UNIVERSITY OF PAVIA
FACULTY OF ENGINEERING

DEPARTMENT OF ELECTRICAL, COMPUTER, BIOMEDICAL ENGINEERING
MASTER'S DEGREE IN INDUSTRIAL AUTOMATION ENGINEERING

MASTER THESIS

SIZING OF THE ELECTRICAL EQUIPMENT OF A BIOREACTOR

DIMENSIONAMENTO DELL'APPARECCHIATURA ELETTRICA DI UN BIOREATTORE

Candidate: Ramin Fatholahi

Supervisor: Prof. Stefano Farne

A.A. 2024/2025

Abstract

As the global demand for carbon reduction technologies and sustainable energy solutions continues to grow, photobioreactors have gained significant attention due to their ability to convert carbon dioxide (CO_2) into oxygen (O_2) and biomass using microalgae.

This thesis focuses on the design and sizing of the electrical equipment for a pilot-scale horizontal tubular photobioreactor operating in a closed-loop configuration. This specific system is selected as a reference plant for all calculations, providing a realistic and consistent basis for the analysis of energy requirements and component sizing. Tubular photobioreactors are widely recognized as one of the most suitable configurations for pilot-scale and large-scale applications due to their high illumination surface area and relatively high biomass productivity.

The considered system consists of transparent horizontal tubes in which the culture medium is continuously recirculated using a pump to ensure proper mixing, uniform light exposure, and efficient gas exchange. The photobioreactor is equipped with key subsystems including a circulation pump, CO_2 injection system, LED lighting, and sensor-based monitoring, all powered by a solar energy system.

This study presents a comprehensive methodology for sizing the electrical infrastructure required for the operation of the photobioreactor. The proposed energy system includes photovoltaic panels, battery storage, and an inverter to guarantee continuous and sustainable operation. In addition, motors, pumps, lighting systems, and sensors are selected and sized according to the specific operational requirements of the reference system.

A detailed analysis of energy consumption and system efficiency is performed to identify optimal configurations that reduce energy losses while maintaining reliable operation. The integration of automation and real-time monitoring enhances process stability and allows optimal control of environmental conditions within the reactor.

The results demonstrate that proper sizing of electrical components, based on a clearly defined pilot-scale tubular photobioreactor, significantly improves energy efficiency, reduces operational costs, and enhances system reliability.

This research provides a practical framework for the design of energy-efficient photobioreactor systems and contributes to the development of scalable and sustainable technologies for carbon capture, renewable energy production, and environmental protection.

Keywords: Photobioreactor, Tubular Photobioreactor, Electrical Equipment Sizing, Solar Energy, Microalgae, Pilot-Scale System, Energy Efficiency, Carbon Capture.

Table of Contents

Chapter 1- Introduction

Background and Motivation

The worldwide increase in demand for green energy sources and environmental sustainability has led to significant advancements in biotechnology. One of the most promising solutions is the use of photobioreactors for carbon dioxide (CO_2) mitigation and oxygen (O_2) production. These systems utilize the photosynthetic capability of microalgae to convert CO_2 into oxygen and biomass, offering a sustainable approach to reducing greenhouse gas emissions.

The performance of a photobioreactor strongly depends on precise environmental control, efficient energy utilization, and reliable electrical equipment. Components such as solar panels, inverters, motors, pumps, lighting systems, and sensors play a critical role in ensuring optimal operating conditions. Proper sizing of these electrical systems is essential to achieve energy efficiency, cost-effectiveness, and long-term sustainability.

In this thesis, all analyses and calculations are referred to a specific reference system, namely a pilot-scale horizontal tubular photobioreactor operating in a closed-loop configuration. This system consists of transparent horizontal tubes through which the culture medium is continuously recirculated using a pump, ensuring adequate mixing, light exposure, and gas exchange. The selection of this configuration is based on its widespread use in pilot-scale applications and its suitability for microalgae cultivation, as reported in the literature.

The definition of a specific reference plant is essential to provide consistency in the design and sizing of electrical equipment. All components analyzed in this thesis including power supply systems, motors, pumps, lighting units, and control systems are therefore dimensioned based on the operational requirements of this selected photobioreactor.

While photobioreactors are increasingly used in industrial and environmental applications, challenges remain in optimizing their electrical systems. Inefficient sizing of power supplies, improper energy storage design, and suboptimal integration of control systems can lead to increased energy consumption, higher operational costs, and reduced system reliability. Therefore, a systematic and engineering-based approach to electrical equipment sizing is required.

This thesis was developed on the basic project developed by the the prof Stefano Farné C.F. FRNSFN66E26F205I and by the engineer Ernesto Granelli C.F. GRNRST44T08B817C. Therefore the industrial and intellectual property remains exclusive of the Prof Farné and the engineer Granelli. Any other claim is henceforth to be considered inapplicable.

Evolution of Bioreactors

Bioreactors have evolved over decades, from simple fermentation vessels to highly controlled industrial-scale systems. Initially used in food production processes such as brewing and dairy fermentation, bioreactors have progressively expanded into applications including pharmaceuticals, wastewater treatment, and renewable energy production.

In the mid-20th century, stirred-tank bioreactors became widely used for large-scale fermentation processes such as antibiotic production. Later developments introduced advanced monitoring and aeration systems, improving efficiency and scalability.

In the 21st century, the emergence of photobioreactors has marked a significant shift toward sustainable and environmentally friendly technologies. These systems integrate renewable energy sources, automation, and advanced control strategies to enhance productivity while minimizing environmental impact. Among these, tubular photobioreactors have gained particular attention due to their suitability for pilot-scale and industrial applications. **[1], [6]**

Real-World Applications of Photobioreactors

Photobioreactors are widely applied across multiple sectors due to their ability to convert CO_2 into valuable bioproducts while operating under sustainable conditions.

Carbon Capture and Climate Change Mitigation

Microalgae cultivated in photobioreactors absorb CO_2 from industrial emissions and convert it into biomass and oxygen, contributing to the reduction of greenhouse gases.

