. Nevertheless, adjustments in net primary crop production, improvements in the efficiency of residue mineralization or humification, soil organic matter cycling, and emissions of Methane and Nitrous oxides can affect the net greenhouse gas effect caused by applying biochar to soil. Additionally, Green House Gas emissions from biochar manufacturing, transportation, and soil application themselves must be included in the total effect of biochar additives. (Ippolito et al., 2012)

In an experiment designed by Yao and Zhang (2012), biochar in quantities around 20 Mg per hectare prepared from either pig-excreted waste that was pyrolyzed at 600–800°C or barley stover that was pyrolyzed at 320°C, to two different soils. Next, over 36 days, they monitored the levels of CO_2, CH_4, and N_2O emissions. Depending on the kind of biochar used and the state of the soil, discrepancies were obvious. When biochar containing higher concentrations of nitrogen (such as swine manure biochar) was applied, nitrogen-deficient soil emitted less CO_2 and CH_4, although the decrease in CO_2 and CH_4 emissions were probably compensated by an increase in nitrogen dioxide emissions. (Yao et al, 2012, pp. 1467—1469)

When barley stover biochar was applied to either soil, emissions of greenhouse gases were not enhanced; consequently, Yao & Zhang (2012, pp. 71—75) argue that this biochar is the better amendment material. Kammann et al (2012, pp. 1053—1059) evaluated the effect of peanut husk biochar that was made pyrolyzed between 500 and 800°C and hydrochar that was pyrolyzed at 200°C without or with the addition of organic fertilizers, on soil Greenhouse gases in multiple laboratory incubation trials. Apart from the case combining long-term high soil water levels with inorganic Nitrogen fertilizer additions, other biochar amendment scenarios reduced N_2O emissions significantly. When compared to control soils, biochar treatments resulted in the same or lower emission of CO_2, N_2O, and CH_4. Hydrochar applications resulted in higher CO_2, N_2O, and CH_4 emissions as compared to biochar, and hence may not be a viable material if carbon sequestration is a goal. (Yao et al, 2012, p. 1470)

Augustenborg et al (2012, pp. 1203—1208) assessed nitrogen dioxide and carbon dioxide emissions after applying either peanut husk pyrolyzed at 500°C or Miscanthus pyrolyzed at 550°C biochar to low- or high-organic matter soils with or without soil-feeding earthworms. In the absence of earthworms, the scientists discovered that biochar additions significantly decreased both CO_2 and N_2O emissions when compared to no-biochar controls. Earthworms increased N_2O emissions from controls by up to 13 times; however, both biochar types significantly decreased N_2O emissions when earthworms were present.

It was discovered by Yao and Zhang (2012, pp. 1467—1470) and Kammann et al (2012, pp. 1052—1065) that biochar generated at pyrolytic temperatures resulted in a larger decrease in accumulated CO2 emission than biochar produced at lower pyrolytic temperatures. Abdul et al. (2011, pp. 14038—14043) assessed cumulative CO_2 emitted from three soils supplemented with nothing, wheat straw, hydrochar that was pyrolyzed at 200°C, low-temperature pyrolyzed biochar like sewage sludge pyrolyzed at 400°C or charcoal that was pyrolyzed at 550°C for one year. Cumulative CO2 emissions were typically released in the following order: wheat straw then hydro char then low-temperature biochar then finally charcoal. The study concluded with the fact that the biochar selected should be appropriate for the purpose, with high temperature pyrolyzed biomass being beneficial for soil carbon storage and biomass pyrolyzed at low temperatures may be better for improving soil fertility.

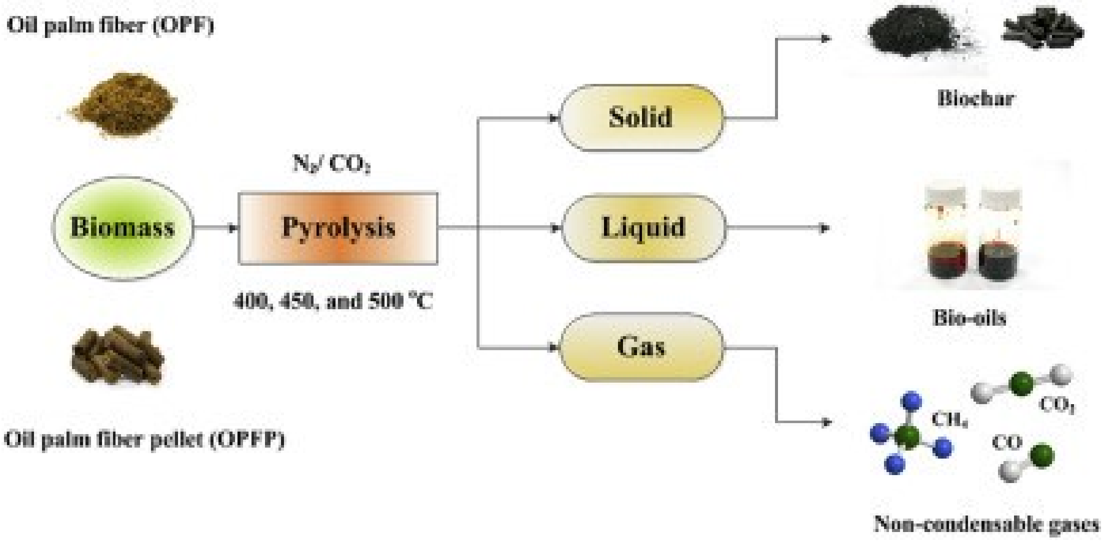
To conclude this section, it is evident that previous works have been done that improve society's understanding of the effects resulting from biochar application, and, in addition to that, the previous works also indicate that there is room for improvement. Numerous publications claim that the type of feedstock, pyrolysis process method, and pyrolysis parameters affect the characteristics of the resultant biochar, ad that biochar qualities impact the environment in an ideal world, we should design types of biochar that have qualities that are suited for a particular agricultural or environmental purpose. While this concept could be realizable for a select few valuable applications, the available possibilities for most applications will be constrained by cost considerations. On the contrary, the principle of "first, do no harm" must serve as the basis, and along with economic optimization, the equilibrium between the advantages and disadvantages will inevitably dictate the accessibility of biochar for use in environmental and agricultural situations and the options that are available to use it. (Ippolito et al, 2012, p. 969)

2.4 Pyrolysis

Organic molecules heated without oxygen break down into simpler compounds during the thermal decomposition process known as pyrolysis. The organic material is heated to a high temperature during pyrolysis, usually between 300 and 900°C, which causes it to break down into solid, liquid, and gas components. The type of organic material being pyrolyzed, together with the temperature and length of the pyrolysis process, all affect the end products. A range of organic resources can be transformed into useful products using the flexible process of pyrolysis. For instance, biomass can be pyrolyzed to create biofuels like bio-oil and syngas or other products like activated carbon and biochar. Moreover, pyrolysis can be used to remediate hazardous waste by turning it into non-hazardous compounds, as well as to transform waste plastic into fuel or other chemicals. Pyrolysis is a promising technique that provides a way to transform waste materials into useful goods while also lessening the environmental impact of waste disposal. There are various versions of pyrolysis operations which are based on the operation conditions and the type of the feedstock. (Andleep, 2021)

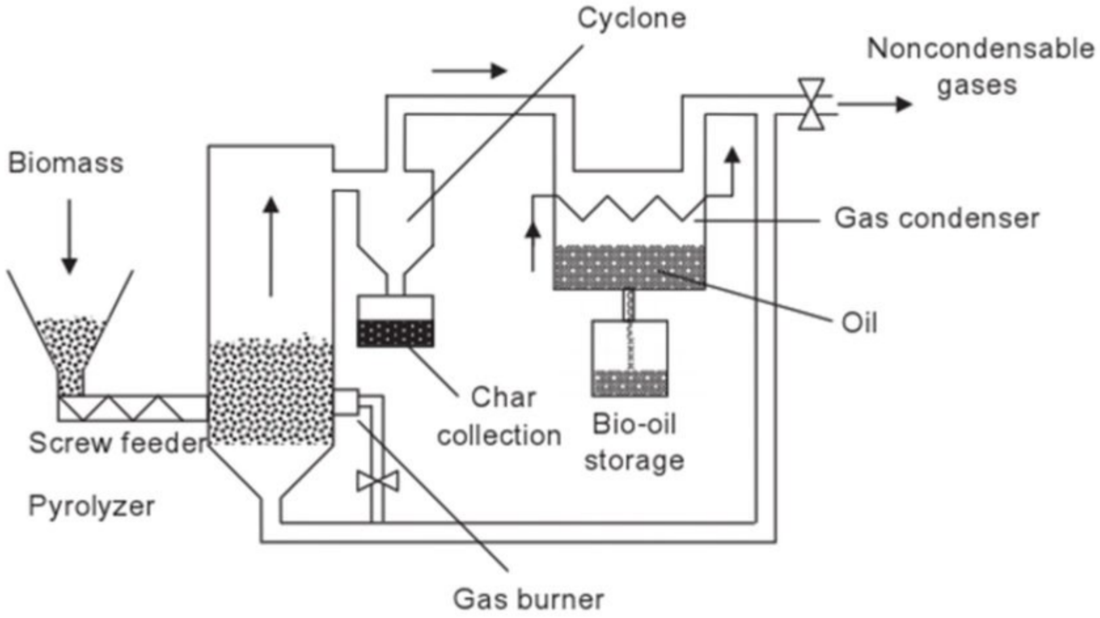
The first thing that comes out of pyrolysis are gases that can condense and solid char. The condensable gas could decompose even more into syngas gases like, Carbon monoxide, carbon dioxide, Hydrogen, and Methane, bio-liquid, and char (Figure 2). This breaking up happens partially via homogeneous reactions in the gas phase and partially through heterogeneous reactions in the gas-solid phase. In gas-phase reactions, the vapor that can condense is broken up into smaller molecules of gases that can't condense, like carbon dioxide and carbon monoxide. The pyrolysis process can be defined by the chemical equation: $C_nH_mO_p \rightarrow \sum liquid\ C_aH_bO_c + H_2O + Char$ (Prabir Basu, 2010, p. 68).

Figure 2. Pyrolysis products (Chen & Lin, 2016, p. 571)



In principle, the pyrolysis process can be defined by the chemical equation: $C_nH_mO_p \rightarrow \sum liquid\ C_aH_bO_c + H_2O + Char$ (Prabir Basu, 2010). In the schematic of a conventional pyrolysis plant, Figure 3 demonstrates the procedure. The temperature at which pyrolysis begins is reached when biomass is introduced to a pyrolysis reactor with hot solids such as a fluidized bed. Although the biomass's condensable and non-condensable vapors escape the chamber, the solid char that is created is shared between the chamber and the gas. After the reactor, the gas is extracted from the biochar and cooled. Bio-oil or pyrolysis oil is formed when the condensable vapor condenses; the non - condensable gases are released as product gas. These gases may either be discharged for additional uses or burned and resupplied to the pyrolysis reactor, as shown in Figure 3. Likewise, the liquid char may be collected and sold, solid char can also be burnt in another reactor to provide the heat required for pyrolysis. As there is no oxygen in this gas, it may be used in part as a heat transporter or fluidizing medium in the pyrolysis chamber. (Prabir Basu, 2010, p. 68)

Figure 3. Schematic layout of a pyrolysis plant (Jaiswal , 2020)



As was previously noted, pyrolysis entails the dissolution of huge, complicated molecules into several smaller ones. Its products are divided into three main categories:

- Solid (biochar)
- Liquid (bio-liquid)
- Syngas like carbon monoxide, water vapors, carbon dioxides, etc. (Basu, 2010, p.69)
- Biochar is the solid by-product achieved when biomass has been successfully pyrolyzed. While over 85% of it is carbon, it may also include some oxygen and hydrogen. Biomass has extremely little inorganic ash, in contrast to fossil fuels. Biomass char has a lower value for heating (LHV) of roughly 32 MJ/kg, which is much greater than its parent biomass or its liquid product (Diebold & Bridgwater, 1997, pp. 5—27). The liquid by-product, often referred to as tar, bio-oil, or crude, is a dark tar-colored fluid containing approximately 20% water content. Mostly homologous phenolic chemicals make up this substance. Complex hydrocarbons combined with

> significant quantities of oxygen and water make up bio-oil. Although the liquid product's lower value for heating is lower than the parent biomass's, which ranges from 19.5 to 21 MJ/kg dry weight basis, it is still higher than that of the parent biomass (Diebold & Bridgewater, 1997, p. 25).

The liquid output, often referred to as bio-oil, is a dark tar-colored fluid with up to 20% water content. Mostly homologous phenolic molecules make up this substance. Complex hydrocarbons with significant oxygen and water content make up bio-oil. (Prabir Basu, 2010)

Biomass' organic constituents such as cellulose, hemicellulose, and lignin are quickly and concurrently depolymerized and fragmented to create bio-oil. A typical process involves rapidly raising the temperature of the biomass, followed by an instantaneous cooling to "freeze" the intermediary pyrolysis by-products. Quick quenching is crucial because it stops additional cleavage, degradation, or molecular interactions. The continuous phase of bio-oil is an aqueous solution including the by-products of cellulose and hemicellulose degradation as well as tiny molecules from lignin decomposition. The pyrolytic lignin macromolecules dominate the discontinuous phase (Piskorz et al, 2001, p. 978). Typical components of bio-oil include cellulose, hemicellulose, and lignin polymer molecular particles that survived the pyrolysis conditions (Diebold & Bridgwater, 1997, pp. 18—22). Condensed bio-molecular oil's weight might be more than 500 Daltons according to Diebold and Bridgwater (1997). Based on the findings of Piskorz et al (2001, pp. 977—996), bio-oil contains the following five major types of compounds:

- Hydroxy aldehydes
- Hydroxyketones
- Sugars and dehydrosugars
- Carboxylic acids
- Phenolic compounds

Both condensable gases and syngas gases are produced during the normal breakdown of biomass. The heavier-molecule-containing vapours cool and condense, increasing the amount of liquid produced by pyrolysis. Syngases including CO_2, carbon monoxide (CO), methane (CH_4), ethane (C_2H_6), and ethylene (C_2H_4) are present in the syngas mixture. When cooler temperatures are introduced to the syngas, they do not condense. Secondary gases are additional syngas gases created by subsequent cracking of the vapor. Hence, a combination of primary and syngas make up the finished syngas gas product. Typically, primary gases have a Lower Heating Value (LHV) of 11 MJ/Nm^3, but pyrolysis gases, which are created when a vapor undergoes significant secondary cracking, have a substantially higher LHV of 20 MJ/Nm^3 (Diebold & Bridgwater, 1997, p. 20).

2.4.1 Types of Pyrolysis

Pyrolysis can be generally categorized as slow pyrolysis and fast pyrolysis based on the rate of heating. If the time, $t_{heating}$, needed to heat the biomass to the pyrolysis temperature, t_r , is significantly longer than the typical pyrolysis reaction time, it is called slow pyrolysis. That is to say:

- Slow pyrolysis: $t_{heating} > t_r$
- Fast pyrolysis: $t_{heating} < t_r$ (Basu, 2010, p. 71)

If we consider a straightforward linear heating rate (T_{pyr} /$t_{heating}$, K/s), then these conditions may also be represented in terms of heating rate. The rate constant, k, measured at the pyrolysis temperature is defined as 1 divided by the typical reaction time, t_r, for a single reaction (Probstein and Hicks, 2006, p. 63). Further variations exist based on the medium and pressure with which the pyrolysis is conducted. Every procedure has its distinctive products and uses depending on the operating circumstances. The following list includes three different forms of pyrolysis: (1) slow pyrolysis, (2) rapid pyrolysis, and (3) hydropyrolysis, the first two of which are dependent on the pace at which the material is heated. Both slow and quick pyrolysis often take place without a medium. Other kinds include hydrous pyrolysis (in water) and hydropyrolysis (In hydrogen), which are both carried out in their mediums. These kinds are mostly employed in the manufacturing of chemicals. The vapor residence time which is the residence period of the vapor in the reactor takes minutes or longer in slow pyrolysis. The two forms of this procedure—carbonization and conventional—are both predominantly utilized for the manufacturing of char. The vapor residence period in rapid pyrolysis lasts for seconds, even milliseconds. The two primary varieties of this pyrolysis, which are typically utilized to produce bio-oil and gas, are flash and ultra-rapid pyrolysis. The comparison of different pyrolysis processes can be seen in Table 1. (Basu, 2010, p.72)

Table 1. Comparisons of different pyrolysis processes (Prabir Basu, 2010, p.72).

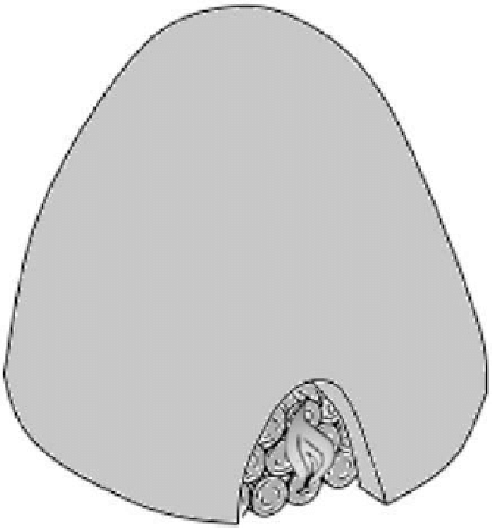
Pyrolysis process	Residence Time	Heating Rate	Final Temperature/ °C	Products
carbonization	Days	Very low	400	Charcoal
conventional	5 to 30 mins	Low	600	Char, bio-oil, gas
fast	Less than 2s	Very high	Approx. 500	Bio-oil
flash	Less than 1s	High	<650	Bio-oil, chemicals, gas

Ultra-rapid	< 0.5s	Very high	Approx. 1000	Chemicals, gas
vacuum	2 to 30s	Medium	400	Bio-oil
hydropyrolysis	< 10s	High	< 500	Bio-oil
Methanol-pyrolysis	< 10s	High	>700	Chemicals

2.4.2 Slow pyrolysis

The main objective of the slow pyrolysis process known as carbonization is to produce charcoal or char. As it has been in use for so long, it is the earliest type of pyrolysis. To optimize the development of char, the biomass is gently heated without oxygen to a relatively low temperature (400 °C) for a lengthy period. Historically, this process continued for many days. A typical beehive oven is seen in Figure 4, where big logs are piled and protected by a clay wall. The necessary heat was generated at the bottom by a tiny fire, and it virtually remained inside the tightly sealed, well-insulated chamber. Condensable vapor can be transformed into biochar and syngas with enough time provided by carbonization. The three main types of pyrolysis products are produced in conventional pyrolysis, that is, gas, liquid, and biochar. Consequently, the biomass is heated to a moderate temperature (about 600 °C) at a moderate pace. The product's residence period is measured in minutes. (Prabir Basu, 2010, p.72)

Figure 4. Beehive oven as a fixed pyrolyzer for charcoal production (Bamido, 2018)



2.4.3 Fast pyrolysis

Maximizing the output of liquid or bio-oil is the main objective of fast pyrolysis. The biomass is heated so quickly that it achieves the maximum temperature for the pyrolysis reaction before it begins to break down. If bio-oil is the desired result, the heating rate can range from 1000 to 10,000 °C/s, but the peak temperature needs to be below 650 °C. Conversely, if gas production is the main concern, the peak temperature may reach up to 1000 °C. Very rapid heating, reaction temperatures between 425 and 600 °C, a short residence period of 3 seconds for vapor in the reactor, and quick quenching of the product gas are four crucial characteristics of fast pyrolysis that aid in increasing the liquid yield. (Basu, 2010, pp. 72—73)

2.4.4 Flash Pyrolysis

During flash pyrolysis, biomass is quickly heated without oxygen to temperatures between 450 and 600 degrees Celsius, which are comparatively low. Condensable and non-condensable syngas is mixed in the product, which exits the reactor after a brief residence period of 30 to 1500 milliseconds (Bridgwater, 1999, pp. 4—10). The condensable vapor is subsequently condensed into bio-oil, a liquid fuel, after cooling. This kind of technique boosts liquid output while decreasing char generation. In flash pyrolysis, the yield of bio-oil is typically between 70 and 75 percent of the overall pyrolysis product. (Basu, 2010, p.73)

2.4.5 Ultra-rapid pyrolysis

During ultra-rapid pyrolysis, biomass and a heat-carrying solid are combined very quickly, leading to an elevated rate of heat transfer and, therefore, heating rate. The pyrolysis takes place in its reactor and is followed by a quick quenching of the main product. The hot heat-carrier solids are returned to the mixer after being separated from the syngas gases and principal product vapors by a gas-solid separator. After that, they are heated in a different combustor. An essential characteristic of ultra-rapid pyrolysis is a tightly regulated, brief residence period. To increase the prospects of gaseous by-products, t The pyrolysis temperature is roughly 1000 °C to produce gas and approximately 650 °C for liquid by-products. (Prabir Basu, 2010, p.73)

2.5 Challenges of the traditional pyrolysis methods

In the previous section, the traditional methods were briefly reviewed, and, in this section, the challenges of such methods will be briefly discussed.

The traditional pyrolysis methods are slow, fast, flash, and ultra-flash pyrolysis. Though those methods offer some benefits, there are also some challenges linked to their application. Slow pyrolysis is disadvantageous in that there can be long processing times. Slow pyrolysis can take several hours to several days to complete, which can limit its commercial viability for large-scale production. Another challenge is the low yield of bio-oil. Slow pyrolysis typically produces a lower yield of bio-oil compared to other pyrolysis methods, which can limit the economic viability of the process. There are also limited feedstock options. Slow pyrolysis is typically used with wood and other lignocellulosic materials, which limits the types of feedstocks that can be used (Basu, 2010, p. 72). Yet another challenge of this process is the release of greenhouse gas emissions. Slow pyrolysis can produce emissions of greenhouse gases and other pollutants, particularly if the process is not properly controlled or the feedstock is not properly prepared. This is mostly because it takes a long time to complete. The final challenge is cost. Slow pyrolysis requires a significant amount of energy to maintain the required temperature for an extended period, which can increase the cost(Basu, 2010, pp. 72—75)

Somehow, since all these processes belong to the family of pyrolysis processes, they have several disadvantages in common. With fast pyrolysis, it also has increased operating costs, primarily due to the requirement of maintaining a high temperature for some time. The difference here is that the period is much shorter, but the demand for a higher temperature plays a central role in affecting the costs. There is also the challenge of contaminating the by-products, which exists in all other forms of pyrolysis too. The end products of fast pyrolysis, such as bio-oil and biochar, can be contaminated with impurities such as heavy metals and other pollutants if the feedstock is not properly prepared or the pyrolysis equipment is not properly maintained. Like slow pyrolysis, there is also the challenge of greenhouse gas emissions in fast pyrolysis. Similarly fast pyrolysis can produce emissions of greenhouse gases and other pollutants, particularly if the process is not properly controlled.

Since liquid and gaseous by-products are more favourable in fast pyrolysis, one challenge therein is that the bio-oil produced by fast pyrolysis requires further upgrading to remove impurities and improve its properties, which can increase costs and reduce the overall efficiency of the process. Similarly, ultra-rapid pyrolysis is comprised of the same challenges to a great extent. There are also the challenges of high operating costs, contamination of the end products, emissions, and inefficiency.

2.6 Advantages of using an automation system for pyrolysis

Pyrolysis is a process of decomposing organic materials by heating them in the absence of oxygen. It is a promising technique for producing valuable products like biofuels, activated carbon, and biochar from waste biomass. However, pyrolysis is a complex process that requires precise control over various parameters such as temperature, pressure, residence time, and feedstock composition. This is where automation can help. The use of automation in pyrolysis has several advantages. Firstly, it improves process efficiency and reduces energy consumption by optimizing the operating conditions. For example, automated control systems can adjust the temperature and residence time to ensure the maximum yield of the desired product with minimum energy input. Secondly, automation enhances product quality and consistency by reducing the variability in feedstock composition and processing parameters. By monitoring the process variables in real-time and adjusting as needed, automation can produce more uniform and high-quality products.

Thirdly, automation improves safety by reducing the risk of human error and exposure to hazardous materials. Automated systems can detect and respond to process deviations quickly, preventing accidents and minimizing downtime. In summary, the advantages of using automation in pyrolysis include increased efficiency, improved product quality and consistency, and enhanced safety. As the demand for sustainable and renewable products grows, automation will play an increasingly important role in the development and commercialization of pyrolysis technologies.

3 Automation System Design

3.1 What is an automation system?

An Automation system is a system that combines the use of sensors, actuators, and controllers to operate a process such that little to no human input is required. In an automation system, some devices receive input such as a sensor or human-machine interface, a control system for processing, and actuators that perform the work. All components are important but the most crucial component in this system is the control system.

Control systems can be further divided into two subgroups such as an open-loop control system and a closed-loop control system. In an open loop control system, the behavior of the controller is not affected by the output of the system, i.e., there is no feedback. In a closed-loop system, the controller’s behavior is affected by the output of the system, i.e., there is feedback. The controller produces a control value based on an error which is the difference between the target value and the actual output value of the process. The controller processes the feedback signal and compares the process output to the desired output and if the desired output has not been attained, then it fine-tunes the signals that are transmitted to the actuator until the target value has been achieved. (Industrial Quick Search*,* n.d.)

3.1.1 Levels of an automation system

More specifically, an automation system can be thought of as being divided into three levels namely, the field level, the control level, the supervisory level, the planning level, and the management level. Essentially at the field level, there are all sensors, actuators, and controllers. The field level is any area in some building such as a factory, where the field devices are in full operation to control and monitor a process. PLCs and PID's operate at the control level. Here, the field devices are manipulated. The PLC intake data from all other field devices and based on a program, decide what actions are performed. At the supervisory level, SCADA which stands for supervisory control and data acquisition, is used to access digital information and control systems from a single point. Human-machine interfaces are commonly found at supervisory levels. (Kumar, 2019)

3.1.2 Advantages of an automation system

By utilizing an automation system, many advantages can be wrought in a process. Benefits are abundant to an automation system that spans across different industries and businesses. By implementing an automation system, one can expect to increase efficiency and productivity. In the context of a factory, when repetitive tasks such as taking measurement samples at regular intervals are automated, then the employees can focus their attention on more cognitively demanding tasks such as developing plans to increase process efficiency. When the efficiency is increased, it follows suit that the productivity will also increase. The result will be that the turnaround time for projects and tasks will be reduced. Cost savings are another benefit of process automation. Organizations can cut labor expenses, lower the possibility of mistakes and delays, and eliminate the need for physical work by simplifying operations. Automation can also help minimize waste and maximize resource use, which will eventually result in additional cost savings. (Impact Networking, 2021)

Process automation could also result in an improvement in quality control. Organizations can make sure that goods and services conform to the intended degree of consistency and quality by standardizing processes and automating quality checks and inspections. This will lower the likelihood of mistakes and problems. Process automation could also result in an improvement in quality control. Organizations can make sure that goods and services conform to the intended degree of consistency and quality by standardizing processes and automating quality checks and inspections. This will lower the likelihood of mistakes and problems. (*Impact Networking*, 2021)

In terms of better data management, by lowering the possibility of human error and guaranteeing that the data is correct and current, automation can also aid enhance data management. Moreover, automation can facilitate more effective data organization and analysis, resulting in greater insights and decision-making. Automation can also boost flexibility and scalability. Organizations can scale up or down operations more quickly in response to changes in demand by automating procedures. This can aid businesses in becoming more agile overall and adjusting to shifting market conditions. Automation can also contribute to improved compliance and security. Organizations may make sure they are complying with legal standards and maintaining the proper level of protection for sensitive data by automating operations like record keeping and reporting. (*Impact Networking*, 2021)

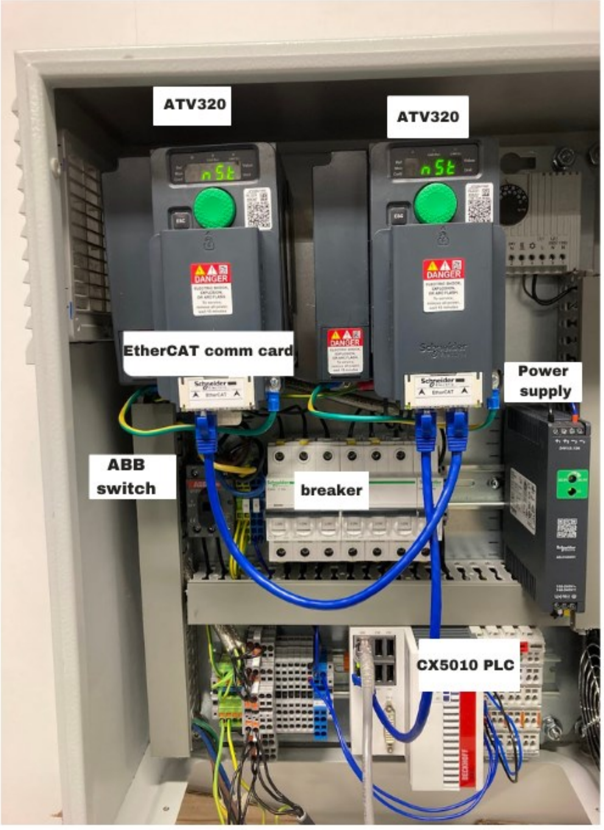
3.2 Components of the automation system

3.2.1 Hardware

In this section, the components intended for the automation system will be covered. It will cover the hardware so that the system could function as intended. On the hardware side, a control cabinet from the manufacturer Rittal was deployed. The depth of the cabinet enclosure was determined based on the deepest component of the system which are the speed drives. The drives had a depth of 158 mm each. The Rittal compact enclosure AX was selected with a depth of 210 mm since it was the closest to the depth of the motors. When selecting the cabinet, it is important not to select it too small or too big. The width of the motor was 140 mm, and the height was 184 mm. The width and height of the cabinet were 380 mm and 300 mm respectively. Additionally, the enclosure had an IP protection category of IP 66 as defined by IEC 60 529 (Rittal, n.d.). The motors that were used were Schneider variable speed drives, Altivar ATV320s with model number ATV320U11N4C. These speed drives were three phases connected with a rated supply voltage of 380 to 500V AC and a nominal voltage rating of 1.1 kW (Schneider Electric, n.d.-b). The optional communication card was used to enable communication directly with the motor, that is the EtherCAT communication module VW3A3601 which had two RJ45 ports (Electric, n.d.-b). Thermocouples and transmitters from the manufacturer RS were also implemented in the system.

The motors had a class C2 EMC filter integrated and an IP20 protection rating (Electric, n.d.-d). In the cabinet, there were also PLC components such as a CX5010 embedded PC with an Intel Atom Processor and several other IO cards such as KL9010, KL2134, and KL1104 (Beckhoff, n.d). They were miniature circuit breakers such as Schneider Acti9 iC60L 3 phase with a 10 Ampere current rating and the iC60N 1 phase miniature circuit breaker with a 6 Ampere current rating. The ABB switch disconnector OT16F3 was also in the cabinet along with a Schneider power supply ABLS1A24031. Terminal blocks and end clips from the manufacturer Phoenix contact were also in use. The cabinet including all these devices is visible in Figure 5 below. A fan was used to remove excess heat to prevent overheating. The fan was controlled by a Rittal SK3110 thermostat. This thermostat is suitable for controlling of fans, heaters, and heat exchangers. Additionally, it can be deployed to monitor the temperature of the cabinet by acting as a signal generator. (Rittal, n.d.)

Figure 5. Cabinet layout



The Veto 60kW biomass boiler (Figure 6) by Ala-talkkari was also in use. This biomass boiler was intended to heat individual residences and modestly sized buildings (Ala-Talkkari, n.d.). This boiler is visually appealing because of its new red-black design (Ala-Talkkari, n.d.). It was designed to be more user-friendly than previously with the new gauge and the hatches (Ala-Talkkari, n.d.). When ordering this kind of boiler, the consumer may choose the boiler's orientation such that the burner head can be on the left side, on the right side, or at the front (Ala-Talkkari, n.d.).

Figure 6. Veto-60 Kw biomass boiler

3.2.2 Software

The main software that was in use was the TwinCAT software made by Beckhoff. The version used was 3.1 build 4024.35. The programming languages SFC (Sequential Function Chart) and ST (Structured text) were predominantly deployed. TwinCAT is a software-based control system for industrial automation and machine control, developed by the German company Beckhoff Automation GmbH. It is a PC-based control software that combines real-time control capabilities with PLC, motion control, and visualization in a single integrated development environment (IDE). (Beckhoff, n.d.)