Biofuel Production

Microalgae can produce bioethanol, biodiesel, and biogas, offering renewable alternatives to fossil fuels. Compared to conventional crops, algae require less land and water while providing higher yields.

Wastewater Treatment

Photobioreactors can remove nutrients, heavy metals, and pollutants from wastewater, improving water quality while generating usable biomass.

Pharmaceuticals and Nutraceuticals

Microalgae are used to produce valuable compounds such as omega-3 fatty acids, vitamins, and antioxidants, widely applied in health and pharmaceutical industries.

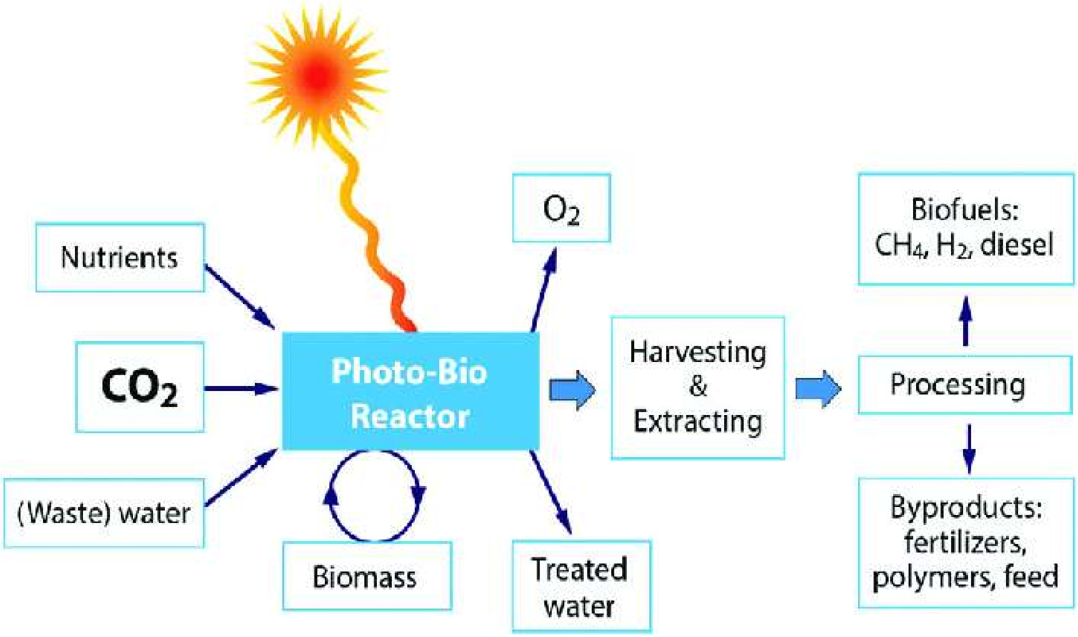

Figure 1: Photobioreactor Applications for CO_2 Conversion

Objective of the Thesis

The main objective of this thesis is to design, analyze, and optimize the electrical equipment of a pilot-scale tubular photobioreactor, ensuring that all components are properly sized according to the system's energy requirements. **[1], [5]**

The specific objectives are:

- To evaluate the power requirements of key electrical components, including motors, pumps, sensors, lighting systems, and control units.
- To design a solar-powered energy system by selecting appropriate photovoltaic panels, batteries, and inverters. **[7], [11]**
- To analyze the performance and reliability of energy storage systems for continuous operation.
- To optimize motors and pumps for efficient fluid circulation and gas exchange.

- To integrate automation and sensor-based monitoring systems for real-time control. To perform an energy efficiency analysis to reduce power losses and improve system sustainability.

All these objectives are developed with reference to the selected pilot-scale tubular photobioreactor, ensuring consistency and practical applicability.

Structure of the Thesis

This thesis is organized into several chapters to provide a comprehensive analysis of electrical equipment sizing and system efficiency in a pilot-scale tubular photobioreactor:

Chapter 2: Overview of Bioreactors – Presents the classification, working principles, and applications of bioreactors, with a focus on photobioreactors.

Chapter 3: Electrical Equipment in a Bioreactor – Describes the main electrical components required for operation, including motors, pumps, lighting systems, and sensors.

Chapter 4: Sizing of Electrical Equipment – Provides detailed calculations for the sizing of electrical components based on the selected reference system.

Chapter 5: Power Consumption and Efficiency Analysis – Evaluates energy consumption and proposes optimization strategies.

Chapter 6: Cost Analysis and Economic Viability – Assesses the economic feasibility and return on investment (ROI).

Chapter 7: Conclusion and Future Trends – Summarizes findings and discusses future developments in photobioreactor technology.

Chapter 2- Overview of Bioreactors

Overview of Bioreactors

Bioreactors are essential systems in biotechnology and environmental engineering, designed to support biological reactions by providing controlled conditions for microbial, cellular, or enzymatic processes. These reactors play a crucial role in applications such as biofuel production, wastewater treatment, pharmaceuticals, and carbon capture. By maintaining key environmental parameters such as temperature, pH, dissolved oxygen, and nutrient availability bioreactors enable efficient biological activity and improved productivity.

Among the different types of bioreactors, photobioreactors (PBRs) are specifically designed for the cultivation of photosynthetic microorganisms such as microalgae. These systems utilize light as the primary energy source and are increasingly used in sustainable technologies. **[1], [3]**

In this thesis, particular focus is given to a pilot-scale horizontal tubular photobioreactor operating in a closed-loop configuration, which is selected as the reference system for all analyses and calculations. This type of reactor is widely used in pilot and industrial applications due to its high surface-to-volume ratio, efficient light utilization, and suitability for continuous operation.

Modern bioreactors integrate advanced technologies such as automation, Internet of Things (IoT) sensors, and artificial intelligence (AI)-based control systems to improve efficiency and reduce energy consumption. Electrical components play a fundamental role in ensuring proper operation, making their correct sizing essential for system performance and sustainability.