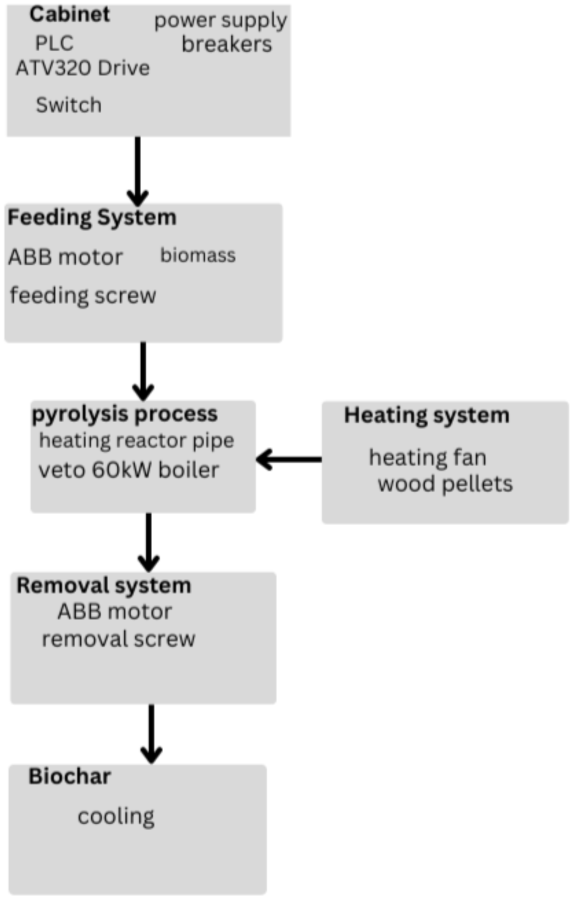
TwinCAT is used in a wide range of applications, including machine control, process control, robotics, building automation, and more. It is designed to be scalable, allowing users to choose the level of functionality they need based on the size and complexity of their application. (Beckhoff, n.d.)

TwinCAT supports a variety of programming languages, including ladder logic, structured text, and function block diagram. It also supports open communication protocols such as EtherCAT and OPC UA, which enable easy integration with other automation systems and devices. Overall, TwinCAT provides a comprehensive platform for industrial control and automation, allowing users to develop and deploy complex control systems quickly and efficiently. (Beckhoff, n.d.)

3.2.3 Process flowchart

The process was designed to operate logically, starting with the automation of the feeding and drying system and then ending with the removal and cooling of the biochar. The purpose of the flowchart is to make the entire process clearer and more readable so that in case where someone else would like to implement the same concept, it will be less troublesome to execute. The automation system starts with the devices in the cabinet such as the ATV320 speed drives, Beckhoff PLC, power supply, and miniature circuit breakers, and ends with the removal system where the ABB motor and the removal screw were utilized. The automation system is illustrated in figure 7 below. In its entirety, the automation system is comprised of the CX5010 embedded PC, the IO cards, power supply, speed drives, miniature circuit breakers, the main switch, the EtherCAT communication card, and the motors.

Figure 7. Automation system flowchart



3.2.4 Design Considerations and trade-offs

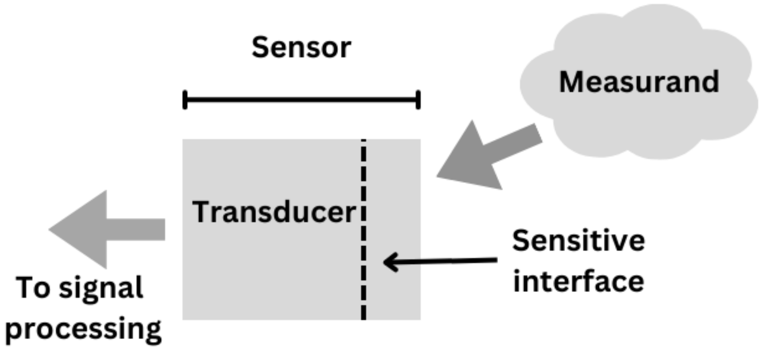
Several things had to be taken into consideration when designing this automation system, each of which will be discussed in this section. Due to the volume of the interior portion of the boiler and the overall shape of the boiler itself, careful attention had to be paid to the location of sensors and even the design of the reactor pipe itself. In this case, a curved design was employed, and the sensors were mounted at the front of the pipe close to the door and the middle. The space where the cabinet was stored had to be extended to facilitate the additional motor, screw, and cooling equipment. The door frame in front of the boiler had to be displaced to provide more space for the feeding system’s motor and screw which resulted in increased costs to implement the desired system.

3.2.5 Sensors and actuators used in the System

A sensor is a tool that reacts to inputs by producing meaningful outputs that may be processed. These outputs have a functional relationship with the input stimuli, also known as measurands. Although there are slight distinctions, the second word that is sometimes used in place of the term sensor is a transducer. An apparatus that transforms one kind of energy into another is called a transducer. Many different devices, including sensors, actuators, and transistors, may be referred to as transducers. (Kalantar-Zadeh, 2013, p.1)

A sensitive element and a transducer are the two main parts of a sensor in most cases. The sensitive element can interact with a target measurement object and alter the transducer's behavior. The transducer responds to this shift by producing a signal, which is then converted into usable data by a signal processing system (Kalantar-Zadeh, 2013, p.1). Systems designed by men to a great extent retrieve information from the external environment in the form of 0s and 1s then processes them and consequently make the data usable for an end-user. The central role of sensors in such a system is to retrieve information and thus by utilizing sensors, communication between the external environment and an internal system is made possible (Kalantar-Zadeh, 2013, p.2). The schematic of a sensor is presented in Figure 8.

Figure 8. Schematic of a sensor. (Kourosh Kalantar-Zadeh, 2013, p.2)



Sensors such as thermocouples were predominantly used. These were from the manufacturer RS. They were RS PRO Type K thermocouples with a length of 150 mm and 3mm diameter. Additionally, they could withstand temperatures from -40 to 1100 degrees Celsius. The thermocouples were mineral insulated with an accuracy of ± 1.5 °C. The probe diameter was 3mm each and they both complied with IEC standards (RS, n.d.) The thermocouples resemble the one shown the Figure 9 below

Figure 9. RS PRO Type K thermocouple. (RS, n.d.)

There were also temperature transmitters in use from the same manufacturer, RS. Temperature transmitters, as seen in Figure 10, are devices that receive signals from temperature sensors and then forward that signal to another device such as a PLC in a standardized format such as a 4 to 20 mA signal. A Controller receives the signal sent by the temperature transmitter, decides what action is necessary, and then produces the necessary output signal. Process control nowadays uses either a PLC or a DCS as a controller. (Mortenson, 2021)

The temperature transmitter in use was a platinum resistance Pt100 In-head temperature transmitter, with an operating temperature range of 0°C to 70°C. Its diameter is 43 mm, and it has a depth of 21 mm. It requires a supply voltage of 10 to 30V DC.

Figure 10. RS PT100 Temperature Transmitter. (RS, n.d.)

4 Control System Architecture

4.1 Control System Definition

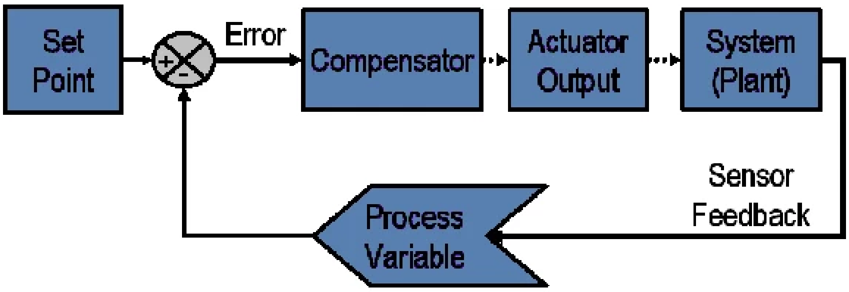
According to Distefano et al. (2013, p. 2) from an abstract point of view, a system is an arrangement of things connected or related in such a manner as to form an entirety or whole. If we rewrite the definition of a system from a slightly more scientific point of view, it is a collection of physical elements joined or related in a way that they form and/or function as a single unit (Distefano et al., 2013, p.1). During our day-to-day lives, there are control systems in full operation in nature. Before expounding upon this phenomenon, the words input, and output play an integral role in the transmission of the concept to the reader, hence they must be defined to make sense of what a control system is in its entirety. The input can be defined as a signal, whether digital or analogue that is sent to the control system to provoke a response from the system. The signal is from an external source. (Distefano et al., 2013, p.2)

The output, also called the process variable, is the response obtained from a control system which could be proportional to the magnitude of the input but not necessarily. Inputs can be in the form of physical variables or abstract quantities such as a setpoint or desired values for the output of the control system. The outputs and inputs of a control system are usually defined by the purpose of the control system, i.e., what process the control system will regulate. In some cases, if the input and output are given it is usually possible to identify the nature of the system components. Additionally, control systems could have multiple inputs and outputs. (Distefano et al., 2013, p.2)

4.1.1 Open-loop and closed-loop control system

Control systems are typically classified into two general categories such as open loop and closed-loop systems. The main difference between the two is that the closed loop utilizes feedback to maintain the process while the open loop does not utilize feedback. To define an open loop control system more formally, we could say that it is a system where the controller output is independent of the process variable. On the contrary, the closed loop is one where the controller output is directly dependent on the process variable. Feedback is a property of closed-loop systems that facilitates the comparison of the output to the input of the system so that the required controller signal can be produced as a function of the output and input. In a system that contains a closed sequence of cause-and-effect relations between system variables, it is highly likely that feedback exists (Distefano et al., 2013, p.4). A block diagram for a closed-loop system can be seen below in Figure 11.

Figure 11. closed-loop control block diagram. (National Instruments, n.d.)



4.1.2 Deadtime

Deadtime is a major process dynamics component in any process that involves the transfer of mass. It's the period following an adjustment to a process variable during which nothing is available about the condition of the process. The transit delay or time lag is another name for this phenomenon. Deadtime is the number one enemy of effective control, thus it's important to do all possible to reduce it. The existence of dead time in a process causes a rightward shift in the whole process's response curve. After the lag period, the process begins to react at its normal rate. (Wolfgang, 2005, p.84)

In the context of a pyrolysis system, the dead time is the time from the insertion of the biomass until it arrives at the reactor. Effective control aims to reduce dead time and the dead time to time constant ratio. The likelihood of the control system functioning correctly decreases as this ratio increases. Transportation delays may be decreased by increasing the motor speed and thus the feeding rate and by moving the feeding system closer to the reactor, etc., all of which have a positive impact on dead time. (Wolfgang Altmann & Macdonald, 2005, p.84)

4.2 Control algorithms

4.2.1 Feedforward control

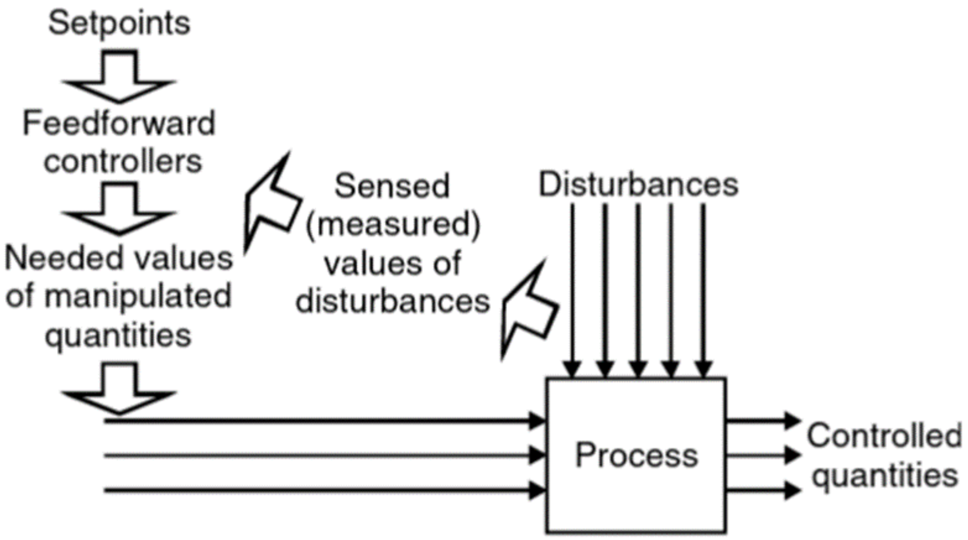
A process control system's feedback action gets very ineffectual in attempting to remedy these excessive deviations if big changes to the process variable or lag time happen. These variations often cause the process to operate outside of its normal range, and the feedback controller has a restricted chance of accurately or quickly correcting the process to the desired setpoint. Therefore, the process accuracy and quality deteriorate to an undesirable level. Before they may disrupt the closed or feedback loop characteristics, these disturbances are found and fixed via a feedforward controller as illustrated in Figure 12. To make the influence of the disturbance and feedback control equal, it is important to keep in mind that feedforward control does not consider the process variable; rather, it responds to felt or measured, or suspected process disturbances. (Wolfgang Altmann & Macdonald, 2005, p.142)

Feedforward control’s main purpose is to stop or reduce errors from entering or interfering with a control loop in a process. Within the confines of a closed-loop control system, mistakes brought on by process disturbances may be tracked down and corrected with the assistance of feedback. By using feedforward control, it is possible to anticipate and rectify mistakes of this kind before they influence the parameters of the control loop. (Wolfgang Altmann & Macdonald, 2005, p.142)

4.2.2 Automatic Feedforward Control

Figure 12 depicts the idea of automated feedforward control. It is possible to identify and quantify disturbances that are on the verge of entering a process. The values of the feedforward controllers' manipulated variables are then altered by the feedforward controllers based on the comparison of these measurements to the values of the controller's separate setpoints. (Wolfgang Altmann & Macdonald, 2005, p.143)

Figure 12. Automatic Feedforward control. (Wolfgang Altmann & Macdonald, 2005, p.143)

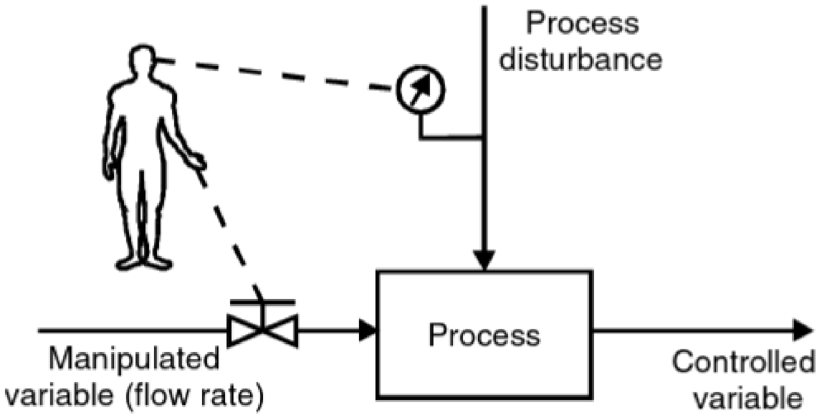


To be effective, feedforward controllers need to perform a wide variety of computations, from basic on/off logic to complex equations. All the precise impacts that the disturbances will have on the controlled variables must be included in these calculations. Although feedforward control is an appealing idea, it requires a high level of mathematical analysis and process knowledge from both the systems designer and the operator. For that reason, we won't often see feedforward control used in less crucial plant loops. In practice, feedforward control is often used as part of a larger feedback loop, where it helps the feedback controller operate by dampening the effects of excessive process disturbances. (Wolfgang Altmann & Macdonald, 2005, p.144)

4.2.3 Manual Feedforward Control

The notion of feedforward differs greatly from that of feedback control. Figure 13 depicts a hand-operated example of feedforward control. Here, the process operator detects and quantifies an incoming disturbance as it occurs. The operator then makes a calculated adjustment to the controlled variable to dampen the system's response to the observed disturbance. The success of this feedforward control method is dependent on the skill of the operator and their familiarity with the process. The controlled variable will wander from the target value if the operator makes a mistake or fails to foresee a disturbance, and if feedforward is the sole control, the error will persist. (Wolfgang Altmann & Macdonald, 2005, p.143)

Figure 13. Manual Feedforward control. (Wolfgang Altmann & Macdonald, 2005, p.143)



4.2.4 Selection and implementation of the control system

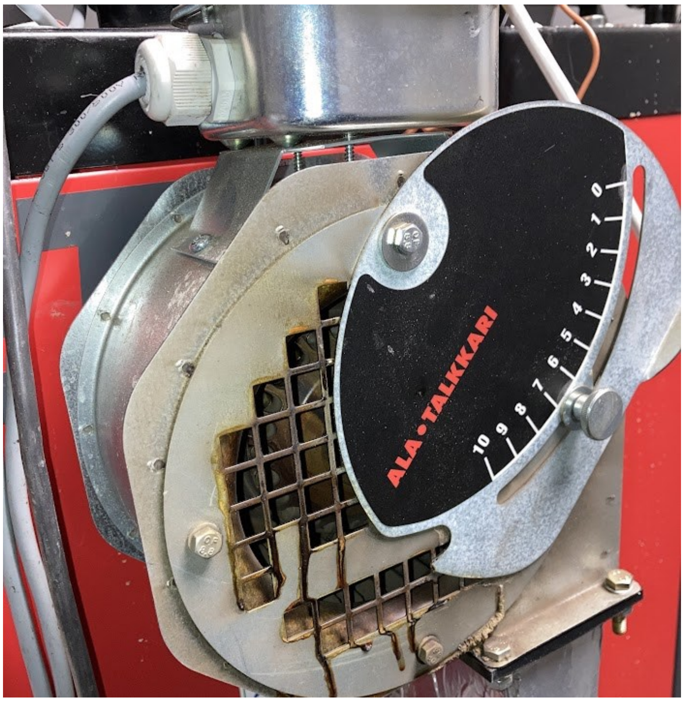
The control system that was implemented was chosen because of its appropriateness for the process. Although the operation of the process itself is automatic, there is still the need for an operator to check occasionally that all components are collaborating. Due to the limitations regarding the internal space of the boiler, it was not possible to integrate a lambda sensor (oxygen sensor) which could have been used to indicate the amount of oxygen already present inside locations such as the boiler and feeder before or during combustion. This information could have been sent to a device that removes oxygen such as a vacuum thus reducing the magnitude of the disturbance caused by it.

Due to the nature of the set-up, it would have been good to include the measurement of moisture in the decision-making process, but it was not feasible due to the aforementioned reason. In this case, the moisture was a source of disturbance that affected the maintenance of high temperatures for prolonged periods, and it also affected the drying of the biomass. Since these two problems persisted, the most suitable control algorithm was the manual feedforward control. Regarding the amount of moisture, it was manually measured by the operator and the corresponding temperatures were applied by manually adjusting the opening of the air intake such that the fire would receive enough oxygen fuel. Hence, the biomass could be dried better.

4.2.5 Variables in the System

The variables selected for the control system will be discussed here and justified. The control inputs or manipulated variables in this system were the amount of biomass and the amount of air coming through the inlet (figure 14). These were selected as such variables since the operator of the system is the one who is directly affecting the quantity of these variables. These are the variables that will change based on the operator’s knowledge of the process. The process disturbances were factors such as the pre-existence of air inside the boiler, air inside the reactor pipe, inside the biomass feeding system, and inside the sections of the heating system such as the shutting feeder that rotates to allow more pellet fuel inside the screw pipe.

Figure 14. Air inlet fan for the combustion of fuel



When it rotates, the air gets inside to some extent which is uncontrollable in this case. There was also air inside the char removal system such as in the screw pipes. These were selected as disturbances because they affected the performance of the process and thus the process variable in the sense that the optimum temperature could have been achieved much faster if such disturbances weren’t present. Another disturbance was the presence of moisture in the wood pellets. The moisture for a sample of 280 grams of wood pellets was measured by the Humimeter BP1 to be 6.9% (figure 15). Since it was 15kg of wood pellets in total, and if we divide 15kg by 280 the result is approximately 53.57. This value of 53.57 is multiplied by 6.9% which results in roughly 369.64 % moisture in 15kg of pellets.

Figure 15. Humimeter BP1 measuring the moisture of 280 grams of wood pellets

5 Implementation details

5.1 System implementation details

5.1.1 Cabinet selection

The implementation of the automation system will be discussed in the consequent paragraphs. The system starts with the selection of the cabinet from the manufacturer Rittal as previously mentioned in Chapter 3 section 3.2. The cabinet size was dependent upon the depth of the ATV320 speed drives which was 158 mm per drive. The size of the cabinet was 210 mm deep. The selected type of cabinet was the compact enclosure AX Basic enclosure AX made from sheet steel with a protection rating of IP 66.

5.1.2 Device selection criteria

The devices that were employed in this cabinet were selected based on their ability to tolerate the required levels of voltage, cost, and user-friendliness. The drives were selected as such since they could be configured directly by using a communication card that was equipped with the EtherCAT protocol. This makes the job of the programmer less tedious since there doesn’t need to be the utilization of the Modbus protocol, rather it can be programmed by plugging an ethernet cable into the communication card. Additional selection criteria included the power of the motor, which was 0.75kW in this case, the voltage rating, which was 380 to 500 V, and finally the 3-phase rating. The speed drives featured a user interface with a dial whereby the operator can configure the motors’ parameters. (Electric, n.d.-b)

The power supply ABLS1A24031 from Schneider was selected mainly for its compactness and tolerance of a wide AC voltage range. The AC rating spans from 100 – 240 V AC with an output current rating of 3.1 Amperes at 24 V DC and a rated power output of 75W. Based on the manufacturer, the power supply specializes in supplying DC for automation equipment used in applications such as mass feeding. The power supply has overload protection and short circuits since it automatically restarts after an overload. It was installable via rail mounting. (Electric, n.d.-a)

The MCB or miniature circuit breaker was selected as Acti9 i-C60L. These series of breakers were low-voltage miniature breakers with 3 phases and 3 protected poles. The current rating was 10 Amperes with a MA tripping curve. According to Electric (n.d.-a), there was a rated short circuit breaking capacity of 40kA at 220 V AC to 240 V AC. The electrical endurance was up to 10 000 cycles and the mechanical endurance was approximately 20 000 cycles. The rated insulation voltage was 500 V AC, and the miniature circuit breaker was DIN rail compatible. Based on these characteristics, it was selected as the suitable MCB. (Electric, n.d.-a)

The switch disconnector by ABB with model number OT16F3 was chosen based on several characteristics. These are its voltage rating, DIN rail compatibility, 3-phase compatibility, size, user-friendliness, and rated operational voltage. The rated operation voltage of the main circuit was 750 volts, the dimensions were width 35 mm, height 68 mm, and depth 56 mm. The switch was operated via a two-state knob that switches between 0 and 1. (ABB, 2023)

The terminal blocks were from the manufacturer Phoenix contact. The type of terminal block was PT6 fed through the terminal block. It had a nominal voltage rating of 1kV, and a nominal current of 41 A and utilized the push-in connection method. The rated wire cross-section was 6 mm^2. The rated surge voltage was 8 kV, and the material was polyamide otherwise known as nylon. It was selected based on these properties as they made it an appropriate choice for this application. (Phoenix Contact, 2018)

From the same manufacturer, there were also end clamps, earthing, and neutral terminals. The end clamps served the purpose of keeping the terminal blocks in place as well as other devices such as the MCBs, power supply, and main disconnector switch. The CLIPFIX 35 was selected as the end clamp model. It was also made from polyamide material and can operate in temperatures from -60 to 105 degrees centigrade (Phoenix Contact, 2019). The PT 6-PE - Ground modular terminal block was used for the earthing terminals. These also featured the push-in connection method (Phoenix Contact, 2018). The neutral terminal blocks were selected as UT 4 BU. They are fed through terminal blocks with a nominal voltage of 1000 Volts and in addition to that, they possess the screw-in method. Based on these criteria, it was selected. (Phoenix Contact, 2019)

The PLC selected was the CX5010 embedded PC with an Intel Atom processor. It had a Z510 intel atom processor with a clock speed of 1.1 GHz. Additionally, it comes with a DVI-D connection so that visualizations can be created when the PLC is directly connected to a monitor. The CX5010 only has one core and has a RAM capacity of 512 MB. It also has the Windows Embedded CE 6 operating system. The IO cards selected like KL1104, KL2134, and KL9010 were chosen because of their ability to receive and send signals to and from devices. The KL1104 is a 4-channel digital input card that acquires signals from field devices and transmits them to the control unit. (Beckhoff, n.d.-a)

The KL2134 card is a 4-channel digital output that connects the control unit level to the actuators at the field level. (Germany, n.d.-b) The KL9010 is necessary for communication between the bus coupler and the bus terminals. Besides the function, the KL9010 does not serve any other significant purpose. (Germany, n.d.-c).

5.1.3 Connections

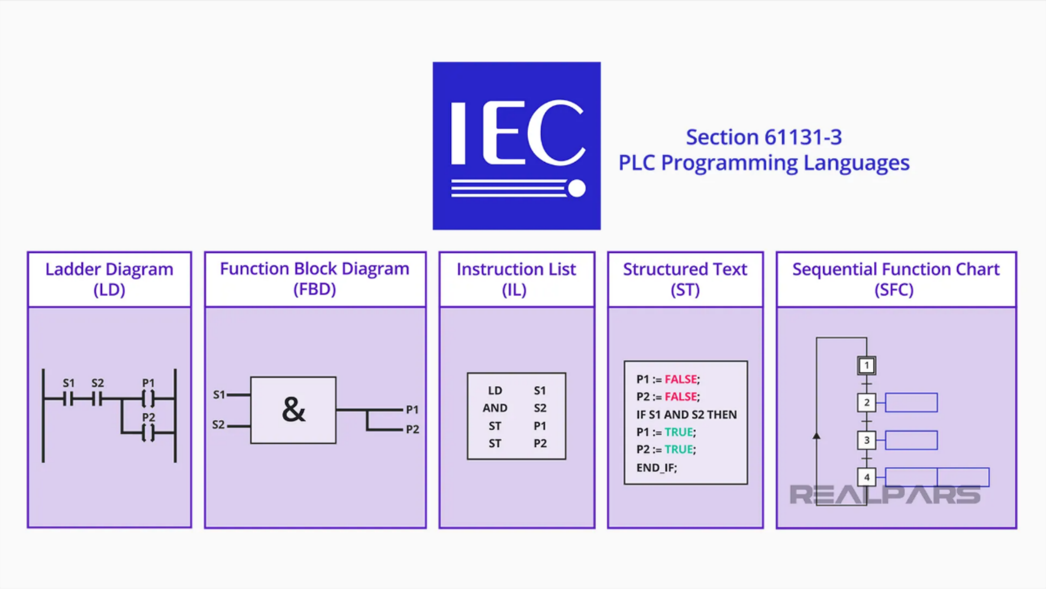
The cabinet was connected as follows. The mains power supply of 400/230 V AC was a three-phase source, and it was connected to the ABB main disconnector switch OT25F3. From the ABB switch disconnector, there was a connection to the miniature breaker (Acti9 i-C60L). The ABB main disconnector switch had three screw connections for the three phases and from each of these screw connections on the lower end of the switch disconnector, there were wires connected to the MCB’s lower end in the corresponding locations. The mains power supply of 400 V AC was connected to the Schneider power supply ABLS1A24031 via a black wire at the lower end where the L+ symbol was marked. In addition to those, there was an earth potential wire and a blue negative terminal wire. On the upper end of the power source, there were two wires which were black and blue. The black wire was connected to the ‘+’ symbol and the blue wire was connected to the ‘- ’symbol. From the upper end of the power supply, the black wire was connected to a grey Phoenix contact terminal block, and the blue was also connected to a Phoenix contact terminal block which was coloured blue. The PLC’s power terminal cards were supplied from the power supply hence it was also connected to the same terminal block as its wires. This means wires for the positive terminal marked as ‘24 V’ on the PLC and ‘0 V’.

The speed drives had their own 24 V power supply internally. The speed drives were connected to a terminal block that had markings such as L1, L2, and L3 respectively. The control signals from the drives were transferred to the motors M1 and M2 via three-phase wires that were connected to the same terminal. All devices had their respective connections to earth potential terminals which were green and yellow coloured and negative terminals which were coloured blue.

5.2 PLC Program

The motor control PLC program was constructed using the Sequential Function Chart programming language in the TwinCAT 3 programming environment. The SFC language is one of the five programming languages provided by the IEC 61131-3 standard (figure 16). The requirements of PLC systems are outlined in standard IEC 61131, which provides a guideline. These guidelines apply to the programming system and PLC hardware. The standard incorporates both extra novel programming techniques and widely used principles that are already used in PLC programming. The standard was developed by the IEC (International Electrotechnical Commission) working group SC65B WG7 (originally SC65A WG6), which is made up of representatives from various PLC manufacturers, software companies, and users. (John & Tiegelkamp, 2010, p.13)

Figure 16. IEC 61131-3 programming languages. (Antonsen, 2022)



```
LD      S1
AND     S2
ST      P1
ST      P2
```

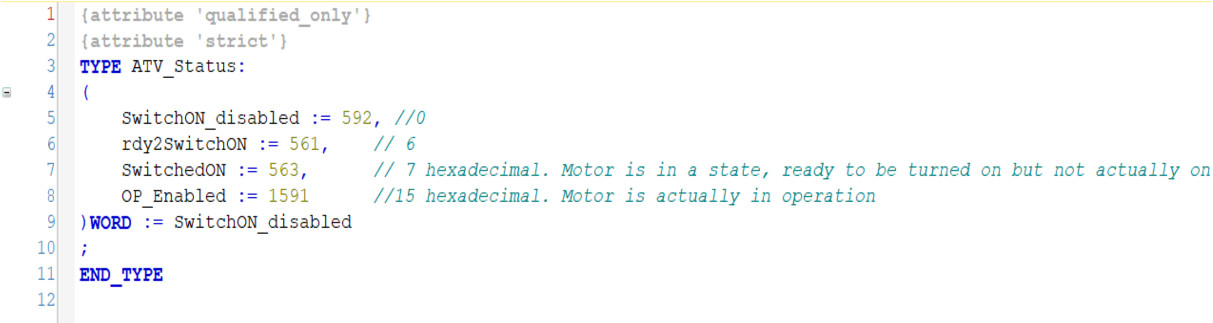
```
P1 := FALSE;
P2 := FALSE;
IF S1 AND S2 THEN
P1 := TRUE;
P2 := TRUE;
END_IF;
```

The IEC 61131-3 language SFC was created to decompose complex programs into smaller, more manageable units and to characterize the control flow between these units (Karl Heinz John et al., 2010, p.169). In an SFC program, there are steps and transitions. The first step is always the Init or the initial step, then there are normal steps then transitions. The Init step is a square that has a double line around it. The normal steps have a single line, and the transitions are horizontal lines that contain conditions. (Antonsen, 2022)

5.2.1 Data Unit Type

A data unit type defines a user-created data type (*Beckhoff Information System - English*, n.d.). The type of DUT selected was an enumeration. An enumeration is a data unit type that contains a series of integer constants (*Beckhoff Information System,* n.d.). The name of the enumeration was “ATV_Status” as depicted in Figure 17. The variables contained integer numbers that were representative of the different states of the motor. In addition to the integer numbers, the drives were operated with the hexadecimal equivalent of those integer numbers. The data type for “ATV_Status” was the data type “WORD”. The variable “SwitchON_disabled” was used to indicate that the switch-on state was off. The variable “rdy2SwitchON” indicated that the switch-on state was ready to be switched on. The variable “SwitchedON” indicated that the switch-on state was active and the variable “OP_Enabled” indicated when the motor was in operation.