Types of Bioreactors

Bioreactors can be classified based on their operational mode, energy source, and design configuration. Each type is suited for specific industrial and research applications. **[5], [6]**

Table 1: Classification of Bioreactors

Category	Type	Description	Applications
By Operation Mode	Batch	Operates in cycles; all inputs added initially	Antibiotics, yogurt, beer fermentation
	Continuous	Fresh medium continuously supplied; output collected	Large-scale bioprocessing, biofuels
	Fed-Batch	Nutrients added in intervals; prevents depletion	Pharmaceutical production
By Energy Source	Mechanical	Uses mechanical agitation for mixing	Stirred-tank bioreactors,
	Photobioreactors	Uses light energy for photosynthesis	Algae cultivation, biofuels, CO_2 capture
By Design	Stirred-Tank	Uses an impeller for mixing and aeration	Fermentation, pharmaceutical
	Airlift	Uses gas bubbles for circulation	Wastewater treatment, bioethanol
	Tubular	Long tubes maximize light exposure	Latrge-scale applications
	Flat-Panel	Thin, transparent panels	Carbon sequestration, biofuels

Among the different configurations listed above, tubular photobioreactors are selected in this study as the reference system, due to their suitability for pilot-scale applications and their compatibility with continuous flow and solar energy integration.

Working Principles of a Photobioreactor

A photobioreactor (PBR) is a specialized system that uses light energy to drive biological processes. In this thesis, the working principles described refer specifically to a horizontal tubular photobioreactor, where the culture medium circulates through transparent tubes exposed to light. **[3], [4]**

Core Components of a Photobioreactor

A typical photobioreactor includes the following components:

- **Light Source** – Natural sunlight and/or artificial LED lighting for photosynthesis.
- **CO_2 Supply System** – Provides carbon dioxide to enhance microalgal growth.
- **Mixing System** – Ensures uniform distribution of light, nutrients, and gases.
- **Aeration System** – Facilitates gas exchange and oxygen removal.
- **Sensors and Monitoring Devices** – Measure parameters such as pH, temperature, and dissolved oxygen.

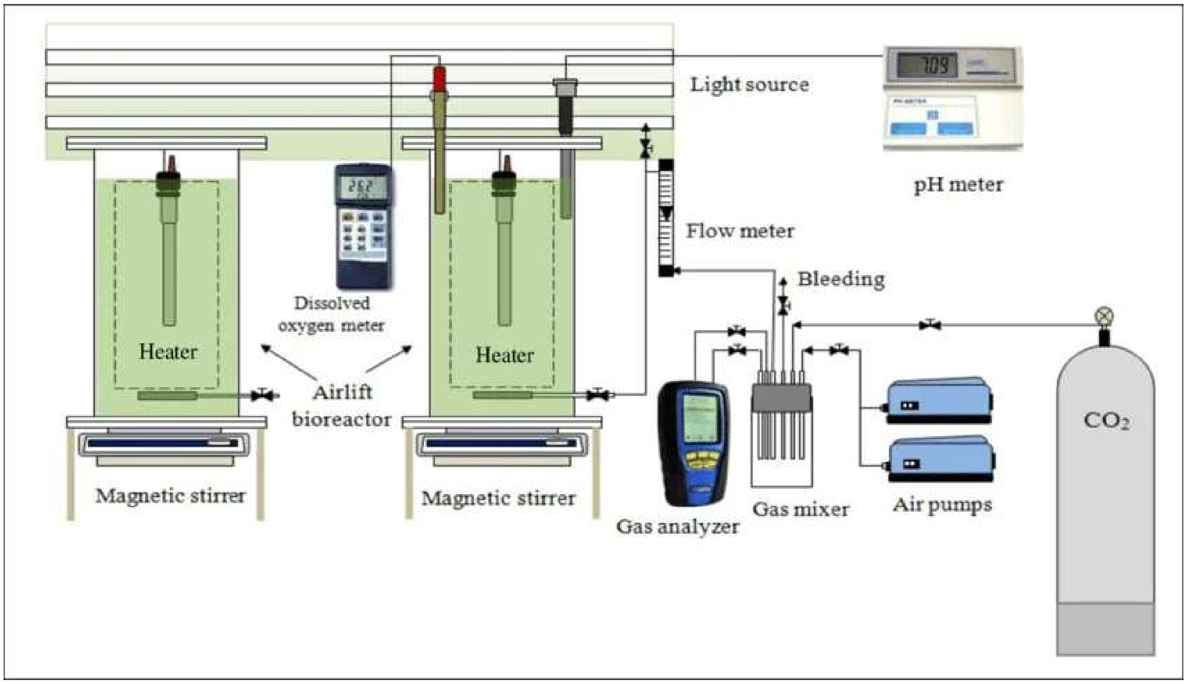

Figure 2: Schematics Diagram of The Photobioreactor Setup [15]

How Photobioreactors Work

1. Microalgae absorb light and CO_2 to produce oxygen and biomass through photosynthesis.
2. A circulation system ensures continuous mixing and nutrient distribution.
3. Sensors and control systems regulate environmental conditions in real time.

In tubular photobioreactors, these processes occur continuously along the length of the tubes. The recirculation of the culture medium ensures uniform exposure to light and improves mass transfer efficiency.

Figure 3: 6 Horizontal Tubular Photobioreactor Microalgae Cultivation System and Biorefinery [16]

Importance of Electrical Systems in Bioreactors

In the selected pilot-scale tubular photobioreactor, electrical systems play a fundamental role in ensuring continuous operation, efficient energy use, and process automation. **[10]**

Effective electrical design is necessary in order to:

Power Supply and Distribution

Bioreactors require a stable and continuous power supply. Renewable energy sources, particularly solar power, are often integrated to improve sustainability. Energy storage systems such as batteries ensure operation during periods of low solar availability.

Figure 4: Innovative Algae Bioreactor System With Solar Power

Lighting Optimization

Artificial lighting, typically based on LED technology, is used to provide the required light spectrum for photosynthesis. Proper design of lighting systems improves biological productivity while minimizing energy consumption.