Figure 17. Data unit Type "ATV_Status"

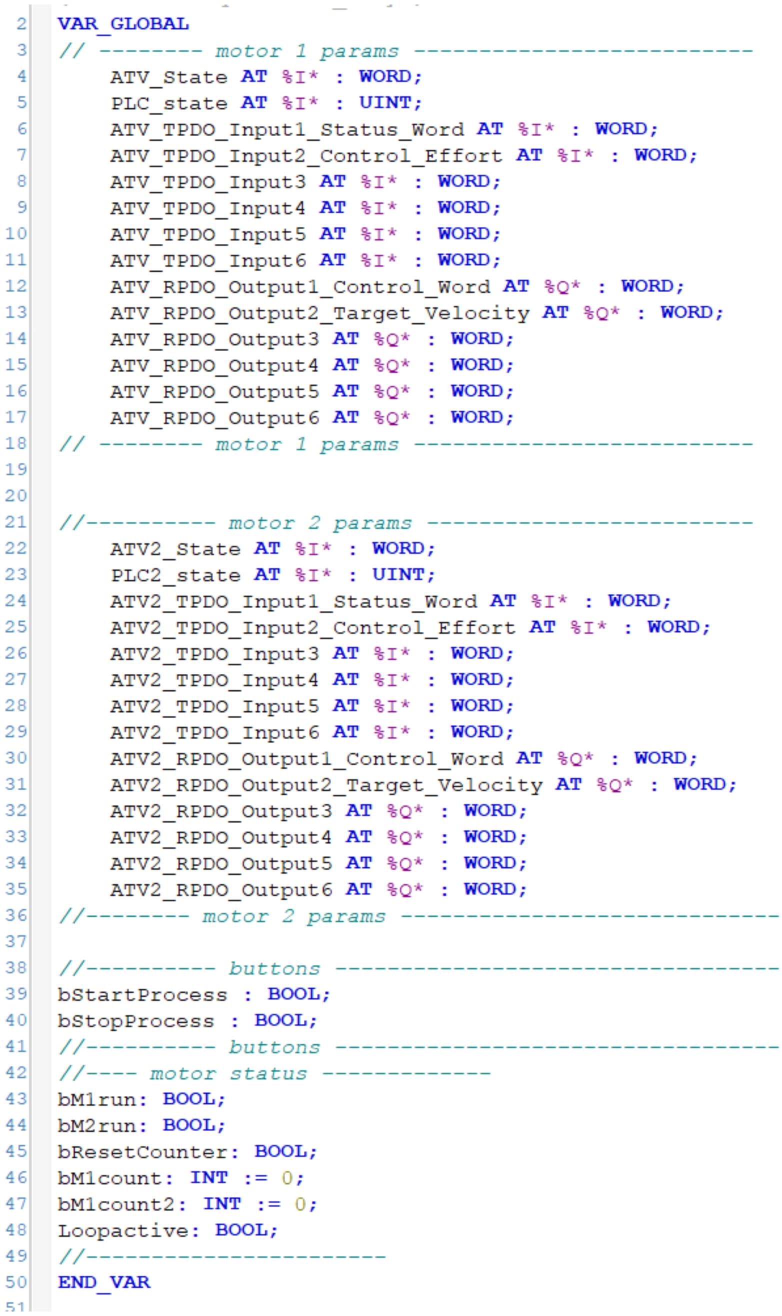


```
{attribute 'qualified_only'}
{attribute 'strict'}
TYPE ATV_Status:
(
    SwitchON_disabled := 592, //0
    rdy2SwitchON := 561,    // 6
    SwitchedON := 563,      // 7 hexadecimal. Motor is in a state, ready to be turned on but not actually on
    OP_Enabled := 1591      //15 hexadecimal. Motor is actually in operation
)WORD := SwitchON_disabled
;
END_TYPE
```

5.2.2 Global Variables (GVL)

Global variables are variables whose value can be accessed anywhere in a program. They are not only locally available within a program organization unit but also wherever they are called. In this program, the global variable list (figure 18) was given the name “Drive”. The sections marked as “motor 1 params” and “motor 2 params” contained all the default variables for communication with the drive. The section marked as “buttons” contained the variables used for starting and stopping the process. The section marked as “motor status” was used to indicate the motors’ status.

Figure 18. Global variable list “Drive”



```
VAR_GLOBAL
// -------- motor 1 params --------------------------
    ATV_State AT %I* : WORD;
    PLC_state AT %I* : UINT;
    ATV_TPDO_Input1_Status_Word AT %I* : WORD;
    ATV_TPDO_Input2_Control_Effort AT %I* : WORD;
    ATV_TPDO_Input3 AT %I* : WORD;
    ATV_TPDO_Input4 AT %I* : WORD;
    ATV_TPDO_Input5 AT %I* : WORD;
    ATV_TPDO_Input6 AT %I* : WORD;
    ATV_RPDO_Output1_Control_Word AT %Q* : WORD;
    ATV_RPDO_Output2_Target_Velocity AT %Q* : WORD;
    ATV_RPDO_Output3 AT %Q* : WORD;
    ATV_RPDO_Output4 AT %Q* : WORD;
    ATV_RPDO_Output5 AT %Q* : WORD;
    ATV_RPDO_Output6 AT %Q* : WORD;
// -------- motor 1 params --------------------------


//---------- motor 2 params ------------------------
    ATV2_State AT %I* : WORD;
    PLC2_state AT %I* : UINT;
    ATV2_TPDO_Input1_Status_Word AT %I* : WORD;
    ATV2_TPDO_Input2_Control_Effort AT %I* : WORD;
    ATV2_TPDO_Input3 AT %I* : WORD;
    ATV2_TPDO_Input4 AT %I* : WORD;
    ATV2_TPDO_Input5 AT %I* : WORD;
    ATV2_TPDO_Input6 AT %I* : WORD;
    ATV2_RPDO_Output1_Control_Word AT %Q* : WORD;
    ATV2_RPDO_Output2_Target_Velocity AT %Q* : WORD;
    ATV2_RPDO_Output3 AT %Q* : WORD;
    ATV2_RPDO_Output4 AT %Q* : WORD;
    ATV2_RPDO_Output5 AT %Q* : WORD;
    ATV2_RPDO_Output6 AT %Q* : WORD;
//-------- motor 2 params ----------------------------

//---------- buttons ----------------------------------
bStartProcess : BOOL;
bStopProcess : BOOL;
//---------- buttons ----------------------------------
//---- motor status -------------
bM1run: BOOL;
bM2run: BOOL;
bResetCounter: BOOL;
bM1count: INT := 0;
bM1count2: INT := 0;
Loopactive: BOOL;
//-----------------------
END_VAR
```

5.2.3 Sequential Function Chart

The purpose of this program organization unit (figure 19) was to control the operation of two 3-phase motors. The first motor was responsible for feeding the biomass while the second motor was responsible for removing the biomass. In the Init step, the variables

“drive.ATV_RPDO_Output1_Control_Word” and
“drive.ATV2_RPDO_Output1_Control_Word” were assigned the value of 0. The result of this is that when the program has just started, the motors will be off. The transition “drive.bStartProcess” checks if the button is pressed. At the step, “StartDelay” there is a small delay of 1 second for the starting of the sequence. The “Init_Feed” step and the transition “Init_Feed.t = pyrotime.tInitFeed” contains the commands to start the motor for the user-defined time which is 344 seconds. The step “waitTemp” waits until the pyrolysis temperature has been reached at 600 degrees centigrade. The “ShortFeed” step feeds the biomass and the transition “ShortFeed.t = pyrotime.tShortFeed” causes it to feed for 118 seconds or for how long the operator has defined.

The idle steps were necessary otherwise the current configuration would not have been possible. After the idle step, there comes a transition “idlestep.t >= t#3s”. This transition checks if the Idlestep2 has been active for 3 seconds or more. This is used to cause a delay before the step Valve2 can be executed. The step Valve2 controls the opening and closing of pneumatic valves.

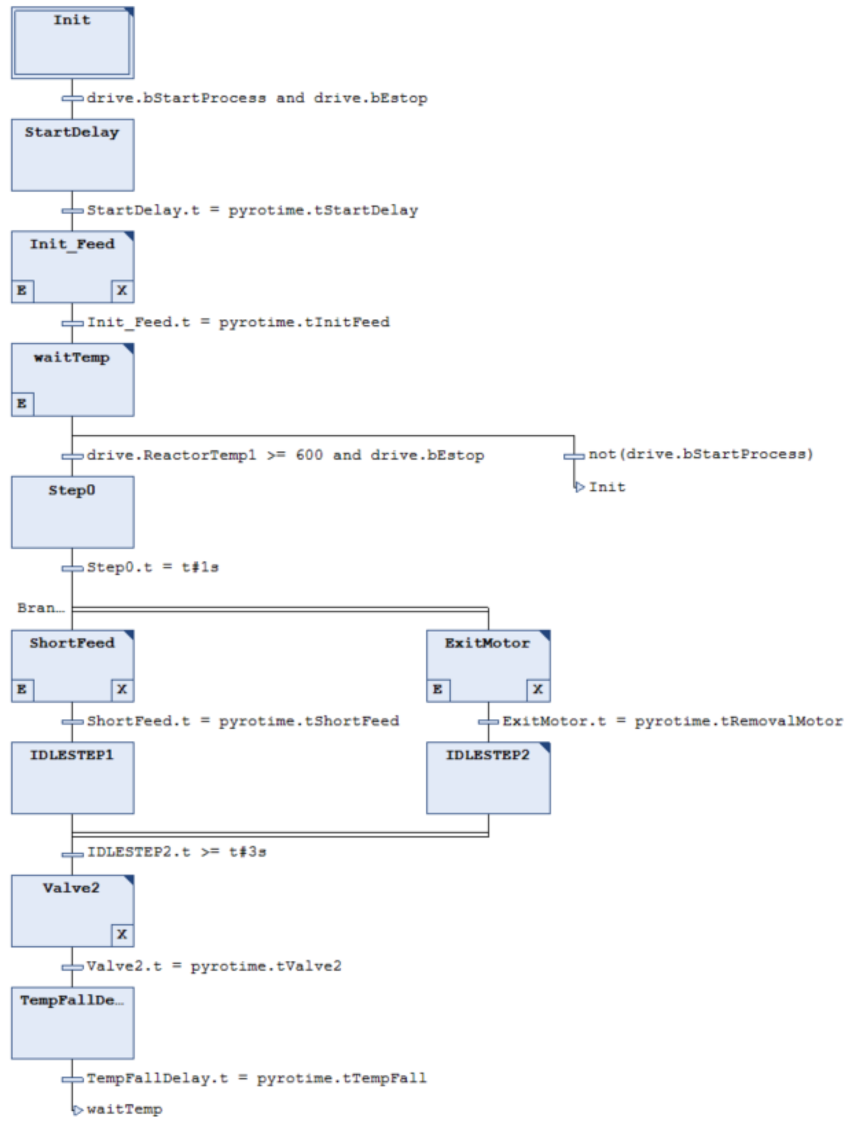
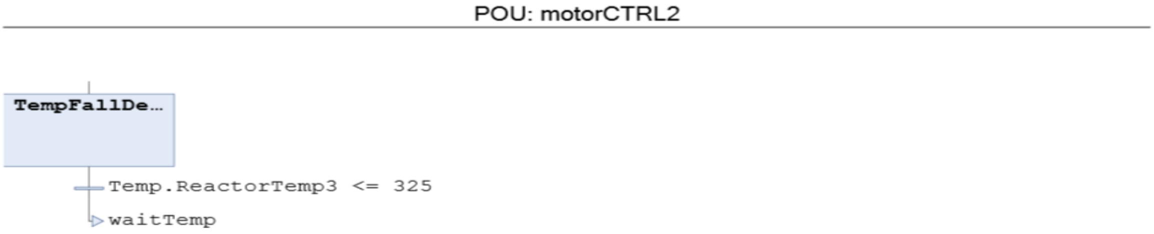


Figure 19. Sequential function chart program for the 3-phase motor control

The step “TempFallDelay” and transition “Temp.ReactorTemp3 <= 325” (Figure 20) waits until the temperature has fallen below a value defined by the operator. After this, there is a jump that goes back to the waitTemp step.

Figure 20. TempFallDelay step



POU: motorCTRL2

TempFallDe…

`Temp.ReactorTemp3 <= 325`

waitTemp

6 Results

The results from the completed automation system will be discussed here. Several trials were done during the periods of November 2022 to March 2023 but due to the scope of this paper, only the trials with meaningful results will be taken into consideration.

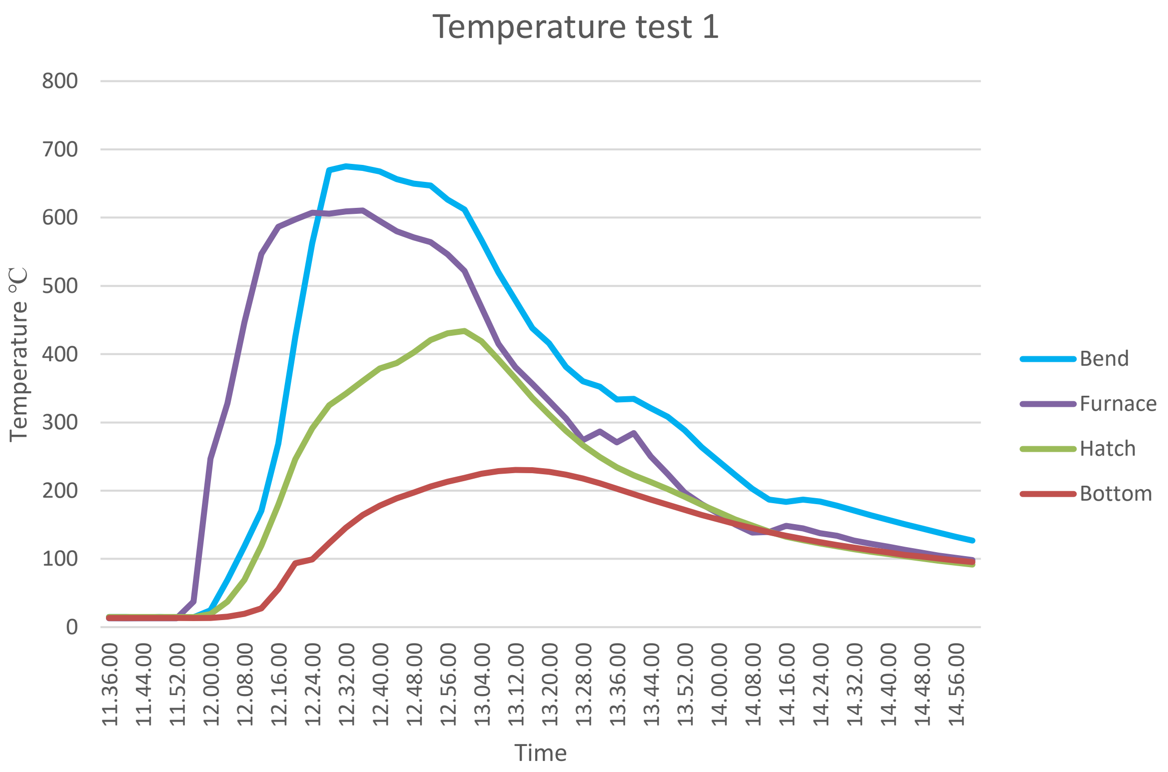
6.1 Temperature tests

The temperature tests were done to determine the limits of the heating system. It was necessary to know how hot the boiler could get using the available fuel source. Using this information, it was possible to determine appropriate residence times for the biomass. The first temperature test, which was carried out in November 2022, lasted a total of 3 hours and 52 minutes. During this trial, the automation system was not in use but was rather manually operated by the operator. Observing Figure 20, the temperature was the highest at the bend (figure 21) then the furnace, then the hatch which is also the door of the boiler while on the other hand, it was coolest at the bottom of the boiler.

Figure 21. Reactor pipe with bend

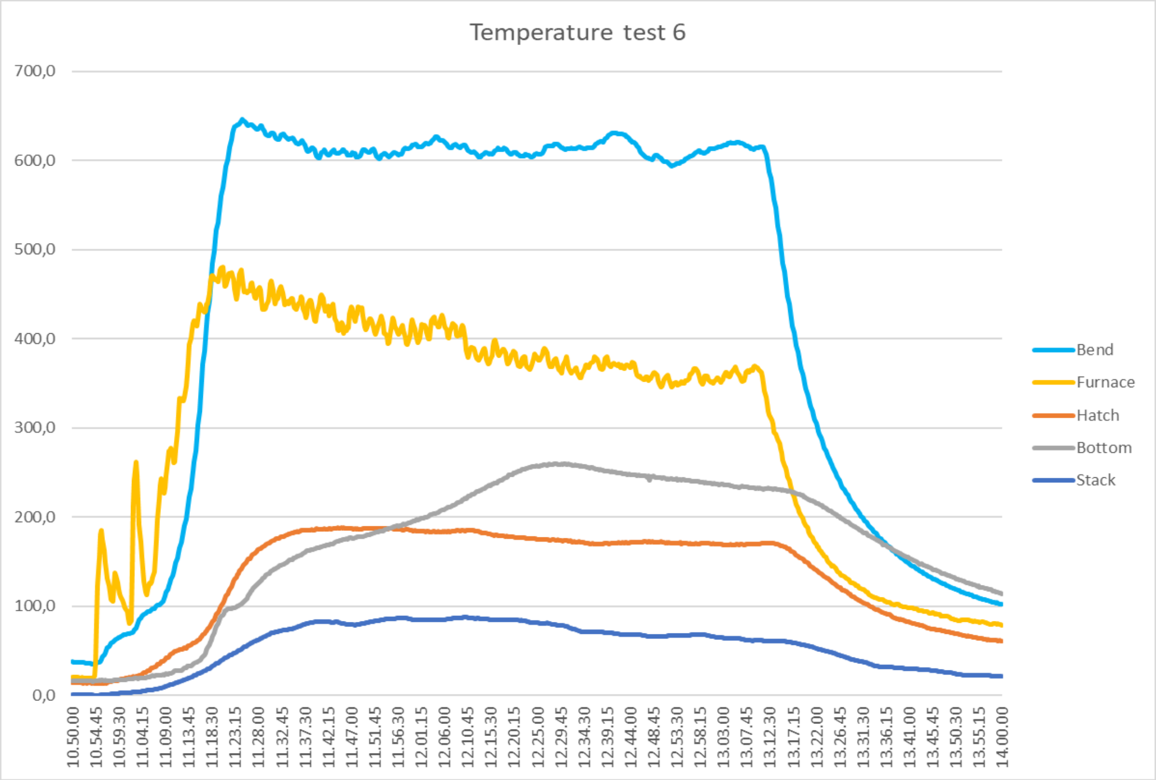
The most important part of the reactor is the bend (figure 21) since that is where the char formation occurs. Most biomass will be converted to char in this area hence it is logical to be the hottest part. The highest temperature achieved at the bend was 675.2 degrees centigrade. In Figure 22, the temperatures above 600 were only sustained for 32 minutes which in theory is not bad but for certainty of better products and thorough conversion of biomass to biochar, sustaining high temperatures for longer plays a significant role. If high temperatures can be sustained for longer, the residence time can be significantly reduced. The reason for the poor performance seen here might be due to the moisture content of the pellets that were used as the fuel source.

Figure 22. Temperature test 1



In Figure 23, which depicts the temperature test 6, the automation system was deployed, and the improvement was noticeable. The temperatures above 600 degrees centigrade were sustained for longer, lasting 1 hour and 51 minutes. This is an improvement of 1 hour and 19 minutes over the previous time. It is also evident that the furnace temperature was also maintained for a longer period consistently when compared to temperature test 1.

Figure 23. Temperature test 6



6.2 Quality of biochar produced by the automation system

The quality of the char was good when judged based on appearance and properties. The char produced was dark and had somewhat of a flaky texture. Based on the composition of the product in the 7th test, on average it contained 82.2% carbon by mass percent. On average, by mass percent, it also contained 2.7% hydrogen, 0% sulphur, and 0.1% nitrogen. The average molar ratio of hydrogen to carbon was 0.39 while the average oxygen to carbon molar ratio was 0.09. In the 8th test that was conducted, the results based on mass percent were 0% nitrogen, 82.9% carbon, and 3.2% hydrogen. The molar ratio of hydrogen to carbon was 0.46 while the molar ratio of oxygen to carbon was 0.10. Figure 24 shows the biochar obtained from three tests.

Figure 24. Char formed at the "bend" of the reactor

7 Conclusion

7.1 Benefits and limitations of the automation system

The automation system was used in pyrolysis to control and optimize various aspects of the process, including temperature, feedstock delivery, and product collection. The benefits of using automation resulted in increased efficiency. The efficiency was increased in the sense that the desired temperature was maintained for a longer period with few variations in the heating rate. This indicated that the fuel source selected for the fire ignition system was combusted thoroughly with little to no waste. Another benefit of the automation system is that it provided the possibility for consistency and repeatability. The automation system helped to ensure that the pyrolysis process was carried out consistently and with a high degree of repeatability, which is important for achieving consistent product quality and yields. Safety is important in any process and with the automation system, safety was improved by reducing the need for human intervention and by reducing human error.

No system is perfect, therefore there are limitations to this automation system. The initial cost of setting up an automated pyrolysis system can be high, and ongoing maintenance and repair costs can also be significant. Automated pyrolysis systems can be complex and require specialized knowledge and expertise to design, operate, and maintain. Thus, the average farmer who has not been trained in the field of engineering, cannot adapt to such a complex system. Automated pyrolysis systems are typically designed for specific feedstocks and operating conditions, which can limit their flexibility and adaptability to changing feedstocks or process parameters. Another significant limitation is that automated pyrolysis systems rely on technology such as sensors, controllers, and software, which can be vulnerable to malfunction or failure, leading to downtime and reduced productivity.

7.2 Future Works and Improvements

In the future, there may be the possibility to modify the current setup in such a way that the liquid by-product will be the target product. Since pyrolysis creates other by-products, it is useful to explore them and their potential uses. The bio-oil can be used as a cleaner alternative to machines operated on diesel for example. Using bio-oil produces less harmful by-products hence the environment will not be inconvenienced by its usage.

Improvements could be that a custom-made boiler or reactor should be used in the future since the current boiler from Ala-Talkkari proved to be extremely challenging when the pipe reactor was being designed. The boiler was very compact and there was limited internal space. Due to the limited space, additional parameters could not be measured such as the mass of the biomass immediately after the pyrolysis or during the pyrolysis. The mass is a parameter by which the end of the pyrolysis process can be indicated without a doubt. In this system, the end of the pyrolysis process was indicated by the falling of the temperature value below a certain point which in practice is not bad but is less reliable and accurate.

The application of the control system could be significantly improved by adding sensors that could detect the disturbances beforehand such as a lambda sensor for oxygen and a moisture sensor. Since there were no such sensors in the setup that could immediately detect the disturbance before it entered the system, the operator had to adjust certain parts of the system such as the opening of the air intake which influences the temperature. Such adjustments can become tedious overtime but if the operator ensures that the biomass is already dry enough beforehand and the moisture content is extremely low, in this case less than 1%, then the operator does not have to adjust this variable often.

It is a downside of this system but the control of other subprocesses is fully automatic such as feeding of the biomass, removal of the char, combustion of wood pellets for the fire and the measuring of the temperatures. Even though the operator still plays a role in the process, it is still minimal if compared to the situation where he had to do feeding of the biomass, removal of the products, and manually combusting the wood pellets as well as recording temperatures.

7.3 Concluding remarks

At the beginning of this thesis, many things were unclear regarding the system. This topic of pyrolysis contains a lot of chemistry, and it was not immediately clear how to apply automation to something like this. With the advice of the supervisors and teachers, the process became clearer, and new insights were gained regarding how to successfully apply the necessary automation principles to this topic.

In conclusion, the development and implementation of an automation system for the production of biochar from pyrolysis using locally acquired biomass has been successfully achieved. The automation system is designed to improve the efficiency and effectiveness of the biochar production process by reducing manual labor, minimizing the risk of errors, and optimizing the use of resources.

References

ABB. (n.d.). *Detailed information for: OT16F3*. ABB Asea Brown Boveri Ltd. Retrieved April 18, 2023, from https://new.abb.com/products/1SCA104811R1001/ot16f3

Abdul, Q., Abdul, R., Muhammad, A., & Matthew, A. J. (2011). Water stress causes differential effects on germination indices, total soluble sugar and proline content in wheat (Triticum aestivum L.) genotypes. *African Journal of Biotechnology*, *64*, 14038–14045. https://doi.org/10.5897/ajb11.2220

Ala Talkkari. (n.d.). *Veto 60 Biomass boiler*. Retrieved April 5, 2023, from https://ala-talkkari.fi/en/biomass-boiler-veto-60/

Andleep, Z. (2021, September 18). *Types of Pyrolysis Processes*. My Waste Solution. https://blog.mywastesolution.com/types-of-pyrolysis-processes-to-conserve-renewable-resources/

Antonsen, T. M. (2022, September 5). *Sequential Function Chart (SFC) Programming for Beginners*. https://realpars.com/sequential-function-chart/

Atkinson, C. J., Fitzgerald, J. D., & Hipps, N. A. (2010). Potential mechanisms for achieving agricultural benefits from biochar application to temperate soils: a review. *Plant and Soil*, *337*(1-2), 1–18. https://doi.org/10.1007/s11104-010-0464-5

Augustenborg, C. A., Hepp, S., Kammann, C., Hagan, D., Schmidt, O., & Müller, C. (2012). Biochar and Earthworm Effects on Soil Nitrous Oxide and Carbon Dioxide Emissions. *Journal of Environmental Quality*, *41*(4), 1203–1209. https://doi.org/10.2134/jeq2011.0119

Ayodele, A., Oguntunde, P., Joseph, A., & Dias Junior, M. de S. (2009). Numerical analysis of the impact of charcoal production on soil hydrological behavior, runoff response and erosion susceptibility. *Revista Brasileira de Ciência Do Solo*, *33*(1), 137–146. https://doi.org/10.1590/s0100-06832009000100015

Azam, M., Khan, A. Q., Abdullah, H. B., & Qureshi, M. E. (2015). The impact of CO2 emissions on economic growth: evidence from selected higher CO2 emissions economies. *Environmental Science and Pollution Research*, *23*(7), 6376–6389. https://doi.org/10.1007/s11356-015-5817-4

Bamido, A. (2018). *Design of A Fluidized Bed Reactor For Biomass Pyrolysis* [Master's Thesis]. https://www.researchgate.net/publication/330335978_Design_of_A_Fluidized_Bed_Reactor_For_Biomass_Pyrolysis

Basu, P. (2010). *Biomass gasification and pyrolysis : practical design and theory*. Academic.

Beckhoff Automation GmbH & Co KG. (n.d.-a). *Bus Terminal, 4-channel digital input, 24 V DC, 3 ms, 2-/3-wire connection*. Retrieved April 4, 2023, from https://www.beckhoff.com/en-en/products/i-o/bus-terminals/kl1xxx-digital-input/kl1104.html

Beckhoff Automation GmbH & Co KG. (n.d.-b). *Bus Terminal, 4-channel digital output, 24 V DC, 0.5 A*. Retrieved April 19, 2023, from https://www.beckhoff.com/en-en/products/i-o/bus-terminals/kl2xxx-digital-output/kl2134.html

Beckhoff Automation GmbH & Co KG. (n.d.-c). *End terminal*. Retrieved April 19, 2023, from https://www.beckhoff.com/en-en/products/i-o/bus-terminals/kl9xxx-system/kl9010.html

Beckhoff Automation GmbH & Co KG. (n.d.-d). *TwinCAT 3 Engineering*. Retrieved April 3, 2023, from https://www.beckhoff.com/en-en/products/automation/twincat/texxxx-twincat-3-engineering/te1000.html

Beckhoff Information System. (n.d.). Object DUT; Beckhoff. Retrieved May 5, 2023, from https://infosys.beckhoff.com/english.php?content=../content/1033/tc3_plc_intro/2530071691.html&id=

Beesley, L., Moreno-Jiménez, E., Gomez-Eyles, J. L., Harris, E., Robinson, B., & Sizmur, T. (2011). A review of biochars' potential role in the remediation, revegetation and restoration of contaminated soils. *Environmental Pollution*, *159*(12), 3269–3282. https://doi.org/10.1016/j.envpol.2011.07.023

Brewer, C. E., Schmidt-Rohr, K., Satrio, J. A., & Brown, R. C. (2009). Characterization of biochar from fast pyrolysis and gasification systems. *Environmental Progress & Sustainable Energy*, *28*(3), 386–396. https://doi.org/10.1002/ep.10378

Bridgwater, A. V. (1999). Principles and practice of biomass fast pyrolysis processes for liquids. *Journal of Analytical and Applied Pyrolysis*, *51*(1-2), 3–22. https://doi.org/10.1016/s0165-2370(99)00005-4

Buss, W., Kammann, C., & Koyro, H.-W. (2012). Biochar Reduces Copper Toxicity in *Chenopodium quinoa* Willd. in a Sandy Soil. *Journal of Environmental Quality*, *41*(4), 1157–1165. https://doi.org/10.2134/jeq2011.0022

Chen, W.-H., & Lin, B.-J. (2016). Characteristics of products from the pyrolysis of oil palm fiber and its pellets in nitrogen and carbon dioxide atmospheres. *Energy*, *94*, 569–578. https://doi.org/10.1016/j.energy.2015.11.027

Choppala, G. K., Bolan, N. S., Megharaj, M., Chen, Z., & Naidu, R. (2012). The Influence of Biochar and Black Carbon on Reduction and Bioavailability of Chromate in Soils. *Journal of Environmental Quality*, *41*(4), 1175–1184. https://doi.org/10.2134/jeq2011.0145

CLIPFIX 35 - End clamp. (n.d.). Phoenixcontact.com; Phoenix Contact. Retrieved April 19, 2023, from https://www.phoenixcontact.com/en-pc/products/end-clamp-clipfix-35-3022218

Diebold, J. P., & Bridgwater, A. V. (1997). Overview of Fast Pyrolysis of Biomass for the Production of Liquid Fuels. *Developments in Thermochemical Biomass Conversion*, 5–23. https://doi.org/10.1007/978-94-009-1559-6_1

FiksuHiili. (n.d.). Hämeen ammattikorkeakoulu. Retrieved March 17, 2023, from https://www.hamk.fi/projektit/fiksuhiili/#in-english

Funke, A., & Ziegler, F. (2010). Hydrothermal carbonization of biomass: A summary and discussion of chemical mechanisms for process engineering. *Biofuels, Bioproducts and Biorefining*, *4*(2), 160–177. https://doi.org/10.1002/bbb.198

Gajić, A., & Koch, H.-J. (2012). *Sugar beet (L.) growth reduction caused by hydrochar is related to nitrogen supply. 41*(4), 1067–1075. https://doi.org/10.2134/jeq2011.0237

Glaser, B., Lehmann, J., & Zech, W. (2002). Ameliorating physical and chemical properties of highly weathered soils in the tropics with charcoal - a review. *Biology and Fertility of Soils*, *35*(4), 219–230. https://doi.org/10.1007/s00374-002-0466-4

Hilber, I., Blum, F., Leifeld, J., Schmidt, H.-P., & Bucheli, T. D. (2012). Quantitative Determination of PAHs in Biochar: A Prerequisite To Ensure Its Quality and Safe Application. *Journal of Agricultural and Food Chemistry*, *60*(12), 3042–3050. https://doi.org/10.1021/jf205278v

Impact Networking. (2021, November 24). *10 Advantages of Process Automation*. https://www.impactmybiz.com/blog/advantages-of-process-automation/

International Biochar Initiative. (n.d.). *About Biochar*. https://biochar-international.org/about-biochar/

Ippolito, J. A., Laird, D. A., & Busscher, W. J. (2012). Environmental Benefits of Biochar. *Journal of Environmental Quality*, *41*(4), 967–972. https://doi.org/10.2134/jeq2012.0151

Ippolito, J. A., Stromberger, M. E., Lentz, R. D., & Dungan, R. S. (2014). *Hardwood Biochar Influences Calcareous Soil Physicochemical and Microbiological Status*. *43*(2), 681–689. https://doi.org/10.2134/jeq2013.08.0324

Jaiswal, R. (2020). Simple schematic layout of a pyrolysis plant. In *Research Gate*. https://www.researchgate.net/figure/Simple-schematic-layout-of-a-pyrolysis-plant-3_fig2_343427601

Jawhari, T., Roid, A., & Casado, J. (1995). Raman spectroscopic characterization of some commercially available carbon black materials. *Carbon*, *33*(11), 1561–1565. https://doi.org/10.1016/0008-6223(95)00117-v

Johanson, D. C., Edgar, B., & Brill, D. L. (1996). *From Lucy to language*. Simon & Schuster Editions.