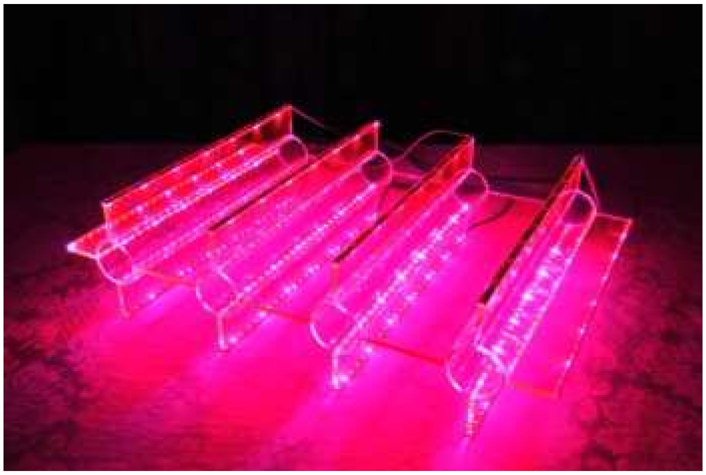

Figure 5: Artificial lighting for photobioreactors Innovative Algae Bioreactor System With Solar Power

Motor and Pump

Motors and pumps are essential for fluid circulation, mixing, and gas exchange. Their proper sizing directly affects energy efficiency and system performance.

Figure 6: Geared Motors

Figure 7: Circulation Pump for Temperature Module – Bioreactors

Sensor and Automation

Sensors continuously monitor parameters such as temperature, pH, and CO_2 concentration. Automation systems use this data to adjust operating conditions, ensuring optimal performance and reducing manual intervention.

Figure 8: Bioreactor pH Sensor

Conclusion

This chapter provided an overview of bioreactor technologies, focusing on photobioreactors and their working principles. A pilot-scale horizontal tubular photobioreactor was identified as the reference system for this thesis due to its suitability for microalgae cultivation, efficient light utilization, and compatibility with continuous operation. The next chapter will focus on the electrical equipment required for this specific system, including power supply units, motors, pumps, lighting systems, and automation components.

Chapter 3- Electrical Equipment in a Photobioreactor

Introduction

The efficient operation of a photobioreactor (PBR) depends on a well-designed electrical system that ensures precise environmental control, energy efficiency, and automation. Electrical components such as motors, pumps, lighting systems, sensors, and inverters work together to maintain optimal conditions for microalgal growth, CO_2 fixation, and biofuel production.

This chapter explores the key electrical components, their functions, and their impact on the overall efficiency of a bioreactor.

Power Supply System

Overview

The power supply system provides the electrical energy required for all components of the photobioreactor. In the selected pilot-scale tubular system, a hybrid energy solution based on solar power is considered. **[11], [8]**

The main elements of the power supply system include:

- Photovoltaic (PV) panels
- Battery storage system
- Inverter
- Charge controller

These components work together to ensure continuous power availability, even during periods of low solar radiation.

Photovoltaic (PV) Panels

Photovoltaic panels convert solar energy into electrical energy. In this system, PV panels are used as the primary energy source to reduce dependence on conventional electricity and improve sustainability.

The sizing of PV panels depends on:

- Total power consumption of the system
- Daily energy demand
- Solar irradiance conditions

Battery Storage System

Batteries are used to store excess energy generated by the PV panels. This stored energy is used when solar power is not available, such as during nighttime or cloudy conditions. **[9]**

Proper battery sizing is essential to:

Ensure uninterrupted operation

Maintain system stability

Extend battery lifespan

Inverter and Charge Controller

The inverter converts direct current (DC) from the PV panels and batteries into alternating current (AC) required by most electrical components.

The charge controller regulates the voltage and current supplied to the batteries, preventing overcharging and deep discharge, which can damage the storage system.

Motors and Pumps

Role in Tubular Photobioreactor

In a horizontal tubular photobioreactor, pumps play a crucial role in circulating the culture medium through the tubes. **[3], [10]**

This circulation ensures:

- Uniform light exposure
- Proper mixing of nutrients
- Efficient gas exchange

Pump Selection Criteria

The selection of pumps depends on:

- Flow rate requirements
- Pressure losses in the tubes
- Fluid properties (density, viscosity)
- System geometry

Efficient pump operation is essential to minimize energy consumption while maintaining adequate circulation.

Motor Efficiency

Electric motors drive the pumps and other mechanical components. High-efficiency motors are preferred to:

- Reduce energy losses
- Improve overall system performance
- Lower operational costs

Lighting System

Role of Lighting in Photobioreactors

Light is the primary energy source for microalgae growth. In tubular photobioreactors, natural sunlight is often supplemented with artificial lighting to ensure consistent productivity. **[13]**

LED Lighting

LEDs are widely used due to their:

- High energy efficiency
- Long lifespan
- Ability to provide specific light wavelengths

The lighting system must be designed to provide adequate light intensity while minimizing energy consumption.

Sensors and Monitoring Systems

Key Parameters Monitored

Sensors are essential for maintaining optimal operating conditions. **[10]**

The main parameters monitored include:

- Temperature
- pH
- Dissolved oxygen
- CO_2 concentration

Automation and Control

Automation systems use sensor data to regulate the operation of pumps, lighting, and gas supply. This ensures:

- Stable operating conditions
- Improved efficiency
- Reduced human intervention

Energy Management and System Integration

The integration of all electrical components into a unified system is essential for efficient operation.

In the selected pilot-scale tubular photobioreactor, energy management involves:

- Balancing energy generation and consumption
- Optimizing battery usage
- Prioritizing critical loads (e.g., circulation pump)

A well-designed energy management strategy improves system reliability and reduces operational costs.

Safety and Reliability Considerations

Electrical systems must be designed with safety and reliability in mind. Key considerations include:

- Protection against overload and short circuits
- Proper grounding and insulation
- Use of circuit breakers and protection devices
- Ensuring system redundancy for critical components

These measures are essential to ensure safe and continuous operation of the photobioreactor.

Electrical Diagram for the Bioreactor System

The following diagram illustrates the electrical configuration of the bioreactor system powered by a photovoltaic (PV) system. The system consists of a PV panel that generates DC electricity, which is regulated by a charge controller before being stored in a battery bank. The inverter converts the stored DC power into AC, which is used to operate the bioreactor system. The improved spacing ensures that the labels for each component are clearly readable.

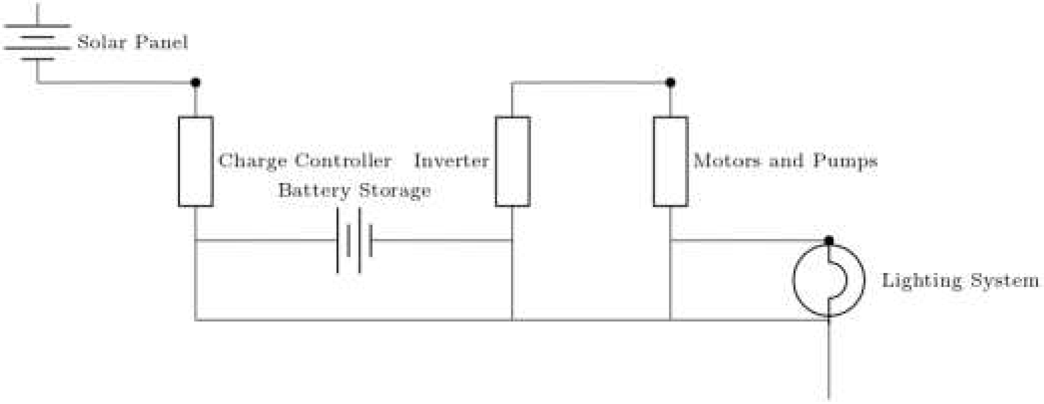

Figure 9: Electrical Diagram for the Bioreactor System

Conclusion

This chapter presented the main electrical components required for the operation of a pilot-scale horizontal tubular photobioreactor.

The power supply system, motors, pumps, lighting systems, sensors, and control units were described in relation to their role in maintaining optimal operating conditions.

The integration of these components into a cohesive system ensures efficient and reliable operation.

The next chapter will focus on the detailed sizing of these electrical components, based on the energy requirements of the selected reference system.

Chapter 4- Sizing of Electrical Equipment

Introduction

The proper sizing of electrical equipment is essential to ensure the efficient and reliable operation of a photobioreactor system.

In this chapter, all calculations and sizing procedures are referred to a specific reference system: a pilot-scale horizontal tubular photobioreactor operating in a closed-loop configuration.

This system consists of transparent horizontal tubes through which the culture medium is continuously recirculated using a pump. The operation requires electrical energy for fluid circulation, lighting, gas injection, monitoring, and control systems.

The methodology presented in this chapter provides a systematic approach to determine the electrical requirements of each component and to design a suitable power supply system. **[8], [11]**

Description of the Reference System

The reference system considered in this thesis is a pilot-scale horizontal tubular photobioreactor characterized by the following features:

- Closed-loop tubular configuration
- Continuous circulation of culture medium
- Integration of solar energy as the primary power source
- Supplementary LED lighting system
- CO_2 injection for enhanced microalgal growth
- Sensor-based monitoring and automated control

Main Electrical Loads

The main electrical loads of the system are:

- Circulation pump
- LED lighting system
- CO_2 injection system (compressor or valve system)

- Sensors and control units
- Auxiliary devices

All subsequent calculations are based on these loads.

Load Estimation

General Methodology

The total electrical load of the system is calculated as the sum of the power requirements of all components:

$$P_{total} = \sum_{i=1}^{n} P_i$$

Where:

- P_i = power of each component

Circulation Pump Power

The pump is the most critical component in a tubular photobioreactor. Its power requirement is estimated using: **[10]**

$$P_{Pump} = \frac{\rho \times g \times Q \times H}{\eta}$$

Where:

- ρ = fluid density
- g = gravitational acceleration
- Q = flow rate
- H = head loss
- η = pump efficiency

In tubular systems, head losses are influenced by pipe length, diameter, and friction.

LED Lighting Power

$$P_{LED} = A \times \mathrm{I} \times \frac{1}{\eta_{LED}}$$

Where:

- A = illuminated area
- I = required light intensity
- η_{LED} = efficiency of LED system

CO₂ Injection System

The power required for CO₂ injection depends on the gas flow rate and pressure requirements. In pilot-scale systems, this is typically lower than pump power but must be considered for continuous operation.

Sensors and Control Systems

Sensors and control systems have relatively low power consumption but are essential for system stability. Their power is typically estimated as a fixed percentage of total load or based on manufacturer specifications.

Daily Energy Consumption

The daily energy demand is calculated as:

$$E_{daily} = P_{total} \times \mathrm{t}$$

Where:

- t = operating time (hours per day)

This value is fundamental for sizing the solar energy system and battery storage.

Sizing of Photovoltaic (PV) System

Required PV Power

The required PV power is calculated as: **[8], [11]**

$$P_{PV} = \frac{E_{daily}}{H_{sun} \times \eta_{system}}$$

Where:

- H_{sun} = daily solar irradiation
- $\eta =$ overall system efficiency

Number of PV Panels

$$N_{panels} = \frac{P_{PV}}{P_{panel}}$$

Where:

- P_{panel} = rated power of one panel

Battery Storage Sizing

The battery capacity is calculated as: **[9]**

$$C_{battery} = \frac{E_{daily} \times \text{Days of Autonomy}}{V\ \times \text{DOD}}$$

Where:

- Days of Autonomy = number of backup days
- $V =$ system voltage
- DOD $=$ depth of discharge

Proper battery sizing ensures continuous operation during low solar conditions.

Inverter Sizing

$$P_{inverter \geq 1.2 \times} P_{total}$$

A safety factor is included to account for peak loads and system losses.