Kammann, C., Ratering, S., Eckhard, C., & Müller, C. (2012). Biochar and Hydrochar Effects on Greenhouse Gas (Carbon Dioxide, Nitrous Oxide, and Methane) Fluxes from Soils. *Journal of Environment Quality*, *41*(4), 1052. https://doi.org/10.2134/jeq2011.0132

Keiluweit, M., Nico, P. S., Johnson, M. G., & Kleber, M. (2010). Dynamic Molecular Structure of Plant Biomass-Derived Black Carbon (Biochar). *Environmental Science & Technology*, *44*(4), 1247–1253. https://doi.org/10.1021/es9031419

Kim, J.-S., Sparovek, G., Longo, R. M., De Melo, W. J., & Crowley, D. (2007). Bacterial diversity of terra preta and pristine forest soil from the Western Amazon. *Soil Biology and Biochemistry*, *39*(2), 684–690. https://doi.org/10.1016/j.soilbio.2006.08.010

Kloss, S., Zehetner, F., Dellantonio, A., Hamid, R., Ottner, F., Liedtke, V., Schwanninger, M., Gerzabek, M. H., & Soja, G. (2012). Characterization of Slow Pyrolysis Biochars: Effects of Feedstocks and Pyrolysis Temperature on Biochar Properties. *Journal of Environment Quality*, *41*(4), 990. https://doi.org/10.2134/jeq2011.0070

Kourosh Kalantar-Zadeh. (2013). *Sensors An Introductory Course*. Boston, Ma Springer Us.

Kumar, R. (2019, August 1). *(92) What is the five layer automation pyramid?* Medium. https://medium.com/world-of-iot/92-what-is-the-five-layer-automation-pyramid-d0ccc1b903c3

Kuzyakov, Y., & Bol, R. (2006). Sources and mechanisms of priming effect induced in two grassland soils amended with slurry and sugar. *Soil Biology and Biochemistry*, *38*(4), 747–758. https://doi.org/10.1016/j.soilbio.2005.06.025

Laird, D., Fleming, P., Wang, B., Horton, R., & Karlen, D. (2010). Biochar impact on nutrient leaching from a Midwestern agricultural soil. *Geoderma*, *158*(3-4), 436–442. https://doi.org/10.1016/j.geoderma.2010.05.012

Lehmann, J. (2007). A handful of carbon. *Nature*, *447*(7141), 143–144. https://doi.org/10.1038/447143a

Lehmann, J., Gaunt, J., & Rondon, M. (2006). Bio-char Sequestration in Terrestrial Ecosystems – A Review. *Mitigation and Adaptation Strategies for Global Change*, *11*(2), 395–419. https://doi.org/10.1007/s11027-005-9006-5

Lehmann, J., & Joseph, S. (2009). *Biochar for Environmental Management*. Earthscan. https://www.css.cornell.edu/faculty/lehmann/publ/First%20proof%2013-01-09.pdf

Lehmann, J., Rillig, M. C., Thies, J., Masiello, C. A., Hockaday, W. C., & Crowley, D. (2011). Biochar effects on soil biota – A review. *Soil Biology and Biochemistry*, *43*(9), 1812–1836. https://doi.org/10.1016/j.soilbio.2011.04.022

Macdonald, D. M., & Altmann, W. (2005). *Practical process control for engineers and technicians*. Elsevier Newnes.

Marris, E. (2006). Black is the new green. *Nature*, *442*(7103), 624–626. https://doi.org/10.1038/442624a

McBeath, A. V., Smernik, R. J., Krull, E. S., & Lehmann, J. (2014). The influence of feedstock and production temperature on biochar carbon chemistry: A solid-state 13C NMR study. *Biomass and Bioenergy*, *60*, 121–129. https://doi.org/10.1016/j.biombioe.2013.11.002

Mortenson, T. (2021, November 22). *Temperature Transmitter Explained | Connection and Calibration*. https://realpars.com/temperature-transmitter/

Mukome, F. N. D., Zhang, X., Silva, L. C. R., Six, J., & Parikh, S. J. (2013). Use of Chemical and Physical Characteristics To Investigate Trends in Biochar Feedstocks. *Journal of Agricultural and Food Chemistry*, *61*(9), 2196–2204. https://doi.org/10.1021/jf3049142

National Instruments. (n.d.). *The PID Controller & Theory Explained*. Retrieved April 7, 2023, from https://www.ni.com/fi-fi/shop/labview/pid-theory-explained.html

Novak, J. M., Lima, I. M., Gaskin, J. W., Steiner, C., Ahmedna, M., Watts, D. G., & Schomberg, H. H. (2009). *CHARACTERIZATION OF DESIGNER BIOCHAR PRODUCED AT DIFFERENT TEMPERATURES AND THEIR EFFECTS ON A LOAMY SAND*. *3*(1), 195–206.

Paik, S.-S., Jeong, E., Jung, S. W., Ha, T. J., Kang, S., Sim, S., Jeon, J. H., Chun, M.-H., & Kim, I.-B. (2012). Anthocyanins from the seed coat of black soybean reduce retinal degeneration induced by N-methyl-N-nitrosourea. *Experimental Eye Research*, *97*(1), 55–62. https://doi.org/10.1016/j.exer.2012.02.010

Peng, X., Ye, L. L., Wang, C. H., Zhou, H., & Sun, B. (2011). Temperature- and duration-dependent rice straw-derived biochar: Characteristics and its effects on soil properties of an Ultisol in southern China. *Soil and Tillage Research*, *112*(2), 159–166. https://doi.org/10.1016/j.still.2011.01.002

Phoenix Contact. (n.d.-a). *PT 6 - Feed-through terminal block* . Retrieved April 18, 2023, from https://www.phoenixcontact.com/en-pc/products/feed-through-terminal-block-pt-6-3211813

Phoenix Contact. (n.d.-b). *UT 4 BU - Feed-through terminal block* . Retrieved April 19, 2023, from https://www.phoenixcontact.com/en-pc/products/feed-through-terminal-block-ut-4-bu-3044115

Phoenix Contact. (2018). *PT 6-PE - Ground modular terminal block*. https://www.phoenixcontact.com/en-pc/products/ground-modular-terminal-block-pt-6-pe-3211822

Piskorz, J., Czernik, S., & Bridgwater, A. V. (2001). *An Overview of Fast Pyrolysis. Progress in Thermochemical Biomass Conversion, 2, 977-997. - References - Scientific Research Publishing*. Www.scirp.org. https://www.scirp.org/(S(351jmbntv-nsjt1aadkposzje))/reference/referencespapers.aspx?referenceid=2442856

Probstein, R. F., & Edwin Hicks, R. (2006). *Synthetic Fuels*. Dover Publications.

Raman, J. (2021, September 14). *What is Oxidation? - Definition, Process & Examples* . https://study.com/academy/lesson/what-is-oxidation-definition-process-examples.html

Rittal GmbH & Co. (n.d.). *3110000 Thermostat Enclosure internal thermostat*. Retrieved April 28, 2023, from https://www.rittal.com/com-en/products/PG0168KLIMA1/PGR1953KLIMA1/PGR2008KLIMA1/PRO12215?variantId=3110000

Rogovska, N., Laird, D., Cruse, R. M., Trabue, S., & Heaton, E. (2012). Germination Tests for Assessing Biochar Quality. *Journal of Environment Quality*, *41*(4), 1014. https://doi.org/10.2134/jeq2011.0103

RS Components Ltd. (n.d.). *RS PRO Type K Thermocouple*. Retrieved April 5, 2023, from https://uk.rs-online.com/web/p/thermocouples/3971264

Sarmah, A. K., Srinivasan, P., Smernik, R. J., Manley-Harris, M., Antal, M. J., Downie, A., & van Zwieten, L. (2010). Retention capacity of biochar-amended New Zealand dairy farm soil for an estrogenic steroid hormone and its primary metabolite. *Soil Research*, *48*(7), 648. https://doi.org/10.1071/sr10013

Schimmelpfennig, S., & Glaser, B. (2012). One Step Forward toward Characterization: Some Important Material Properties to Distinguish Biochars. *Journal of Environment Quality*, *41*(4), 1001. https://doi.org/10.2134/jeq2011.0146

Schneider Electric. (n.d.-a). *A9F90310 - Miniature circuit breaker (MCB), Acti9 iC60L, 3P, 10A, MA curve, 20kA (IEC/EN 60947-2)* . Retrieved April 18, 2023, from https://www.se.com/ww/en/product/A9F90310/miniature-circuit-breaker-mcb-acti9-ic60l-3p-10a-ma-curve-20ka-iec-en-609472/?%3Frange=7556-acti9-ic60&parent-subcategory-id=1605&filter=business-4-low-voltage-products-and-systems&selected-node-id=12144424351

Schneider Electric. (n.d.-b). *ABLS1A24031 - Regulated Power Supply, 100-240V AC, 24V 3.1 A*. Retrieved April 18, 2023, from https://www.se.com/ww/en/product/ABLS1A24031/regulated-power-supply-100240v-ac-24v-3-1-a-single-phase-optimized/

Schneider Electric. (n.d.-c). *ATV320U02M2C* . Retrieved April 3, 2023, from https://eref.se.com/ww/en/web-product-data-sheet/product/ATV320U02M2C

Schneider Electric. (n.d.-d). *ATV320U11N4C - Variable speed drive, Altivar Machine ATV320, 1.1 kW, 380...500 V, 3 phases*. Retrieved April 4, 2023, from https://www.se.com/ww/en/product/ATV320U11N4C/variable-speed-drive-altivar-machine-atv320-1-1-kw-380-500-v-3-phases-compact/

Schneider Electric. (n.d.-e). *VW3A3601 - Ethercat 2 x RJ45 communication module*. Retrieved April 4, 2023, from https://www.se.com/ww/en/product/VW3A3601/ethercat-2-x-rj45-communication-module/

Schnell, R. W., Vietor, D. M., Provin, T. L., Munster, C. L., & Capareda, S. (2012). Capacity of Biochar Application to Maintain Energy Crop Productivity: Soil Chemistry, Sorghum Growth, and Runoff Water Quality Effects. *Journal of Environmental Quality*, *41*(4), 1044–1051. https://doi.org/10.2134/jeq2011.0077

Shackley, S., Carter, S., Knowles, T., Middelink, E., Haefele, S., Sohi, S., Cross, A., & Haszeldine, S. (2012). Sustainable gasification–biochar systems? A case-study of rice-husk gasification in Cambodia, Part I: Context, chemical properties, environmental and health and safety issues. *Energy Policy*, *42*, 49–58. https://doi.org/10.1016/j.enpol.2011.11.026

Smith, J.-L. (2022, December 12). *Decomposition Process & Examples | What is Decomposition in Biology?* https://study.com/academy/lesson/decomposition-process-examples-biology.html

Sohi, S. P., Krull, E., Lopez-Capel, E., & Bol, R. (2010). A Review of Biochar and Its Use and Function in Soil. *Advances in Agronomy*, 47–82. https://doi.org/10.1016/s0065-2113(10)05002-9

Sohi, S., Lopez-Capel, E., Krull, E., & Bol, R. (2009). *Biochar, climate change and soil: a review to guide future research (CSIRO Land and Water Science Report 05/09)*. https://repository.rothamsted.ac.uk/item/8q382/biochar-climate-change-and-soil-a-review-to-guide-future-research-csiro-land-and-water-science-report-05-09

Spokas, K. A., Cantrell, K. B., Novak, J. M., Archer, D. W., Ippolito, J. A., Collins, H. P., Boateng, A. A., Lima, I. M., Lamb, M. C., McAloon, A. J., Lentz, R. D., & Nichols, K. A. (2012). Biochar: A Synthesis of Its Agronomic Impact beyond Carbon Sequestration. *Journal of Environmental Quality*, *41*(4), 973–989. https://doi.org/10.2134/jeq2011.0069

Spokas, K. A., Koskinen, W. C., Baker, J. M., & Reicosky, D. C. (2009). Impacts of woodchip biochar additions on greenhouse gas production and sorption/degradation of two herbicides in a Minnesota soil. *Chemosphere*, *77*(4), 574–581. https://doi.org/10.1016/j.chemosphere.2009.06.053

Streubel, J. D., Collins, H. P., Garcia-Perez, M., Tarara, J., Granatstein, D., & Kruger, C. E. (2011). Influence of Contrasting Biochar Types on Five Soils at Increasing Rates of Application. *Soil Science Society of America Journal*, *75*(4), 1402–1413. https://doi.org/10.2136/sssaj2010.0325

Tiegelkamp, M., & John, K. H. (2010). *IEC 61131-3: Programming Industrial Automation Systems : Concepts and Programming Languages, Requirements for Programming Systems, Decision-Making Aids*. Springer Berlin Heidelberg.

Uchimiya, M., Bannon, D. I., Wartelle, L. H., Lima, I. M., & Klasson, K. T. (2012). Lead Retention by Broiler Litter Biochars in Small Arms Range Soil: Impact of Pyrolysis

Temperature. *Journal of Agricultural and Food Chemistry*, *60*(20), 5035–5044. https://doi.org/10.1021/jf300825n

University of Idaho. (n.d.). *Ultisols* . Retrieved April 25, 2020, from https://www.uidaho.edu/cals/soil-orders/ultisols#:~:text=Ultisols%20(from%20Latin%20ultimus%2C%20%22

Verheijen, F., Jeffery, S., Bastos, A., Van Der Velde, M., & Diafas, I. (2010). *Biochar Application to Soils A Critical Scientific Review of Effects on Soil Properties, Processes and Functions*. https://doi.org/10.2788/472

Xue, Y., Gao, B., Yao, Y., Inyang, M., Zhang, M., Zimmerman, A. R., & Ro, K. S. (2012). Hydrogen peroxide modification enhances the ability of biochar (hydrochar) produced from hydrothermal carbonization of peanut hull to remove aqueous heavy metals: Batch and column tests. *Chemical Engineering Journal*, *200-202*, 673–680. https://doi.org/10.1016/j.cej.2012.06.116

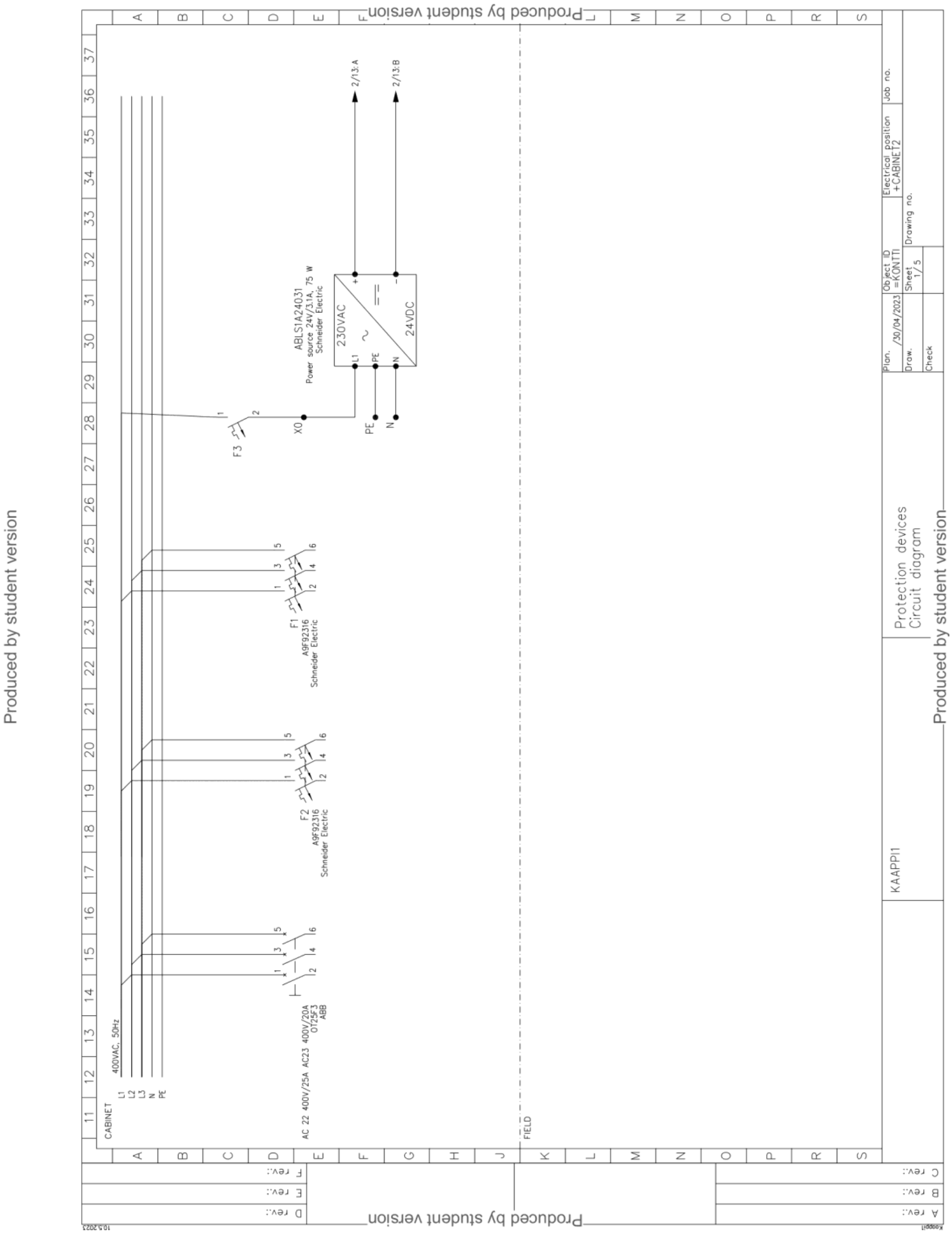
Yao, Y., Gao, B., Zhang, M., Inyang, M., & Zimmerman, A. R. (2012). Effect of biochar amendment on sorption and leaching of nitrate, ammonium, and phosphate in a sandy soil. *Chemosphere*, *89*(11), 1467–1471. https://doi.org/10.1016/j.chemosphere.2012.06.002

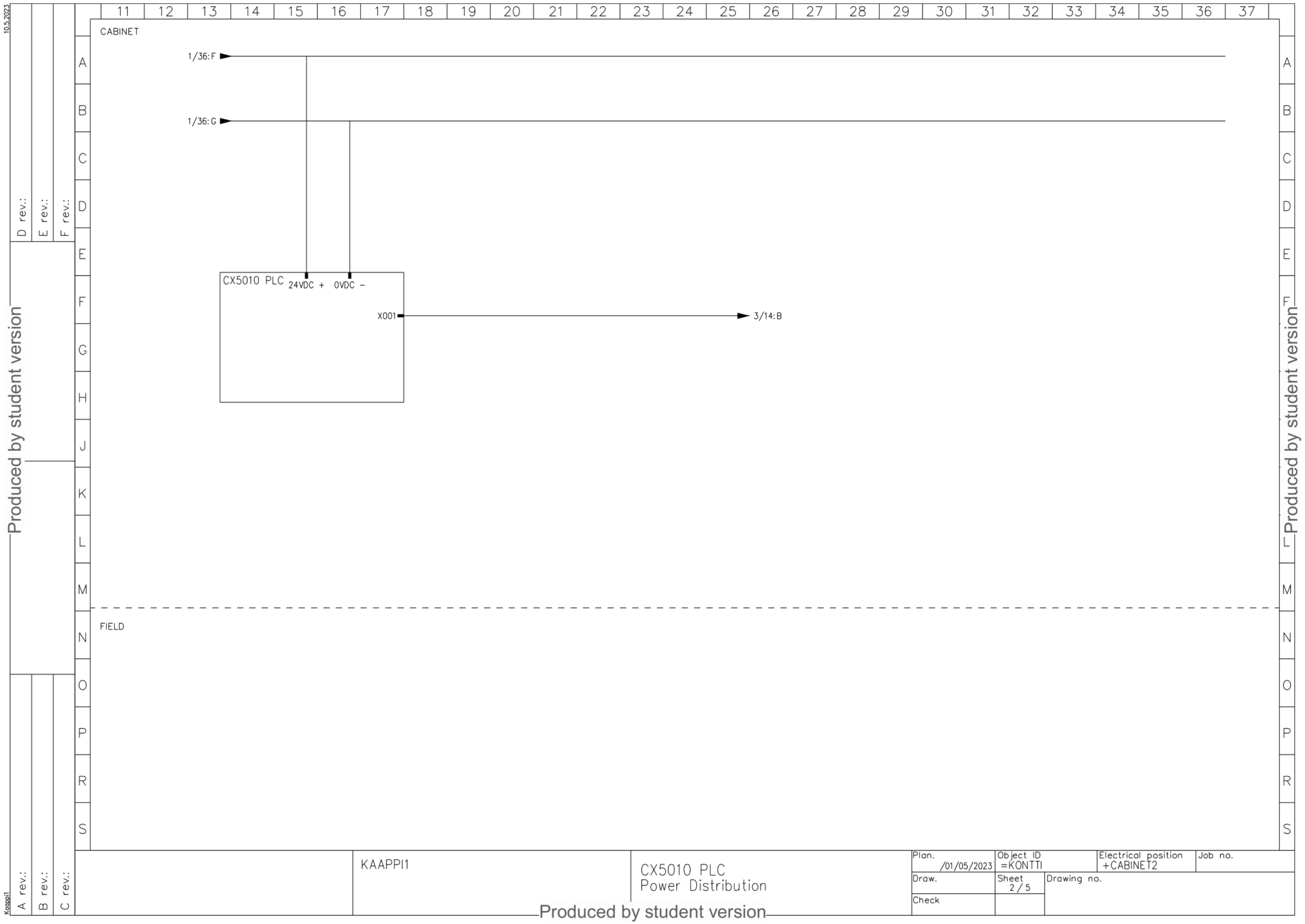
Yong Sik Ok, Uchimiya, S. M., Chang, S. X., & Bolan, N. (2015). *Biochar : Production, Characterization, and Applications*. CRC Press.

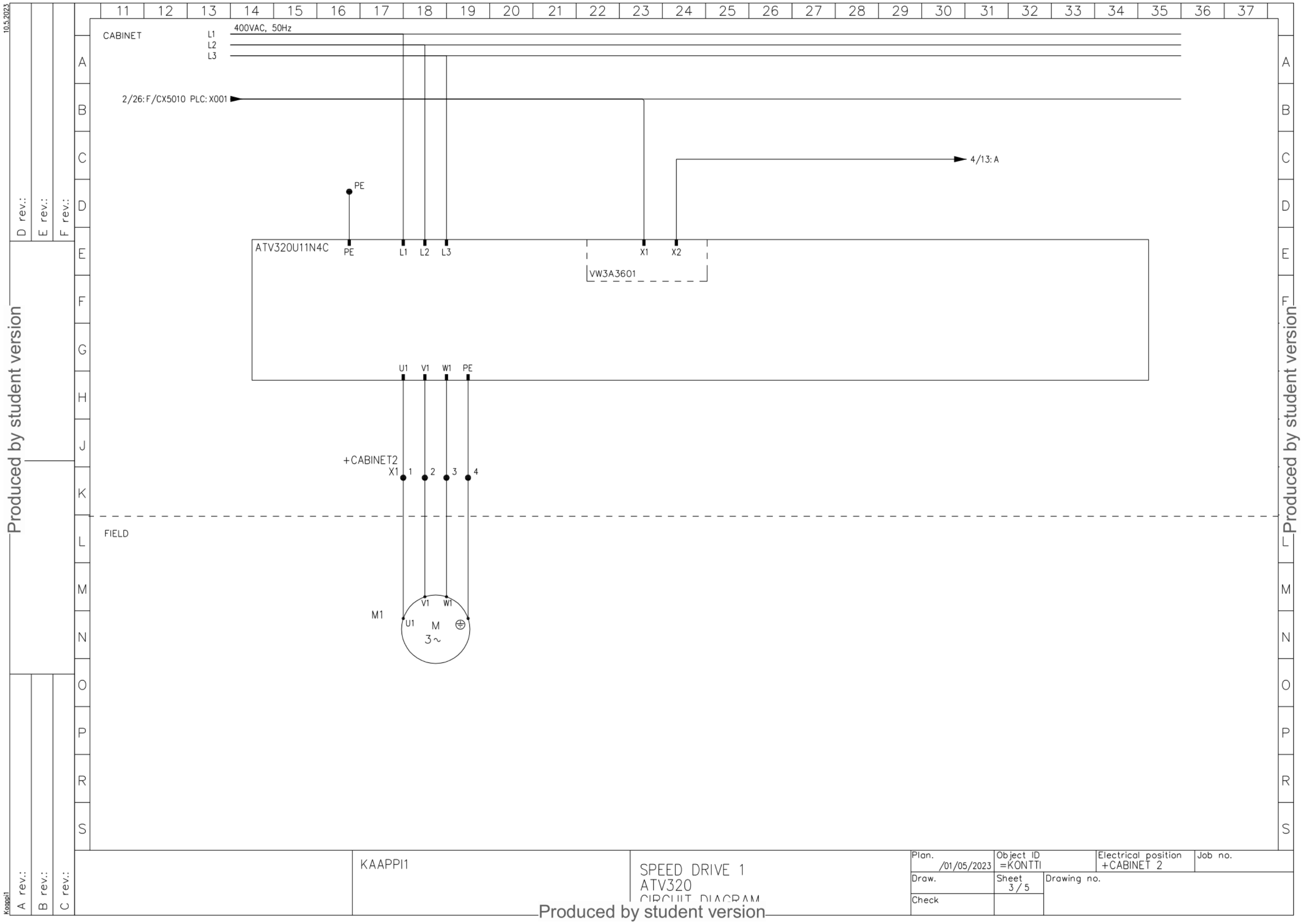
Zhang, H., Lin, K., Wang, H., & Gan, J. (2010). Effect of Pinus radiata derived biochars on soil sorption and desorption of phenanthrene. *Environmental Pollution*, *158*(9), 2821–2825. https://doi.org/10.1016/j.envpol.2010.06.025

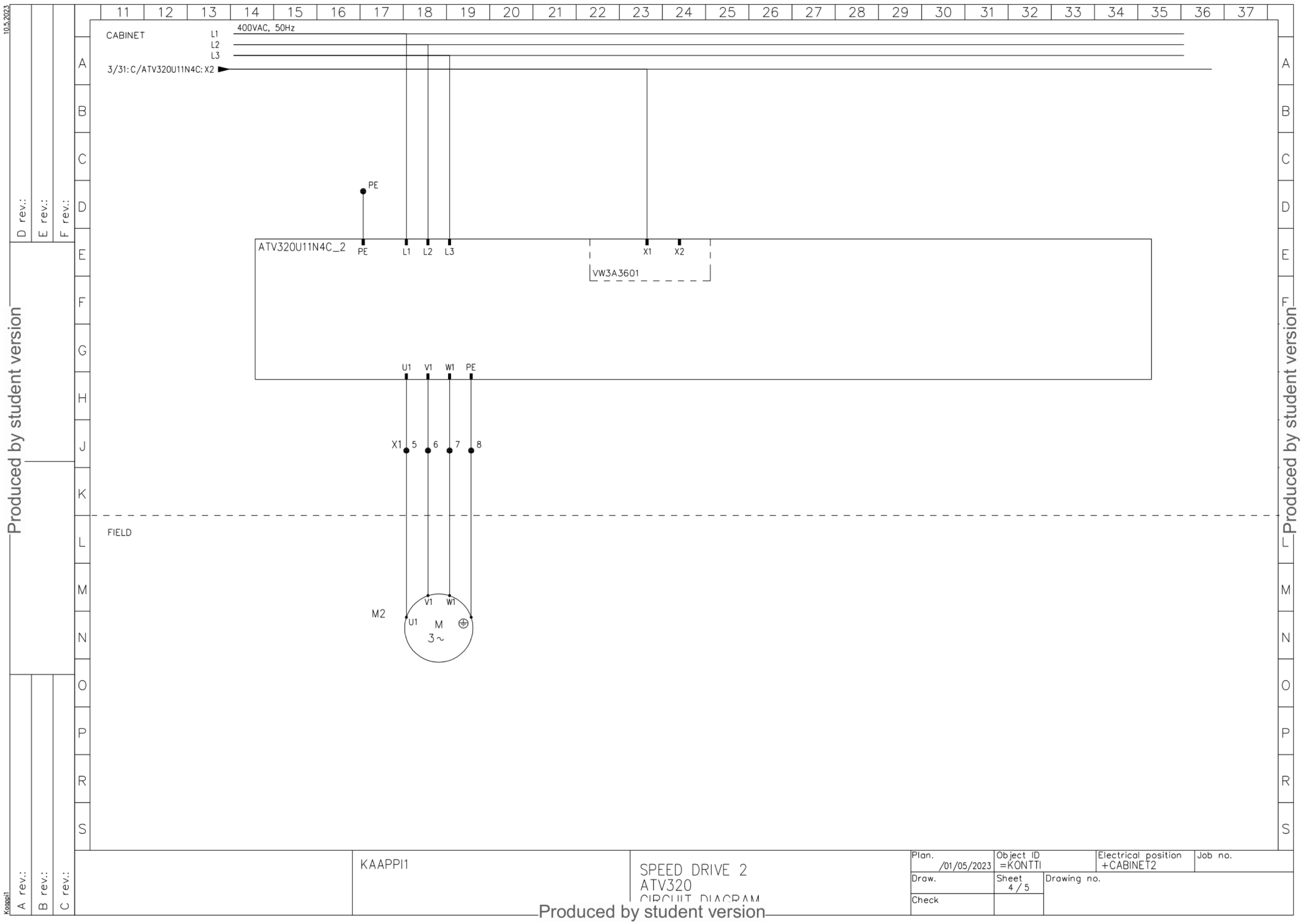
Zimmerman, A. R., Gao, B., & Ahn, M.-Y. (2011). Positive and negative carbon mineralization priming effects among a variety of biochar-amended soils. *Soil Biology and Biochemistry*, *43*(6), 1169–1179. https://doi.org/10.1016/j.soilbio.2011.02.005

Appendix 1. Circuit diagrams




11
12
13
14
15
16
17
18
19
20
21
22
23
24
25
26
27
28
29
30
31
32
33
34
35
36
37
A
B
C
D
E
F
G
H
J
K
L
M
N
O
P
R
S
CABINET
1/36:F
1/36:G
CX5010 PLC
24VDC +
0VDC -
X001
3/14:B
FIELD
D rev.:
E rev.:
F rev.:
A rev.:
B rev.:
C rev.:
10.5.2023
Kaappi1
KAAPPI1
CX5010 PLC
Power Distribution
Plan.
/01/05/2023
Draw.
Check
Object ID
=KONTTI
Sheet
2 / 5
Electrical position
+CABINET2
Drawing no.
Job no.


CABINET
L1
L2
L3
400VAC, 50Hz
2/26:F/CX5010 PLC:X001
4/13:A
PE
ATV320U11N4C
PE
L1
L2
L3
X1
X2
VW3A3601
U1
V1
W1
PE
+CABINET2
X1
1
2
3
4
FIELD
M1
U1
V1
W1
M
3~
KAAPPI1
SPEED DRIVE 1
ATV320
CIRCUIT DIAGRAM
Plan.
/01/05/2023
Draw.
Check
Object ID
=KONTTI
Sheet
3/5
Electrical position
+CABINET 2
Job no.
Drawing no.
A rev.:
B rev.:
C rev.:
D rev.:
E rev.:
F rev.:
10.5.2023
Kaappi1


11 12 13 14 15 16 17 18 19 20 21 22 23 24 25 26 27 28 29 30 31 32 33 34 35 36 37
A B C D E F G H J K L M N O P R S
CABINET
L1
L2
L3
400VAC, 50Hz
3/31:C/ATV320U11N4C:X2
PE
ATV320U11N4C_2
PE
L1
L2
L3
X1
X2
VW3A3601
U1
V1
W1
PE
X1
5
6
7
8
FIELD
M2
U1
V1
W1
M
3~
10.5.2023
D rev.:
E rev.:
F rev.:
A rev.:
B rev.:
C rev.:
Kaappi1
KAAPPI1
SPEED DRIVE 2
ATV320
CIRCUIT DIAGRAM
Plan.
/01/05/2023
Draw.
Check
Object ID
=KONTTI
Sheet
4 / 5
Electrical position
+CABINET2
Job no.
Drawing no.