Efficiency Considerations

Energy losses occur in:

- Pumps and motors
- Power conversion systems

- Wiring and distribution

Improving efficiency reduces total energy demand and system cost.

Numerical Example of Electrical Sizing

To validate the proposed methodology, a numerical example is developed based on typical values reported in the literature for pilot-scale tubular photobioreactors. **[1], [3], [8]**

Assumptions

The following assumptions are considered:

- Flow rate: $Q = 0.005 \frac{m^3}{s}$
- Head loss: $H = 5\ m$
- Pump efficiency: $\eta = 0.7$
- Fluid density: $\rho = 1000 \frac{\text{kg}}{m^3}$
- LED power: 300W
- CO_2 system: 100 W
- Sensors/contro: 50 W
- Operating time: t =24 $\frac{\text{h}}{day}$
- Solar irradiation: $H_{sun} = 5 \frac{\text{h}}{day}$
- System efficiency: $\eta_{system} = 0.75$
- Panel rating: 400 W
- Battery Voltage: 24 V
- Depth of discharge: DOD = 0.8

Pump Power Calculation

$$P_{Pump} = \frac{1000 \times 9.81 \times 0.005 \times 5}{0.7} \approx 350\ W$$

Total Power Consumption

$$P_{total} = 350 + 300 + 100 + 50 = 800\ W$$

Daily Energy Demand

$$E_{daily} = 800 \times 24 = 19200\,Wh = 19.2\,\frac{kWh}{day}$$

PV System Sizing

$$P_{PV} = \frac{19200}{5 \times 0.75} \approx 5120\,W$$

$$N_{panels} = \frac{5120}{400} \approx 13\,panels$$

Battery Sizing

$$C_{battery} = \frac{19200}{24 \times 0.8} \approx 1000\,Ah$$

Inverter Selection

$$P_{inverter} \geq 1.2 \times 800 = 960\,W$$

Selected: **1 kW inverter**

Summary of Result

Parameter	Value
Pump Power	~350 W
Total Power	~800 W
Daily Energy	19.2 kWh
PV System	~5.1 kW
Panels	13
Battery	~1000 Ah
Inverter	1 kW

Discussion

The numerical results show that the circulation pump and LED lighting system dominate the total energy consumption, accounting for more than 80% of the total load.

This behavior is characteristic of tubular photobioreactors, where continuous circulation and sufficient illumination are essential for efficient operation.

The results also demonstrate that a solar-based system can reliably support the operation of the photobioreactor, provided that sufficient battery storage is included.

Summary of Sizing Procedure

The sizing process for the electrical system of the pilot-scale tubular photobioreactor follows these steps:

1. Define the reference system
2. Identify all electrical loads
3. Calculate individual power requirements
4. Determine total power consumption
5. Estimate daily energy demand
6. Size the PV system
7. Size the battery storage
8. Select inverter capacity
9. Evaluate system efficiency

This structured approach ensures consistency and accuracy in the design process.

Conclusion

This chapter presented a comprehensive methodology for the sizing of electrical equipment in a pilot-scale horizontal tubular photobioreactor.

A numerical example was developed to validate the approach and to provide realistic design values. The results obtained in this chapter form the basis for the energy efficiency analysis (Chapter 5) and the economic evaluation (Chapter 6).

Chapter 5- Power Consumption and Efficiency Analysis

Introduction

The performance of a photobioreactor system is strongly influenced by its energy consumption and overall efficiency. **[3], [5]**

In this chapter, the power consumption and efficiency of a pilot-scale horizontal tubular photobioreactor operating in a closed-loop configuration are analyzed, based on the sizing results obtained in Chapter 4.

The objective is to evaluate energy distribution among system components, identify major sources of energy loss, and propose strategies to improve efficiency and reduce operational costs.

Power Consumption Analysis

Total Power Demand

Based on the numerical example presented in Chapter 4, the total electrical load of the system is:

- Total power: ~800 W
- Daily energy consumption: ~19.2 kWh/day

The total power demand is distributed among the main components of the tubular photobioreactor system**.**

Total Power Demand

The approximate contribution of each component is:

Component	**Power (W)**	**Contributions (%)**
Pump	350	44 %
LED Lighting	300	38 %
CO_2 System	100	12 %
Sensors & Control	50	6 %

The circulation pump and lighting system together account for more than 80% of total energy consumption. **[1], [6]**

Efficiency Analysis of Components

Pump Efficiency

The pump efficiency directly affects the overall system performance. Losses occur due to:

- Friction in pipes
- Hydraulic inefficiencies
- Motor losses

Improving pump efficiency (e.g., from 70% to 80%) can significantly reduce total energy consumption.

Lighting Efficiency

LED systems are efficient but still consume a large portion of energy. Efficiency depends on: **[13]**

- Light spectrum optimization
- Light distribution
- Distance from reactor surface

Using optimized wavelengths for microalgae growth can improve energy utilization.

Power Conversion Efficiency

Losses occur in:

- Inverter (typically 90–95%)
- Battery storage (80–90%)
- Wiring and connections

These losses must be considered when designing the system. **[11]**

Energy Loss Analysis

The total system losses can be categorized as:

Electrical Losses

- Inverter losses

- Battery charging/discharging losses
- Cable losses

Mechanical Losses

- Pump inefficiencies
- Friction lossesin tubing

Operational Losses

- Over-lighting or inefficient illumination
- Non-optimal flow rates

System Efficiency

The overall system efficiency can be expressed as:

$$\eta_{system} = \frac{E_{useful}}{E_{input}}$$

Where:

- E_{useful} = energy effectively used for biological processes
- E_{input} = total supplied energy

In practical systems, efficiency is reduced due to cumulative losses in all components.

Optimization Strategies

To improve the efficiency of the pilot-scale tubular photobioreactor, the following strategies are recommended:

Pump Optimization

- Use high-efficiency pumps
- Optimize flow rate to reduce unnecessary circulation
- Minimize pipe length and bends

Lighting Optimization

- Use wavelength-specific LEDs
- Implement smart lighting control (on/off cycles)
- Maximize use of natural sunlight

Energy System Optimization

- Improve battery management
- Use high-efficiency inverters
- Optimize PV panel orientation

Control System Optimization

- Implement automated control systems
- Use real-time monitoring to reduce energy waste

Impact of Renewable Energy Integration

The use of solar energy significantly improves the sustainability of the system:

- Reduces dependency on fossil fuels
- Lowers operational costs
- Decreases environmental impact

However, variability in solar energy requires proper battery sizing and energy management.

Economic Implications

Energy efficiency has a direct impact on system cost: **[9]**

- Lower energy consumption → reduced operational cost
- Higher efficiency → faster return on investment (ROI)

Optimizing electrical components is therefore essential not only for performance but also for economic viability.

Discussion

The analysis shows that:

- The pump and lighting system dominate energy consumption
- Energy losses occur at multiple levels (electrical + mechanical)
- Optimization can significantly improve system performance

The results confirm that proper electrical design is critical for efficient operation of tubular photobioreactors.

Conclusion

This chapter analyzed the power consumption and efficiency of a pilot-scale horizontal tubular photobioreactor based on the sizing results obtained in Chapter 4.

The study identified the main energy-consuming components and evaluated the sources of energy losses.

Optimization strategies were proposed to improve efficiency, reduce operational costs, and enhance system reliability.

The next chapter will focus on the economic analysis and cost evaluation of the proposed system.

Chapter 6- Cost Analysis and Economic Viability

Introduction

The economic feasibility of a photobioreactor system is a key factor in determining its practical applicability.

In this chapter, the cost and economic performance of a pilot-scale horizontal tubular photobioreactor operating in a closed-loop configuration are analyzed, based on the electrical system design developed in previous chapters.

The objective is to estimate the total system cost, evaluate operational expenses, and assess the economic viability of the proposed solution.

Capital Cost Estimation (CAPEX)

The capital cost includes all initial investments required to build and install the system.

Main Components Cost

Based on the sizing results (Chapter 4), the estimated costs are:

Component	Specification	Estimated Cost (€)
PV Panels (13× 400W)	~5.1 kW system	5,000
Battery System (24V, 1000 Ah)	Energy storage	4,000
Inverter (1 kW)	DC-AC conversion	500
Pump & Motor	Circulation system	600
LED Lighting System	300 W	800
Sensors & Control	Monitoring system	400
Installation & Wiring	Cables, supports	700

Total Capital Cost

$$\text{CAPEX} \approx 12{,}000 \text{ €}$$

Operational Cost (OPEX)

Operational costs include expenses required to run the system.

Energy Cost

Since the system uses solar energy, electricity cost is significantly reduced. However, minor costs may arise from:

- Grid backup (if used)
- System inefficiencies

Estimated annual energy cost:

Without solar power, the daily electricity cost is: [8], [11]

$$\approx 200\ €/\mathrm{year}$$

The annual electricity cost is estimated considering that the majority of the energy demand is supplied by the photovoltaic system. Assuming that approximately 90% of the total energy demand is covered by solar energy (The International Renewable Energy Agency (IRENA) estimates that 90% of the world's electricity can and should come from renewable energy by 2050 to meet climate goals.), only 10% is provided by the electrical grid. Based on a total annual energy demand of approximately 7000 kWh and an electricity price of 0.25 €/kWh (typical in Europe), the resulting electricity cost is about 200 €/year.

Maintenance Cost

The system provides economic value through:

CO_2 Reduction

Reduction in carbon emissions can have economic value in carbon credit systems.

Biomass Production

Microalgae biomass can be used for:

- Biofuels
- Nutraceuticals

- Animal feed

Energy Savings

Using solar energy reduces dependence on grid electricity. **[7]**

Payback Period Analysis

The payback period is estimated as:

$$Payback = \frac{CAPEX}{Anual\ Savings}$$

Assumption:

- Annual savings (energy + biomass value): ~2,000 €/year

$$Payback \approx \frac{12{,}000}{2{,}000} = 6 years$$

Cost Optimization Strategies

To improve economic viability, the following strategies can be applied:

Reduce Capital Cost

- Use cost-effective PV panels
- Optimize battery size

Reduce Operational Cost

- Improve system efficiency (Chapter 5)
- Reduce maintenance frequency

Increase Revenue

- Improve biomass productivity
- Use high-value microalgae products

Sensitivity Analysis

The economic performance depends on several variables:

Parameter	Impact
Solar irradiation	Affects energy production
Energy efficiency	Affects operating cost
Biomass value	Affects revenue
Battery cost	Affects CAPEX

Improving efficiency (Chapter 5) has a direct impact on economic performance.

Discussion

The analysis shows that:

- Initial investment is moderate for a pilot-scale system
- Solar energy significantly reduces operating costs
- Payback period is reasonable (~6 years)

The system becomes more economically attractive at larger scales.

Conclusion

This chapter evaluated the economic feasibility of a pilot-scale horizontal tubular photobioreactor.

The analysis demonstrated that, despite the initial capital investment, the system can achieve reasonable economic performance due to low operational costs and potential revenue from biomass production.

The integration of renewable energy further enhances sustainability and reduces long-term expenses.

Chapter 7- Conclusion and Future Trends

Conclusion

This thesis presented the design, sizing, and analysis of the electrical equipment required for a pilot-scale horizontal tubular photobioreactor operating in a closed-loop configuration.

A specific reference system was defined at the beginning of the study to ensure consistency across all calculations and analyses. This approach allowed a structured and engineering-based methodology to be developed for the selection and sizing of electrical components.

The study first introduced the fundamental principles of photobioreactors, highlighting their role in carbon capture, renewable energy production, and sustainable biotechnology. Among the various configurations, the tubular photobioreactor was selected due to its suitability for pilot-scale applications, efficient light utilization, and compatibility with continuous operation. **[1], [6]**

A detailed analysis of the electrical system was carried out, including power supply design, motors, pumps, lighting systems, sensors, and control units. The integration of a solar energy system consisting of photovoltaic panels, battery storage, and an inverter enabled a sustainable and energy-efficient solution.

The sizing methodology developed in this thesis allowed the estimation of power requirements for each component. A numerical example demonstrated that the total system load is approximately 800 W, with a daily energy consumption of about 19.2 kWh. The results showed that the circulation pump and lighting system are the dominant energy consumers, accounting for the majority of energy usage.

The efficiency analysis highlighted the main sources of energy losses, including pump inefficiencies, power conversion losses, and suboptimal operating conditions. Optimization strategies were proposed to improve system performance, such as enhancing pump efficiency, optimizing lighting systems, and implementing advanced control strategies.

The economic analysis demonstrated that the system is economically feasible, with an estimated capital cost of approximately €12,000 and a payback period of around 6 years. The use of solar energy significantly reduces operational costs and improves long-term sustainability.

Overall, the results confirm that a properly designed and sized electrical system can significantly improve the performance, efficiency, and economic viability of tubular photobioreactors.

Main Contributions of the Thesis

The main contributions of this thesis can be summarized as follows: **[7], [11]**

- Definition of a specific pilot-scale tubular photobioreactor as a reference system for engineering analysis
- Development of a systematic methodology for electrical equipment sizing
- Integration of renewable energy (solar power) into the photobioreactor system
- Quantitative analysis of power consumption and energy efficiency
- Identification of key energy consumers and system losses
- Evaluation of economic feasibility and payback period

Limitations of the Study

Despite the comprehensive analysis, some limitations should be acknowledged:

- The study is based on simplified assumptions for a pilot-scale system
- Environmental factors such as temperature variations and seasonal solar changes were not fully modeled
- Biological performance (e.g., microalgae growth rate) was not deeply analyzed
- The economic analysis is based on approximate cost estimations

These limitations suggest that further detailed studies are required for full-scale implementation.

Future Work

Future research can extend this work in several directions:

Technical Improvements

- Development of advanced control systems using artificial intelligence
- Optimization of fluid dynamics in tubular photobioreactors
- Integration of hybrid renewable energy systems (e.g., wind + solar)

Biological Optimization

- Study of different microalgae species for higher productivity
- Optimization of nutrient supply and CO_2 utilization

Energy System Enhancement

- Use of more efficient batteries and energy storage technologies
- Implementation of smart energy management systems

Scale-Up Analysis

- Extension of the study to industrial-scale photobioreactors
- Evaluation of large-scale economic feasibility

Final Remarks

The increasing need for sustainable technologies and carbon reduction solutions makes photobioreactors a promising area of research and development.

This thesis demonstrated that combining photobioreactor technology with renewable energy systems can lead to efficient, sustainable, and economically viable solutions.

The methodology developed in this work provides a practical framework for future studies and real-world applications of tubular photobioreactors.

References

[1] C. U. Ugwu, H. Aoyagi, and H. Uchiyama, “Photobioreactors for mass cultivation of algae,” Bioresource Technology, vol. 99, no. 10, pp. 4021–4028, 2008. https://doi.org/10.1016/j.biortech.2007.01.046

[2] A. Richmond (Ed.), Handbook of Microalgal Culture: Applied Phycology and Biotechnology, Blackwell Science, 2004.

[3] E. Molina Grima, F. G. Acién Fernández, F. García Camacho, and Y. Chisti, “Photobioreactors: light regime, mass transfer, and scale-up,” Journal of Biotechnology, vol. 70, pp. 231–247, 1999.

[4] J. C. Ogbonna and H. Tanaka, “Photobioreactor design for photobiological production of hydrogen,” in Biohydrogen II, Pergamon, 2001.

[5] M. R. Tredici and G. Chini Zittelli, “Efficiency of sunlight utilization: tubular versus flat photobioreactors,” Biotechnology and Bioengineering, vol. 57, pp. 187–197, 1998.

[6] Y. Chisti, “Raceway ponds and tubular photobioreactors for microalgae production,” Biotechnology Advances, vol. 25, pp. 294–306, 2007.

[7] International Energy Agency, Photovoltaic Systems and Renewable Energy Reports, 2020. https://www.iea.org/reports

[8] E. Koutroulis, D. Kolokotsa, A. Potirakis, and K. Kalaitzakis, “Methodology for optimal sizing of stand-alone photovoltaic systems,” Solar Energy, vol. 80, no. 9, pp. 1072–1088, 2006.

[9] A. H. Fathima and K. Palanisamy, “Renewable hybrid energy systems: review of control and applications,” Renewable and Sustainable Energy Reviews, vol. 52, pp. 907–916, 2015.

[10] J. Villadsen, J. Nielsen, and G. Lidén, Bioreaction Engineering Principles, 3rd ed., Springer, 2011.

[11] R. Messenger and J. Ventre, Photovoltaic Systems Engineering, 3rd ed., CRC Press, 2010.

[12] National Renewable Energy Laboratory (NREL), “Solar Resource Data,” [Online]. Available: https://www.nrel.gov

[13] W. Blanken, M. Cuaresma, R. H. Wijffels, and M. Janssen, “Cultivation of microalgae on artificial light comes at a cost,” Algal Research, vol. 2, pp. 333–340, 2013.

[14] IEEE, IEEE Std 141-1993: Electric Power Distribution for Industrial Plants, 2016.

[15] Mahmood AL-MASHHADANI | Cited by 572 | of University of Baghdad, Baghdad | Read 37 publications, Entisar M.Khudhair "Cultivation of Chlorella Vulgaris Using Airlift Photobioreactor Sparged with 5%CO2-Air as a Biofixing Process"

[16] 6 Horizontal tubular photobioreactor microalgae cultivation system and biorefinery at AlgaePARC Research Facility, Wageningen University and Research Centre, Netherlands (Image source: AlgaePARC, Wageningen UR, 2013).